Green Energy and Technology

Muhammad Shahbaz
Daniel Balsalobre *Editors*

Energy and Environmental Strategies in the Era of Globalization

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Green Energy and Technology

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Contents

The Long-Term Effect of Economic Growth, Energy Innovation, Energy Use on Environmental Quality

Daniel Balsalobre-Lorente, Agustín Álvarez-Herranz and Muhammad Shahbaz

Abstract This study advances in the analysis of the relationship between economic growth and environmental degradation, and how innovation and energy use impact on per capita greenhouse gas (GHG) emissions, in 17 selected OECD countries with over the period spanning from 1990 to 2012. The empirical model is found in the empirical hypothesis of the environmental Kuznets curve (EKC) scheme. The econometric results reveal a complete significant relationship, where economic growth, renewable electricity use and innovation correct environmental pollution, while biomass consumption and fossil electricity consumption affect negatively environmental correction process. This study implements a novel methodology in the analysis of the relationship between per capita GHG emissions and selected auxiliary variables, through an interaction effect which moderates the relationship between energy variables and economic cycle over per capita greenhouse gas (GHG) emissions. Hence, this study also incorporates De Leeuw's finite lags effect in auxiliary variables, in order to validate the long-run effect of these variables over per capita GHG emissions. Consequently, the results validate the positive role that regulatory energy policies, linked with energy innovation processes and the replacement of polluting sources, have on environmental correction. The outcomes of this study demonstrate that in the long run, renewable electricity consumption and energy innovation measures delay the technical obsolescence. These results enable certain strengthened conclusions that help to explain the interaction between energy regulation, economic growth and

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per capita GHG emissions, and how are necessary the adoption of regulations which reduce energy dependency and mitigate the negative effect of dirty energy sources on per capita GHG emissions.

Keywords Economic growth · Energy innovation · EKC · Energy use

Highlights

- There is an N-shaped relationship between economic growth and per capita GHG emission for selected 17 countries, between 1990 and 2012.
- The promotion of renewable sources and energy innovation processes delays the long-term return to increasing pollution levels.
- In the early stages of the development, the implementation of energy regulation policies involves a higher income threshold, because the implementation of these measures entails a cost that societies have to assume.
- Energy use is moderated by the economic cycle. This interaction affects the overall impact on the correction of per capita GHG emissions.

1 Introduction

The International Energy Outlook [1] predicts that global energy-induced CO_2 emissions would increase around 35.6 billion metric ton in 2010 which will add up to 7.6% in 2040, to 43.2 billion metric ton. These predictions also contend that ascending emissions are highly sensitive in the developed nations that continue to rely on fossil fuel to gear the pace of economic growth to employ energy demand. This awareness for environmental problems is relatively recent in the economic literature. Meadows' report [2] recognized the existence of an economic problem between economic growth and public concern for environmental problems. Otherwise, it will not be till early 1990 when the empirical hypothesis of Environmental Kuznets Curve (EKC) provides an extended methodology to analyse the association between economic growth and environmental degradation [3, 4, 5, 6]. By the way, an extension of the EKC empirical evidence admits as an extension of the primary model the effect that additional explanatory variables as innovation or energy use exert the correction of environmental degradation process [6–16].

During the last years, the energy mix has been altered by the ascending promotion of renewable energy sources and the application of energy innovation policies to conducive to a more sustainable and less dependence economic system [17]. Otherwise, the energy security problems, defined as energy supply failures and energy price shocks, have several outcomes over economic development and growth. While security problem breaks down trade balances and leads to inflationary pressures in countries, affecting negatively the final output and competitiveness of countries [18, 19], this situation also increases the dependency of energy-importing in these countries [20]. This lengthy awareness reflects the need to increase environmental sustainability through the use of low-carbon and more efficient technologies.

Our study identifies how energy innovation (public budget in energy research development and demonstration—RD&D) and the use of selected energy sources (renewable electricity consumption, fossil electricity consumption and biomass energy consumption) affect the correction of per capita GHG emissions. These variables help to explore the effect that innovation and adjustments in the energy mix exert per capita GHG emissions, where the evolution from dirty economic structures to developed and cleaner economic systems upsets environmental correction process [20–23].

The novelty of this study is the incorporation of finite delays in auxiliary variables to test the long term that these variables exert environmental pollution. The presented model also explores the effect that economic cycle has over-selected energy variables and how it affects per capita GHG emissions.

The remainder of the paper is organized as follows: Sect. 2 presents some literature review of theoretical considerations proposed in previous studies. In Sect. 3, we present the empirical model, the data description and methodology used to validate our hypotheses. Section 4 shows the econometric results and discussion. Finally in Sect. 5, we discuss results and new energy strategy guides.

2 Literature Review

Many studies have explored the nexus between energy–environment and income–environment, which traditionally explored through two main lines of research (Soytas and Sari 2009). The first line focuses on the relationship between economic growth and energy consumption [24], while the second one focuses on the relationship between environmental degradation and economic growth, through the EKC model [3, 5]. Our study also incorporates an interaction between energy use and income level, trying to advance in an amplified model that covers both lines of study.

The primary empirical EKC hypothesis proposed the existence of a U-inverted (Fig. 1) relationship between economic growth and environmental pollution [3–5, 25] (Stern et al. 1996; Dasgupta et al. 2002; Stern 2004).

Figure 1 shows a U-inverted relationship between income and environmental degradation. In the early stages of economic growth, environmental pollution levels rise until reaching a certain turning point, beyond which economies experience a reduction in pollution levels. This behaviour also implies that economic growth will affect environmental quality through three channels: scale, composition and technical effects [3]. The *scale effect* discloses that the increase of energy requirements of the production function leads to greater use of fossil sources and, consequently, increased pollution [26, 27]. The *composition effect* reveals the transition from capital-intensive industrial sectors to service sectors under technology-intensive knowledge economies, which employ cleaner energy procedures. Finally, the *technical effect* reflects that high-income economies allocate more resources to energy

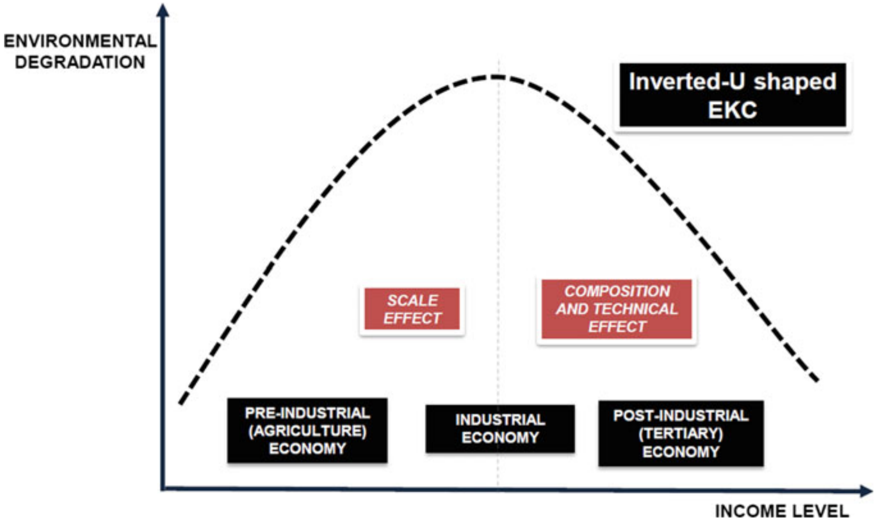


Fig. 1 U-inverted EKC: scale, technical and composition effects. *Source* Self extract and Halkos [126]

innovation processes. Under this statement, high-income societies replace old, dirty and inefficient technologies with new, more efficient ones, thereby enhancing environmental quality [14, 15, 28, 29]. In other words, when the net effect of the relationship between economic growth and environmental pollution is broken down, the technical effect is considered to be the main factor in the correction of the environmental pollution process (Deacon and Norman 2006) [9, 14, 30].

Torras and Boyce [27] contemplate that when economies begin to push their technological limits, they experiment a return to a rising pollution path due to a scale effect that overshadows the joint impact of the composition and technical effects. So, in order to verify this subject, our study accepts that once an economy achieves a certain high level of income, societies will demand regulatory measures and efforts, in order to protect environmental quality [31]. According to this premise, recent studies have proposed the existence of an additional effect, the technical obsolescence effect [15], which seems when economies reach a determinate second turning point and economies experiment again ascending emissions. In this regard, *technical obsolescence* will lead to the re-emergence of increasing pollution levels once the scale effect exceeds once more the composition and technical effects. While Fig. 1 does not reflect such behaviour, the N-shaped (Fig. 2) pattern presents the return to rising pollution levels occurs once economies have achieved long-term high-income levels.

Figure 2 shows an enlarged behaviour that amplifies the income–environmental pollution relationship in the long term [5, 6, 27, 31–34]. The N-shaped behaviour suggests that environmental degradation, in a developing stage of economic growth, increases with ascending income levels, then decreases after a given income thresh-

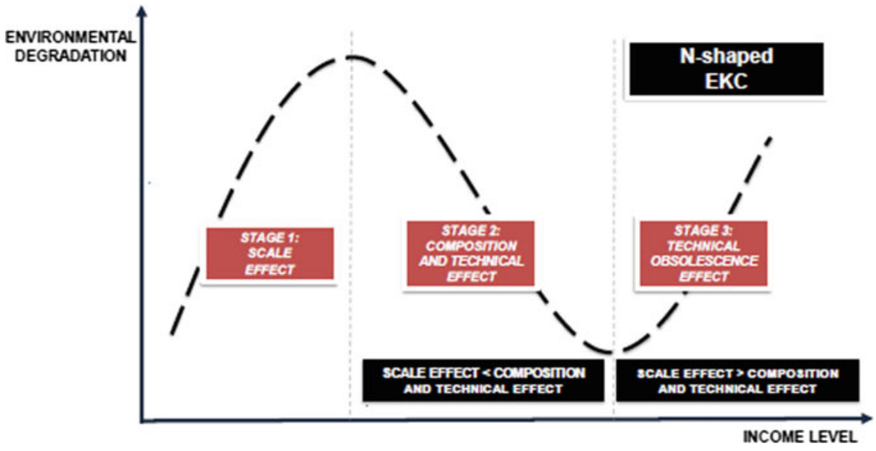


Fig. 2 N-shaped EKC and the technical obsolescence effect. *Source* Balsalobre and Álvarez [15]

old is reached and finally, marked by high-income levels but low economic growth rates, begins to increase again. The N-shaped EKC path makes possible to analyse the potential return to rising emissions once economies have achieved negative pollution rates, and environmental technical obsolescence appears [15]. To verify an N-shaped EKC pattern for selected 17 OECD countries,[1] this study attempts to demonstrate how, in the absence of energy regulation policies, linked with promotion of renewable sources and energy innovation procedures, economies will reach technical obsolescence sooner [14, 35]. This study tries to validate that technological progress helps to improve environmental quality and, by extension, that the technical effect is the main driver to delay the return to an ascending stage of environmental degradation process [36, 37]. Additionally, this study contains the effect that selected energy sources exert per capita GHG emissions [24, 33, 38]. We include as selected energy sources renewable electricity consumption, fossil electricity consumption and biomass energy consumption where renewable energy sources play a prominent role in reducing carbon dioxide emission [39].

Many studies consider that energy consumption contributes to economic growth, by different ways, in the context of four hypotheses that support the interdependence between energy use and economic growth [24, 40, 41, 42, 39–52]. (1) The *growth hypothesis* considers that energy consumption is an important complement in the process of economic growth, based on the unidirectional causality running from energy consumption to economic growth. Thus, the decrease in energy consumption has a negative impact on economic growth [41, 42, 53, 54, 55]. (2) The *conservation hypothesis* supports the existence of unidirectional causality running from economic growth to energy consumption. In this case, reducing energy consumption will not affect economic growth adversely [55–60]. (3) The *feedback hypothesis* reflects a

[1] Austria, Canada, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK, USA.

bidirectional causality between energy consumption and economic growth. This relationship shows that reducing energy consumption has a negative impact on economic growth and vice versa [52, 56, 60–66]. (4) The *neutrality hypothesis* provides for causality between economic consumption and economic growth, whereby reducing energy consumption does not adversely affect economic growth [67, 68]. Our study proposed an additional explanation based on the connection between energy use, economic growth and environmental degradation, through the interaction between energy use income and environmental degradation [15, 17]. To validate the existence of a link between economic cycle, energy use and environmental degradation, we propose an interaction which moderates the relationship between energy use and per capita GHG emissions, through a finite delay in explanatory variables which assemble the long-term impact of these variables on per capita GHG emissions. To build these variables, we employ a time lag model based on the finite lag model proposed by De Leeuw [69].

The study evaluates the following hypothesis in order to assess the relationship between economic growth and per capita GHG emissions in the panel of selected OECD countries.

H1: There is an N-shaped relationship between economic growth and per capita GHG emissions for selected countries, between 1990 and 2012.
H2: The promotion of renewable sources and energy innovation processes delays the long-term return to increasing pollution levels.
H3: In the early stages of development, the implementation of energy regulation policies involves a higher income threshold, because the implementation of these measures entails a cost that societies have to assume.
H4: Energy use is moderated by the economic cycle. This interaction affects the overall impact on the correction of per capita GHG emissions.

3 Empirical Model

Grossman and Krueger [33] proposed an N-shaped connection between environmental degradation and economic growth, expressed as follows:

$$\mathrm{ED}_{it} = \alpha_i + \beta_1 \mathrm{GDPpc}_{it} + \beta_2 \mathrm{GDPpc}_{it}^2 + \beta_3 \mathrm{GDPpc}_{it}^3 + \beta_4 Z_{it} + \varepsilon_{it} \quad (1)$$

ED_{it} is an environmental degradation of country i in the year t, GDPpc is income level per capita, and Z_{it} determines additional variables that impact environmental pollution. The coefficient α_i accumulates environmental pressure when the average income level is of no particular relevance in country i in the year t. The β coefficients represent the relative importance of exogenous variables, and ε_{it} is the error term, which is normally distributed with zero mean and constant variance.

This study fills the gap in the EKC analysis through the validation of a long-term effect of innovation and the *interaction* between income and selected energy sources on the correction of GHG emission levels. To validate this long term, we employ relationship and propose a finite *lag* distribution [69]. These additional variables enable analysis of the role of energy regulation and energy use in the evolution of per capita GHG emission levels. To validate this hypothesis, we built Eq. (2):

$$\begin{aligned}\text{GHGpc}_{it} = {} & \alpha_i + \beta_1\text{GDPpc}_{it} + \beta_2\text{GDPpc}_{it}^2 + \beta_3\text{GDPpc}_{it}^3 + \sum_{j=0}^{4}\delta_j\text{RDDTpc}_{it-j} \\ & + \sum_{j=0}^{4}\mu_j\text{RNWpc}_{it-j} + \sum_{j=0}^{4}\gamma_j\left[\text{RNWpc}_{it-j} * \text{GDPpc}_{it-j}\right] \\ & + \sum_{j=0}^{4}\theta_j\text{FSSpc}_{it-j} + \sum_{j=0}^{4}\rho_j\left[\text{FSSpc}_{it-j} * \text{GDPpc}_{it-j}\right] \\ & + \sum_{j=0}^{4}\varphi_j\text{BMSpc}_{it-j} + \sum_{j=0}^{4}\omega_j\left[\text{BMSpc}_{it-j} * \text{GDPpc}_{it-j}\right] + \varepsilon_{it} \qquad (2)\end{aligned}$$

where

$$\delta_j = \begin{cases} (j+1)\delta & 0 \le j \le s/2 \\ (s-j+1)\delta & s/2+1 \le j \le s \end{cases};$$

$$\mu_j = \begin{cases} (j+1)\mu & 0 \le j \le s/2 \\ (s-j+1)\mu & s/2+1 \le j \le s \end{cases};$$

$$\gamma_j = \begin{cases} (j+1)\gamma & 0 \le j \le s/2 \\ (s-j+1)\gamma & s/2+1 \le j \le s \end{cases};$$

$$\theta_j = \begin{cases} (j+1)\theta & 0 \le j \le s/2 \\ (s-j+1)\theta & s/2+1 \le j \le s \end{cases};$$

$$\rho_j = \begin{cases} (j+1)\rho & 0 \le j \le s/2 \\ (s-j+1)\rho & s/2+1 \le j \le s \end{cases};$$

$$\varphi_j = \begin{cases} (j+1)\varphi & 0 \le j \le s/2 \\ (s-j+1)\varphi & s/2+1 \le j \le s \end{cases};$$

$$\omega_j = \begin{cases} (j+1)\omega & 0 \le j \le s/2 \\ (s-j+1)\omega & s/2+1 \le j \le s \end{cases}$$

The estimation of a distributed lag model of Eq. (2) faces two challenges: first, each additional delay lag reduces the freedom degrees of the model and, thus, the accuracy of the estimates; secondly, since the reference variable appears as an explanatory variable at different times, the model can exhibit multicollinearity. To eradicate the problems of multicollinearity, in this lag distribution model, it is necessary to transform Eq. (2) into Eq. (3).

$$\begin{aligned} GHGpc_{it} = \alpha_i + \beta_1 GDPpc_{it} + \beta_2 GDPpc_{it}^2 + \beta_3 GDPpc_{it}^3 + \delta ZRDD_{it} + \mu ZRNWpc_{it} \\ + \gamma ZRNWGDPpc_{it} + \theta ZFSSpc_{it} + \rho ZFSSGDPpc_{it} \\ + \varphi ZBMSpc_{it} + \omega ZBMSGDPpc_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

Equation (3) has a structure of finite delays of the fourth order, forming a finite inverted V-shaped lag [69]. These variables contain the *multiplier effect* of the explanatory variables (RDD_{it-j}, RNW_{it-j}, FSS_{it-j} and $BMSpc_{it-j}$) on the endogenous variable $GHGpc_{it}$, which increases until reaching its maximum intensity at the $j = 2$ value, after which its intensity begins to decline [69], where:

$$ZRDD_{it} = \left[\sum_{j=0}^{s/2}(j+1) + \sum_{j=(s/2)+1}^{s=4}(s-j+1)\right] RDD_{it-j} \tag{4}$$

$$ZRNWpc_{it} = \left[\sum_{j=0}^{s/2}(j+1) + \sum_{j=(s/2)+1}^{s=4}(s-j+1)\right] RNWpc_{it-j} \tag{5}$$

$$\begin{aligned} ZRNWGDPpc_{it} = \left[\sum_{j=0}^{s/2}(j+1) + \sum_{j=(s/2)+1}^{s=4}(s-j+1)\right] \\ * \left(RNWpc_{it-j} * GDPpc_{it-j}\right) \end{aligned} \tag{6}$$

$$ZFSS_{it} = \left[\sum_{j=0}^{s/2}(j+1) + \sum_{j=(s/2)+1}^{s=4}(s-j+1)\right] FSSpc_{it-j} \tag{7}$$

$$\begin{aligned} ZFSSGDPpc_{it} = \left[\sum_{j=0}^{s/2}(j+1) + \sum_{j=(s/2)+1}^{s=4}(s-j+1)\right] \\ * \left(FSSpc_{it-j} * GDPpc_{it-j}\right) \end{aligned} \tag{8}$$

$$ZBMS_{it} = \left[\sum_{j=0}^{s/2}(j+1) + \sum_{j=(s/2)+1}^{s=4}(s-j+1)\right] BMSpc_{it-j} \tag{9}$$

$$\begin{aligned} ZBMSGDPpc_{it} = \left[\sum_{j=0}^{s/2}(j+1) + \sum_{j=(s/2)+1}^{s=4}(s-j+1)\right] \\ * \left(BMSpc_{it-j} * GDPpc_{it-j}\right) \end{aligned} \tag{10}$$

The main equation specification for this study takes the form of Eq. (3), where $GHGpc_{it}$ as proxy of environmental degradation is per capita GHG emissions (million ton of CO_2 equivalent) for country *i* in the year *t* (OECD 2017); $GDPpc_{it}$ represents the income level in per capita terms, in millions of dollars in purchasing power parity (U$D, 2011, current PPPs) for country *i* and year *t*. Following N-shaped

EKC(pollution increases with income, up to a threshold point, then starts decreasing and finally increases again), $\hat{\beta}_1$ is expected positive, $\hat{\beta}_2$ is expected negative and $\hat{\beta}_3$ is expected positive again, for the analysed countries over the period (OECD 2017). $ZRDD_{it}$, proxy of energy innovation, is the public budget in energy research development and demonstration (U$D, 2011, current prices, PPPs) in country i over the period $t - j$, (where $j = 0, 1, 2, 3, 4$ corresponds to time lag). $ZRNWpc_{it}$ is per capita renewable electricity consumption, as a proxy of renewable energy use, for country i in the year $t - j$ according to De Leeuw's finite delays (IEA 2017). $ZFSSpc_{it}$ is the per capita fossil electricity consumption, as a proxy of fossil energy use for country i in the year $t - j$ according to De Leeuw's finite delays. Finally, $ZBMSpc_{it}$ is the per capita biomass energy consumption, as a proxy of biomass use, for country i in the year $t - j$ according to De Leeuw's finite delays (www.materialflows.net2017). These explanatory variables reflect the delay in the periods $t-j$, which is incorporated in Eq. (3). Therefore, $ZRDD_{it}$, $ZRNWpc_{it}$, $ZFSS_{it}$ and $ZBMSpc_{it}$ contain a fourth-order finite delay structure, forming a finite V or inverted V-shaped delay [69] tj ($j = 0$, 1, 2, 3 and 4 periods). Despite the extensive literature investigating the EKC hypothesis, there is a lack of research incorporating delays in auxiliary variables [70, 15] (Aghion 2014; Dechezleprêtre et al. 2013) found that spillovers from low-carbon innovation are over 40% greater than conventional technologies (in the energy production and transportation sectors). Popp [71, 72] finds evidence that the likelihood of citations to new energy patents falls over time, suggesting that the quality of knowledge available for inventors to build upon also falls. This evidence suggests a behaviour where it is necessary to include a finite lag distribution to test it. Balsalobre and Álvarez [15] demonstrate the existence of V-inverted finite lag distribution in energy innovation processes in selected OECD countries between 1990 and 2012. Finally, the explanatory variables related to the energy use of $ZRNWGDPpc_{it}$ $ZFSSGDPpc_{it}$ and $ZBMSGDPpc_{it}$ incorporate an interaction between energy use and income in $t - j$ periods. These variables reveal the magnitude and/or direction of the relationship between the explanatory variables ($RNWpc_{it-j}$, $FSSpc_{it-j}$ and $BMSpc_{it-j}$) and the response variable ($GHGpc_{it}$), amplifying or even reversing the causal effect.

Table 1 shows the descriptive statistics of the variables. These statistics are shown as a rough sketch of the candidate variables in the panel of selected countries.

The study further employs two-stage panel least-square (TSPLS) estimation that avoids spurious regression by using appropriate instruments. Previously, this study checks different panel unit root tests to validate the stationarity series of the candidate variables. Brown and McDonough [74] suggest that the EKC is a long-run phenomenon, so it is necessary to test the unit root properties of variables such as economic growth and carbon emissions, and co-integration association between the variables in order to estimate the polynomial carbon emission function. The application of panel co-integration analysis is justified by many factors such as the dimension and characteristic of the data. With small T and large N usually found in microeconomic data sets such as surveys, the traditional panel methods (random effect, fixed effect, etc.) remain suitable. However, the analysis of panel data with $T > N$ generates spurious results, since the feature of the data behaviour tends to be close to time

Table 1 Summary statistics

	GHGpc	GDPpc	$GDPpc^2$	$GDPpc^3$			
Mean	0.012342	31,711.06	1.09E+09	4.05E+13			
Median	0.011143	30,518.63	9.31E+08	2.84E+13			
Maximum	0.025288	66,357.73	4.40E+09	2.92E+14			
Minimum	0.006051	12,901.31	1.66E+08	2.15E+12			
Std., dev.	0.004843	9188.215	6.58E+08	3.94E+13			
Skewness	1.179892	0.752810	1.687161	2.752694			
Kurtosis	3.549441	3.810430	7.119733	13.48720			
Jarque–Bera	79.00668	39.34795	381.6548	1888.078			
Prob.	0.000000	0.000000	0.000000	0.000000			
Sum	3.986568	10242672	3.52E+11	1.31E+16			
SumSqD.	0.007552	2.72E+10	1.40E+20	5.00E+29			
Observ.	323	323	323	323			
	ZRNWpc	ZRNWGDPpc	ZRDDW	ZFSSpc	ZFSSGDPpc	ZBMSpc	ZUBMSGDPpc
Mean	0.040475	1329.161	111.6747	0.032833	982.3263	0.051699	1447.991
Median	0.011773	389.9347	98.87453	0.035657	851.7292	0.034793	1059.677
Maximum	0.257753	14547.05	687.7149	0.092459	4330.295	0.255522	6602.913
Minimum	0.000601	12.26330	2.852430	0.000235	4.887306	0.005014	136.9827
Std., dev.	0.057877	2346.130	89.00779	0.022199	840.1209	0.051201	1221.370

(continued)

Table 1 (continued)

	GHGpc	GDPpc	$GDPpc^2$	$GDPpc^3$			
Skewness	2.450479	3.611346	1.868069	0.528142	1.548092	2.771539	2.037644
Kurtosis	8.771881	17.55766	10.24433	3.182963	6.401170	10.59228	7.742875
Jarque–Bera	771.6201	3554.248	894.1581	15.46650	284.7018	1189.292	526.2589
Prob.	0.000000	0.000000	0.000000	0.000438	0.000000	0.000000	0.000000
Sum	13.07341	429,318.9	36,070.91	10.60506	317,291.4	16.69862	467,700.9
SumSqD.	1.078626	1.77E+09	2,551,009.0	0.158685	2.27E+08	0.844138	4.80E+08
Observ.	323	323	323	323	323	323	323

Sources OECD [127]; materialflows.net (2016), IEA [73]) series. The spuriousness increases when analysing macroeconomic variables (which is the case for this study), as series in macro-data are usually non-stationary [75]. To handle the problem generated by the accumulation of observations over time, Baltagi [76] suggests two possible options: firstly, heterogeneous regressions for each individual to avoid the homogeneity of coefficients that would be obtained with a single regression, and secondly the application of time series processes to panels to deal with non-stationary and co-integrations among series. The panel co-integration is an extension of time series analysis to panel data with large T. In addition to its capacity to pool long-run information included in panels, by allowing the short-run dynamics and fixed effect to be heterogeneous across the panel [77], the panel co-integration approach provides short- and long-run estimates. The process can be summarized as follows: the preliminary investigation is a unit root test. If a series were found to be integrated, one would check the possible co-integration among variables by running a co-integration test. Finally, if variables are co-integrated, in other words if there is a long-run relationship among variables, one would estimate the long-run coefficients. In doing so, we have applied LLC, Breitung, IPS, ADF and PP panel unit tests and results are shown in Table 2.

Table 2 contains different techniques applied to estimate the order of integration of series in panel data. Levin et al. [78] suggest a panel unit root test (LLC) as an extension of the augmented Dickey–Fuller (ADF):

$$\Delta y_{it} = \varphi_{it\beta_{it-1}} + \rho y_{it-1} + \sum_{j=1}^{ni} \phi - \varphi_{ij} \Delta y_{i,t-j} + \xi_{it} \tag{11}$$

where φ contains individual deterministic components (such as fixed effect, trend or a mixture of fixed effects and trend); ρ is the autoregressive coefficient; ξ is the error term; and n is the lag order. However, the *LLC test* assumes ρ constant across panels, which may suffer from loss of power [79]. Im et al. [80] extend the LLC test by allowing ρ to vary across panels (IPS test):

$$\Delta y_{it} = \varphi_{it\beta_{it-1}} + \rho_i y_{it-1} + \sum_{j=1}^{ni} \phi - \varphi_{ij} \Delta y_{i,t-j} + \xi_{it} \tag{12}$$

Breitung [79] proposes a test that corrects bias generated in the application of LLC or IPS. The bias generally comes from the difference in size between N and T (LLC and IPS appear stronger when T is larger than N), or from the inclusion of an individual deterministic trend in the tests. Besides, the Fisher tests (ADF and Phillips–Perron) suggested by Choi [81] use the time series, ADF and PP tests, as a framework and application to panel data. The most distinctive feature is that the tests combine each series, p-value, resulting from their unit root tests, instead of averaging individual test statistics as suggested by IPS (2003). LLC, Breitung, IPS and Fisher test the null hypothesis that each series is non-stationary across individuals (H_0: $\rho i = 0$) against the alternative that at least one individual in the series is stationary (H_1:

Table 2 Panel unit root test

	(A)	(B)		
	LLC test	IPS test	ADF–Fisher chi-square	PP–Fisher chi-square
GHGpc	1.210	1.852	30.220	20.710
GPDpc	1.570	6.921	7.487	2.096
GDPpc^2	5.168	9.632	10.634	0.730
GDPpc^3	7.294	10.876	16.188	0.465
ZRDD	2.566		11.669	29.134
ZRNWpc	4.726	3.69705	51.934***	12.657
ZRNWGDPpc	6.532	6.06315	30.089	8.275
ZFSS	2.3118		21.398	11.240
ZFSSGDPpc	5.480		13.858	1.6982
ZBMSpc	−0.929	0.90329	36.096	25.891
ZBMSGDPpc	2.02433	6.44828	17.210	11.023
ΔGHGpc	−11.706*	−12.225*	202.903*	249.415*
ΔGPDPC	−9.452*	−9.885*	157.435*	168.653*
ΔGDPpc^2	−8.762*	−8.29099*	133.895*	147.896*
ΔGDPpc^3	−8.698*	−7.5967*	123.510*	135.060*
ΔZRDD	−4.825*		73.538*	81.877*
ΔZRNWpc	1.391	−2.734*	81.443*	30.594
ΔZRNWGDPpc	−3.922*	−7.55198*	124.106*	14.163
ΔZFSSpc	−8.074*		107.097*	73.435*
ΔZFSSGDPpc	−2.208*		61.586*	48.698**
ΔZBMSpc	−3.712*		101.792*	57.542*
ΔZBMSGDPpc	−4.714*	−5.702*	111.461*	34.649

Automatic selection of maximum lags. Newey–West automatic bandwidth selection and Bartlett kernel probabilities for Fisher tests are computed using an asymptotic chi-square distribution. All other tests assume asymptotic normality. *Notes* (A): null: unit root (assumes common unit root process); (B): null: unit root (assumes individual unit root process); (1) estimated by Breitung *t*-stat. *t*-statistic and *p*-value are given in [ ] and ( ), respectively; *, **, *** show significance at 1%, 5% and 10%, respectively. ** Probabilities for Fisher tests are computed using an asymptotic chi-square distribution. All other tests assume asymptotic normality

$\rho i < 0$), and the Hadri test assumes the opposite (null hypothesis: no unit root against the alternative that some or all series are non-stationary). In addition, the LLC and Breitung tests are based on homogeneity in the unit root process ($\rho i = \rho$ across panels), while the IPS and Fisher tests assume the autoregressive coefficient to be heterogeneous.

The panel unit root tests specified in this study include individual effects and the deterministic time trend.

The LLC and Breitung tests do not reject the null hypothesis of non-stationarity of variables included in our main model, although IPS and the Fisher-type two tests (ADF and PP) reject the null hypothesis. In addition, Phillips–Perron (PP–Fisher-type) test does not reject the null hypothesis of non-stationarity of the variable per capita GHGpc.

The presence of three co-integrating vectors validates the co-integration relationship between the selected variables. The presence of stationary process at first difference and co-integration between the variables motivates us further to investigate the association between economic growth and carbon emissions along with other determinants of per capita GHG emissions for selected OECD countries to confirm either N-shaped EKC exists between economic growth and carbon emissions or not. After finding co-integration between the variables, we analyse the econometric results obtained from Eq. (3) in order to check whether the incorporation of auxiliary variables in the relationship between economic growth and environmental degradation influences the results obtained.

Having explained the theoretical model, we will now estimate and analyse the econometric results obtained from Eq. (3) in order to verify the effect that, together with economic growth, the explanatory variables ($ZRDD_{it}$, $ZRNWpc_{it}$, $ZFSSpc_{it}$, $ZBMSpc_{it}$, $ZRNWGDPpc_{it}$, $ZFSSGPDpc_{it}$ and $ZBMSGDP_{it}$) have on the correction of per capita GHG emissions. Equation (3) is estimated as a fixed-effect panel data model, which is appropriate if there is unobserved heterogeneity in specific countries. To estimate the econometric model proposed in Eq. (3), we used the panel least squares (PLS) method. This method is suitable when the source of the dependent variable has individual heterogeneity, unobservable, and biases caused by faulty specification. On the other hand, the EKC model is often criticized for the large sensitivities frequently registered among EKC studies, which report very differently shaped EKCs depending on the selected time period or country samples [3, 5] or the existence of omitted variable. In order to mitigate the problems of endogeneity, it is necessary to incorporate an instrumental variable approach in the regressions both with and without fixed effects to identify the coefficient of GDPpc. The incorporated instruments were as follows: $AGED_{it}$ is the age dependency ratio (% of working-age population) in country i and year t [82]. The higher the age dependency ratio is, the lower the rates of growth and GDPpc, both because countries with large populations of young people are likely to be less productive on average and because poorer countries tend to have this demographic profile (Lomborg and Pope 2003) [82]. $URBP_{it}$ is the per cent of urban population in the total population of country i. $URBP_{it}$ represents the share of people living in urban areas. The data were collected and smoothed by the United Nations Population Division (UNPD [83]. Bruno and Easterly [84], Anwar and Sun [85] and Álvarez et al. [13] empirically tested the impact of urban population on economic growth and showed how this variable has a statistically significant influence on economic growth.

Therefore, $AGED_{it}$ and $URBP_{it}$ are plausible and appropriate instruments for $GDPpc_{it}$ [15, 86]. These instruments are correlated with $GDPpc_{it}$, whereas they did not affect the quality of $GHGpc_{it}$, except through their effect on $GDPpc_{it}$. The instrumental variables must be sensibly reliable and correlated instruments for $GDPpc_{it}$, but they only affect $GHGpc_{it}$ through their effect on $GDPpc_{it}$. For this study, the exogenous variables $URBP_{it}$ and $AGEDP_{it}$ were considered instruments for the variables $GDPpc_{i}$, $GDPpc^2_{it}$ and $GDPpc^3_{it}$, making it necessary to verify whether these instruments are individually and jointly significant in Eqs. (13), (14) and (15) up to a reasonably small significance level (not more than 5%), as can be seen in the *t*-statistic and Wald test (Tables 3 and 4).

$$\begin{aligned} \mathrm{GDPpc}_{it} = {} & \pi_0 + \pi_1\mathrm{ZRDD}_{it} + \pi_2\mathrm{ZRNWpc}_{it} + \pi_3\mathrm{ZRNWpc} * \mathrm{GDPpc}_{it} \\ & + \pi_4\mathrm{ZFSSpc}_{it} + \pi_5\mathrm{ZFSS} * \mathrm{GDPpc}_{it} + \pi_6\mathrm{ZBMSpc}_{it} \\ & + \pi_7\mathrm{ZRNWpc} * \mathrm{GDPpc}_{it} + \pi_8\mathrm{URBP}_{it} + \pi_9\mathrm{AGED}_{it} \\ & + \pi_{10}\mathrm{URBP}^2_{it} + \pi_{11}\mathrm{AGED}^2_{it} + \pi_{12}\mathrm{URBP}^3_{it} + \pi_{13}\mathrm{AGED}^3_{it} + \widehat{V}_{1it} \end{aligned} \tag{13}$$

$$\begin{aligned} \mathrm{GDPpc}^2_{it} = {} & \pi_0 + \pi_1\mathrm{ZRDD}_{it} + \pi_2\mathrm{ZRNWpc}_{it} + \pi_3\mathrm{ZRNWpc} * \mathrm{GDPpc}_{it} \\ & + \pi_4\mathrm{ZFSSpc}_{it} + \pi_5\mathrm{ZFSS} * \mathrm{GDPpc}_{it} + \pi_6\mathrm{ZBMSpc}_{it} \\ & + \pi_7\mathrm{ZRNWpc} * \mathrm{GDPpc}_{it} + \pi_8\mathrm{URBP}_{it} + \pi_9\mathrm{AGED}_{it} \\ & + \pi_{10}\mathrm{URBP}^2_{it} + \pi_{11}\mathrm{AGED}^2_{it} + \pi_{12}\mathrm{URBP}^3_{it} + \pi_{13}\mathrm{AGED}^3_{it} + \widehat{V}_{2it} \end{aligned} \tag{14}$$

$$\begin{aligned} \mathrm{GDPpc}^3_{it} = {} & \pi_0 + \pi_1\mathrm{ZRDD}_{it} + \pi_2\mathrm{ZRNWpc}_{it} + \pi_3\mathrm{ZRNWpc} * \mathrm{GDPpc}_{it} \\ & + \pi_4\mathrm{ZFSSpc}_{it} + \pi_5\mathrm{ZFSS} * \mathrm{GDPpc}_{it} + \pi_6\mathrm{ZBMSpc}_{it} \\ & + \pi_7\mathrm{ZRNWpc} * \mathrm{GDPpc}_{it} + \pi_8\mathrm{URBP}_{it} + \pi_9\mathrm{AGED}_{it} \\ & + \pi_{10}\mathrm{URBP}^2_{it} + \pi_{11}\mathrm{AGED}^2_{it} + \pi_{12}\mathrm{URBP}^3_{it} + \pi_{13}\mathrm{AGED}^3_{it} + \widehat{V}_{3it} \end{aligned} \tag{15}$$

To capture the unobservable effects specific to each country that do not vary over time, a fixed-effect regression method was used, implementing $GDPpc_{it}$, $GDPpc^2_{it}$ and $GDPpc^3_{it}$ with regard to $AGED_{it}$ dependence and the level of $URBP_{it}$, including both the square and the cubic expressions of these instruments. The estimation results provided in Table 3 show that there was no correlation between the instrumental variables for Eqs. (13), (14 and (15) and the error term in Eq. (3).

It is now necessary to check that the $URBP_{it}$ and $AGED_{it}$ variables are instruments of the $GDPpc_{i}$, $GDPpc2_{it}$ and $GDPpc3_{it}$ variables (Table 3).

Table 3 reflects the first stage of the econometric estimation results, where Eq. (3) is estimated by panel least squares (PLS) to find the reduced form of the endogenous explanatory variable based on the exogenous variables and possible instrumental variables. The estimation results of Eq. (3) reveal the existence of specific individual effects in each country affecting its decisions. If the model does not consider these latent effects, there will be a problem of omitted variables and the explanatory variable estimators will be biased. Therefore, the next step of the study is to check for the existence of endogeneity. The existence of any endogenous explanatory variable in Model 1 implies that the PLS method was inconsistent, making it necessary to apply the instrumental variable method (two-stage least squares—TSLS), which is unbiased and consistent. In order to mitigate the endogeneity, it was necessary to

Table 3 Estimation of GDPpc regressions in Eqs. (13), (14) and (15) by panel least squares (PLS)

Dependent variable: GDPpc, $GDPpc^2$, $GDPpc^3$
Method: Panel EGLS (cross-sectional weights)
Sample (adjusted): 1994–2012
Cross sections included: 17
Linear estimation after one-step weighting matrix

Variable	Dependent variable: GDPpc	Dependent variable: $GDPpc^2$	Dependent variable: $GDPpc^3$
C	649,212.3*	4.88E+10*	2.30E+15**
	[2.521]	[2.698]	[2.137]
ZDRDD	−11.55031*	−338,795.4	1.08E+10
	[−3.485]	[−1.356]	[0.723]
ZRNWpc	−14421.92	−2.50E+09	−4.52E+14**
	[−0.285]	[−0.667]	[−2.129]
ZRNWGDPpc	3.356898*	332,322.4*	2.46E+10*
	[12.650]	[14.551]	[15.009]
ZFSSpc	−238,587.7*	−2.14E+10*	−1.39E+15*
	[−5.687]	[−7.675]	[−9.253]
ZFSSGDPpc	8.701806*	749,524.3*	4.79E+10*
	[11.545]	[15.775]	[19.383]
ZBMSpc	192,677.4*	1.06E+10*	4.57E+14*
	[5.415]	[4.370]	[3.621]
ZBMSGDPpc	8.912841*	347,470.6*	5.77E+09**
	[14.581	[7.929]	[2.385]
AGED	−24,589.05	−1.68E+09	−6.83E+13
	[−1.6310]	[−1.569]	[−1.054]
URBP	−14,975.46*	−1.10E+09*	−5.56E+13*
	[−4.224]	[−4.399]	[−3.918]
$AGED^2$	514.2946***	33,993,167	1.35E+12
	[1.742]	[1.620]	[1.060]
$URBP^2$	245.5688*	16,963,671*	8.32E+11*
	[4.666]	[4.549]	[3.926123]
$AGED^3$	−3.469196***	−224,423.9	−8.75E+09
	[−1.805]	[−1.642]	[−1.054]
$URBP^3$	−1.242237*	−82,417.21*	−3.96E+09*
	[−4.944]	[−4.624]	[−3.906]

(continued)

Table 3 (continued)

Effect specification: Cross-sectional fixed (dummy variables): weighted statistics			
R-squared	0.9579	0.95114	0.94286
Adjusted R-squared	0.9538	0.9463	0.93720
F-statistic	230.3559	196.6855	166.7278
Prob(F-statistic)	0.0000	0.0000	0.0000

Notes t-statistic and p-value are given in [ ] and ( ), respectively;
*, **, *** show significance at 1, 5 and 10%, respectively

Table 4 Wald test: Eqs. (13), (14) and (15)

	Equation (13): GDPpc	Equation (14): GDPpc^2	Equation (15): GDPpc^3
Test statistic	Value df Prob.	Value df Prob.	Value df Prob.
F-statistic	37.9053	15.7991*	5.7791*
	(6.293)*	(6.293)*	(6.293)*
Chi-square	227.4324*	94.7948*	34.6749*
	6	6	6

Notes Null hypothesis: $C(9) = C(10) = C(11) = C(12) = C(13) = C(14) = 0$; Wald test validates the instrumental variables
*, **, *** show significance at 1, 5 and 10%, respectively

restructure the model (Eq. 3), using instrumental variables without fixed effects to determine the income coefficient. We used the Wald test to check for the endogeneity of the GDPpc_{it}, GDPpc^2_{it} and GDPpc^3_{it} variables.

The explanatory variables GDPpc_{it}, GDPpc^2_{it} and GDPpc^3_{it} will not be correlated with the error term (ε_{it}), if and only if the error terms $\widehat{\text{V}}_{1it}$, $\widehat{\text{V}}_{2it}$ and $\widehat{\text{V}}_{3it}$ are uncorrelated with ε_{it}. To verify this lack of correlation, we included these error terms in the second step and estimated Eq. (3), which became Eq. (3*):

$$\begin{aligned}\text{GHGpc}_{it} &= \alpha_i + \beta_1\text{GDPpc}_{it} + \beta_2\text{GDPpc}^2_{it} + \beta_3\text{GDPpc}^3_{it} + \delta\text{ZRDD}_{it} \\ &+ \mu\text{ZRNWpc}_{it} + \gamma\text{ZRNWGDPpc}_{it} + \theta\text{ZFSSpc}_{it} + \rho\text{ZFSSGDPpc}_{it} \\ &+ \varphi\text{ZBMSpc}_{it} + \omega\text{ZBMSGDPpc}_{it} + \delta_1\widehat{V}_{1it} + \delta_2\widehat{V}_{2it} + \delta_3\widehat{V}_{3it} + \varepsilon_{it}\end{aligned} \tag{3*}$$

Table 5 shows the estimation of the residues of Eqs. (13), (14) and (15). Once the three variables $\widehat{V}_{1it}$, $\widehat{V}_{2it}$ and $\widehat{V}_{3it}$ were obtained, they were entered in the PLS estimated equation to check for the existence of endogeneity with regard to GDPpc_{it}, GDPpc^2_{it} and GDPpc^3_{it}. The combined significance of $\widehat{V}_{1it}$, $\widehat{V}_{2it}$ and $\widehat{V}_{3it}$ tested through the Wald test (Table 5) confirms the endogeneity of the variables GDPpc_{it}, GDPpc^2_{it} and GDPpc^3_{it}.

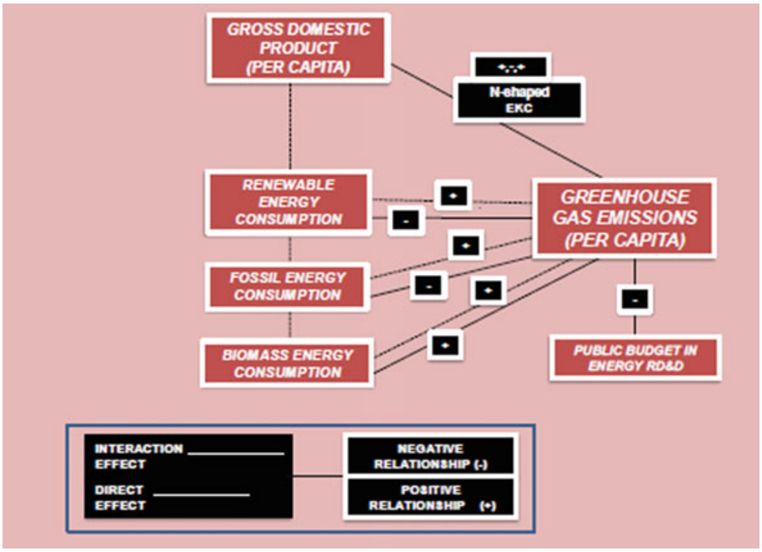


Fig. 3 Conceptual scheme.

We then estimated Eq. (3*) by TSPLS verifying that the coefficients δ, μ, γ, θ, ρ, φ and ω are statistically significant (Table 6) (Fig. 3).

4 Discussion of Results

The EKC hypothesis reveals that the economic growth is compatible with environmental improvements, where the main contribution of our study is to show evidence of the link between income and air pollution, through the correction of the endogeneity of the variable income level. Moreover, we have included a set of additional variables in Eq. (3*) that help to explain the EKC behaviour, including the effect that

Table 5 Estimation of the residues of Eqs. (13), (14) and (15)

Dependent variable: GHGpc Method: Panel EGLS (cross-sectional weights) Sample (adjusted): 1994–2012 Linear estimation after one-step weighting matrix White cross-sectional standard errors and covariance (df corrected)	
Variable	Coefficient
C	0.007216*
	[8.264]

(continued)

Table 5 (continued)

GDPpc	1.85E−07**		
	[1.908]		
$GDPpc^2$	−8.56E−12*		
	[−2.653]		
$GDPpc^3$	6.47E−17***		
	[1.4632]		
ZRDD	−5.41E−06*		
	[−5.961]		
ZRNWBPC	−0.017872***		
	[−1.234]		
ZRWGDPpc	7.01E−07***		
	[1.504]		
ZFSSPC	0.098312*		
	[4.0122]		
ZFSSGDPpc	4.73E−08		
	[0.056]		
ZBMSpc	0.046293*		
	[5.418]		
ZBMSGDPpc	4.78E−07*		
	[3.400]		
$\widehat{V}_1$	−4.15E−10		
	[−0.022]		
$\widehat{V}_2$	2.82E−12**		
	[2.526]		
$\widehat{V}_1$	−1.77E−17		
	[−0.581]		
Effect specification: Cross-sectional fixed (dummy variables): weighted statistics			
R-squared	0.9937	Mean dependent var	0.015098
Adjusted *R*-squared	0.9931	S.D. dependent var	0.006495
S.E. of regression	0.0005	Sum squared resid	7.73E−05
F-statistic	1599.537	Durbin–Watson stat.	0.997541
Prob(*F*-statistic)	0.000000		

(continued)

Table 5 (continued)

Unweighted statistics			
R-squared	0.9887	Mean dependent var	0.012342
Sum squared resid	8.53E–05	Durbin–Watson stat	0.990920
Wald test:			
Test statistic	Value	df	Probability
F-statistic	26.5756	(3293)	0.0000
Chi-square	79.7270	3	0.0000

Null hypothesis: $C(12) = C(13) = C(14) = 0$
Notes *, **, *** show significance at 1, 5 and 10%, respectively

both the replacement by renewable sources and energy innovation exert air pollution levels. The estimation results of Eq. (3*) reveal that GDPpc_{it}, GDPpc_{it}^2 and GDPpc_{it}^3 are endogenous explanatory variables of the variables $\widehat{V}_{1it}$, $\widehat{V}_{2it}$ and $\widehat{V}_{3it}$, which are statistically significant (Table 5). Thus, to solve the endogeneity problem of Eq. (3), we have used the instrumental variable method TSLS to obtain unbiased and efficient estimators (Table 6).

The coefficients $\hat{\beta}_1 > 0$, $\hat{\beta}_2 < 0$ and $\hat{\beta}_3 > 0$ (Eq. 3*) confirm the N-shaped cubic shape of the EKC for selected OECD countries between 1990 and 2012. The behaviour of the remaining coefficients also helps explain the relationship between income level and GHGpc emissions. The result of the regression implies that, in an initial stage, increases in income levels lead to increases in GHGpc emissions until the first turning point is reached[2] ($X(1) =$ U$D 14,078.90). Beyond this point, higher income levels are inversely related to GHGpc levels (GHGpc levels start to decrease) until GDPpc reaches the second turning point ($X(2) =$ U$D 85,016.44) after which GHGpc starts to increase again (Fig. 4).

The additional explanatory variables, included in Eq. (3*) related to energy innovation processes (ZRDD_{it}) and energy use (ZRNWpc_{it}, ZRNWGDPpc_{it}, ZFSSpc_{it}, ZFSSGPDpc_{it}, ZBMSpc_{it} and ZBMSGDPpc_{it}), extend the analysis of the relationship between income and environmental pollution. With regard to energy innovation, the negative coefficient $\delta = -4.91\text{E}{-}06$ proves that increases in public budget in energy RD&D reduce in long-term per capita GHG emissions. Aghion and Howitt [87] proved that innovation achievements aimed at environmental correction measures are premised on the idea that the expansion of clean technologies will promote a reduction in environmental pollution levels. Fisher-Vanden et al. [88] evidence that public budget on energy RD&D exerts a positive impact on reducing energy intensity and, by extension, on the reduction of per capita GHG emissions. Smulders and

[2]The formula used for the estimation of turning points for the cubic model is as follows (Diao et al. 2009):

$$Xj = \frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}, \quad \forall j = 1,\ 2 \qquad (16)$$

Table 6 Estimation result of Eq. (3*) by two-stage least squares (TSLS)

Dependent variable: GHGpc
Method: Panel two-stage EGLS (cross-sectional SUR)
Sample (adjusted): 1994–2012
Periods included: 19
Cross sections included: 17
Total panel (balanced) observations: 323
Linear estimation after one-step weighting matrix
Instrument specification Model 1: C AGED URBP $AGED^2$ $URBP^2$ $AGED^3$ $URBP^3$ ZRDD ZRNWPC ZRNWGDPpc ZFSSpc ZFSSGDPpc ZBMSpc ZBMSGDPpc
Instrument specification Model 2: C AGED URBP $AGED^2$ $URBP^2$ $AGED^3$ $URBP^3$ ZRDD ZRNWpc ZRNWGDPpc ZFSSpc ZFSSGDPpc ZBMSpc ZBMSGDPpc

	Model 1 (Eq. 3*)
C	0.008330*
	[30.470]
GDPpc	1.72E−07*
	[7.139]
$GDPpc^2$	−7.12E−12*
	[−10.339]
$GDPpc^3$	4.79E−17*
	[5.190]
ZRDD	−4.91E−06*
	[−29.519]
ZRNWpc	−0.043404*
	[−7.5080]
ZRNWGDPpc	6.43E−07*
	[7.7925]
ZFSSPC	0.076341*
	[17.629]
ZFSSGDPpc	−2.02E−07**
	[−2.228]
ZBMSpc	0.050728*
	[17.824]
ZBMSGDPpc	6.13E−07*
	[16.268]
Effect specification: Cross-sectional fixed (dummy variables): weighted statistics	
R-squared	0.9997
Adjusted *R*-squared	0.9997
S.E. of regression	1.0464
F-statistic	10864.05
Prob(*F*-statistic)	0.0000
Instrument rank	30

(continued)

Table 6 (continued)

Mean dependent var	48.5320
S.D. dependent var	88.2392
Sum squared resid	324.1416
Durbin–Watson stat	2.0718
Second-stage SSR	1338.4990
Unweighted statistics	
R-squared	0.9855
Sum squared resid	0.0001
Mean dependent var	0.01234
Durbin–Watson stat	0.91114

Notes t-statistic and *p*-value are given in [ ] and ( ), respectively
*, **, *** show significance at 1, 5 and 10%, respectively

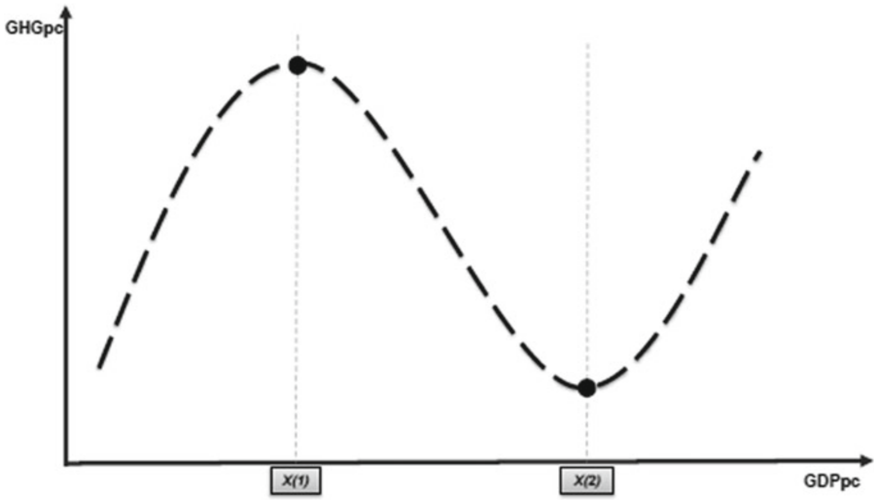


Fig. 4 Equation (3*): Turning points. *Note* $X(1)$: first turning point; $X(2)$: second turning point. *Source* Prepared by authors

Bretschger [89] show that the relationship between economic growth and environmental quality is the result of technological change, sectoral shifts and changes in environmental regulation. Balsalobre and Álvarez [15] demonstrate that ascending public budget in energy RD&D reduces per capita GHG emissions, under a *V*-finite delay scheme of De Leeuw [69]. Our study validates that the environmental correction process requires substantial efforts in energy innovation measures to reorient the economic system towards more efficient and less polluting sectors. Therefore, to avoid a return to a path of increasing contamination, energy regulation measures must be implemented that expand improvements in the energy sector with the aim of avoiding the trap of decreasing technical returns on a path to technical obsolescence.

The negative coefficient $\mu = -0.043404$ (Eq. 3*) reveals that renewable energy sources ($ZRNWpc_{it}$) exert a positive effect over the correction of per capita GHG emissions. In addition, the coefficient $\gamma = 6.43E{-}07$ of Eq. (3*) confirms a moderation effect in the interaction between renewable use and income levels ($ZRNWGDPpc_{it}$). This result implies that income reduces the net effect of renewable sources in the correction of GHGpc emissions. The impact of renewable electricity consumption over environmental degradation process will depend on the economic cycle and the structure and developmental stage of the economy [90]. In other words, instead of the positive effect of renewable energy sources on the correction of per capita GHG emissions, when we consider the interaction between income and renewable energy use, the net effect implies a reduction of the positive effect of renewable energy use on environmental correction. This effect confirms that renewable electricity use is linked to economic cycle, where under an economic system dominates by fossil sources, an expansive economic cycle, will also increase "dirty" energy sources, which impact directly on per capita GHG emissions [91], Balsalobre and Shahabaz [17]. The coefficient $\theta = 0.076341$ reflects the negative effect that fossil electricity consumption exerts environmental correction process. The fossil energy use has influence over numerous environmental concerns such as global warming, energy security, climate change, local air pollution or energy dependency [92, 93]. By contrast, the negative coefficient $\rho = -2.02E{-}07$ suggests that an ascending economic cycle will reduce the net effect of fossil sources ($ZFSSGPDpc_{it}$), mainly by higher renewable use and an increase of energy efficiency by the existence of innovations which reduce the negative effect of fossil sources on per capita GHG emissions [14]. The coefficients γ and ρ reveal that the positive effect of economic cycle over the reduction of fossil sources ($ZFSSGPDpc_{it}$) is not enough to supply the global negative effect of the ascending requirements of energy, where renewable use ($ZRNWGDPpc_{it}$) is not enough to control environmental degradation process.

Finally, the positive coefficients $\varphi = 0.050728$ imply that increases in biomass energy use ($ZBMSpc_{it}$) increase per capita GHG emissions [4, 92–105]. The positive coefficient $\omega = 6.13E{-}07$ reflects the interaction between income and biomass use ($ZBMSGDPpc_{it}$). This positive result validates the existence of a transition from traditional biomass use to modern biomass use when economies increase income levels [106]. When economies present a transition to a developed stage, traditional biomass energy use (e.g. wood and cooking) decreases, while indirect or modern biomass use (e.g. biofuel) experiments increase [104]; IEA [140]. Yemane [107] showed that the transition from traditional biomass energy consumption to commercial fossil fuels energy consumption could accelerate the penetration of commercial fossil fuels, reducing the share of traditional biomass energy consumption. These results also confirm that fresh biomass energy can be considered an alternative for reducing foreign oil dependency [108]. By contrast, some studies postulate the existence of a negative relationship between biomass energy consumption and CO_2 emissions, where energy efficiency innovations help to correct environmental degradation in newly industrialized countries [94]. There are socio-economic benefits of biomass energy use identified as a driving force in increasing the share of bioenergy in the total energy supply, where biomass energy use can help to reduce energy dependency and support national energy security; instead, this type of energy use also increases emissions [109, 110]. Reinhardt and Falkenstein [110] compare the efficiency of biofuels and fossil fuels, and they conclude that, although biofuel has some negative effects on environment, in terms of energy savings and GHG criteria, the biofuel is favourable in comparison with fossil alternatives, where the efficiency of bioenergy depends on largely the cost of production of it, where at the moment the cost of energy production from biomass is twice the cost of energy production from coal [111, 112]. Although biomass has barriers in terms of production cost and conversion efficiency, it is considered extensively for transportation sector [113, 114] and for production of electricity [111]. One may see also other seminal works focusing on biomass's substantiality through its ecological and economic effects [114–117]. Therefore, the substitution of fossil fuels with biomass helps to mitigate energy imports of energy importer countries, and thus these countries may decrease trade deficits [118, 119]. On the other hand, biomass energy increases CO_2 emissions; instead, it may renew infertile soils and increase the biological diversity and water retention and fertility of the soil [120].

Our study proposes a long-term relationship has been explored in the long term through the use of a scheme of finite delays of De Leeuw [69]. Figure 5 reflects the econometric results, though De Leeuw's multiplier achieves its maximum impact two years out. This multiplier improves the long-term impact of auxiliary variables over emissions. The implementation and effectiveness of environmental regulations will play a decisive role in the long-term evolution of environmental pollution levels [32, 121].

Figure 5 reflects the empirical evidence, which reveals that both energy innovation and selected energy sources have the greatest effect on correcting pollution at lag 2. These econometric results validate that energy innovation measures take two years to reach their fullest potential [15]. Additionally, the energy explanatory variables also confirm De Leeuw's finite lag behaviour, so it implies that energy use in selected energy sources has a long-term effect over per capita GHG emissions.

Finally, we isolate the effect of energy regulations linked with innovation and renewable use and promotion in the relationship between income level and air pollution (Model 2), omitting the variables ZRDD_{it}, ZRNWpc_{it} and $\mathrm{ZRNWGDPpc}_{it}$ (Eq. 3**). The Model 2 allows us to compare the turning points adjusted for the omission of regulatory variables. This step helps to demonstrate the relevance of energy regulation policies to solving environmental pollution problems.

$$\begin{aligned}\mathrm{GHGpc}_{it} = {} & \alpha_i + \beta_1 \mathrm{GDPpc}_{it} + \beta_2 \mathrm{GDPpc}_{it}^2 + \beta_3 \mathrm{GDPpc}_{it}^3 + \theta \mathrm{ZFSSpc}_{it} \\ & + \rho \mathrm{ZFSSGDPpc}_{it} + \varphi \mathrm{ZBMSpc}_{it} + \omega \mathrm{ZBMSGDPpc}_{it} \\ & + \delta_1 \widehat{V}_{1it} + \delta_2 \widehat{V}_{2it} + \delta_3 \widehat{V}_{3it} + \varepsilon_{it} \end{aligned} \quad (3^{**})$$

When we compare Model 1 (Eq. 3*) with Model 2 (Eq. 3**), the results of the estimation of Eq. (3**) (Table 7) reflect that energy innovation and promotion

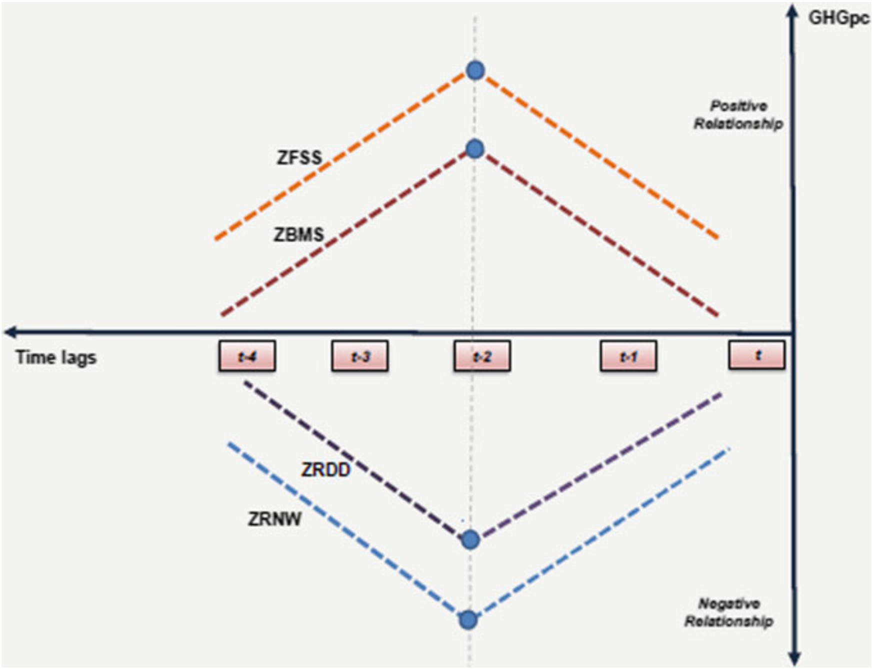


Fig. 5 De Leeuw evolution. *Source* Prepared by authors

of renewable use reduce the income requirements necessary to achieve reductions in per capita GHG emissions (Fig. 6). Otherwise, Eq. (3**) reveals that when we omit selected energy regulation processes the second turning point is touched sooner (Fig. 6).

Figure 6 reveals that when economies first apply energy regulation processes, society reduces the initial cost to reduce emission levels ($X(1)$ = U$D 14,078.90 < U$D 14.177,26). Another consequence of implementing energy regulation measures is that the income threshold for the second turning point (Stage 2) and the return to increasing pollution levels is higher when economies implement regulatory improvements ($X(2)$ = US$ U$D 85,016.44 > $X(6)$ = U$ 49.083,08) and ($X(2) > X(5)$). The reach of this second stage indicates the effectiveness of energy-related regulatory policies. Regulatory measures in the energy sector are partly justified by delays in the long-term ascending pollution phase. In other words, when economies implement regulatory policies in the energy sector, it helps to prevent the scale effect and, thus, technical obsolescence.

One consequence of the results obtained *i* is that without energy innovation measures and promotion of renewable sources, technical obsolescence forces the return to a stage of increasing environmental degradation.

We can conclude that technological innovation practices make environmental correction possible at lower income levels [121–123]. Moreover, the implementa-

Table 7 Estimation result of Eq. (3**)

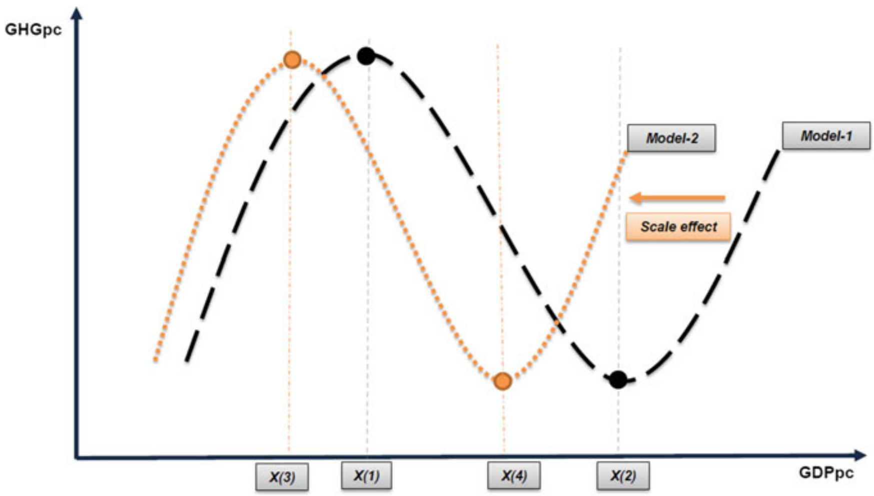
Dependent variable: GHGPC Method: Panel two-stage EGLS (cross-sectional SUR) Sample (adjusted): 1994–2012 Periods included: 19 Cross sections included: 17 Total panel (balanced) observations: 323 Linear estimation after one-step weighting matrix *Instrument specification Model 1*: C AGED URBP AGED^2 URBP^2 AGED^3 URBP^3 ZRDD ZRNWpc ZRNWGDPpc ZFSSpc ZFSSGDPpc ZBMSpc ZBMSGDPpc *Instrument specification Model 2*: C AGED URBP AGED^2 URBP^2 AGED^3 URBP^3 ZRDD ZRNWPC ZRNWGDPpc ZFSSPC ZFSSGDPpc, ZBMSpc, ZBMSGDPpc	
Model 2 (Eq. 3**)	
C	0.005679*
	[21.623]
GDPpc	2.86E−07*
	[10.399]
GDPpc^2	−1.30E−11
	[−13.963]
GDPpc^3	1.37E−16*
	[−14.776]
ZRDD	–
	–
ZRNWpc	–
	–
ZRNWGDPpc	–
	–
ZFSSpc	0.131589*
	[32.845]
ZFSSGDPpc	−1.17E−06*
	[−27.273]
ZBMSpc	0.041297*
	[21.539]
ZBMSGDPpc	6.33E−07*
	[13.878]
Effect specification: Cross-sectional fixed (dummy variables): weighted statistics	
R-squared	0.9992
Adjusted *R*-squared	0.9992
S.E. of regression	1.0431
F-statistic	4503.091
Prob(*F*-statistic)	0.0000
Instrument rank	27

(continued)

Table 7 (continued)

Mean dependent var	13.0195
S.D. dependent var	35.9653
Sum squared resid	325.3617
Durbin–Watson stat	2.0500
Second-stage SSR	1334.725
Unweighted statistics	
R-squared	0.9836
Sum squared resid	0.0001
Mean dependent var	0.0123
Durbin–Watson stat	0.7895

Notes *t*-statistic and *p*-value are given in [ ] and ( ), respectively
*, **, *** show significance at 1, 5 and 10%, respectively



X(1)= U$D 14,078.90 >	X(2)= US$ U$D 85,016.44 >
X(2)=U$D 14.177,26	X(4)=U$ 49.083,08

Fig. 6 Comparison of turning points between Model 1 (Eq. 3*) and Model 2 (Eq. 3**). *Source* Prepared by authors

tion of measures to promote energy innovations and renewable sources will result in a deviation from the diminishing technological returns, thereby helping to reverse the upward trajectory of the EKC [27]. Therefore, the applicable energy policies that can decrease the dependency of fossil sources and minimize the environmental damages are needed to reach sustainable economic growth. On the other hand, these policies may include some risks and costs as well. In comparison between advantages and costs of energy resources, the renewable energy sources might have some potential advantages compared with other energy sources [124, 125]. When economies undergo increased economic growth, energy demand will increase, decreasing the share of renewable sources in the overall energy mix. Consequently, the key to solving this problem lies in promoting renewable sources able to reduce the share of fossil sources and traditional biomass in the energy mix.

5 Conclusions and Policy Implications

This paper tests the EKC hypothesis for 17 selected OECD countries during 1990–2012 period using TSPLS estimation, expanding the state of knowledge regarding the consequences on environmental quality, energy use and energy innovation processes. This study further incorporates as newness a long-term analysis which incorporates a finite delay effect in the explanatory variables in order to examine the enduring effect of these variables on per capita GHG emissions. This study also includes the interaction between income and energy use in order to observe how economic cycle affects selected energy sources over their role on per capita GHG emissions. These are new advances in the EKC literature, where results imply an advance in the study of the relationship of income–environmental degradation.

The econometric results confirm the existence of a positive long-standing relationship between energy innovations, selected energy sources and the reduction of GHG_{pc} emissions. When economies are at low-income stage, both the promotion of renewable sources and energy innovation measures help for achieving a reduction in per capita GHG emissions. Once economies reach a developed stage, they have to continue increasing their energy regulation procedures in order to delay the scale effect.

On the other hand, the findings indicate that fossil electricity consumption and biomass energy consumption increase per capita GHG emissions. When we incorporate the interaction between income and selected energy sources, the results validate that economic cycle interacts with these variables. In the economic stages characterized by high-energy requirements, economies with higher energy demand will demand higher share of energy sources and it will affect negatively the environment, justified by a predominate share of fossil sources in the energy mix. In other words, an ascending economic cycle entails an increase in the consumption of fossil sources to accelerate economic growth that negatively affects air pollution levels. These results reveal that it would also be appropriate to consider the need to increase the share of renewable energy sources in the energy mix in order to reduce the negative effect of overall energy demand on an ascending economic cycle involving an increase in GHGpc emissions.

In keeping with the findings of this study, policy-makers should thus implement regulatory measures, both to promote renewable sources with regard to energy innovation measures and to correct air pollution levels. Such measures help to delay technical obsolescence and also control the scale effect that drives economies to a return to increasing pollution levels. Although the promotion of renewable sources has a direct impact on the reduction of per capita GHG emissions in the short term, in the long term it is necessary to implement energy innovation measures to delay technical obsolescence and, thus, the return to a stage of increasing GHG emissions. One policy implication of this study implies that the relationship between both innovation and energy use requires a time lag to become fully efficient. This finding confirms that these measures have a long-term effect. Moreover, the process of replacing conventional energy sources with renewable ones positively contributes to reducing emissions. These results also connect economic cycle with energy use, which is necessary to modify the energy mix, to control environmental degradation under ascending requirements of energy use.

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Investigating the Trans-boundary of Air Pollution Between the BRICS and Its Neighboring Countries: An Empirical Analysis

Ilhan Ozturk and Usama Al-Mulali

Abstract This study investigates whether air pollution from the BRICS countries influences air pollution of their neighboring countries for the period of 1990–2013. To realize the aim of this study, five panel models were established by utilizing CO_2 emissions of each of the BRICS neighboring countries as the dependent variable and gross domestic product (GDP), electricity consumption, trade openness, urbanization, and CO_2 emissions of the BRICS countries as the independent variables. Based on the Kao cointegration test results, the variables in each of the five models were cointegrated and indicating the existence of a long-run relationship. Moreover, the panel fully modified ordinary least square also revealed that electricity consumption, GDP growth, trade openness, urbanization, and CO_2 emissions of the BRICS countries increase CO_2 emissions of their neighboring countries in the long run. In addition, the VECM Granger causality results show the existence of a number of causal relationships between CO_2 emissions of the BRICS countries and their neighboring countries' CO_2 emissions, electricity consumption, GDP growth, trade openness, and urbanization. Based on the results obtained, a number of policy recommendations are provided for the investigated countries.

Keywords BRICS countries · CO_2 emissions · Trade · Urbanization · Trans-boundary of air pollution

1 Introduction

Brazil, Russia, India, China, and South Africa (BRICS) witnessed a substantial escalation of industrialization, urbanization, trade, population, and energy consumption

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for the last 15 years. Specifically in 2012, 24% of the world industrial output [1], 37% of the world urban population, 35% of the world trade, 22% of the world gross domestic product, and 25% of the world total electricity consumption [2] came from the BRICS countries. The boost in their economic development substantially increased the levels of air pollution during the period of 1990–2013. Furthermore, from 1990 to 2013, the level of CO_2 emissions increased by 75%, and CO_2 emissions that were produced in these countries in 2013 represented 41% of CO_2 emissions produced globally [2].

The increase in the economic development and pollution in the BRICS countries attracted the attention of several scholars who sought to examine the link between human activities and pollution. Most of the scholars examined the effect of economic development in these countries on their pollution levels (see Table 1). According to the studies presented in Table 1, in almost all studies GDP growth increases carbon dioxide emissions. However, despite the well-established literature, most of the previous studies did not examine whether the pollution from a country transfers to another country. Principally, pollution can easily be carried by the movement of the wind from one country to another. Therefore, population health issues, damage to environment, and economic impacts resulted from air pollution can be related to the pollution produced from within the country as well as the pollution transmitted from neighboring countries. This phenomenon is called the spillover effect whereby the increase of pollution due to the increase in economic activities in a country might affect the pollution levels in another country. If the spillover effect does exist, it will have an important consequence for policy implications.

Therefore, this study will contribute to the literature by investigating whether air pollution produced by BRICS countries affects the levels of air pollution of their neighboring countries for the period of 1990–2013 or not.

Table 1 Literature review summary

Author	Period	Country	Method	Variables	Empirical findings
Zhang and Cheng [9]	1960–2007	China	Toda–Yamamoto (TY) Granger causality	CO_2 emission, GDP, energy consumption, capital, and urbanization	GDP only has causal relationship with CO_2 emission
Bloch et al. [10]	1965–2008	China	Vector autoregression (VAR) tests and VECM Granger causality	CO_2 emission, coal consumption, capital, labor, and coal prices	Bidirectional causality between coal consumption and CO_2 emission

(continued)

Table 1 (continued)

Author	Period	Country	Method	Variables	Empirical findings
Ozturk and Uddin [11]	1971–2007	India	Johansen cointegration, Granger causality test	CO_2 emission, GDP, and energy consumption	Energy consumption increases CO_2 emission and feedback causal relationship between energy consumption and economic growth
Yang and Zhao [12]	1970–2008	India	Granger causality test and directed acyclic graphs (DAGs)	CO_2 emission, GDP, energy consumption, trade openness, and capital	GDP, energy consumption, and trade openness causal effect CO_2 emission
Pao and Tsai [13]	1971–2005	Brazil, Russia, India, and China (BRIC)	Pedroni, Kao, and Johansen cointegration, and VECM Granger causality	CO_2 emission, GDP, and energy consumption	GDP and energy consumption increase CO_2 emission and have causal effects as well
Wang et al. [14]	1995–2007	China	Pedroni cointegration and VECM Granger causality	CO_2 emission, energy consumption, and GDP	GDP and energy consumption increase CO_2 emission and have causal effects as well
Jayanthakumaran et al. [15]	1971–2007	China and India	ARDL bound testing	CO_2 emission, GDP, energy consumption, and trade openness	GDP and energy consumption increase CO_2 emission in China only

(continued)

Table 1 (continued)

Author	Period	Country	Method	Variables	Empirical findings
Shahbaz et al. [16]	1965–2008	South Africa	ARDL bound testing and VECM Granger causality	CO_2 emission, coal consumption, GDP, financial development, urbanization, and trade openness	GDP and coal consumption increase CO_2 emission while trade openness, urbanization, and the financial development reduce it. All variables causal effect CO_2 emission
Kohler [17]	1960–2009	South Africa	VAR-based Johansen cointegration, ARDL bound testing, and VECM Granger causality	CO_2 emission, energy consumption, GDP, and trade openness	Energy consumption increases CO_2 emission, while trade openness reduces it. All the variables have causal effects on CO_2 emission as well
Pao and Tsai [18]	1980–2007	BRIC countries	Pedroni, Johansen, and Kao cointegration and VECM Granger causality	CO_2 emission, GDP, FDI, and energy consumption	Energy consumption, GDP, and FDI increase CO_2 emission. All the variables have causal effect on CO_2 emission
Pao et al. [19]	1990–2007	Russia	Johansen cointegration and VECM Granger causality	CO_2 emission, GDP, and energy consumption	Energy consumption and GDP causal effect CO_2 emission

(continued)

Table 1 (continued)

Author	Period	Country	Method	Variables	Empirical findings
Zhang et al. [20]	1982–2007	China	System GMM	Industrial waste, GDP, energy consumption, labor, and capital	GDP and energy consumption increase industrial waste
Jalil and Mahmud [21]	1975–2005	China	ARDL bound testing and pair-wise Granger causality	CO_2 emission, GDP, energy consumption, and trade openness	GDP and energy consumption increase CO_2 emission, while trade openness has no effect. GDP and energy consumption have causal effect on CO_2 emission
Cowan et al. [22]	1990–2010	BRICS countries	The bootstrap panel causality approach	CO_2 emission, GDP, and electricity consumption	GDP has a causal effect on CO_2 emission in Russia, China, and South Africa. Electricity consumption has a causal effect on CO_2 emission in India only
Govindaraju and Tang [23]	1965–2009	China and India	Bayer and Hanck cointegration, VAR and VECM Granger causality for India and China, respectively	CO_2 emission, GDP, and coal energy consumption	GDP and coal consumption have causal effects on CO_2 emission in the short run for India and the both short run and long run for China

(continued)

Table 1 (continued)

Author	Period	Country	Method	Variables	Empirical findings
Wang et al. [24]	1995–2011	China	Pedroni cointegration, DOLS, and VECM Granger causality	CO_2 emission, urbanization, and energy consumption	Urbanization and energy consumption have a positive long-run effect on CO_2 emission and causal effect on CO_2 emission as well
Pao and Tsai [25]	1980–2007	Brazil	The gray prediction model (GM), Johansen cointegration, and VECM Granger causality	CO_2 emission, GDP, and energy consumption	GDP and energy consumption increase CO_2 emission in the long run. Both variables have causal effect on CO_2 emission
Haisheng et al. [26]	1990–2002	China	Fixed and random effects panel models	Sulfur dioxide (SO_2) emission, industrial water waste, and GDP	GDP increases SO_2 emission and industrial waste
Guangyue and Deyong [27]	1990–2007	China	Residual-based cointegration and panel mixed least squares estimation method (PLS)	CO_2 emission and GDP	GDP increases CO_2 emission in the long run

(continued)

Table 1 (continued)

Author	Period	Country	Method	Variables	Empirical findings
Llorca and Meunié [28]	1996–1999	China	Fixed effects panel model	SO_2 emission, GDP, electricity production, the tertiary sector, the state-owned enterprises, FDI, and the heavy industries' output	GDP, electricity production, and heavy industries' output increase SO_2 emission, while the state-owned enterprises and FDI reduce it
Chang [29]	1981–2006	China	Johansen cointegration and VECM Granger causality	CO_2 emission, GDP, oil, coal, natural gas, and electricity energy consumption	GDP and energy consumption types increase CO_2 emission. All the variables have causal effect on CO_2 emission
Zhang et al. [30]	1978–2011	China	ARDL bound testing and VECM Granger causality	CO_2 emission intensity, GDP growth, industrial output, and urbanization	GDP growth, industrial output, and urbanization increase CO_2 emission intensity

2 Data and Methodology

This study utilized annual data taking the period of 1990–2013 to investigate whether air pollution from Brazil, Russia, India, China, and South Africa affects the levels of pollution of their neighboring countries. Similar to the reviewed studies, this study utilized CO_2 emissions as a pollution indicator. Moreover, the gross domestic product (GDP), urbanization, electricity consumption, and trade openness were used as indicators of human activities that affect air pollution. The empirical panel models can be presented as follows:

$$\begin{aligned} &\mathrm{CO}_{2_{it}} \text{ of the neighboring countries of Brazil} \\ &= f\left(\mathrm{GDP}_{it} + \mathrm{UR}_{it} + \mathrm{EC}_{it} + \mathrm{TD}_{it} + \mathrm{CO}_{2_{it}} \text{ of Brazil} + \varepsilon_{it}\right) \end{aligned} \tag{1}$$

$$\begin{aligned} &\mathrm{CO}_{2_{it}} \text{ of the neighboring countries of Russia} \\ &= f\left(\mathrm{GDP}_{it} + \mathrm{UR}_{it} + \mathrm{EC}_{it} + \mathrm{TD}_{it} + \mathrm{CO}_{2_{it}} \text{ of Russia} + \varepsilon_{it}\right) \end{aligned} \tag{2}$$

$$\begin{aligned} &\mathrm{CO}_{2_{it}} \text{ of the neighboring countries of India} \\ &= f\left(\mathrm{GDP}_{it} + \mathrm{UR}_{it} + \mathrm{EC}_{it} + \mathrm{TD}_{it} + \mathrm{CO}_{2_{it}} \text{ of India} + \varepsilon_{it}\right) \end{aligned} \tag{3}$$

$$\begin{aligned} &\mathrm{CO}_{2_{it}} \text{ of the neighboring countries of China} \\ &= f\left(\mathrm{GDP}_{it} + \mathrm{UR}_{it} + \mathrm{EC}_{it} + \mathrm{TD}_{it} + \mathrm{CO}_{2_{it}} \text{ of China} + \varepsilon_{it}\right) \end{aligned} \tag{4}$$

$$\begin{aligned} &\mathrm{CO}_{2_{it}} \text{ of the neighboring countries of South Africa} \\ &= f\left(\mathrm{GDP}_{it} + \mathrm{UR}_{it} + \mathrm{EC}_{it} + \mathrm{TD}_{it} + \mathrm{CO}_{2_{it}} \text{ of South Africa} + \varepsilon_{it}\right) \end{aligned} \tag{5}$$

where t represents time (1990–2013), i resembles cross section (number of countries), and ε resembles the error term. CO_2 is carbon dioxide emissions from consumption of energy measured in thousands of metric ton, GDP is gross domestic product measured in millions of 2005 of constant US dollars, UR is urban population as an indicator of urbanization measured in thousands of individuals, EC is total electricity consumption measured in millions of kilowatt-hours, and TD is total value of goods and services as an indicator of trade openness measured in millions of 2005 constant US dollars. All the data were retrieved from the Euromonitor database [2].

Table 2 displays the neighboring countries of BRICS countries. Table 2 shows that Russia and China are neighboring countries as well as China and India. Therefore, the pollution spillover effect between BRICS countries might also exist.

Data sets that contain time series require testing their stationarity levels. This can be achieved by using unit root tests. This step is important as nonstationary variables can negatively affect the accuracy of the empirical results. Two types of panel unit root tests were used in the analysis. These tests are the Im–Pesaran–Shin (IPS) [3] and Fisher-type augmented Dickey–Fuller (ADF) tests [4]. Both Fisher-ADF and IPS panel unit root tests permit the individual unit root processes which, consequently, allow the autoregressive coefficients ρ_i to vary across the cross sections. For the IPS test, it utilizes the following ADF regression for each cross section:

Table 2 BRICS neighboring countries

BRICS countries	Neighboring countries
Brazil	Argentina, Bolivia, Colombia, Paraguay, Uruguay, and Venezuela
Russia	Azerbaijan, China, Kazakhstan, Mongolia, North Korea, Belarus, Estonia, Georgia, Latvia, Lithuania, Poland, Ukraine, Finland, and Norway
India	Afghanistan, Bangladesh, Bhutan, China, Myanmar, Nepal, Pakistan, and Sri Lanka
China	India, Japan, Kazakhstan, Kyrgyzstan, Nepal, Pakistan, Vietnam, and Russia
South Africa	Botswana, Lesotho, Mozambique, Namibia, Swaziland, and Zimbabwe

$$\Delta y_{it} = \alpha y_{it-1} + \sum_{j=1}^{p_i} \beta_{ij} \Delta y_{it-j} + X'_{it}\delta + \epsilon_{it} \tag{6}$$

where i is the cross section, t is the time series, α is the constant, ρ_i is the autoregressive coefficients, y is the dependent variable, X is the exogenous variables, and ϵ is the error. The Fisher-ADF unit root utilizes Fisher's [5] results to run tests that combine the ρ-values from the individual unit root test for each cross section. The formula that the Fisher-ADF test uses is presented below:

$$P = -2\sum_{i=1}^{N} \ln \rho_i \tag{7}$$

where ρ is the autoregressive coefficients, i is the cross sections, and N is the degree of freedom. One of the important advantages of utilizing this test is its capacity to perform with unbalanced panel data.

Both tests classify their null hypothesis as the existence of a unit root and their alternative hypothesis as the nonexistence of a unit root. If the variables are not stationary, then the null hypothesis of a unit root cannot be rejected. However, if the variables are stationary, the null hypothesis can be rejected and the alternative hypothesis is accepted.

If the variables are stationary at the first difference (integrated in order one), the next step is to confirm whether the long-run relationship between the variables does exist. This can be achieved by applying the panel Kao [6] cointegration test. Kao cointegration is based on Engle–Granger cointegration test. It utilizes two types of tests, the Dickey–Fuller (DF) and the augmented Dickey–Fuller (ADF) tests. This research used the Kao cointegration based on the ADF test which calculates the estimated residuals (e) from Eq. (8):

$$\hat{\beta} = \left[\sum_{i=1}^{N}\sum_{t=1}^{T} \tilde{x}_{it}\tilde{x}'_{it}\right]^{-1}\left[\sum_{i=1}^{N}\sum_{t=1}^{T} x_{it}\tilde{y}_{it}\right] \tag{8}$$

The ADF test is represented by the Eq. (9):

$$\hat{e}_{it} = \rho\hat{e}_{it-1} + \sum_{j=1}^{p} \psi_j \Delta\hat{e}_{it-j} + v_{it} \tag{9}$$

Through the null hypothesis of no cointegration, the statistics of the ADF can be written as follows:

$$\text{ADF} = \frac{t^{\text{ADF}} + \frac{\sqrt{6N\hat{\sigma}_v}}{2\sigma 0v}}{\sqrt{\frac{\hat{\sigma}_{0v}^2}{2\sigma_v^2} + \frac{2\sigma_v^2}{10\hat{\sigma}_{0v}^2}}} \tag{10}$$

where t_{ADF} is the t-statistics for the ρ that is presented in Eq. (9) and σ is the estimated variance. To determine the existence of cointegration, the significance of t-statistics must be determined. If t-statistics is significant, it means that the null hypothesis of no cointegration can be rejected. Therefore, the cointegration between the variables is present.

If cointegration is confirmed among the variables, then the fully modified ordinary least square (FMOLS) can be applied due to its popularity and utilization among scholars increased in recent years. The FMOLS and other similar tests have the advantage of producing unbiased and normally distributed coefficient outcomes. Therefore, this study utilized the group weight FMOLS established by Pedroni [7] and Kao and Chiang [8] which can be used for panels whereby the long-run variance differs across the cross sections. To obtain the residuals test utilizes, the first-stage is the estimations of long-run and regressor equations. Moreover, the researchers also estimated the individual long-run variances, namely:

$$\hat{\Lambda}_i \text{ and } \hat{\Omega}_i \text{ and } \hat{\lambda}_{12i}^{+} = \hat{\lambda}_{12i} - \hat{\omega}_{12i}\hat{\Omega}_{22i}^{-1}\hat{\Lambda}_{22i} \tag{11}$$

and

$$\hat{y}_{it}^{++} = \hat{y}_{it} - \hat{\omega}_{12}\Omega_{22}^{-1}\hat{u}_2 - \omega_{1.2i}^{1/2}\left(\omega_{1.2i}^{1/2}\tilde{X}_{it'} - \left(\hat{\omega}_{12i}\tilde{X}_{it}\right)'\right)\hat{\beta}_0 \tag{12}$$

where y and X are the corresponding data removed from the individual deterministic trends and the symbol $\hat{\beta}_0$ is an initial estimate of the long-run coefficient. Subsequently, the following weighted variables were formed:

$$\tilde{X}_{it^*} = \hat{\Omega}_{22i}^{-1/2} \cdot \tilde{X}_{it} \tag{13}$$

$$\hat{y}_{it^*} = \hat{\omega}_{1.2i}^{-1/2} \cdot \tilde{y}_{it}^{++} \tag{14}$$

$$\hat{\lambda}_{12i^*} = \omega_{1.2i}^{-1/2} \cdot \lambda_{12i}^{+} \cdot \Omega_{22i}^{-1/2\prime} \tag{15}$$

Therefore, the estimator is presented below:

$$\hat{\beta}_{FW} = \left(\sum_{i=1}^{N}\sum_{t=1}^{T}\tilde{X}_{it^*}X_{it^{*\prime}}\right)^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\left(\tilde{X}_{it^*}y_{it^*} - \lambda_{12i}^{*\prime}\right) \tag{16}$$

Moreover, through the use of a moment estimator based on Pedroni [7], the asymptotic covariance was estimated and it is displayed below:

$$\hat{V}_{FW} = \left(1\frac{1}{n}\sum_{i=1}^{N}\left(\frac{1}{T^2}\sum_{t=1}^{T}\tilde{X}_{it^*}X_{it^{*\prime}}\right)\right)^{-1} \tag{17}$$

If cointegration is confirmed among the variables, there should be causal relationship between the variables at least from one direction. Therefore, the Granger causality was implemented. The panel Granger causality is based on the vector error correction model (VECM) which can only be applied if cointegration exists. The VECM Granger causality can capture both short-run and long-run causality. The short-run causality is based on the *F*-statistics while the long-run causality is based on the lagged error correction term ect(−1). The VECM Granger causality models are displayed below:

$$\begin{bmatrix} \Delta \mathrm{LCO2}_{it} \\ \Delta \mathrm{LEC}_{it} \\ \Delta \mathrm{LGDP}_{it} \\ \Delta \mathrm{LTD}_{it} \\ \Delta \mathrm{LUR}_{it} \\ \Delta \mathrm{LBCO2}_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix}$$

$$\times \begin{bmatrix} \Delta \mathrm{LCO2}_{it-p} \\ \Delta \mathrm{LEC}_{it-p} \\ \Delta \mathrm{LGDP}_{it-p} \\ \Delta \mathrm{LTD}_{it-p} \\ \Delta \mathrm{LUR}_{it-p} \\ \Delta \mathrm{LBCO2}_{it-p} \end{bmatrix} + \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} \mathrm{ect}_{it-1} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{5it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} \Delta \mathrm{LCO2}_{it} \\ \Delta \mathrm{LEC}_{it} \\ \Delta \mathrm{LGDP}_{it} \\ \Delta \mathrm{LTD}_{it} \\ \Delta \mathrm{LUR}_{it} \\ \Delta \mathrm{LRCO2}_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_5 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix}$$

$$\times \begin{bmatrix} \Delta \mathrm{LCO2}_{it-p} \\ \Delta \mathrm{LEC}_{it-p} \\ \Delta \mathrm{LGDP}_{it-p} \\ \Delta \mathrm{LTD}_{it-p} \\ \Delta \mathrm{LUR}_{it-p} \\ \Delta \mathrm{LRCO2}_{it-p} \end{bmatrix} + \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} \mathrm{ect}_{it-1} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{5it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{19}$$

$$\begin{bmatrix} \Delta \mathrm{LCO2}_{it} \\ \Delta \mathrm{LEC}_{it} \\ \Delta \mathrm{LGDP}_{it} \\ \Delta \mathrm{LTD}_{it} \\ \Delta \mathrm{LUR}_{it} \\ \Delta \mathrm{LINCO2}_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_2 \\ \alpha_3 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix}$$

$$\times \begin{bmatrix} \Delta\text{LCO2}_{it-p} \\ \Delta\text{LEC}_{it-p} \\ \Delta\text{LGDP}_{it-p} \\ \Delta\text{LTD}_{it-p} \\ \Delta\text{LUR}_{it-p} \\ \Delta\text{LINCO2}_{it-p} \end{bmatrix} + \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} \text{ect}_{it-1} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} \Delta\text{LCO2}_{it} \\ \Delta\text{LEC}_{it} \\ \Delta\text{LGDP}_{it} \\ \Delta\text{LTD}_{it} \\ \Delta\text{LUR}_{it} \\ \Delta\text{LCCO2}_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65rp} & \beta_{66,p} \end{bmatrix}$$

$$\times \begin{bmatrix} \Delta\text{LCO2}_{it-p} \\ \Delta\text{LEC}_{it-p} \\ \Delta\text{LGDP}_{it-p} \\ \Delta\text{LTD}_{it-p} \\ \Delta\text{LUR}_{it-p} \\ \Delta\text{LCCO2}_{it-p} \end{bmatrix} + \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} \text{ect}_{it-1} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{21}$$

$$\begin{bmatrix} \Delta\text{LCO2}_{it} \\ \Delta\text{LEC}_{it} \\ \Delta\text{LGDP}_{it} \\ \Delta\text{LTD}_{it} \\ \Delta\text{LUR}_{it} \\ \Delta\text{LSAO2}_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65rp} & \beta_{66,p} \end{bmatrix}$$

$$\times \begin{bmatrix} \Delta\text{LCO2}_{it-p} \\ \Delta\text{LEC}_{it-p} \\ \Delta LGDP_{it-p} \\ \Delta\text{LTD}_{it-p} \\ \Delta\text{LUR}_{it-p} \\ \Delta\text{LSAO2}_{it-p} \end{bmatrix} + \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} \text{ect}_{it-1} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{5it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{22}$$

However, if cointegration does not exist, the Granger causality that is based on the vector autoregression (VAR) model can be utilized. Nonetheless, it can only capture the short-run causality. Its models are presented below:

$$\begin{bmatrix} \Delta LCO2_{it} \\ \Delta LEC_{it} \\ \Delta LGDP_{it} \\ \Delta LTD_{it} \\ \Delta LUR_{it} \\ \Delta LBCO2_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_3 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix} \times \begin{bmatrix} \Delta LCO2_{it-p} \\ \Delta LEC_{it-p} \\ \Delta LGDP_{it-p} \\ \Delta LTD_{it-p} \\ \Delta LUR_{it-p} \\ \Delta LBCO2_{it-p} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{23}$$

$$\begin{bmatrix} \Delta LCO2_{it} \\ \Delta LEC_{it} \\ \Delta LGDP_{it} \\ \Delta LTD_{it} \\ \Delta LUR_{it} \\ \Delta LRCO2_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix} \times \begin{bmatrix} \Delta LCO2_{it-p} \\ \Delta LEC_{it-p} \\ \Delta LGDP_{it-p} \\ \Delta LTD_{it-p} \\ \Delta LUR_{it-p} \\ \Delta LRCO2_{it-p} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{24}$$

$$\begin{bmatrix} \Delta LCO2_{it} \\ \Delta LEC_{it} \\ \Delta LGDP_{it} \\ \Delta LTD_{it} \\ \Delta LUR_{it} \\ \Delta LINCO2_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_3 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix} \times \begin{bmatrix} \Delta LCO2_{it-p} \\ \Delta LEC_{it-p} \\ \Delta LGDP_{it-p} \\ \Delta LTD_{it-p} \\ \Delta LUR_{it-p} \\ \Delta LINCO2_{it-p} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{25}$$

$$\begin{bmatrix} \Delta \text{LCO2}_{it} \\ \Delta \text{LEC}_{it} \\ \Delta \text{LGDP}_{it} \\ \Delta \text{LTD}_{it} \\ \Delta \text{LUR}_{it} \\ \Delta \text{LCCO2}_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_3 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43,p} & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix} \times \begin{bmatrix} \Delta \text{LCO2}_{it-p} \\ \Delta \text{LEC}_{it-p} \\ \Delta \text{LGDP}_{it-p} \\ \Delta \text{LTD}_{it-p} \\ \Delta \text{LUR}_{it-p} \\ \Delta \text{LCCO2}_{it-p} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{26}$$

$$\begin{bmatrix} \Delta \text{LCO2}_{it} \\ \Delta \text{LEC}_{it} \\ \Delta \text{LGDP}_{it} \\ \Delta \text{LTD}_{it} \\ \Delta \text{LUR}_{it} \\ \Delta \text{LSAO2}_{it} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_3 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{p=-1}^{r} \begin{bmatrix} \beta_{11,p} & \beta_{12,p} & \beta_{13,p} & \beta_{14,p} & \beta_{15,p} & \beta_{16,p} \\ \beta_{21,p} & \beta_{22,p} & \beta_{23,p} & \beta_{24,p} & \beta_{25,p} & \beta_{26,p} \\ \beta_{31,p} & \beta_{32,p} & \beta_{33,p} & \beta_{34,p} & \beta_{35,p} & \beta_{36,p} \\ \beta_{41,p} & \beta_{42,p} & \beta_{43}p & \beta_{44,p} & \beta_{45,p} & \beta_{46,p} \\ \beta_{51,p} & \beta_{52,p} & \beta_{53,p} & \beta_{54,p} & \beta_{55,p} & \beta_{56,p} \\ \beta_{61,p} & \beta_{62,p} & \beta_{63,p} & \beta_{64,p} & \beta_{65,p} & \beta_{66,p} \end{bmatrix} \times \begin{bmatrix} \Delta \text{LCO2}_{it-p} \\ \Delta \text{LEC}_{it-p} \\ \Delta \text{LGDP}_{it-p} \\ \Delta \text{LTD}_{it-p} \\ \Delta \text{LUR}_{it-p} \\ \Delta \text{LSAO2}_{it-p} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix} \tag{27}$$

where i represents the cross section (number of countries), t denotes the time, ε_{it} is the error term, and ect is the lagged error correction term.

3 Empirical Results

The first step in the econometric analysis is to examine the integration by testing the stationarity of each variable. Therefore, the IPS panel and ADF unit root tests were utilized. The results of the panel unit root tests can be seen in Table 3. The results reveal that all the variables are not significant when they are integrated in order (0). Therefore, all the variables are not stationary at levels. Consequently, the null hypothesis of a unit root can be rejected. However, all the variables are significant when they are integrated in order (1). Therefore, the null hypothesis of a panel unit root can be rejected. Consequently, the variables are stationary at the first difference.

Table 3 Panel unit root test results

Variables	Level		First difference	
	Intercept	Intercept and trend	Intercept	Intercept and trend
Panel I: Im–Pesaran–Shin (IPS)				
Brazil's neighboring countries group				
LCO2	1.33493	−0.85266	−8.24695[a]	−6.87197[a]
LEC	0.59735	−1.08683	−9.04238[a]	−7.55159[a]
LGDP	4.20888	3.23508	−5.02151[a]	−3.76267[a]
LTD	3.82577	2.01786	−6.84091[a]	−5.52184[a]
LUR	−0.40395	−0.02778	−2.64557[a]	−5.76902[a]
LBCO2	3.97188	1.54592	−4.68139[a]	−2.78807[a]
Russia's neighboring countries group				
LCO2	−0.45090	0.64675	−3.86455[a]	−2.72766[a]
LEC	1.58515	0.42779	−1.98753[b]	−3.33976[a]
LGDP	0.63810	−0.22928	−2.86599[a]	−1.73431[b]
LTD	2.31043	−1.01896	−3.06177[a]	−1.56068[c]
LUR	2.16641	−1.17394	−1.84054[b]	−4.95629[a]
LRCO2	0.61032	1.65241	−3.19393[a]	−1.42470[c]
India's neighboring countries group				
LCO2	0.46390	1.01245	−3.63920[a]	−2.46275[a]
LEC	1.36543	−1.08604	−5.54199[a]	−4.43965[a]
LGDP	4.20487	−0.00354	−3.65031[a]	−2.40266[a]
LTD	0.63208	−0.70947	−7.16933[a]	−5.65416[a]
LUR	2.13282	0.44007	−4.54990[a]	−9.17220[a]
LINCO2	4.15906	1.02867	−6.50637[a]	−4.46730[a]
China's neighboring countries group				
LCO2	0.26869	−1.15974	−4.33357[a]	−3.01686[a]
LEC	0.36260	−1.10732	−2.24988[b]	−1.55251[c]
LGDP	1.10552	−1.05670	−1.96401[b]	−3.28973[a]
LTD	0.91550	−1.42392	−9.29875[a]	−8.30093[a]
LUR	1.33552	1.60143	−6.66285[a]	−4.92869[a]
LINCO2	4.15906	1.02867	−6.50637[a]	−4.46730[a]
South Africa's neighboring countries group				
LCO2	0.85794	−1.15460	−8.55598[a]	−7.51512[a]
LEC	1.20355	0.36081	−4.95260[a]	−3.53769[a]
LGDP	2.98865	0.50653	−4.02601[a]	−2.63781[a]
LTD	1.58312	−0.44869	−4.65092[a]	4.10150[a]
LUR	1.03555	−1.23040	−2.37136[a]	−3.09868
LSACO2	1.30880	1.24853	−3.61513[a]	−4.86387[a]

(continued)

Table 3 (continued)

Variables	Level		First difference	
	Intercept	Intercept and trend	Intercept	Intercept and trend
Panel II: ADF-Fisher chi-square				
Brazil's neighboring countries group				
LCO2	6.23269	13.4602	77.4895[a]	59.0532[a]
LEC	10.2311	16.9604	85.3534[a]	64.8748[a]
LGDP	1.77037	2.03466	46.3958[a]	33.9696[a]
LTD	1.63141	3.59935	63.3806[a]	47.4435[a]
LUR	13.6320	13.7095	29.3231[a]	64.9406[a]
LBCO2	0.60746	3.31281	43.7041[a]	26.5417[a]
Russia's neighboring countries group				
LCO2	27.3001	19.4637	57.3529[a]	42.2114[b]
LEC	17.4203	22.9558	73.0874[a]	53.0421[a]
LGDP	27.2928	25.9914	49.0931[a]	40.0472[c]
LTD	11.7036	32.9828	50.8389[a]	70.2085[a]
LUR	24.8121	32.8313	38.2222[c]	77.6769[a]
LRCO2	10.5136	4.19921	46.3640[a]	142.147[a]
India's neighboring countries group				
LCO2	13.1293	9.39320	40.2592[a]	29.7634[b]
LEC	12.2886	25.3493	60.7383[a]	47.7997[a]
LGDP	3.09859	16.3815	42.3526[a]	34.1312[a]
LTD	12.3054	18.8740	78.7543[a]	59.1535[a]
LUR	12.7163	13.9864	72.7183[a]	292.930[a]
LINCO2	1.07870	6.92715	70.7562[a]	46.9104[a]
China's neighboring countries group				
LCO2	13.2255	23.1386	47.7711[a]	35.0980[a]
LEC	16.2121	10.2641	29.5601[b]	23.9621[c]
LGDP	10.3171	15.8095	23.7800[c]	41.0036[a]
LTD	9.65891	19.7278	104.067[a]	86.7883[a]
LUR	18.5404	14.6259	73.7020[a]	52.4559[a]
LINCO2	1.07870	6.92715	70.7562[a]	46.9104[a]
South Africa's neighboring countries group				
LCO2	9.17012	16.8842	83.4722[a]	67.6126[a]
LEC	5.79255	7.71158	47.2262[a]	34.1202[a]
LGDP	4.41027	12.3445	39.8354[a]	27.5567[a]
LTD	5.02368	13.8489	45.6893[a]	51.6859[a]

(continued)

Table 3 (continued)

Variables	Level		First difference	
	Intercept	Intercept and trend	Intercept	Intercept and trend
LUR	4.92240	8.99287	24.9761[a]	33.24955[a]
LSACO2	7.77747	21.4997	42.0468[a]	29.7287[a]

The unit root tests were done with individual trends and intercept for each variable
Lag length was selected automatically using the Schwarz information criteria (SIC)
[a]Indicate statistical significance at the 1%
[b]Indicate statistical significance at the 5% levels
[c]Indicate statistical significance at the 10% levels

As the variables are stationary at the first difference, it is essential to investigate whether the long-run correlation between the variables does exist in the five models. Thus, the Kao cointegration test was utilized. The results of the Kao cointegration test are presented in Table 4. For the neighboring countries of Brazil, Russia, and China, the *t*-statistics show 1% of significance while for the neighboring countries of India and South Africa, the *t*-statistics is significant at the 5% level. However, the significance of the *t*-statistics for all the models implies that the null hypothesis of no cointegration can be rejected and the long-run relationship among LCO2, LEC, LGDP, LTD, LUR, and the CO2 emission of the BRICS countries exists.

As the variables are cointegrated, the next step is to examine the positive or the negative long-run elasticity between the independent variables and the dependent variable. Hence, the fully modified OLS was utilized. Table 5 displays the results of the FMOLS panel.

The results for Brazil's neighboring countries show that electricity consumption, GDP growth, trade openness, urbanization, and Brazil's CO_2 emission increase CO_2 emissions of Brazil's neighboring countries significantly in the long run. The increase in electricity consumption, GDP growth, trade openness, urbanization, and Brazil's CO_2 emissions by 1% will increase CO_2 emissions of Brazil's neighboring countries by 0.249960, 0.160261, 0.322313, 0.207915, and 0.239158%, respectively. Moreover, the results were comparable for the rest of the groups whereby all the variables increase CO_2 emissions in these groups of countries significantly in the long run. The increase in electricity consumption by 1% will increase CO_2 emissions of Russia's, India's, China's, and South Africa's neighboring countries by 0.260571, 0.102806, 0.786588, and 0.224598%, respectively. In addition, the increase in GDP growth by 1% will increase the levels of CO_2 emissions of Russia's, India's, China's, and South Africa's neighboring countries by 0.106254, 0.508670, 0.435858, and 0.154207%, respectively. Similarly, the increase in trade openness by 1% will increase CO_2 emissions of Russia's, India's, China's, and South Africa's neighboring countries by 0.049543, 0.084803, 0.233588, and 0.095377%, correspondingly. Furthermore, a 1% increase in urbanization will increase CO_2 emissions of Russia's, India's, China's, and South Africa's neighboring countries by 0.654416, 0.130598, 0.128215, and 0.025907%, respectively. Lastly, the increase in CO_2 emissions of Russia, India,

Table 4 Kao cointegration results

Brazil's neighboring countries group		*t*-statistic	Prob.
	ADF	-3.395063^{a}	0.0003
	Residual variance	0.006041	
	HAC variance	0.004228	
Russia's neighboring countries group		*t*-statistic	Prob.
	ADF	-3.842444^{a}	0.0001
	Residual variance	0.007358	
	HAC variance	0.007976	
India's neighboring countries group		*t*-statistic	Prob.
	ADF	-1.851656^{b}	0.0320
	Residual variance	0.020922	
	HAC variance	0.027390	
China's neighboring countries group		*t*-statistic	Prob.
	ADF	-2.416842^{a}	0.0078
	Residual variance	0.007546	
	HAC variance	0.007236	
South Africa's neighboring countries group		*t*-statistic	Prob.
	ADF	-1.997830^{b}	0.0229
	Residual variance	0.021583	
	HAC variance	0.012143	

The null hypothesis is that there is no cointegration among the variables
The automatic lag length selection is used based on SIC
The Newey–West automatic bandwidth selection and Bartlett Kernel are used

China, and South Africa by 1% will increase the level of CO_2 emissions of their neighboring countries by 0.528594, 0.522726, 0.279096, and 0.586294%, respectively.

Since the variables are cointegrated on all models (1–5), the Granger causality based on the VECM was utilized. Table 6 represents the VECM Granger causality test results.

For Brazil's neighboring countries, the VECM Granger causality results reveal the existence of bidirectional long-run causality between CO_2 emissions, electricity consumption, GDP growth, trade openness, and Brazil's CO_2 emissions. The same long-run causality results were found in South Africa's neighboring countries. Moreover, two-way long-run causality does exist in the long run between CO_2 emissions, GDP growth, and urbanization for Russia's neighboring countries. However, for India's

Table 5 Results of FMOLS panel

Model	Dependent variable: LCO2				
	LEC	LGDP	LTD	LUR	The BRICS LCO2
Brazil's neighboring countries group	0.249960[a] (10.20888)	0.160261[a] (4.193391)	0.322313[a] (8.427833)	0.207915[a] (9.236633)	0.239158[a] (9.259175)
Russia's neighboring countries group	0.260571[a] (11.76781)	0.106254[a] (7.921555)	0.049543[c] (1.666908)	0.654416[a] (5.312728)	0.528594[a] (5.588433)
India's neighboring countries group	0.102806[a] (4.691779)	0.508670[a] (3.294004)	0.084803[a] (6.612658)	0.130598[a] (7.414804)	0.522726[a] (8.296541)
China's neighboring countries group	0.786588[a] (3.526903)	0.435858[a] (5.965175)	0.233588[a] (6.931728)	0.128215[a] (8.276170)	0.279096[a] (5.243913)
South Africa's neighboring countries group	0.224598[a] (3.892079)	0.154207[a] (7.615094)	0.095377[b] (2.534703)	0.025907[a] (3.421373)	0.586294[a] (6.902340)

a, b, and c denote significance at the 1, 5, and 10% levels, respectively
LECP denotes the electricity production by type
Figures in the parenthesis ( ) are the *t*-statistics

neighboring countries, the bidirectional long-run causality is only present between India's neighboring countries' CO_2 emissions and India's CO_2 emissions. Also bidirectional long-run causality between electricity consumption and GDP growth was found in China's neighboring countries.

Focusing on the short-run causality, the results reveal the existence of one-way causality from electricity consumption to CO_2 emissions in the neighboring countries of Brazil, India, and South Africa. However, a unidirectional causality from CO_2 emissions to electricity consumption was found in China's neighboring countries. In addition, in the neighboring countries of Brazil, Russia, and China, the causality between GDP growth and CO_2 emissions was unidirectional from GDP growth to CO_2 emissions. However, the direction of the causality was found from CO_2 emissions to GDP growth with no feedback in South Africa's neighboring countries while feedback causality between the two variables does exist in India's neighboring countries. Moreover, a bidirectional causality was found between CO_2 emissions and trade openness in Brazil's neighboring countries, while a one-way directional causality was found from trade openness to CO_2 emissions in the neighboring coun-

Table 6 VECM Granger causality results

	Brazil's neighboring countries group						
	DLCO2	DLEC	DLGDP	DLTD	DLUR	DLBCO2	ECT(−1)
DLCO2	–	5.023687[a]	1.960093[c]	2.644566[a]	1.695803	2.118991[c]	−2.301918[b]
DLEC	1.518218	–	3.870594[a]	0.665757	0.783419	1.599097	−1.730289[c]
DLGDP	0.894577	0.613094	–	20.69669[a]	0.690816	1.408632	−1.740947[c]
DLTD	1.966228[c]	0.570536	20.50922[a]	–	0.704311	14.23570[a]	−2.047513[b]
DLUR	0.742305	1.060835	1.228463	0.463756	–	1.080985	1.224174
DLBCO2	1.159444	0.242120	2.845731[b]	14.20257[a]	0.379445	–	−2.358407[b]
	Russia's neighboring countries group						
	DLCO2	DLEC	DLGDP	DLTD	DLUR	DLRCO2	ECT(−1)
DLCO2	–	0.700715	3.089744[a]	0.207725	3.449643[a]	1.892117[c]	−1.983124[b]
DLEC	0.742704	–	3.943716[b]	0.799939	0.200404	0.323010	0.086483
DLGDP	1.635350	1.023200	–	18.94368[a]	3.140495[a]	0.614624	−1.987716[c]
DLTD	0.254445	0.812157	18.58132[a]	–	1.291137	7.120652[a]	0.084644
DLUR	1.142251	0.940305	0.320481	0.969842	–	0.754693	−7.262278[a]
DLRCO2	0.759460	0.267813	1.064401	9.381936[a]	0.835783	–	0.523391
	India's neighboring countries group						
	DLCO2	DLEC	DLGDP	DLTD	DLUR	DLINCO2	ECT(−1)
DLCO2	–	6.159449[a]	3.506260[a]	1.250316	2.276965[b]	1.150809	−4.378547[a]
DLEC	1.130841	–	2.919644[b]	2.904576[b]	3.052702[a]	1.033595	−0.660173
DLGDP	3.119817[a]	1.746534	–	3.815933[a]	1.938809[c]	0.588335	−0.261813
DLTD	0.913590	1.927185[c]	2.432525[b]	–	0.899260	0.943980	−0.128974
DLUR	1.558985	0.462457	2.006777[c]	1.224279	–	1.745695	0.099251
DLINCO2	2.440819[b]	0.679227	2.768951[b]	2.072053[c]	1.392606	–	−5.368605[a]

(continued)

Table 6 (continued)

	China's neighboring countries group						
	DLCO2	DLEC	DLGDP	DLTD	DLUR	DLCCO2	ECT(−1)
DLCO2	–	0.581110	3.330323[a]	3.770706[a]	0.760605	3.146799[a]	0.404674
DLEC	4.154943[a]	–	1.470841	0.564575	1.621484	1.834346	−2.735574[a]
DLGDP	0.712347	1.578904	–	8.110074[a]	0.311985	1.261080	−2.621553[a]
DLTD	1.591261	6.098599[a]	2.182544[c]	–	2.857208[b]	2.139315[c]	−1.314483
DLUR	1.392837	1.109855	1.498265	3.057548[a]	–	2.156600[c]	0.111509
DLCCO2	0.837051	1.610382	0.457029	2.556750[b]	0.721461	–	0.820218
	South Africa's neighboring countries group						
	DLCO2	DLEC	DLGDP	DLTD	DLUR	DLSACO2	ECT(−1)
DLCO2	–	0.466119	0.615050	0.204513	0.620155	2.254907[c]	−2.626360[b]
DLEC	2.278625[b]	–	1.596559	2.377965[b]	1.557199	14.95615[a]	0.027031
DLGDP	2.498984[c]	2.469894[c]	–	3.079841[b]	1.822640	0.237563	−2.204662[b]
DLTD	0.286729	0.544367	5.142944[a]	–	2.149956[c]	1.025298	−2.263183[b]
DLUR	1.208349	22.17632[a]	2.734011[b]	1.045260	–	1.165198	−0.049686
DLSACO2	0.235630	0.701788	1.045970	3.238531[a]	−2.891289[b]	–	−3.078753[a]

Notes The optimal lag based on the AIC. D represents the first difference. Only F-statistics for the explanatory lagged variables in first differences are reported here. The ect(−1) is based on the t-statistic, and a, b, and c denote significance at the 1, 5, and 10% levels tries of China and South Africa. The results also revealed the existence of a one-way causal relationship from urbanization to CO_2 emissions in the neighboring countries of Russia and India.

However, in China's neighboring countries, the causality was from CO_2 emissions to urbanization. Moreover, the causality from Brazil's, Russia's, China's, and South Africa's CO_2 emissions to CO_2 emissions of their neighboring countries does exist. Conversely, the causality from CO_2 emissions of India's neighboring countries to its CO_2 emissions was confirmed. Moreover, there is unidirectional causality from GDP growth to electricity consumption for Brazil, Russia, and India neighboring countries while the causality goes from electricity consumption to GDP growth in South Africa's neighboring countries. The causality between electricity consumption and trade openness is bidirectional for India's neighboring countries, while the causality is unidirectional from electricity consumption to trade openness for China's neighboring countries and from trade openness to electricity consumption in South Africa's neighboring countries. Moreover, a one-way causality was found from urbanization to electricity consumption in India's neighboring countries, while the direction of the causality was from electricity consumption to urbanization in South Africa's neighboring countries. The causality between CO_2 emissions of BRICS countries and electricity consumption of their neighboring countries does exist only in South Africa, and it is one direction from South Africa's CO_2 emissions to electricity consumption of its neighboring countries. Moreover, the causality between trade openness and GDP growth is bidirectional for all the neighboring countries of the BRICS. The causal relationship between urbanization and GDP growth is bidirectional for India's neighboring countries and unidirectional from urbanization to GDP growth for Russia's neighboring countries. However, the direction of the causality is from GDP growth to urbanization for South Africa's neighboring countries. The causality between the BRICS's CO_2 emissions and GDP growth of its neighboring countries does only exist in the neighboring countries of Brazil and India, and it is unidirectional from GDP growth to CO_2 emissions of Brazil and India. In addition, a bidirectional causality between urbanization and trade openness was found in China's neighboring countries, while causality was unidirectional from urbanization to trade openness for South Africa's neighboring countries. Lastly, there is a unidirectional causality from China's CO_2 emissions to its neighboring countries' urbanization and from the urbanization of South Africa's neighboring countries to South Africa's CO_2 emissions.

4 Discussion of Results

The results from the fully modified OLS reveal that electricity consumption, GDP growth, and urbanization are the main contributors of CO_2 emissions in the BRICS's neighboring countries in the long run. These results are consistent with most of the previous literature as these determinants are heavily dependent on energy and sizable portion of it comes from fossil fuels which are the main source of greenhouse gas emission. Moreover, CO_2 emissions from the BRICS countries increase CO_2 emissions of its neighboring countries in the long run. This shows that rapid increase in the economic activities that the BRICS countries had witnessed not only increases its greenhouse gas emission but also the greenhouse gas emission of its neighboring countries. Thus, it is clear that air pollution can travel to neighboring countries for long distances due to the air movement. Moreover, the Granger causality also revealed that electricity consumption, GDP growth, trade openness, and urbanization have positive causal effects on CO_2 emissions in most of the BRICS's neighboring countries. In addition, CO_2 emissions of Brazil, Russia, China, and South Africa have a positive causal effect on CO_2 emissions of its neighboring countries. However, for the case of India, CO_2 emissions of its neighboring countries have positive causality influence on India's CO_2 emissions.

Moreover, the main determinants of CO_2 emissions of the BRICS's neighboring countries have positive causal effects on CO_2 emissions of the BRICS countries. For instance, GDP growth of Brazil's neighboring countries has a positive causal effect on Brazil's CO_2 emissions. Moreover, the increase in Russia's neighboring countries trade causes an increase in Russia's CO_2 emissions, while the increase in urbanization and GDP growth of India's neighboring countries will increase India's CO_2 emissions. Furthermore, urbanization of China's neighboring countries will cause an increase in China's CO_2 emissions, and also the increase in urbanization and trade openness in South Africa's neighboring countries will increase South Africa's CO_2 emissions.

The results in general reveal that there is a trade of pollution between the BRICS countries and their neighboring countries. Moreover, the economic activities of the neighboring countries (electricity consumption, GDP growth, trade openness, and urbanization) can influence the pollution levels of BRICS countries. Furthermore, the economic activities of BRICS countries may also have an effect on their neighboring countries.

5 Conclusion and Policy Implications

This study investigated whether air pollution of BRICS countries influences air pollution of its neighboring countries. To achieve the study's goal, five panel models were built taking the period of 1990–2013. The study utilized CO_2 emissions as an indicator of air pollution and electricity consumption, GDP growth, trade openness, urbanization, and CO_2 emissions of BRICS countries as the main determinants. Based on the Kao cointegration test results, the mentioned above variables are cointegrated, which indicates the existence of the long-run relationship between the variables. Moreover, the fully modified OLS (FMOLS) results indicate that electricity consumption, GDP growth, trade openness, and urbanization increase CO_2 emissions in the long run. In addition, the FMOLS results also confirm that CO_2 emissions of the BRICS countries increase CO_2 emissions of its neighboring countries. Moreover, the VECM Granger causality reveals that the BRICS countries' CO_2 emissions have causal relationships with their neighboring countries' CO_2 emissions. Moreover, the results also reveal that the economic activities (electricity consumption, GDP growth, trade openness, and urbanization) have causal effects on CO_2 emissions of BRICS countries in the most cases.

From the outcomes of this research, a number of policy recommendations can be provided for the investigated countries. Since fossil fuels play a sizable portion of the total electricity generation, not only for BRICS countries but also for the neighboring countries, these countries should reduce their consumption of fossil fuels to decrease the trade of air pollution between the countries. Thus, the reduction in fossil fuels as well as substituting carbon fossil fuels with cleaner-type energy sources, such as natural gas and higher-grade coal, are effective solutions to reduce air pollution. In addition, replacing fossil fuels with renewable sources of energy can also help to lessen air pollution levels in the BRICS countries. Moreover, it is essential for the BRICS countries to increase their national laws and regulations for the purpose of protecting their environment. However, these laws and regulations will be less effective on the air pollution that is transported from another country. Hence, creating and applying the same environmental laws and regulations can help BRICS and their neighboring countries tackle trans-boundary air pollution. This can be done by creating a union between the BRICS countries and their neighboring countries to establish laws and regulations that are designed to effectively reduce pollution levels. In addition, a similar type of Kyoto protocol between BRICS countries and its neighbors can also be helpful to reduce the effects of pollution in the region.

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Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation

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Abstract This study examines the validity of the environmental Kuznets curve (EKC) hypothesis by augmenting the model with renewable energy consumption, fossil fuel energy consumption, urbanization, and deforestation. The ten countries that jointly own two-thirds of the global forest area are studied over the period of 2000–2015. This study fills the gap in the environmental economics literature by introducing deforestation for the first time as a variable affecting environmental degradation, instead of as a measure of environmental degradation. The long-run equilibrium relationship between the variables was confirmed by Kao (J Econ 90(1):1–44, [40])and Pedroni (Fully modified OLS for heterogeneous cointegrated panels. Emerald Group Publishing Limited, 93–130, [59]) panel cointegration tests. Fully modified ordinary least squares' (FMOLS) results support the validity of the deforestation-induced EKC hypothesis, and the pairwise Dumitrescu and Hurlin Granger causality test suggests the existence of a causal relationship among the variables. The empirical results suggest that policies which induce afforestation—such as afforestation grants, tax exemptions for plantations, and tariffs on imports for forest products—are crucial to reducing the carbon dioxide (CO_2) emissions in host countries.

Keywords Environmental Kuznets curve · Deforestation · FMOLS · Granger causality

JEL Codes C23 · Q53 · Q58

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1 Introduction

The world has seen serious changes in its biosphere. In the 1700s, approximately 50% of the world biosphere was wild, and about 45% was in a semi-natural state. However, these percentages have nearly reversed themselves. By 2000, about 55% of the terrestrial biosphere had been converted into either human settlements or agricultural land, 20% remained in a semi-natural state, and only about 25% was in a purely natural state [29]. This drastic change in the natural order has brought many changes to the environment, the most significant of which is increased greenhouse gas (GHG) emissions. The negative effect of GHGs on the environment is well-established in the environmental economics literature.

Many human-induced factors, such as burning fossil fuel for electricity, transportation, heat, and industry, are major causes of GHG emissions. Approximately one-quarter of the total amount of human-induced GHG emissions is attributable to the agriculture, forest, and other land-use sectors, with deforestation being the biggest contributor [73]. Deforestation is, in fact, the second highest human-induced cause of carbon emissions, even higher than the entire world transportation sector emissions and only lower than the emissions from the global energy sector [79]. The forest biomass absorbs carbon dioxide (CO_2) emissions from the atmosphere, and about 300 billion ton (approximately 30 times the per annum emissions from burning fossil fuels) are stored up in this biomass [21]. About three billion tons of carbon is estimated to be released yearly into the air as a result of deforestation [10, 36]. A possible cost-effective policy option for carbon emission control that is often overlooked is deforestation management. Stern [75] claims that a single hectare of forest is valued at approximately 25,000 USD in terms of its carbon sequestration ability, whereas each ton of CO_2 emissions released into the atmosphere is valued at about 85 USD in terms of its negative impact on the world economy.

The Kuznets curve concept was first introduced by Kuznets [47] when he asserted that there was a relationship between per capita income and income inequality. He further claimed that the relationship produces an inverted U-shaped curve, suggesting that income inequality rises to a maximum and then begins to decline as per capita income increases over time. His idea was eventually adopted by the environmental policy literature in the 1990s as a means for studying the relationship between environmental quality and per capita income. Grossman and Krueger [33] were the first to uncover the existence of an inverted U-shaped association between pollution and per capita income. Not long afterward, Shafik and Bandyopadhyay [69] also put forward evidence in support of an inverted U-shaped association between the quality of the environment and economic growth by tracing the environmental transformation patterns of nations at various levels of national income. Panayotou [58] similarly investigated the growth-environmental quality relationship and, like others before him, also found an inverted U-shaped relationship between the variables. It was he who named the environmental Kuznets curve (EKC). Following the precedent set by these pioneering empirical studies, a generation of EKC empirical studies also examined the income-environmental quality nexus with a focus on only these two variables [34, 67, 68]. Figure 1 graphically represents the main idea of the EKC hypothesis.

Over time, several patterns of augmentation of the traditional EKC model have emerged. The first set of researchers augmented the EKC model with energy consumption. The argument for this is that energy consumption, economic growth, and pollution are intricately intertwined and therefore should be studied within an integrated framework. Most of these studies focused primarily on total fossil fuel energy consumption as the most significant measure of energy consumption [1, 6, 17, 20, 44, 66, 76, 80]. Others have used specific forms of energy consumption in their studies, such as coal consumption [78], natural gas consumption [74], and electricity consumption [49, 65].

Researchers have built expanded significantly on these earlier studies by extending the traditional EKC model with macroeconomic, demographic, and institutional variables. For example, Chang [18] augmented his model with labor and capital. Al-Mulali et al. [5], in addition to labor and capital, also factored in foreign trade. Solarin et al. [74] and Tang and Tan [77] all included foreign direct investment in their studies. Trade openness has also been extensively used in EKC studies (see Jalil and Mahmud [38], Kohler [45], Lau et al. [48], Shahbaz et al. [70]. Examples of studies that model demographic variables in addition to the traditional EKC variables include the following: Ahmed and Long [2], Azam and Khan [9], Kang et al. [39], and Onafowora and Owoye [56]. Also, Apergis and Ozturk [7], Ozturk and Al-Mulali [57], and Yin et al. [82] augmented their models with institutional variables.

Several studies have examined deforestation within the EKC framework. Their approach, however, has mainly been to treat deforestation as a measure of environmental degradation rather than as an explanatory variable. According to Miah et al. [54], the inverted U-shape observed for deforestation is due to the fact that the people

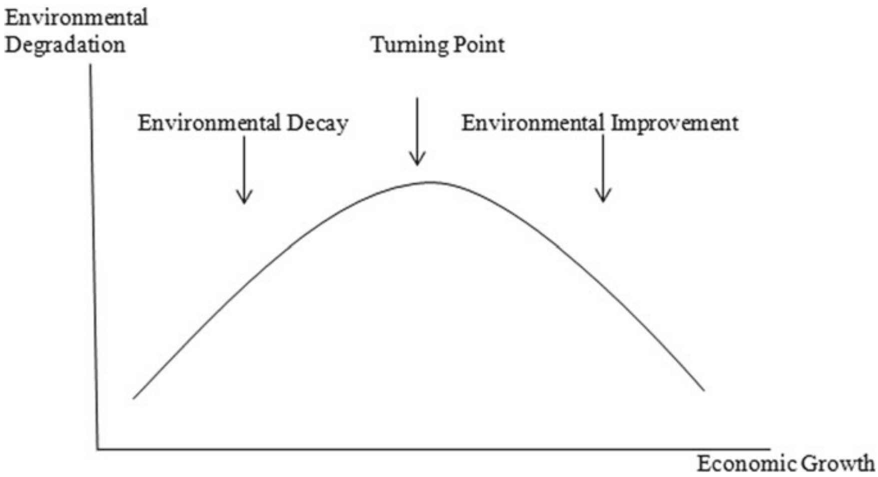

Fig. 1 Environmental Kuznets curve

who depend largely on forest products are at the lower levels of income per capita, but, beyond a certain income level, forest products begin to be replaced with substitutes which have no negative impact on forests. Studies treating deforestation as an environmental degradation indicator include Benedek and Fertő [12], Bhattarai and Hammig [13], Culas [22, 23], Galinato and Galinato [31], Koop and Tole [46], and Polomé and Trotignon [64]. The general consensus of these studies is that deforestation is strongly correlated with economic growth. For example, Ehrhardt-Martinez et al. [28] investigated the sources of EKC for deforestation relative to the economic performance of developing countries from 1980 to 1995; when applying ordinary least squares (OLS) estimation techniques, they found strong evidence in support of the inverted U-shaped EKC. Ahmed et al. [3] examined the EKC hypothesis in Pakistan from 1980 to 2013 by applying time series estimation techniques, such as the autoregressive distributed lag (ARDL) bounds test for the level relationship, and the results suggested a level relationship between growth and deforestation, in addition to a few other variables. Their results also showed that the economic growth Granger-causes deforestation. Table 1 summarizes the literature on the EKC augmentation pattern.

It stands to reason that the traditional EKC model should be augmented with deforestation for two reasons: (1) Deforestation is a major source of carbon emissions, and (2) deforestation is correlated with economic growth. Therefore, not explicitly controlling for the effects of deforestation in a typical EKC model will result in an omitted variable bias and a violation of the zero conditional mean assumption. Our argument is that deforestation, economic growth, and environmental degradation are closely interrelated and, thus, deserve to be studied within a single framework. Consequently, the aim of this study is to test the validity of the EKC hypothesis when the EKC model is augmented with deforestation and other common EKC variables over the period of 2000–2015 for the ten countries that jointly own two-thirds of

Table 1 Summary of EKC augmentation literature

Author	Period	Country/region	Methodology	Variables	EKC hypothesis
Ahmed et al. [3]	1980–2013	Pakistan	ARDL, VECM Granger causality	DEF, economic growth, EC, trade openness, population	Yes
Al-mulali et al. [5]	1981–2011	Vietnam	ARDL	CO_2, GDP, fossil fuels EC, renewable EC, capital, labor, export, imports	No

(continued)

Table 1 (continued)

Author	Period	Country/region	Methodology	Variables	EKC hypothesis
Ang [6]	1960–2000	France	ARDL, VECM Granger causality	CO_2, GDP, GDP^2, EC	Yes
Apergis and Ozturk [7]	1990–2011	14 Asian countries	GMM	CO_2, GDP, GDP^2, population density, land, industry shares in GDP, quality of institutions indicators	Yes
Atasoy [8]	1960–2010	USA	AMG, CCEMG	CO_2, GDP, GDP^2, EC, population	Yes
Azam and Khan [9]	1975–2014	Tanzania, China, Guatemala, USA	OLS	CO_2, GDP, energy usage, trade openness, trade volume, urbanization growth rate	Yes for low-income countries
Bakirtas and Cetin [11]	1982–2011	MIKTA countries	PVAR, PVAR Granger causality	CO_2, GDP, GDP^2, EC, FDI	No
Benedek and Fertő [12]	1990–2010	67 countries where forest cover increased between 1990 and 2010	OLS, instrumental variables	Forest cover change and DEF index, GDP, GDP^2, trade in forestry, economic freedom, protected area coverage, arable land	Yes

(continued)

Table 1 (continued)

Author	Period	Country/region	Methodology	Variables	EKC hypothesis
Bhattarai and Hammig [13]	1972–1991	66 countries of Latin America, Africa, and Asia	FE	DEF, GDP^2, GDP^3, political institution, black market forex, debt, population, change in cereal yield	Yes
Bilgili et al. [14]	1977–2010	17 OECD countries	Panel DOLS, FMOLS	CO_2, GDP, GDP^2, renewable energy	Yes
Chang [18]	2000–2010	G-7, Brazil, Russia, India, China, and South Africa	Data envelopment analysis	CO_2, GDP, labor, capital, energy use	No
Cho et al. [20]	1992–2004	132 developed and developing countries	OLS	CO_2, GDP, GDP^2	Yes
Culas [22]	1972–1994	14 tropical developing countries from Latin America, Africa, and Asia	Pooled regression, FE, RE	DEF, GDPPC, $GDPPC^2$, contract enforceability, absolute forest area, proportion of forest area, population, agricultural production, export price index	Yes
Culas [23]	1970–1994	43 countries from Latin America, Africa, and Asia	Pooled regression, FE, RE	DEF, GDPPC, $GDPPC^2$, GDP growth, absolute forest area, proportion of forest area, population density, agricultural production, foreign debt, export price, time trend	Mixed results

(continued)

Table 1 (continued)

Author	Period	Country/region	Methodology	Variables	EKC hypothesis
Dogan and Turkekul [26]	1960–2010	USA	ARDL	CO_2, GDP, GDP^2, EC, trade openness, urbanization, FD	No
Ehrhardt-Martinez et al. [28]	1980–1995	LDCs with available forest cover estimates that experienced net deforestation between 1980 and 1995	OLS	DEF rate, forest stock, population pressure R/U migration, labor in services, secondary education, protected areas, government scope, democracy, debt level/GDP, change in debt, forest exports/GDP, forest export/global forest exports, forest import/global forest imports, imports/export	Yes
Galinato and Galinato [31]	1990–2003	22 countries from Latin America and Asia	OLS, FE, RE	Crop area harvested, GDPPC, crop price index, FDI, political stability, corruption control index, trade openness, unpaved road, investment price	No

(continued)

Table 1 (continued)

Author	Period	Country/region	Methodology	Variables	EKC hypothesis
Gill et al. [32]	1970–2011	Malaysia	ARDL	CO_2, GDP, GDP^2, portion of renewable energy in total energy production	Yes
Jalil and Mahmud [38]	1975–2005	China	ARDL, pairwise Granger causality	CO_2, GDP, GDP^2, EC, trade openness	Yes
Katircioğlu and Katircioğlu [44]	1960–2013	Turkey	ARDL, Maki cointegration	CO_2, GDP, GDP^2, EC, urban population	No
Katircioğlu [43]	1971–2010	Singapore	Maki cointegration, DOLS, VECM Granger causality	CO_2, energy use, GDP, GDP^2, total number of international tourists	Yes
Kasman and Duman [42]	1992–2010	New EU member and candidate countries	Panel FMOLS	CO_2, GDP, GDP^2, EC	Yes
Kohler [45]	1960–2009	South Africa	ARDL, Johansen cointegration, VECM, Granger causality	CO_2, GDP, GDP^2, EC, trade openness	Yes
Koop and Tole [46]	1961–1992	76 developing countries	Pooled regression, FE, RE	DEF, GDPPC, $GDPPC^2$, change in GDP, population density, change in population	No
Lau et al. [48]	1970–2008	Malaysia	ARDL, VECM Granger causality	CO_2, GDP, GDP^2, FDI, trade openness	Yes

(continued)

Table 1 (continued)

Author	Period	Country/region	Methodology	Variables	EKC hypothesis
Lean and Smyth [49]	1980–2006	ASEAN	Johansen-Fisher panel cointegration, DOLS, VECM Granger causality	CO_2, GDP, GDP^2, electricity consumption	Yes
Liu et al. [52]	1970–2013	ASEAN	Pedroni, Kao cointegration, OLS, DOLS, FMOLS, VECM Granger causality	CO_2, GDP, GDP^2, renewable energy, agriculture	No
Onafowora and Owoye [56]	1970–2010	Brazil, China, Egypt, Japan, Mexico, Nigeria, South Korea, and South Africa	ARDL, VECM Granger causality	CO_2, GDP, GDP^2, EC, trade openness, population	Yes for Japan and South Korea
Ozturk and Al-mulali [57]	1996–2012	Cambodia	GMM, TSLS	GDP, urbanization, trade openness, control of corruption, governance	No
Polomé and Trotignon [64]	1975–2014	Brazil	VECM	DEF, GDPPC, $GDPPC^2$	No
Saboori and Sulaiman [65]	1980–2009	Malaysia	ARDL, Johansen cointegration, VECM Granger causality	CO_2, GDP, GDP^2, total energy, coal, gas, electricity, oil consumption	No
Shahbaz et al. [71]	1980–2010	Romania	ARDL	CO_2, GDP, GDP^2, EC	Yes
Shahbaz et al. [70]	1971–2009	Pakistan	ARDL, Gregory–Hansen cointegration, VECM Granger causality	CO_2, GDP, GDP^2, EC, trade openness	Yes

(continued)

Table 1 (continued)

Author	Period	Country/region	Methodology	Variables	EKC hypothesis
Shahbaz et al. [72]	1971–2011	Malaysia	ARDL, VECM Granger causality	CO_2, EC, FD, FD square, trade openness, FDI	Yes
Tan et al. [76]	1975–2011	Singapore	Johansen cointegration, VAR Granger causality	CO_2, GDP, GDP^2, EC	No
Tang and Tan [77]	1976–2009	Vietnam	Johansen cointegration, VECM Granger causality	CO_2, GDP, GDP^2, EC, FDI	Yes
Tiwari et al. [78]	1966–2011	India	ARDL, Johansen cointegration, VECM Granger causality	CO_2, GDP, GDP^2, coal consumption, trade openness	Yes
Wang et al. [80]	1995–2007	China	Pedroni cointegration test, VECM Granger causality	CO_2, GDP, GDP^2, EC	Yes
Yin et al. [82]	1980–2012	China	Pooled regression, FE, RE	CO_2, GDPPC, $GDPPC^2$, regulation, technological progress, population, energy efficiency, energy structure, industrial structure, trade, FDI	Yes

the global forest area. Other variables included for control are renewable energy consumption, fossil fuel energy consumption, and urbanization. To the best of our knowledge, this is the first instance in the EKC literature that deforestation has been introduced as an independent variable affecting environmental degradation, instead of as a measure of environmental degradation.

The remainder of this study is organized as follows: Sect. 2 provides information about data, model specification, and methodology; Sect. 3 summarizes the empirical results of the study; and the conclusion and policy implications are discussed in Sect. 4.

2 Data, Model Specification, and Methodology

The ten countries (Australia, Brazil, Canada, China, Congo, India, Indonesia, Peru, Russia, and the USA) that jointly account for two-thirds of the world's forest area, based on Food and Agriculture Organization (FAO) statistics, were chosen as the sample for this study. Annual data from these ten countries, covering the years 2000–2015, were obtained for seven variables and were dependent on their availability. In our model, in addition to CO_2 emissions, gross domestic product (GDP), the square of GDP, we included deforestation, urbanization, renewable energy consumption, and fossil fuel energy consumption, which are generally accepted as determinants of pollution and extensively used in EKC literature. The EKC literature has established that both urbanization and energy consumption cause increases in carbon emissions [51, 81], while increased use of renewable energy forms lowers the level of carbon emissions [55, 83]. Table 2 represents the variables, measures, and expected impacts of the independent variables on the dependent variable.

Table 2 List of variables

Variable	Measure	Notation	Expectation
Dependent variable			
Carbon dioxide emissions	CO_2 emissions (metric ton per capita)	CO_2	
Independent variables			
Gross domestic product	GDP per capita	GDPPC	+
Squared gross domestic product	(GDP per capita)^2	GDPPC^2	–
Deforestation	Forest area (% of land area)	DF	–
Fossil fuel energy consumption	Fossil fuel energy consumption (% of total)	FOSS	+
Renewable energy consumption	Renewable energy consumption (% of total)	REN	–
Urbanization	Urban population (% of total)	UR	+

The following econometric model is specified in order to test the augmented EKC hypothesis:

$$\begin{aligned}\mathrm{LCO}_{2it} = \beta_0 + \beta_1 \mathrm{LGDPPC}_{it} + \beta_2 \mathrm{LGDPPC}^2_{it} + \beta_3 \mathrm{LUR}_{it} \\ + \beta_4 \mathrm{LREN}_{it} + \beta_5 \mathrm{LFOSS}_{it} + \beta_6 \mathrm{LDF}_{it} + \varepsilon_{it},\end{aligned} \quad (1)$$

where LCO_{2it}, LGDPPC_{it}, LGDPPC^2_{it}, LUR_{it}, LREN_{it}, LFOSS_{it}, and LDF_{it} are the logarithmic forms of CO_2 emissions, GDP per capita, squared GDP per capita, urbanization, renewable energy consumption per capita, fossil fuel energy consumption per capita, and deforestation, respectively.

2.1 Panel Unit Root Tests

The panel unit root tests of Levin–Lin–Chu (LLC) [50], Im, Pesaran and Shin (IPS) [37], and ADF–Fisher chi-square test (ADF–Fisher) are applied to test for the presence of panel stationarity. All these tests have a null hypothesis that there is a unit root against the alternative that variables are stationary. The most widely used of these tests is the one created by Levin et al. [50], given as:

$$\Delta y_{it} = \alpha_i + \beta_i y_{it-1} + \sum_{j=1}^{p_i} p_i \Delta y_{it-j} + e_{it}, \quad (2)$$

where Δy_{it} is the difference of y_{it} for ith country in time period $t = 1, \ldots, T$. This test is based on the assumption of homogeneity such that $H_0 : \beta = \beta_i = 0$.

The test of Im et al. [37] introduces heterogeneity into Eq. (2) by allowing β_i vary across cross sections; i.e., under the alternative hypothesis, some but not all of the individual series may be non-stationary. The nonparametric, heterogeneous Maddala and Wu [53], Fisher [30] test based on p values is our final panel unit root test. The test statistic is shown as:

$$p = -2 \sum_{i=1}^{N} \ln \beta_i \quad (3)$$

2.2 Panel Cointegration Test

Cointegration tests of Kao [40] and Pedroni [59] are conducted to check the existence of a long-run relationship among variables. The Kao test is a parametric, residual-based test for the null hypothesis of no cointegration. It is founded on LSDV regression equation given as:

$$y_{it} = \alpha_i + \beta X_{it} + e_{it} \tag{4}$$

Dickey-Fuller [24] and augmented Dickey-Fuller [25] tests are applied to the residuals obtained from the estimation of the regression equation. All the five variations of the Kao test slope coefficient (β) are cross-sectional invariant. Pedroni [59]—also a residual-based cointegration test for the null of no cointegration—relaxes the homogeneity assumption of Kao [40]. The underlying Pedroni [59] regression equation is specified thus:

$$y_{it} = \alpha_i + \delta_i t + \beta_i X_{it} + e_{it}, \tag{5}$$

where α_i, δ_i and β_i are free to vary across cross sections. Two types of statistics are considered by Pedroni [59] based on the method of pooling residuals obtained from Eq. (5); the first type pools the obtained residuals on the within dimension (homogenous panel cointegration statistics), and the second type on the other hand pools the obtained residuals along the between dimension (heterogeneous group mean statistics).

2.3 Estimating the Cointegration Relationship with Weighted FMOLS

We use fully modified ordinary least squares (FMOLS) to estimate cointegrated panel regressions [19]. FMOLS is a very commonly used panel estimation technique. It is a nonparametric approach that produces optimal cointegrating regression results [63], and it is designed to make adjustments for serial correlation and endogeneity due to the presence of cointegrating relationships [62]. We adopt the Pedroni [60] and Kao and Chiang [41] pooled FMOLS estimators for heterogeneous panels that are cointegrated (weighted FMOLS). The approach allows changes in long-run variances across cross sections. The corresponding estimator and asymptotic covariance are given, respectively, as:

$$\hat{\beta}_{fw} = \left[\sum_{i=1}^{N} \sum_{t=1}^{T} X_{it}^{*} X_{it}^{*'} \right]^{-1} \sum_{i=1}^{N} \sum_{t=1}^{T} \left(X_{it}^{*} y_{it}^{*} - \lambda_{12i}^{*'} \right) \tag{6}$$

$$\widehat{V}_{fw} = \left[\frac{1}{N} \sum_{i=1}^{N} \left[\frac{1}{T^2} \sum_{t=1}^{T} X_{it}^{*} X_{it}^{*'} \right] \right]^{-1} \tag{7}$$

2.4 Panel Granger Causality Tests

The presence of cointegration is an indication that causal relationships possibly exist between the variables. To detect the existence and direction of causal relationships, we adopt the Dumitrescu and Hurlin [27] Granger causality test. The general form of the multivariate regressions in panel Granger causality testing is:

$$\begin{aligned} y_{it} &= \alpha_{0i} + \alpha_{1i} y_{it-1} + \cdots + \alpha_{li} y_{it-1} + \beta_{1i} X_{it-1} + \cdots \\ &\quad + \beta_{1i} X_{it-1} + \cdots + \beta_{2i} Z_{it-1} + \cdots \beta_{2i} Z_{it-1} + \varepsilon_{it} \end{aligned} \tag{8}$$

$$\begin{aligned} X_{it} &= \alpha_{0i} + \alpha_{1i} X_{it-1} + \cdots + \alpha_{li} X_{it-1} + \beta_{1i} y_{it-1} + \cdots \\ &\quad + \beta_{1i} y_{it-1} + \cdots + \beta_{2i} Z_{it-1} + \cdots \beta_{2i} Z_{it-1} + \varepsilon_{it} \end{aligned} \tag{9}$$

$$\begin{aligned} Z_{it} &= \alpha_{0i} + \alpha_{1i} Z_{it-1} + \cdots + \alpha_{li} Z_{it-1} + \beta_{1i} X_{it-1} + \cdots \\ &\quad + \beta_{1i} X_{it-1} + \cdots + \beta_{2i} y_{it-1} + \cdots \beta_{2i} y_{it-1} + \varepsilon_{it} \end{aligned} \tag{10}$$

Under the Dumitrescu and Hurlin [27] panel causality test, Granger causality regressions are performed for each of the cross sections from which test statistic averages are generated.

2.5 Cross-Sectional Dependence Test

Asymptotic and finite sample properties of panel unit root and cointegration tests applied in this study are based on the assumption that there is no cross-correlation between the error terms (zero error covariance). A relaxation of the cross-sectional dependence assumption means that the variance–covariance matrix will likely increase with the number of cross sections and consequently, and the test distributions will become invalid [16]. Commonly used cross-sectional dependence tests include Breusch and Pagan [15] LM, Pesaran [61] scaled LM, and Pesaran [61] CD tests. We apply the Pesaran [61] CD test since it deals with the size distortion problem present in the others. The Pesaran CD test is formulated from pairwise correlation coefficient averages for the null of no cross-sectional dependence and is shown as:

$$\mathrm{CD_p} = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij} \hat{\rho}_{ij} \rightarrow N(0, 1) \tag{11}$$

3 Empirical Results

Initially, we applied the Pesaran cross-sectional dependence (CD) test, and the insignificant *p* value (0.13) shows that our data do not suffer from cross-correlated error terms, thus justifying the application of first-generation models. Next, we performed several unit root tests to determine the order of integration of the variables as a precondition for panel cointegration tests. We tested all of the variables both with and without trend and both in level and first differences. Our test results predominantly indicate the presence of unit roots at the level and the absence of unit roots at first difference. Unit root test results are presented in Table 3.

Following the confirmation that all variables were integrated of order one, I(1), we proceeded to the cointegration test to determine the existence of long-run relationships among the variables. Table 4 presents the Kao [40] and Pedroni [59, 60] cointegration test results. Considering first the homogenous panel cointegration tests, two out of four Pedroni tests within dimension-based tests (panel PP-statistic and panel ADF-statistic), and Kao tests, we found that all document the presence of a long-run relationship among the variables. More importantly, the heterogeneous (between dimension-based) cointegration tests are more realistic, and two out of three indicate that the variables are cointegrated. Furthermore, we based our final conclusion that the variables are cointegrated on the result of the group PP-statistic which is both heterogeneous and nonparametric, especially as nonparametric tests are suitable for data that are not normally distributed, and also because it has the most power in the Pedroni and Kao tests [35].

We continued on to estimate the coefficients of long-run relationship with a FMOLS estimator, and the results are shown in Table 5. This is also a nonparametric estimation technique and is valid even when the normality assumption does not hold. The results obtained are interesting. First, in conformity with the EKC hypothesis, GDP per capita and its square have significant positive and negative coefficients, respectively. Based on the results, a percentage increase in these variables will cause carbon emission to increase and decrease by 0.46 and 0.02%, respectively. A coefficient of −0.41 for deforestation suggests that, for each percentage increase in the ratio of forest to land area which indicates less deforestation, CO_2 emissions are expected to decrease by 0.41%. This result is significant at 1% and also in agreement with our a priori expectation. Second, we observed a negative and significant long-run relationship between renewable energy consumption and carbon emission—a percentage rise in renewable energy consumption results in a 0.33% decline in carbon emissions, justifying the argument of Al-Mulali et al. [4] for the inclusion of renewable energy consumption in the EKC framework. It is also in concert with the findings of Myers et al. [55] and Zhai et al. [80]. Third, both fossil fuel consumption and urbanization are also found to positively affect the level of carbon emissions. In the long run, a 1% increase in both variables will cause CO_2 emissions to increase by 1.14 and 1.56%, respectively. This is in consonance with the findings of Li and Yao [51], and Wei et al. [81]. Both fossil fuel consumption and urbanization are shown to be the most powerful influences on carbon emissions within the model.

Table 3 Panel unit root analysis

Variables		LLC		IPS		ADF–Fisher chi-square	
		No trend	Trend	No trend	Trend	No trend	Trend
Level	LCO2	−1.11242	−0.11169	3.56829	0.52931	8.3737	13.0064
	LDF	−0.34715	−3.1482***	1.71590	−0.32842	15.9776	23.2238
	LGDPPC	−2.933***	4.97634	0.40682	5.25693	13.1271	3.29380
	LGDPPC2	−2.5117***	4.75068	−2.51171	4.9012	11.6324	3.91071
	LFOSS	−1.13918	−0.6818	0.51804	0.61357	18.4436	17.4781
	LREN	−0.7426	3.13589	1.50971	2.01233	14.6255	6.96493
	LUR	2.89047	7.43263	3.50667	7.37388	20.2213	9.34919
1st difference	ΔLCO2	−13.353***	−11.806***	−9.3305***	−7.3396***	98.3720***	80.6701***
	ΔLDF	−1709.1***	−1031.0***	−370.30***	−309.47***	45.7961***	40.1419***
	ΔLGDPPC	2.42980***	−5.3502***	−2.3439***	−1.54191*	33.3142**	29.9079*
	ΔLGDPPC2	−2.5674***	−4.8561***	−2.4386***	−1.14284	34.0972**	27.5231
	ΔLFOSS	−8.1080***	−9.8876***	−6.8682***	−6.2221***	79.1836***	70.2830***
	ΔLREN	−9.2318***	−12.113***	−7.3162***	−7.0152***	82.4323***	77.2796***
	ΔLUR	7.61161	−45.883***	4.88611	−25.362***	6.34362	86.8213***

Notes (1) *, **, and *** mean statistic relationship significant at 10, 5, 1%, respectively; (2) Levin, Lin, and Chu t^* presuppose a common unit root process; (3) Im, Pesaran and Shin W-stat, and ADF–Fisher chi-square presupposes individual unit root process; (4) Δ denotes the first difference

Table 4 Panel cointegration analysis

	Within dimension (homogenous)			Between dimension (heterogeneous)	
No trend	Tests	Statistic	Weighted statistic	Tests	Statistic
Pedroni [59, 60]	Panel v-statistic	−2.538274	−3.462572	Group rho-statistic	4.954619
	Panel rho-statistic	3.749107	3.642602	Group PP-statistic	-13.20545^{***}
	Panel PP-statistic	-1.774534^{**}	-9.746416^{***}	Group ADF-statistic	-2.629404^{***}
	Panel ADF-statistic	−0.456837	-3.002905^{***}		
Kao [40]	ADF t-statistic -4.526694^{***}				
Trend	Tests	Statistic	Weighted statistic	Tests	Statistic
Pedroni [59, 60]	Panel v-statistic	−3.330932	−4.639787	Group rho-statistic	5.473123
	Panel rho-statistic	4.144648	4.270092	Group PP-statistic	-15.26644^{***}
	Panel PP-statistic	-10.40605^{***}	-15.55456^{***}	Group ADF-statistic	-3.560869^{***}
	Panel ADF-statistic	-4.062218^{***}	-4.415027^{***}		

Notes (1) **, and *** mean statistic relationship is significant at 10 and 5%, respectively; (2) 160 observations; (3) automatic lag length based on Schwarz information criterion for lag selection is used

Table 5 FMOLS results

Regressors	Coefficient	Standard error	p value
LDF	−0.413557	0.008891	0.0000
LFOSS	1.138035	0.047426	0.0000
LGDPPC	0.460709	0.020295	0.0000
LGDPPC2	−0.022049	0.010746	0.0430
LREN	−0.332514	0.016707	0.0000
LUR	1.556768	0.000421	0.0000
R-squared	0.99759		
S.E. of regr.	0.07047		
D-W-stat.	1.71623		
Long-run variance	0.00096		

Notes (1) Long-run covariance is estimated via the Bartlett kernel and the Newey–West fixed bandwidth; (2) pooled (weighted) panel estimator for heterogeneous panels is used

Table 6 Pairwise Dumitrescu and Hurlin Granger causality test

	LCO2	LDF	LGDPPC	LGDPPC2	LFOSS	LUR	LREN
LCO2	–	0.8224	0.0613*	0.0499**	0.0174**	0.7756	0.1612
LDF	0.0545*	–	0.2511	0.3276	0.1212	0.5832	0.0601**
LGDPPC	0.0262**	0.4645	–	0.9707	0.5266	0.8624	0.0318**
LGDPPC2	0.0501*	0.3618	0.9136	–	0.5702	0.9215	0.0237**
LFOSS	0.0069***	0.9907	0.0582*	0.0912*	–	0.9403	0.8419
LUR	0.0375**	0.7229	0.3551	0.4037	0.382	–	0.0708*
LREN	0.4613	0.5634	0.0783*	0.0726*	0.3938	0.5519	–

Note *, **, and *** mean statistic relationship significant at 10, 5, 1%, respectively

Furthermore, since the cointegration tests results indicate that the variables are cointegrated, we also carried out Granger causality tests in order to determine causal relationship among the variables; Table 6 presents the test results. We infer bidirectional long-run causality for the following variables: carbon emissions and GDP per capita, carbon emissions and squared GDP per capita, carbon emissions and fossil fuel consumption, renewable energy and GDP per capita, and renewable energy and second power of GDP per capita. The unidirectional causality was found, running from urbanization to carbon emissions, deforestation to renewable energy consumption, fossil fuel consumption to GDP per capita, fossil fuel consumption to GDP per capita, urbanization to renewable energy, and, most importantly, from deforestation to carbon emissions. The unidirectional causality from deforestation to carbon emissions provides additional evidence in support of the results obtained from the FMOLS estimations about the relationship between both variables' consumption.

4 Conclusion

The intent of our study is to explore how deforestation influences pollution, and also to determine if the EKC hypothesis holds. To the best of our knowledge, no previous study has augmented the EKC hypothesis with deforestation as an independent variable. Given the important role played by forests in the carbon cycle, we make a case for its inclusion in the EKC model in order to avoid an omitted variable bias problem.

The results from the unit root tests suggest that the variables are integrated into an order of one. The results of both Kao and Pedroni cointegration tests indicate that the variables are cointegrated. This is an indication that long-run relationship exists among the variables. Furthermore, FMOLS results indicate that less deforestation has a negative and significant impact on air pollution, which is in line with our prior expectation. Moreover, the EKC hypothesis holds when deforestation is included in the main model for the case of the ten countries that jointly own two-thirds of the global forest area. From the results, we find that the level of income has a significant and positive long-run coefficient, while the square of income has a significant and negative coefficient. This means that the level of income contributes to CO_2 emissions, while a higher level of income causes improvements in the air pollution.

Our empirical findings are of great importance, especially for policymakers. Given the negative relationship that exists between deforestation and carbon emissions, a relatively simple, easy, and inexpensive means of addressing the pollution problem is to design and/or enforce forest conservation policies. Examples include the creation of protected areas, provision of payments for ecosystem services, and formulation of concession policies that keep deforestation below a national baseline. Policies that induce afforestation, such as afforestation grants, tax exemptions for plantations, and tariffs on imports, are also crucial to reducing carbon emissions. It is safe to say that the cost of planting trees is relatively minimal when compared to the other options available for controlling emissions.

Also, since renewable energy use reduces pollution and non-renewable energy use aggravates it, a strong case is made for greater use of renewable energy sources as opposed to non-renewable energy sources. Policies that encourage renewable energy use, such as eco-taxes, feed-in tariffs, and renewable energy certificates, will be beneficial. Those that promote non-renewable energy by either lowering fossil fuel prices for consumers or by lowering exploitation and exploration costs for producers should at best be abolished or at least drastically reduced.

Our findings on the impact of urbanization on carbon emissions also call into question the effectiveness of urban planning policies which are supposedly designed to take into consideration environmental issues while addressing the problem of urban development. In spite of such policies, our findings show that urbanization is still responsible for a very large share of emissions. There is a need to revisit such urban planning policies and their implementation, especially those concerned with transportation management, land use, and industrialization, in order to ensure that environmental issues such as pollution and deforestation are taken seriously.

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Rediscovering the EKC Hypothesis on the High and Low Globalized OECD Countries

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Abstract The global warming is considered a huge threat for humanity, and for several years, economic growth was considered the main cause for environmental degradation. However, in the reality of an era of globalization and with an increasing economic activity what are the consequences on environment? The present analysis intends to show the effect of globalization on environmental quality. This study is focused on the analysis of the relationship between economic growth and environmental degradation for 28 Organisation for Economic Co-operation and Development (OECD) countries, by considering energy consumption, renewable and non-renewable, efficiency and globalization. This analysis is performed using the environmental Kuznets curve (EKC) based on annual data from 1990 to 2015. The EKC is assessed through the autoregressive distributed lag model and the Driscoll–Kraay estimator. The 28 countries were divided into two groups, namely the high globalized countries (HGC) and the low globalized countries (LGC), by recurring to the globalization ranking available in 2018. This division by the group of countries allows to understand the influence of different globalization levels. The results obtained show that there is evidence for the EKC hypothesis for the HGC, while for the LGC the U-shaped relationship was verified. The era of globalization lived had both consequences on environmental, restrictive and expansive carbon dioxide (CO_2) emissions. The HGC need to prepare to the social globalization, which in turn imply an increase of the economic activity and considering the results causes an increase of the CO_2 emissions. The LGC has to promote the conversion of the technologies, namely by using more electricity and less fossil technologies.. Therefore, the HGC could be considered policy-makers and the LGC could be considered policy takers.

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1 Introduction

For several years, it was believed that economic growth was the main reason for environmental degradation, and simultaneously that it was the only tool for sustainable development. The environmental Kuznets curve (EKC) emerged to describe the relationship between economic growth and environmental degradation. The inverted U-shaped is based on the explanation that initial economic growth, the first phase of the EKC, is linked with an increasing industrialization, which in turn increases environmental degradation. After the achievement of the turning point (TP), which corresponds to a specific income level, economy continues to grow, and environmental degradation starts to decrease. In short, with a high level of income the population starts to require a better environmental quality. The EKC, which analyses the relationship between economic growth and environmental quality, supports the inclusion of additional variables that also could have an effect on environmental degradation. The environmental degradation is commonly analysed through dioxide carbon (CO_2) emissions or greenhouse gas (GHG) emissions. Hereupon, in the reality of an era of globalization, the question that arises is: What are the repercussions of globalization on environment?

The concept of globalization is similar to the concepts of internationalization, liberalization, universalization and westernization. However, each one has a distinct definition, sometimes difficult to achieve. The present chapter focuses on the globalization concept. Scholte [1] suggests a definition of each concept and defines globalization as supra-territorial relationships. Globalization consists of the creation of network with the objective of connecting actors at distances. Furthermore, globalization transposes national borders, incorporates national economies, cultures, technologies and governance and still generates complex relationships with mutual interdependence. Communication and exchanging ideas between citizens of different countries or governments working together can be a demonstration of globalization [2]. However, globalization is difficult both to measure and to quantify, and it should be interpreted as a multifaceted concept. Accordingly, the KOF globalization index introduced by Dreher [3] is a composite indicator which allows to incorporate several variables into one single index and measures various globalization aspects. Nevertheless, the composite indicators could incur into a risk of oversimplification that may lead to a distorted interpretation of globalization. Hereupon, the KOF globalization index proposed in 2006 was revised by Gygli et al. [2], with the objective to propose an index which is more flexible and incorporates more variables and characteristics of globalization. In such a way, the revised index introduced two new measures, de facto and de jure.

The distinction between de facto and de jure globalization, according to some authors, has some advantages. Gygli et al. [2] followed Martens et al. [4] to propose the revised KOF globalization index, and according to Martens et al. [4] the combination of the measures de facto and de jure propitious the distortion of the results. The measure of globalization de facto is constituted by variables that represent the flows and activities, while the measure of globalization de jure is constituted by variables that represent policies that allow the flows and activities. De facto and de jure measures are divided into three dimensions, namely: economic, social and political. In a short way, the economic dimension represents the flows of goods, capital and services, and market exchanges. The social represents the diffusions of ideas, information and people. By its turn, the political represents the propagation of government policies. Through three dimensions and the two measures, the KOF globalization index can be employed in innumerable contexts. However, the overall index can be employed, in which all dimensions and characteristics have and play their role.

Save energy and reduce emissions create a challenge for global climate change policies, as well as understanding how economies could develop a low environmental degradation in future. Considering the global warming a huge threat for the humanity, which is mainly caused by the GHG emissions, over the years several mechanisms were developed to reduce the emissions and to help to mitigate this problem. Energy efficiency consists of an increase in the output with the same amount of energy used. This means that, with the implementation of energy efficiency measures, the energy used per unit of output decreases. The energy efficiency becomes the use of energy maximized, and consequently, it reduces emissions and environmental degradation. The governments around the world are stimulated to take advantage of energy efficiency as the first option in their energy strategy [5].

In the majority of the countries, many reasons can provoke changes in the energy demand, such as: efficiency improvements; displacement of the production and consumption structure; and increase of the economic output. The decomposition analysis could be a great tool to understand the relative contribution of each of the factors mentioned before on energy demand changes. Therefore, with the objective of analysing the trajectory of the energy efficiency over time, the Fisher Ideal Index [6] emerged through the decomposition method of Index Decomposition Analysis (IDA). This index allows to measure the evolution of the efficiency if an improvement of energy efficiency occurs or if the countries become more inefficient by using more energy per unit of output. The inclusion of the efficiency index on the EKC estimation could be of particular interest, namely by assessing if the measures of energy efficiency employed have been successful. In other words, it assesses if the efficiency measures have been successful in reducing emissions and improving environmental quality, and if the economies are becoming more efficient.

This chapter analyses the relationship between economic growth and CO_2 emissions, the EKC, with the inclusion of globalization and the efficiency index. The globalization is included in its three dimensions (economic, social and political) and two measures, de jure and de facto. The countries used were divided according to their overall globalization index ranking, resulting in two groups: the high globalized countries (HGC) and the low globalized countries (LGC). Therefore, the analysis was performed for the two groups independently, to understand the behaviour of each variable used on a higher and lower globalization level. The method applied was the autoregressive distributed lag (ARDL), with the Driscoll–Kraay estimator. Overall, this chapter enhances the literature through the inclusion of globalization on the EKC relationship. The globalization is one of the most ignored variables on the EKC estimation. The inclusion of the globalization is emphasizing using a division unusual of countries, HGC and LGC. Moreover, another novelty in this chapter is the inclusion of an efficiency index, the Fisher ideal index on EKC estimation.

From now on, this chapter is organized into six sections, namely; Sect. 2 which includes a literature review; Sects. 3 and 4 which present the data and method used, and the results obtained; and lastly, Sects. 5 and 6 which present the discussions and the conclusions of the study.

2 Debate

The economies have been growing, and simultaneously environment has been degraded increasingly. In an era of globalization, there is a growing environmental awareness worldwide. Over the years, diverse instruments to analyse the relationship between economic growth and environmental impact, as well as to measure of energy savings per economic output, were developed. On the one hand, the EKC arises to study the relationship between economic growth and environmental factors and over the years has been employed with several environmental factors and economic variables. On the other hand, efficiency index was developed to measure the evolution of energy used per unit of economic output.

The first studies start to address the relationship between economic growth and energy consumption [7]. Actually, this relationship continues to merit the attention of the recent literature such as [8, 9]. In the meantime, attention was paid on the relationship between economic growth and environment and between economic growth, energy consumption and environmental pollution [10–13]. The EKC was proposed for the first time by Grossman and Krueger [14].

The method of decomposition and the EKC concept are independent even so they can complement each other. Indeed, on the one hand, the decomposition analysis provides information about the trends in energy used. However, it provides limited information about the effects of energy efficiency in economic activity on a national level of emissions. On the other hand, the EKC provides an analysis of the macroeconomic determinants of emissions.

2.1 Decomposition: Efficiency Index

The Fisher ideal index proposed by Fisher [6] is based on the index decomposition analysis (IDA). The IDA along with the structural decomposition analysis (SDA) has two decomposition models. They are flexible enough to be employed in several contexts and analysis. Through the IDA were also developed the logarithmic mean Divisia index (LMDI) and the arithmetic mean Divisia index (AMDI). According to Ang [15], decomposition models start to be employed in the late 1970s with the objective to analyse the effects of changes in the product mix of industrial energy demand. Since the 1980s, decomposition models start to be employed on energy and environmental analysis. Ang and Zhang [16] provided a survey about decomposition employment on this subject. More recently, decomposition studies are more focused on the analysis of environment and economy [17–20].

Energy efficiency has been an area of study that is widely discussed in the current literature. Over the years, several approaches have been proposed to accurately measure energy efficiency performance. The authors [21] provide a literature review about the energy efficiency research in the last ten years, with several methods and for several areas. The data envelopment analysis (DEA) is a very common approach used and employed in numerous areas, such as transportation sector [22]. Energy efficiency also can be employed on a specific energy source, as renewable energy efficiency [23].

Decomposition techniques are employed to distinguish the effects of a structural shift in economic activity from the reduction in energy use. In this kind of studies, the Fisher ideal index is the preferred decomposition method. This index is divided into two indexes, namely: the activity index and the efficiency index. The activity index corresponds to the structural shift in economic activity. The efficiency index corresponds to the reduction in energy use. The index employed in this study is the efficiency index. The results of this index are commonly referred to sectoral efficiency, and the results reflect the energy used per unit of economic output [24, 25]. However, the Fisher ideal index does not include environmental degradation, but it can be employed together with another method, such as econometrics methods. This combination allows the complementarity of results. For instance, Tajudeen et al. [26] used the efficiency index and simultaneously employed both bias-corrected least square dummy variable (LSDV) and structural time series modelling (STSM) in order to study the effects of the efficiency on emissions.

2.2 Environmental Kuznets Curve

The EKC had origin in the "inverted U hypothesis" developed by Kuznets [27], with the objective to analyse the relationship between economic growth and environmental factors. This hypothesis arises to define how economic development of the countries causes pollution, over time and income [14, 28, 29]. The inverted U-shaped is based on the explanation of initial economic growth linked with an increasing industrialization would increase environmental degradation. Stern et al. [30] conclude that to analyse the relationship between growth and environment the historical experience of the countries should be analysed. The EKC has a strong theoretical information behind, which deserved the attention of the diverse authors, such as [31–33]. A survey of theoretical studies can be found in Kwabena Twerefou et al. [34].

Olale et al. [35] provides a literature review of the EKC theory. Furthermore, Olale et al. [35] explain that the EKC is divided into the three stages of development experienced by an economy: (i) the pre-industrial economy, which in mainly represented by the primary sector; (ii) the industrial economy, which is constituted by the secondary sector; and (iii) the post-industrial economy, which includes the tertiary sector and services. In the stage in which primary sector dominates, in the initial stages of the economic growth, there are limited economic activity and consequently limited formation of waste linked with an abundance of natural resources. With the development and industrialization, the natural resources begin to run out and cause an accumulation of the wastes. This stage represents the first part of the inverted U-shape, before the TP, which exists in a positive relationship between economic growth and environmental degradation. In the second part, with higher levels of development and higher environmental awareness and regulations linked with the most advanced technology, environmental degradation starts to decline.

The EKC hypothesis is commonly tested with gross domestic product (GDP) and CO_2 emissions (e.g. [36–41]) or greenhouse gas (GHG) emissions (e.g. [35, 42, 43]). However, this hypothesis can be tested using another atmospheric pollutant and national data sets, as was noted by Holtz-Eakin and Selden [44]. Shahbaz et al. [45], for instance, substitute the economic growth for industrial production; meanwhile, Zhang et al. [46] use water pollution instead of emissions. Furthermore, the variables, energy consumption (e.g. [47–50]); renewable energy [51]; energy intensity [52]; urbanization [53]; foreign direct investment [54]; corruption [55]; and globalization [34, 56], also can be included in the EKC estimation. A fairly comprehensive summary of the EKC literature can be found in Tiba and Omri [57] for the period 1978–2014, Moutinho et al. [58] for 2001–2017 and Mrabet and Alsamara [41] for 2002–2017.

According to the existing literature, the globalization is one of the most disregarded variables on the EKC subject. The impact of globalization on environment, by reducing or increasing emissions, is quite difficult to determinate without an appropriate econometric analysis. Globalization is linked with human activities that cause pollution, such as on transports, industrial production and deforestation. And it is also linked with the growth of these activities, due to the fact that globalization, in part, means growing international trade [59]. Regarding the effect of globalization on environment, through globalization, multinational corporations are able to relocate their factories to benefit from comparative advantages. This strategy consists of the factories relocated for countries with environmental standards less restrictive or regulated. This means that the country that relocates the factory also relocates the emissions. On the other hand, globalization could be capable of reducing environmental degradation considering that investigation is linked with green and efficient technology.

Over the years, several indices were developed to measure globalization, such as: GlobalIndex [60]; the new globalization index [61]; and the Maastricht Globalization Index [62]. An overview of the most popular globalization indexes is provided by Gygli et al. [2]. However, the KOF globalization index proposed by Dreher [3] has become the index most used in the literature. This index measures globalization phenomenon over three dimensions, namely economic, social and political, for almost every country in the world since 1970. Potrafke [63] revises 120 empirical recent articles which employed the KOF globalization index in its version of 2007. In order to provide a more complete globalization index, the KOF globalization index was revised by Gygli et al. [2]. In addition to the new measures de facto and de jure, the KOF globalization index revisited reveals some advantages over the KOF globalization index of 2007. Indeed, new variables were added, especially variables directed for the de jure measure. The 2018 version of the KOF globalization index incorporates 42 variables compared with 23 variables in the 2007 version.

The EKC is flexible, on its application, on studies for countries individually (e.g. [40, 64–68]) or for a group of countries (e.g. [34, 56, 69, 70]). In addition, besides the inclusion of variables, over the years, the EKC starts to be applied with new techniques such as dynamic estimation [71] and forecasts analysis [72, 73]. The econometric approaches employed to verify the EKC hypothesis are also varied. Some examples are: pooled mean group (PMG) [74]; fully modified ordinary least square (FMOLS) [75]; generalized methods of moments (GMMs) [76]; and ARDL and vector error correction model (VECM) [65]. The authors Riti et al. [77] employed simultaneously several approaches, ARDL model, FMOLS, dynamic ordinary least squares (DOLS) and VECM in a single study. However, considering that the EKC is a long-run concept [78], the ARDL model is the most common approach employed in the literature (e.g. [39–41, 56, 79, 80]).

Despite the extended literature about the EKC, there is no unanimity in the results. Indeed, that lack of consensus on the literature is evident between the studies supporting the validity of the EKC hypothesis (e.g. [36, 39, 67, 68, 81, 82]) and those arguing for the non-validity of the EKC (e.g. [65, 79, 83]). In the studies that confirm the validity of the EKC, in which the turning point (TP) is calculated, it is possible to conclude that the TP values differ. This means, the value of the TP depends on the country or group of countries studied, of the atmospheric pollutant used, among others. The authors Kwabena Twerefou et al. [34] provide examples that support different values of TP. The EKC can be a useful tool to policy-makers, considering that it provides information about the effect of economic growth on environmental degradation. Through the TP calculation, it is possible to know the certain level of income from which the relationship between economic growth and environmental degradation starts to be negative. However, it does not give information about the years to emissions that start to decrease.

3 Data and Methodology

This section includes two subsections. The first one reveals the variables, the time span, the units of measurement, sources and statistics of variables, as well as, the preliminary tests employed upon the statistical characteristics of the variables. The second subsection is also divided into two subsections, which one provides information about one of the two employed methods, namely efficient index and ARDL model.

3.1 Data

This chapter uses data from 1990 to 2015 for a panel of 28 countries belonging to the Organisation for Economic Co-operation and Development (OECD). The time span used was selected in order to use the largest number of countries, which are: Australia, Austria, Belgium, Canada, Chile, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Latvia, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Portugal, Slovenia, Spain, Sweden, Switzerland, UK and USA.

On the EKC estimation, it is usually the presence of energy consumption, as was mentioned in the literature review section. Energy consumption is divided into renewable energy and non-renewable energy. In such a way, it could be tested in the aggregated form or desegregated by source, renewable and non-renewable. While in the non-renewable energy consumption it was possible dividing by oil, coal and gas, renewable energy consumption is taken aggregated due to the fact of missing data of some sources. Indeed, considering that the present analysis starts in 1990, some renewable energy sources were substantially developed only years later, and such is the case of the solar photovoltaic (PV).

Table 1 presents the variables tested in this study, as well as their units of measurement and sources.

The variables *COAL, GAS, OIL* and *RES* were transformed into percentage of primary energy consumption, and the variables CO_2 and *GDP* were transformed into per capita. Both transformations were employed in order to reduce the correlation between the variables. Furthermore, the countries used are divided into two groups, the high globalized countries (HGC) and the low globalized countries (LGC). Based on the ranking of globalization available in 2018, the mean of the ranking of the group of countries was computed. After that, the countries with classification above the mean were included in the HGC and the countries classified below the mean were included in the LGC. Therefore, the HGC are constituted by 15 countries, namely: Austria, Belgium, Canada, Denmark, Finland, France, Germany, Hungary, Ireland, the Netherlands, Norway, Spain, Sweden, Switzerland and UK. And the group of LGC is constituted by 13 countries, namely: Australia, Chile, Greece, Italy, Israel, Japan, Latvia, Luxembourg, Mexico, Portugal, New Zealand, Slovenia and USA. Geographically, the countries under analysis are placed (Fig. 1).

Figure 1 reveals a large concentration of the HGC in the European Union, and they are very close to each other. This could suggest that the European Union and the proximity between the countries have stimulated high globalization. Contrarily, the LGC are more dispersed around the world. Figure 1 also discloses that the LGC have a bigger area and a large population than the HGC.

The descriptive statistics of the variables of the two models are presented in Tables 2 and 3. Table 2 is referent to the HGC and Table 3 to the LGC.

Table 1 Variables

Variable description	Description	Source
GDP	Gross domestic product (constant 2010 prices in US$)	United Nations Statistics Division (UNSD)
CO_2	CO_2 emissions (Mt)	BP Statistical Review of World Energy 2018
OIL	Oil consumption (Mt)	BP Statistical Review of World Energy 2018
COAL	Coal consumption (Mtoe)	BP Statistical Review of World Energy 2018
GAS	Gas consumption (Mtoe)	BP Statistical Review of World Energy 2018
RES	Renewable energy consumption (Mtoe)	BP Statistical Review of World Energy 2018
FEFF	Efficiency index (1990 = 1)	Own calculation
KOFECDF	KOF globalization index economic dimension de facto	KOF Swiss Economic Institute
KOFECDJ	KOF globalization index economic dimension de jure	KOF Swiss Economic Institute
KOFSODF	KOF globalization index social dimension de facto	KOF Swiss Economic Institute
KOFSODJ	KOF globalization index social dimension de jure	KOF Swiss Economic Institute
KOFPODF	KOF globalization index political dimension de facto	KOF Swiss Economic Institute
KOFPODJ	KOF globalization index political dimension de jure	KOF Swiss Economic Institute

Notes: *Mtoe* millions of tonnes in oil equivalent, *Mt* million tonnes

The characteristics of the variables and the countries (cross sections) were exhaustively assessed. The characteristics are crucial to use the most appropriate estimator in order to guarantee robust results. The tests employed include: (i) the cross-sectional dependence test (CD test); (ii) the panel unit root tests; (iii) the correlation matrix values; and (iv) the variance inflation factors (VIFs).

The cross-sectional dependence test (CD test) was performed under the null hypothesis of the variable that does not suffer from cross-sectional dependence. The CD test for the HGC is presented in Table 4 and for the LGC is presented in Table 5.

The CD test appoints to the presence of cross-sectional dependence as follows: for all variables on the HGC and for most variables on LGC. The presence of cross-sectional dependence could be a severe limitation for the validity of the first-generation unit root test and become not reliable. Therefore, the second-generation unit root tests (CIPS) proposed by Pesaran [84] were employed for all variables under the null hypothesis of the series that are $I(1)$.

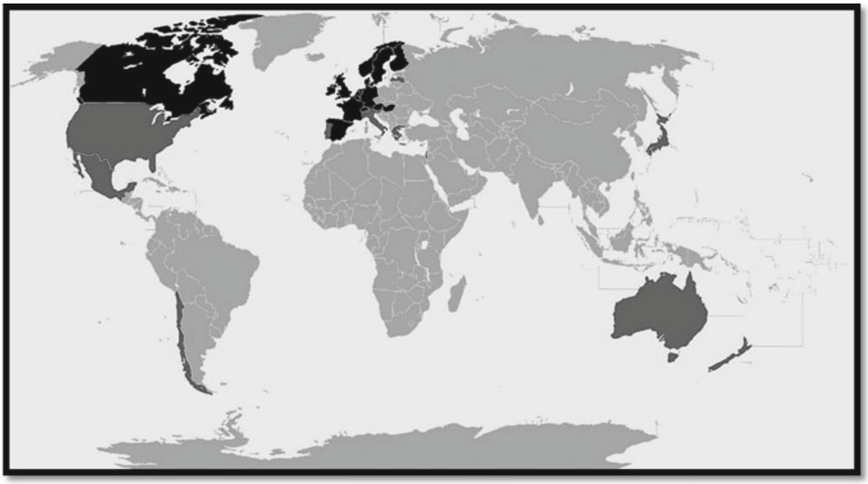

Fig. 1 Geographic position of the countries. *Notes* The HGC are highlighted in black, and the LGC are highlighted in dark grey. *Source* own elaboration

Table 2 Descriptive statistics—HGC

	Mean	Std. dev.	Min.	Max.	Obs.
GDP_pc	4.27E+04	1.70E+04	8.54E+03	91,617.28	390
GDP2_pc	2.11E+09	1.69E+09	7.30E+07	8.39E+09	390
CO_2_pc	9.33E−06	3.21E−06	4.14E−06	0.0000173	390
OIL_p	40.339	8.789	20.709	59.892	390
COAL_p	12.695	8.488	0.31	41.339	390
GAS_p	19.783	11.343	1.075	48.352	390
RES_p	15.979	17.617	0.158	69.301	390
FEFF	0.848	0.159	0.412	1.1864	390
KOFECDF	70.679	13.363	32.094	93.365	390
KOFECDJ	83.077	6.766	47.166	94.13	390
KOFSODF	8.10E+01	5.71E+00	6.50E+01	9.33E+01	390
KOFSODJ	8.16E+01	7.20E+00	5.69E+01	9.30E+01	390
KOFPODF	91.58	4.794	75.73	99.426	390
KOFPODJ	92.523	9.274	49.827	100	390

Notes: *Max.* maximum, *Min.* minimum; *Std. dev.* standard deviation; *Obs.* observations

Table 3 Descriptive statistics—LGC

	Mean	Std. dev.	Min.	Max.	Obs.
GDP_pc	32,515.72	22,805.23	4993.754	111,968.4	312
GDP2_pc	1.58e+09	2.40e+09	2.49e+07	1.25e+10	312
CO_2_pc	9.70e−06	6.09e−06	2.44e−06	0.0000279	312
OIL_p	50.513	12.082	28.417	76.643	312
COAL_p	17.306	11.523	1.239	44.227	312
GAS_p	18.907	9.94	0	39.195	312
RES_p	10.383	9.738	0.023	38.495	312
FEFF	0.8449	0.165	0.429	1.34	312
KOFECDF	56.423	16.181	19.26937	93.117	312
KOFECDJ	75.678	10.941	39.833	97.406	312
KOFSODF	70.772	11.082	44.227	90.563	312
KOFSODJ	74.973	8.863	44.554	90.229	312
KOFPODF	77.223	17.042	30.618	99.364	312
KOFPODJ	84.012	12.513	26.825	99.703	312

Notes: *Max.* maximum, *Min.* minimum; *Std. dev.* standard deviation; *Obs.* observations

Table 4 Cross-sectional dependence test (CD test)—HGC

	CD test	Corr	Abs (corr)		CD test	Corr	Abs (corr)
LGDP_pc	36.83***	0.705	0.955	DLGDP_pc	27.80***	0.543	0.55
LGDP2_pc	36.81***	0.705	0.955	DLGDP2_pc	27.85***	0.544	0.551
LCO2_pc	31.98***	0.612	0.621	DLCO2_pc	16.19***	0.316	0.339
LOIL_p	5.52***	0.106	0.417	DLOIL_p	5.06***	0.099	0.216
LCOAL_p	29.49***	0.564	0.572	DLCOAL_p	7.11***	0.139	0.22
LGAS_p	28.82***	0.552	0.676	DLGAS_p	15.13***	0.295	0.342
LRES_p	29.73***	0.569	0.578	DLRES_p	6.49***	0.127	0.273
LFEFF	44.33***	0.848	0.848	DLFEFF	22.84***	0.446	0.455
LKOFECDF	48.24***	0.923	0.923	DLKOFECDF	21.66***	0.423	0.426
LKOFECDJ	32.06***	0.614	0.653	DLKOFECDJ	26.88***	0.525	0.532
LKOFSODF	37.75***	0.723	0.723	DLKOFSODF	5.28***	0.103	0.187
LKOFSODJ	48.51***	0.928	0.928	DLKOFSODJ	20.47***	0.399	0.399
LKOFPODF	14.01***	0.268	0.35	DLKOFPODF	10.81***	0.211	0.274
LKOFPODJ	49.41***	0.946	0.946	DLKOFPODJ	43.73***	0.853	0.853

Notes *** denotes significance level at 1%

Table 5 Cross-sectional dependence test (CD test)—LGC

	CD test	Corr	Abs (corr)		CD test	Corr	Abs (corr)
LGDP_pc	35.30***	0.827	0.827	DLGDP_pc	16.81***	0.405	0.411
LGDP2_pc	37.07***	0.857	0.857	DLGDP2_pc	17.08***	0.403	0.41
LCO2_pc	11.63***	0.273	0.461	DLCO2_pc	8.10***	0.191	0.242
LOIL_p	5.69***	0.138	0.482	DLOIL_p	2.68***	0.065	0.192
LCOAL_p	−0.44	−0.009	0.507	DLCOAL_p	0.65	0.015	0.153
LGAS_p	10.43***	0.248	0.544	DLGAS_p	0.2	0.006	0.196
LRES_p	16.93***	0.401	0.483	DLRES_p	2.79***	0.066	0.171
LFEFF	34.03***	0.787	0.787	DLFEFF	2.37**	0.056	0.179
LKOFECDF	34.43***	0.796	0.796	DLKOFECDF	7.19***	0.17	0.253
LKOFECDJ	14.29***	0.33	0.508	DLKOFECDJ	14.96***	0.353	0.364
LKOFSODF	35.99***	0.832	0.832	DLKOFSODF	7.54***	0.178	0.244
LKOFSODJ	39.58***	0.915	0.915	DLKOFSODJ	7.68***	0.181	0.238
LKOFPODF	9.95***	0.23	0.451	DLKOFPODF	2.44**	0.058	0.174
LKOFPODJ	39.73***	0.918	0.918	DLKOFPODJ	11.60***	0.274	0.306

Notes **, *** denote significance level at 5 and 1%, respectively

The second-generation unit root test (CIPS) for the HGC is presented in Table 6 and for the LGC is presented in Table 7.

The variables which have not cross-sectional dependence both unit root tests and first- and second generation were employed. The first-generation unit root tests employed were the tests proposed by Levin et al. [85], Maddala and Wu [86] and Choi [87].

The results of the unit root tests suggest the existence of variables stationary in level, i.e. variables $I(0)$ and variables integrated of order one, i.e. $I(1)$. Through the results of the unit root tests, the absence of variables integrated of order two, $I(2)$, was confirmed, which enables the use of dynamic structure following the ARDL procedure. Posteriorly to the unit root test employment, collinearity and multicollinearity must be tested to ensure robust estimations. Hereupon, the correlation matrix values and the VIF were analysed. The results confirm that neither collinearity nor multicollinearity is an uneasiness on estimations.

3.2 Methodology

Two methods were carried out, namely the efficiency index and the ARDL model. This subsection provides an explanation of the choice of these methods, as well as explains their characteristics, advantages and disadvantages and their applicability. The first method to be discussed is the efficiency index due to the fact that this index

Table 6 Second-generation unit root test (CIPS)—HGC

	Lags	Without trend	With trend		Lags	Without trend	With trend
LGDP_pc	0	−0.367	−0.322	DLGDP_pc	0	−5.549***	−3.091***
	1	−1.117	0.945		1	−3.199***	−1.043
LGDP2_pc	0	−0.240	−0.033	DLGDP2_pc	0	−5.337***	−2.940***
	1	−1.109	1.114		1	−2.980***	−0.865
LCO2_pc	0	−2.801***	−2.961***	DLCO2_pc	0	−13.415***	−12.259***
	1	−1.343*	−3.070***		1	−9.142***	−7.464***
LOIL_p	0	−3.625***	−2.522***	DLOIL_p	0	−14.221***	−13.385***
	1	−1.791**	0.153		1	−6.808***	−5.638***
LCOAL_p	0	−1.480*	0.767	DLCOAL_p	0	−12.196***	−10.985***
	1	−0.590	2.023		1	−6.309***	−4.813***
LGAS_p	0	0.528	−0.737	DLGAS_p	0	−12.524***	−12.444***
	1	0.835	0.805		1	−6.666***	−5.756***
LRES_p	0	−1.587*	−3.217***	DLRES_p	0	−14.826***	−14.047***
	1	1.248	−0.072		1	−9.562***	−7.893***
LFEFF	0	−0.396	1.193	DLFEFF	0	−10.369***	−9.416***
	1	0.828	3.382		1	−5.642***	−4.551***
LKOFECDF	0	−2.624***	0.107	DLKOFECDF	0	−8.658***	−7.462***
	1	−5.212***	−2.323**		1	−5.682***	−4.309***
LKOFECDJ	0	−0.833	−2.104**	DLKOFECDJ	0	−13.016***	−11.631***
	1	−1.039	−2.596***		1	−8.895***	−7.442***
LKOFSODF	0	−3.053***	−2.238**	DLKOFSODF	0	−12.339***	−10.995***
	1	−3.490***	−2.478***		1	−7.883***	−6.553***
LKOFSODJ	0	−2.077**	−1.470*	DLKOFSODJ	0	−12.289***	−10.861***
	1	−2.887***	−2.021**		1	−7.877***	−6.393***
LKOFPODF	0	−3.753***	−3.490***	DLKOFPODF	0	−13.231***	−11.856***
	1	−2.740***	−2.496***		1	−9.191***	−7.658***
LKOFPODJ	0	−8.200***	−10.279***	DLKOFPODJ	0	−16.066***	−15.135***
	1	−5.561***	−4.901***		1	−11.320***	−10.207***

Notes *, **, *** denote significance level at 10, 5 and 1%, respectively

will be incorporated into the ARDL model as a variable, in order to understand its impact on the EKC estimation.

Table 7 Second-generation unit root test (CIPS)—LGC

	Lags	Without trend	With trend		Lags	Without trend	With trend
LGDP_pc	0	0.823	−1.461*	DLGDP_pc	0	−6.739***	−5.104***
	1	1.319	−1.194		1	−4.088***	−1.769**
LGDP2_pc	0	1.508	−0.897	DLGDP2_pc	0	−6.688***	−5.219***
	1	1.229	−0.836		1	−4.155***	−2.222**
LCO2_pc	0	−0.010	−0.132	DLCO2_pc	0	−10.038***	−8.488***
	1	1.015	1.013		1	−4.149***	−2.926***
LOIL_p	0	−0.173	−1.245	DLOIL_p	0	−9.990***	−8.385***
	1	−0.057	0.009		1	−5.948***	−4.789***
LCOAL_p	0	1.126	1.717	DLCOAL_p	0	−9.082***	−8.173***
	1	0.252	0.804		1	−4.074***	−3.983***
LGAS_p	0	0.354	1.971	DLGAS_p	0	−9.198***	−8.761***
	1	0.131	1.863		1	−5.916***	−7.785***
LRES_p	0	−5.163***	−3.923***	DLRES_p	0	−12.824***	−11.140***
	1	−4.582***	−2.866***		1	−8.776***	−6.577***
LFEFF	0	−0.969	0.325	DLFEFF	0	−9.062***	−8.738***
	1	0.027	0.390		1	−4.016***	−3.067***
LKOFECDF	0	−1.911**	−2.078**	DLKOFECDF	0	−9.726***	−8.517***
	1	−0.086	−0.470		1	−4.962***	−3.829***
LKOFECDJ	0	−2.138**	0.710	DLKOFECDJ	0	−8.501***	−6.808***
	1	−2.243**	−0.148		1	−4.117***	−2.180**
LKOFSODF	0	−5.275***	−3.514***	DLKOFSODF	0	−11.685***	−10.273***
	1	−4.943***	−3.162***		1	−7.098***	−4.991***
LKOFSODJ	0	−3.408***	−1.755**	DLKOFSODJ	0	−11.591***	−10.117***
	1	−2.128**	−0.953		1	−6.810***	−5.517***
LKOFPODF	0	−2.985***	−2.749***	DLKOFPODF	0	−12.168***	−11.452***
	1	−1.168	−0.081		1	−5.734***	−4.139***
LKOFPODJ	0	−5.570***	−6.203***	DLKOFPODJ	0	−12.882***	−11.463***
	1	−4.804***	−3.952***		1	−8.705***	−7.184***

Notes *, **, *** denote significance level at 10, 5 and 1%, respectively

3.2.1 Efficiency Index

The efficiency index is calculated through the Fisher ideal index, which in turn comes from the decomposition method, IDA. The Fisher ideal index was developed by Fisher [6], and it is usually preferred in the literature considering its capacity to give unbiased decomposition [24]. The efficiency index allows to appraise the share of energy used, per unit of economic output, on a sector or national level. The use of this index makes it possible to assess which are the most and the least efficient sectors. Through this understanding, those sectors that need to invest in more efficient technology and reformulate their efficiency measures can be identified, while those where efficiency measures are being successful and the technology improvement has been advantageous, stand out.

With the objective to calculate the efficiency index, the Fisher ideal index allows to decompose the changes of energy intensity into structural shift and energy efficiency, according to Metcalf [88] through IDA method, Eq. (1).

$$e_t = \frac{E_t}{Y_t} = \sum_i \left(\frac{E_{it}}{Y_{it}}\right)\left(\frac{Y_{it}}{Y_t}\right) = \sum_i e_{it} s_{it}, \tag{1}$$

where e_t represents the aggregate energy intensity; E_t designates the total energy consumption; Y_t designates the total output (GDP); and E_{it} and Y_{it} denote the energy consumption and measure of economic activity (industry gross value added (IGVA)) for sector i in the year t, respectively.

Equation (1) demonstrates that the aggregate energy intensity is the sum of the products of energy intensity of each sector (e_{it}) and the changes in the structure of the economy (s_{it}). Hereupon, the energy intensity index (I_t) is calculated through the ratio between the energy intensity in a year t (e_t) and the energy intensity in a year base 0 (e_0), such as displayed in Eq. (2).

$$I_t = \frac{e_t}{e_0} = \frac{\sum_i e_{it} s_{it}}{\sum_i e_{i0} s_{i0}}. \tag{2}$$

In order to calculate energy intensity index, it is necessary to decompose aggregate energy intensity. As such, the energy intensity index can be decomposed by the efficiency index (EFF_t) and the activity index (ACT_t), according to [89], Eq. (3).

$$I_t = \frac{e_t}{e_0} = \mathrm{EFF}_t * \mathrm{ACT}_t \tag{3}$$

The efficiency index consists of attribute energy intensity to the efficiency changes, keeping economic activity constant. In other words, it analyses the energy used and the economic output, more specifically the energy used per unit of economic output. By its turn, activity index consists of attribute energy intensity to the structural changes of the economic activities, keeping the efficiency constant. In other words, it analyses the economic contribution.

Posteriorly to the decomposition of energy intensity index, efficiency index and activity index are calculated through the Laspeyres (L) and Paasche (P) indices.

Equation (4) represents the Laspeyres index for the efficiency and activity index calculation.

$$L_t^{\mathrm{EFF}} = \frac{\sum_i e_{it} s_{i0}}{\sum_i e_{i0} s_{i0}};\ L_t^{\mathrm{ACT}} = \frac{\sum_i e_{i0} s_{it}}{\sum_i e_{i0} s_{i0}}. \tag{4}$$

Equation (5) represents the Paasche index for the efficiency and activity index calculation.

$$P_t^{\mathrm{EFF}} = \frac{\sum_i e_{it} s_{it}}{\sum_i e_{i0} s_{it}};\ P_t^{\mathrm{ACT}} = \frac{\sum_i e_{it} s_{it}}{\sum_i e_{it} s_{i0}} \tag{5}$$

Such as mentioned before, the Fisher ideal index was developed to provide an unbiased decomposition of the energy intensity into the efficiency and activity index. Hereupon, the Fisher ideal index is recalculated through the weighted average of the Laspeyres and Paasche indexes giving origin to efficiency index $\left(F_t^{\mathrm{EFF}}\right)$ and activity index $\left(F_t^{\mathrm{ACT}}\right)$. The final efficiency and activity index are calculated through Fisher ideal index, Eq. (6).

$$F_t^{\mathrm{EFF}} = \left(L_t^{\mathrm{EFF}} * P_t^{\mathrm{EFF}}\right)^{\frac{1}{2}};\ F_t^{\mathrm{ACT}} = \left(L_t^{\mathrm{ACT}} * P_t^{\mathrm{ACT}}\right)^{\frac{1}{2}} \tag{6}$$

After calculating the efficiency and activity index, intensity index is calculated, Eq. (7).

$$I_t = \frac{e_t}{e_0} = F_t^{\mathrm{EFF}} * F_t^{\mathrm{ACT}} \tag{7}$$

Throughout this section, it demonstrated calculation steps of intensity index, in order to provide a complete explanation of all processes. However, it is worthwhile to note that efficiency index $\left(F_t^{\mathrm{EFF}}\right)$ and activity index $\left(F_t^{\mathrm{ACT}}\right)$ can be used independently.

Regarding the interpretation of the indexes results, on the one hand, the efficiency index provides information about the efficiency evolution. If a successful improvement of the efficiency occurs, then the index value has to decrease, and this means that there is a decrease of energy used per unit of economic output. On the other hand, activity index provides information about the economic contribution, for instance, considering a sectoral analysis, of the share of gross value added (GVA) on GDP. Therefore, if the activity index value increases, this means that the respective sector has a larger weight on the economy. Such as stated before, note that this chapter only uses the efficiency index, which is included in the EKC estimation.

3.2.2 Autoregressive Distributed Lag Model

Such as stated before, this chapter makes use of the panel ARDL model, which was proposed by Pesaran and Smith [90] and Pesaran et al. [91]. Considering the characteristics of the data used, the ARDL approach demonstrates to be appropriate. The ARDL model allows the control of potential particular events in the series, namely by using dummies. Furthermore, the ARDL model can appropriately handle co-integration and it has a useful modelization capable to handle endogeneity among variables. Besides that, the ARDL model provides a separation of short run and long run, and this analysis aims to assess both short-run and long-run adjustments to verify the EKC hypothesis [92]. The structure of the ARDL model is presented in Eq. (8).

$$
\begin{aligned}
DLCO2_{it} = {} & \mu_i + \vartheta_{i1} TREND + \omega_{i1} \sum_{i=1}^{n} DLGDP_{PCit} + \omega_{i2} \sum_{i=1}^{n} \sum_{i=1}^{n} D(LGDP_{PCit})^2 \\
& + \omega_{i3} \sum_{i=1}^{n} DLOIL_{Pit} + \omega_{i4} \sum_{i=1}^{n} DLCOAL_{Pit} + \omega_{i5} \sum_{i=1}^{n} DLGAS_{Pit} \\
& + \omega_{i6} \sum_{i=1}^{n} DLRES_{Pit} + \omega_{i7} \sum_{i=1}^{n} DLFEFF_{it} + \omega_{i8} \sum_{i=1}^{n} DLKOFECDF_{it} \\
& + \omega_{i9} \sum_{i=1}^{n} DLKOFECDJ_{it} + \omega_{i10} \sum_{i=1}^{n} DLKOFSODF_{it} \\
& + \omega_{i11} \sum_{i=1}^{n} DLKOFSODJ_{it} + \omega_{i12} \sum_{i=1}^{n} DLKOFPODF_{it} \\
& + \omega_{i13} \sum_{i=1}^{n} DLKOFPODJ_{it} + \propto_{i1} LCO2\_PC_{it-1} + \propto_{i2} LGDP\_PC_{it-1} \\
& + \propto_{i3} (LGDP\_PC_{it-1})^2 + \propto_{i4} LOIL\_P_{it-1} + \propto_{i5} LCOAL\_P_{it-1} \\
& + \propto_{i6} LGAS\_P_{it-1} + \propto_{i7} LRES\_P_{it-1} + \propto_{i8} LRFEFF_{it-1} \\
& + \propto_{i9} LKOFECDF_{it-1} + \propto_{i10} LKOFECDJ_{it-1} + \propto_{i11} LKOFSODF_{it-1} \\
& + \propto_{i12} LKOFSODJ_{it-1} + \propto_{i13} LKOFPODF_{it-1} \\
& + \propto_{i14} LKOFPODJ_{it-1} + \varepsilon_{it},
\end{aligned} \tag{8}
$$

where μ_i represents the intercept; ϑ_i represents the coefficient of the trend; ω_i denotes the estimated parameters in the short-run; $\propto_i$ represents the estimated parameters in the long run; and ε_{it} denotes the error term.

The model can be estimated with random effects or fixed effects. In order to understand the most appropriate effects for the models, the Hausman test was performed. This test analyses the presence of individual effects on the estimations, testing fixed effects against random effects, with the null hypothesis that the random effects are adequate. The results of the test are displayed in Table 8.

The rejection of the null hypothesis of the Hausman test is suggesting that the consideration of the presence of fixed effects on the estimations is suitable. Then, a set of specification tests are employed, namely: Pesaran's, Frees' and Friedman's test for contemporaneous correlation; the Wald Test for heteroscedasticity; and the Wooldridge test for autocorrelation.

Table 8 Hausman test and *F* test

	HGC	LGC
F test	6.31***	4.79***
Hausman test—FE versus RE	72.71***	49.09***

Notes *** denotes significance level at 1%; *FE* fixed effects; *RE* random effects

Table 9 Specification tests

	HGC	LGC
Pesaran test	1.442	1.112
Frees test	0.080	0.019
Friedman test	31.082***	23.251**
Wald Test	1740.21***	201.42***
Wooldridge test	53.608***	17.497***

Notes ***, ** denote significance level at 1 and 5%, respectively

From Table 9, the tests prove the absence of contemporaneous correlation and the presence of heteroskedasticity and first-order serial autocorrelation. Therefore, the estimator which is robust to handle the features is the Driscoll–Kraay estimator [93]. This estimator has the additional advantage of allowing testing the fixed effects within the regression [94, 95]. Through the semi-elasticities and elasticities, short-run and long-run effects, respectively, are shown. The semi-elasticities come from the coefficients of the variables of short run. By its turn, the elasticities are calculated through the ratio between the coefficient of the long-run variables and the error correction mechanism (ECM) and multiplied by -1.

The EKC is employed to analyse the relationship between economic growth and environmental degradation. The environmental degradation is commonly represented by CO_2 or GHG emissions. Therefore, the EKC shows the trajectory of emissions with a growing income. The EKC is represented by the inverted U-shape, which represents an increasing GDP and two phases of the emission trajectory. The first phase is characterized by the simultaneous increase of income (GDP) and environmental degradation. This phase ends when the TP is achieved. Such as clarified earlier, the TP represents a certain income level, after which emissions start to decrease. In the second phase, there is a decrease of emissions; meanwhile, the income level keeps increasing.

The EKC hypothesis is tested through the signs of the coefficients and elasticities obtained on the ARDL model estimated. Considering that, for testing the EKC hypothesis the variables of emissions should be the variables to explain; meanwhile, the variables of GDP and GDP of square should integrate the vector of explanatory variables. Therefore, in order to verify the EKC hypothesis, the coefficient and elasticity of GDP must be statistically significant and positive, and the coefficient and elasticity of GDP squared must be statistically significant and negative, in the long run, in order to assure the concavity of the curve.

In addition to the inverted U-shaped relationship, i.e. EKC, also the following condition could be verified:

1. $\beta1 = \beta2 = \beta3 = 0$. No relationship between x and y.
2. $\beta1 > 0$ and $\beta2 = \beta3 = 0$. Linear relationship between x and y.
3. $\beta1 < 0$ and $\beta2 = \beta3 = 0$. Decreasing relationship between x and y.
4. $\beta1 > 0$, $\beta2 < 0$ and $\beta3 = 0$. Inverted U-shaped relationship, EKC.
5. $\beta1 < 0$, $\beta2 > 0$ and $\beta3 = 0$. U-shaped relationship.

With the inclusion of the GDP cubed:

6. $\beta 1 > 0$, $\beta 2 < 0$ and $\beta 3 > 0$. Cubic polynomial or N-shaped figure.
7. $\beta 1 < 0$, $\beta 2 > 0$ and $\beta 3 < 0$. Opposed to the N-shaped curve.

where $\beta 1$ is the coefficient of GDP, $\beta 2$ is the coefficient of GDP squared, $\beta 3$ is the coefficient of GDP cubed, in the long run, and y is the environmental indicator and x is the income.

The co-integration equation is presented by Eq. (9).

$$\mathrm{LCO2}_t = \beta_1 LY_t + \beta_2 LY_{t2}, \tag{9}$$

After assessing and validating the EKC hypothesis, the TP can be calculated. The relationship obtained does not give information about the years needed to achieve the TP. The TP only reveals the specific income level. The TP is determined using the following expression, Eq. (10).

$$\mathrm{TP}^* = -\frac{\beta_1}{2\beta_2} \tag{10}$$

Bearing in mind that if the variables suffer a transformation, for instance transformation into their natural logarithms, then after calculating the TP it is necessary to reverse the process to obtain the actual value of GDP at which the TP occurs.

4 Results

The Driscoll–Kraay estimator was employed for both HGC and LGC, following the ARDL structure represented in Eq. (8). The HGC model was estimated for the period of 1990–2015; meanwhile, the LGC model was estimated for the period of 1992–2015. The reason behind the dissimilar start year is that in 1992 the United Nations Framework Convention on Climate Change (UNFCCC) was created, on which several countries are members. Luxembourg, USA and Australia, which belong to the LGC, are some of the country members, and they are among the largest emitters. Considering that, was verified a structural break until 1992 on the series, which, as was confirmed, biased the results.

The results are summarized in Table 10.

In the model estimated for the HGC were applied three dummies to control three events that occur in these countries. In 1995, the UK parliament created new agencies for environmental management, taking into account the cross-border issues. Considering the HGC in the majority European Union countries, in 2002 the sixth Environmental Action Programme was adopted. It is a European Union policy programme for the environment, and one of its priorities is the climate change. Besides that, in 2002 most European Union countries ratified its Kyoto protocol. Lastly, the

Table 10 ARDL estimations for both HGC and LGC

Variable	HGC	LGC
DLOIL_P	0.1419 ***	0.1437**
DLGAS_P		
DLCOAL_P	0.1744***	0.0988***
DLRES_P	−0.0636***	−0.0526***
DLGDP_PC	0.8193***	0.8031***
DLGDP2_PC		
DLFEFF	0.5987***	0.5586***
DLKOFECDF	−0.1134*	
DLKOFECDJ		
DLKOFPODF		−0.0623***
DLKOFPODJ	−0.1401***	
DLKOFSODF		
DLKOFSODJ		
ECM	−0.2410***	−0.2718***
LOIL_P (−1)	0.2354***	
LGAS_P (−1)	0.0442***	0.0057**
LCOAL_P (−1)	0.0428***	0.0203**
LRES_P (−1)	−0.0187***	−0.0114*
LGDP_PC (−1)	0.7019**	−0.3613***
LGDP2_PC (−1)	− 0.0326**	0.0315***
LFEFF (−1)	0.1135***	0.3110***
LKOGECDF (−1)	−0.0433*	−0.0467***
LKOGECDJ (−1)		0.0713***

(continued)

Table 10 (continued)

Variable	HGC	LGC
LKOGSODF (−1)	0.4030***	
LKOGSODJ (−1)	0.1599**	
LKOGPODF (−1)		− 0.0930***
LKOGPODJ (−1)	−0.0749*	0.0771***
C	−9.6533***	− 3.1496***
Dum_1995	−0.0254***	
Dum_2002	−0.0048**	
Dum_2008	−0.0214***	
Elasticities		
LOIL_P (−1)	0.9768***	
LGAS_P (−1)	0.1833***	0.0209*
LCOAL_P (−1)	0.1777***	0.0748***
LRES_P (−1)	−0.0774***	−0.0421*
LGDP_PC (−1)	2.9127*	−1.3294***
LGDP2_PC (−1)	−0.1354*	0.1159***
LFEFF (−1)	0.4708***	1.1442***
LKOGECDF (−1)	−0.1796**	−0.1718***
LKOGECDJ (−1)		0.2623***
LKOGSODF (−1)	1.6724***	
LKOGSODJ (−1)	0.6636**	
LKOGPODF (−1)		−0.3423***
LKOGPODJ (−1)	−0.3106*	0.2838***

Notes *, **, *** denote significance level at 10, 5 and 1%, respectively; *Dum* dummies

2008 dummies represent the financial crisis suffered by the most European Union countries.

The hypothesis of the EKC is verified, in the HGC. This means that the condition verified is $\beta 1 > 0, \beta 2 < 0$ and $\beta 3 = 0$. In the LGC, the relationship founded between economic growth and CO_2 emissions is the U-shaped relationship; i.e. there is evidence for $\beta 1 < 0, \beta 2 > 0$ and $\beta 3 = 0$. Furthermore, the efficiency index has a positive impact on CO_2 emissions on both short run and long run and on the two groups of countries. It is worthwhile to clarify that an increase in the efficiency index represents a reduction of the efficiency. By other words, how much closer to 1 is the index value, and the lower is the efficiency percentage relative to the base year. This means that an increase of the index represents a decrease of the efficiency and causes an increase of CO_2 emissions.

Regarding the globalization index, it deserves to be highlighted the differences between the groups, such as the political dimension on the short run and the social dimension on the long run. Moreover, on the LGC the economic and political dimensions had different impacts on CO_2 emissions, dependent on its measure, de jure or de facto. In addition, the results show that the social dimension has no impact on both models on the short run. In the long run, the social dimension has impact only on the HGC. Overall, these findings deserve further discussion, in the next section. Regarding the ECM, both models have highly significant ECM and with a moderate speed of adjustment to the long-run equilibrium.

The semi-elasticities reveal that an increase of 1 percentage point (pp) of *DLKOFECDF* and *DLKOFPODJ* on the HGC causes a decrease of 0.11 and 0.14 pp on CO_2 emissions, respectively. On the LGC, an increase of 1 pp of the *DLKOFPODF* causes a decrease of the CO_2 emissions in 0.06 pp. On the long run, the elasticities calculated reveal that an increase of 1% of the efficiency index provokes an increase of the 0.47 and 1.14% on CO_2 emissions on the HGC and LGC, respectively. Furthermore, the increase of 1% on the social dimension of globalization on the HGC causes an increase of the 1.67 and 0.66% on CO_2 emissions, de facto and de jure measurements, respectively.

5 Discussion

Based on a set of 28 OECD countries, this chapter looks to understand if the level of globalization influences the environmental performance. To the best of our knowledge, this is the first work analysing the EKC into this context of two groups of countries, which were classified according to their level of globalization. This approach helps to understand the effects of globalization in environment protection. To do that, a group of countries, named as HGC, aggregate the countries with the individual level of globalization above the mean of all countries together. The countries belonging to the group LGC underperform regarding that globalization mean level. This analysis suggests that the HGC have an inverted U-shaped relationship, between economic growth and environmental degradation. By other words, this chapter finds evidence for the EKC on that group of most globalized countries. On contrary, for the LGC there is evidence of a U-shaped relationship between economic growth and environmental degradation. Moreover, globalization dimensions, namely economic, political and social, divided into the measure of de jure and de facto, and their contributions to environmental performance were also appraised.

The inclusion of the energy consumption is a frequent procedure in the EKC literature, and the obtained results are in concordance with the mainstream. Indeed, the consumption of fossil fuel, coal and oil is highly pollutant and the release of CO_2 emissions is implicit. In line with this, in both groups of countries the fossil fuel consumption increases the CO_2 emissions, in both short run and long run. Contrarily, the consumption of gas only provokes CO_2 emissions in the long run for both groups of countries. This finding is not a real surprise given that this energy source is the less pollutant fossil fuel. However, even though the consumption of fossil fuels implies an increase of CO_2 emissions in both groups of countries, this effect occurs in different magnitudes. The semi-elasticities and the elasticities reveal that the HGC have a more accentuated impact from fossil fuels on CO_2 emissions. For example, the increase of 1% of COAL on the HGC provokes an increase of 0.17% on CO_2 emissions, compared with 0.07% on the LGC. This disparity of magnitudes could be explained by the fact that the HGC consume fewer fossil fuels than the LGC.

Regarding the renewable energy, the increase of the consumption coming from renewable source is associated with a decrease of CO_2 emissions, for both groups of countries. This finding is far from surprising, given that larger use of renewable energy consumption means avoid burning fossil fuels. Regarding the magnitude of the effects, and mirroring the results obtained with fossil fuels, renewable energy use in the HGC has a larger impact on CO_2 emissions when compared with the LGC. An increase of 1% of the *RES* causes a decrease of CO_2 emissions in 0.07% in the HGC compared with 0.04 for the LGC. The fact that renewable energy consumption of the HGC is more effective on CO_2 emission mitigation may be a sign that these countries are better prepared in terms of technology used to consume electricity. Whereas the LGC may be stuck with fossil powered technology, and consequently with less potential to mitigate CO_2 emissions through renewable energy consumption.

When considering altogether, the 28 countries are more pollutant in 2015 than in 1990, and the biggest contributors are the LGC, which are more pollutant than the HGC. This could be explained by the LGC consuming more energy and fossil fuels than the HGC. Besides that, the differences in CO_2 emissions could be due to a trend of globalization incentivizing the relocation of some high pollutant industries, namely manufactures. These movements are looking for comparative advantages, namely cheaper labour and less severe environment restrictions. A consequence of the energy efficiency objectives is to reduce the energy consumption and consequently cut the CO_2 emissions. Through the calculation of efficiency index, it was observed that the HGC are more efficient than the LGC. The HGC use less energy per unit of output, which suggests that the HGC recur to more advanced and efficient technology compared with the LGC. In short, besides the LGC consume more energy than the HGC and use energy less efficiently when compared with the HGC. Therefore, it is crucial that in LGC more efficient ways to use energy are stimulated and developed. Only in this way will they be able to reduce their CO_2 emissions.

Regarding the globalization, the indicator of globalization used, besides being divided into their three dimensions, economic, political and social, is also divided into the measures of de jure and de facto. This chapter provides support for those thinking that de facto and de jure measures could have different impacts, and that combining the measures may provoke distorted results. The social dimension of globalization is divided into interpersonal, informational and cultural, and includes various variables which could provoke impacts on CO_2 emissions, such as international tourism, migration or high technology exports, international airports. This dimension of globalization only has an impact in the long run on CO_2 emissions of the HGC. All the measures provoke an increase of the CO_2 emissions. This positive effect could be explained by the exportation of high technology or by the propensity of these countries to be more requested by international students, international tourism and migration. Therefore, an increase of the social globalization implies an increase of the economic activity, which is implicitly associated with an increase of CO_2 emissions.

The economic dimension of globalization, only the measure of de facto, has an impact on CO_2 emissions of the HGC, in the short run, a restrictive impact, meaning that an increase of the economic dimension de facto decreases CO_2 emissions. This effect could be explained by a great foreign direct investment applied in the specialization and in technology more efficiently. At the meantime, the economic dimension de jure is not statistically significant on CO_2 emissions, which could be explained by low taxes, regulations and investment restrictions. In the long run, the same effect of the short run is captured in the HGC, while in the LGC both measures of the economic dimension have an impact on CO_2 emissions. The measure of de facto has a restrictive effect on CO_2 emissions, while the measure of de jure has an expansionist effect. This effect could be explained as follows: in long run, the LGC increase the trade in goods and services and foreign direct investment, which incentivize the investment on efficiency technology. Due to this, the effect in CO_2 emissions is negative. However, the positive effect of the de jure measure could be explained by restrictions on investment which provoke a continuous use of older and more polluting technologies and consequently an increase in CO_2 emissions.

The political dimension of globalization provokes different effects on CO_2 emissions varying with the group of countries considered. Taking into account the two measures of de jure and de facto, each one has an effect on CO_2 emissions of one group of countries. Indeed, on the one hand, political globalization of de jure has an impact on CO_2 emissions of the HGC. On the other hand, political globalization of de facto has an impact on CO_2 emissions of the LGC. The impact of both measures of political dimensions on CO_2 emissions is negative in the short run. In the long run, the same effects of the short run were verified and in the LGC the measure of de jure has also an impact on CO_2 emissions, a positive impact. In short, the measure of de jure could be mostly associated with the HGC, while the measure of de facto could be mostly associated with the LGC. This could be explained by the fact that the HGC are leaders and policy-makers, while the LGC are policy takers. In other words, and simplifying, the HGC design policies, while the LGC execute them.

6 Conclusion

This chapter analyses the relationship between economic growth and environmental quality for 28 OECD countries, including an efficiency index, energy consumption, renewable and non-renewable, and globalization on their three dimensions, economic, political and social, each one divided into the measures de facto and de jure. To fulfil the objective, the EKC was assessed, through the structure of the ARDL model and the Driscoll–Kraay estimator, for the period from 1990 to 2015. The 28 countries were divided into two groups, through the mean calculated for the globalization ranking of the 28 countries, the HGC and the LGC. Therefore, two models were estimated, and the group were analysed individually.

The findings prove that the EKC hypothesis is confirmed for the HGC, while for the LGC a U-shaped relationship is verified. As such, there is no evidence of the EKC for this group of countries. Regarding the globalization, in general, considering three dimensions of globalization, economic, social and political, and the measures de facto and de jure, the globalization on the majority has a restrictive effect on CO_2 emissions of both groups. Besides that, the efficiency index reveals that the investment in efficient technology has been increasing and the countries become more efficient.

Considering the results obtained, the HGC need to prepare for social globalization, which includes migration, international tourism, international students and international airports, which in turn imply an increase of the economic activity, and considering the results causes an increase of CO_2 emissions. Taking into account the efficiency index, the countries should keep going to invest in efficient technology. The results suggest that the mix diversification on the LGC could not have the desired consequences and is not enjoying its full potential. This could be explained by the fact that the LGC are using technologies very dependent on fossil sources. Hereupon, the diversification of the energy mix is not enough. The LGC has to promote the conversion of technologies, namely by using more electricity and less fossil powered engines or technologies.

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Financial Development and Environmental Degradation in Emerging Economies

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Abstract This chapter aims to examine the effect of different financial development indicators (i.e., overall financial development index, banking development index, stock market development index, and bond market development index) on environmental degradation for the period from 1991 to 2013 in 17 emerging economies. For this purpose, the relationship between financial development indicators, real income, urbanization, energy consumption, and ecological footprint is investigated using second-generation panel data methodologies to take into account the cross-sectional dependence. The empirical result reveals that increasing overall financial development index reduces environmental degradation. In addition, it is concluded that stock market development reduces environmental degradation while banking development and bond market development have no significant effect on environment.

Keywords Environmental degradation · Ecological footprint · Financial development · Emerging economies

1 Introduction

In recent decades, the sustainable development goal, particularly environmental sustainability has gained importance as never before, and many countries have funded investments toward these goals. After the pioneering works of Grossman and Krueger [12, 13], the basis of environmental degradation has often been associated with economic growth of countries based on fossil fuel-dependent production structures. In this direction, governments of many countries have turned to renewable energy sources that reduce carbon dioxide emissions in order to prevent environmental degradation and have supported projects that serve to improve renewable energy technologies. However, it is more preferable that such projects are financed by the

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private sector rather than the public sector. Because if the clean energy projects are directly financed by public financing instruments, the assumption that public financing will often be less costly than private financing may lead to a risk of the crowding-out private sector, even if it is more appropriate for private sector [14]. On the other hand, the role of finance sector on environmental quality is still ambiguous.

The possible positive effect of financial sector development has been explained with the view that financial openness encourages the investors to invest in eco-friendly technologies with high energy efficiency, thus promotes environmental quality [17]. However, Sadorsky [27] argues that financial development increases the credit supply and reduces financial costs which encourages consumption and the investments of both households and firms, thus increases the carbon emissions. Based on these contradictory allegations, it is a crucial issue that investigates the role of finance sector on environmental quality.

The other problematic and crucial issue is how to measure the level of environmental degradation. Most of the researchers have utilized with some atmospheric emissions (CO_2, NO_x, and SO_x) as an indicator of environmental degradation. However, reducing atmospheric emissions does not mean that environmental degradation will decline as well. For instance, measures to reduce carbon dioxide emissions may lead to degradation in forest land, grazing land, or water resources. Therefore, ecological footprint developed by Wackernagel and Rees [41] may potentially be more suitable for measuring the level of environmental degradation. Because the ecological footprint is the sum of six subcomponents, i.e., cropland, grazing land, fishing grounds, forest land, built-up land, and carbon footprint [9].

Based on above discussions, the aim of this chapter is to investigate the effect of financial development on ecological footprint in emerging economies. The main reason for the selection of emerging economies is due to the lack of public funds of these countries in financing of green projects when compared to the developed countries. The contributions of this chapter to the existing literature are as follows: (i) Unlike previous studies, this study examines the impact of financial development with different dimensions (i.e., stock market development, bond market development, and banking sector development) on environmental degradation and this situation gives a chance to policy implications in detail. (ii) This study utilizes with the ecological footprint as an indicator of environmental degradation while most of the previous studies used atmospheric emissions. (iii) In order to prevent the possible omitted variable bias, some control variables (i.e., economic growth, energy consumption, and urbanization) are included to the empirical models. (iv) This study employs the second-generation panel data methodologies to take into account the possible cross-sectional dependence among emerging economies.

2 Literature Review

In environmental economics literature, there are many studies that examine the linkage between economic performance and environmental degradation and it is mostly argued that high growth performance reduces environmental degradation with the influence of technological progression. On the other hand, the funding process of these high-cost environmental friendly technologies is generally ignored. Based on the argument that the finance sector may play a key role in financing clean energy projects, we observe the studies that examined the nexus between financial development and environmental quality.

Abbasi and Riaz [1] examined the financial development and environmental degradation nexus for the period from 1971 to 2011 in emerging economies using with ARDL-bound test and concluded that financial development increases carbon dioxide emissions. Saidi and Mbarek [28] investigated the impact of economic growth, trade, urbanization, and financial development on environmental degradation in 19 emerging economies for the period of 1990–2013 using with panel GMM estimation and found that increasing financial activities reduce carbon dioxide emissions. Koengkan et al. [17] probed the relationship between financial openness and carbon dioxide emissions in MERCOSUR countries for the period from 1980 to 2014 with panel ARDL approach and found that financial development increases environmental degradation. Omri et al. [18] looked at the relationship between financial development, economic growth, trade openness, and environmental degradation for the period from 1990 to 2011 in 12 MENA countries using with panel GMM method and concluded that financial development has no statistically significant effect on environmental degradation. Ozturk and Acaravci [19] investigated the nexus between financial development and environmental degradation for the period from 1960 to 2007 in Turkey and concluded that financial development has not significant effect on carbon dioxide emissions. Salahuddin et al. [29] examined the effect of economic growth, electricity consumption, foreign direct investment, and financial development on environmental degradation in Kuwait for the period of 1980–2013 using with ARDL-bound test approach and concluded that financial development reduces carbon dioxide emissions for the long run. Shahbaz et al. [30] searched the nexus between financial development, economic growth, energy consumption, international trade, and environmental degradation in Indonesia for the quarterly period from 1975 q1 to 2011 q4 using with ARDL-bound test and the results show that financial development reduces environmental degradation. Shahbaz et al. [31] probed the effect of financial development on carbon dioxide emissions for the period from 1971 to 2011 in Malaysia utilizing with ARDL-bound test approach and found the reducing effect of financial development on environmental degradation. Shahbaz et al. [32] investigated the impact of financial development, coal consumption, economic growth, and trade openness on environmental quality for the period from 1965 to 2008 in South Africa with ARDL-bound test and the study confirmed the reducing effect of financial development on emissions. Tamazian et al. [36] searched the association between stock market development, banking development, and environmental degradation for the period of 1992–2004 in BRIC countries and the results show that both stock market development and banking sector development reduce environmental degradation. Boutabba 4] examined the impact of financial development, energy consumption, and trade on carbon emissions for the period from 1971 to 2008 in India using with ARDL-bound test approach and found that financial development deteriorates environment. Charfeddine and Khediri [7] probed the nexus between financial development and environmental quality in United Arab Emirates for the period of 1975–2011 and found an inverted U-shaped relationship between financial development and environmental degradation. Shahbaz et al. [33] searched the relationship between financial development, globalization, energy consumption, and carbon emission in India spanning the period from 1970 to 2012 and the results show that financial development accelerates environmental degradation. Dogan and Turkekul [10] applied the ARDL-bound testing approach to determine the impact of financial development on CO_2 emissions in the USA. They found that financial development affects carbon emissions insignificantly. By apply DOLS, Katircioğlu and Taspinar [16] reported that financial development impedes environmental quality by increasing carbon emissions. Solarin et al. [35] examined the impact of foreign direct investment and financial development on CO_2 emissions in Ghana by applying the bound testing approach. They found that foreign direct investment and financial development increase carbon emissions. Jalil and Feridun [15] investigated the effect of economic growth, financial development, and energy consumption on environment for the period of 1953–2006 in China using with ARDL-bound test approach and concluded that financial development reduces carbon emissions.

Paramati et al. [20] focused on the impact of stock market development on environment and examined the impact of foreign direct investment and stock market development on carbon emission for the period of 1991–2012 in emerging economies and the study concluded that stock market development increases environmental degradation. Paramati et al. [21] compared the effect of stock market development on carbon emission observing the period from 1993 to 2012 in EU, G-20, and OECD countries, respectively. The findings of this study show that stock market development increases environmental degradation in OECD countries while it reduces the degradation in EU and G-20 countries. Paramati et al. [22] examined the connection between stock market development and environmental degradation for the period from 1991 to 2012 in G-20 countries and concluded that stock market development increases the carbon emissions in developing G-20 countries while stock market reduces the emission in developed G-20 countries.

As seen from mentioned literature, the environmental degradation level is generally indicated by CO_2 emissions while the level of environmental degradation cannot be captured by only the carbon emissions. In addition, most of these studies examined the effect of financial development on environment and the different dimensions of the financial sector were not considered. These deficiencies constitute the main motivation of the study that investigating the impact of banking sector development, stock market development, and bond market development as well as the overall financial development on ecological footprint.

3 Empirical Strategy

3.1 Model and Data

The annual data used in this chapter covers the period from 1991 to 2013 for 17 emerging economies: Brazil, China, Colombia, Czech Republic, Greece, Hungary, Indonesia, South Korea, Malaysia, Mexico, Peru, Poland, Philippines, Russia, South Africa, Thailand, and Turkey. To examine different financial development indicators on environmental degradation, the panel version of empirical models are constructed as follows:

$$\ln \mathrm{EF}_{it} = \alpha_0 + \alpha_1 \ln \mathrm{GDP}_{it} + \alpha_2 \ln \mathrm{EC}_{it} + \alpha_3 \ln \mathrm{URB}_{it} + \alpha_4 \ln \mathrm{FD}_{it} + u_{it} \quad (1)$$

$$\ln \mathrm{EF}_{it} = \alpha_0 + \alpha_1 \ln \mathrm{GDP}_{it} + \alpha_2 \ln \mathrm{EC}_{it} + \alpha_3 \ln \mathrm{URB}_{it} + \alpha_4 \ln \mathrm{BAD}_{it} + u_{it} \quad (2)$$

$$\ln \mathrm{EF}_{it} = \alpha_0 + \alpha_1 \ln \mathrm{GDP}_{it} + \alpha_2 \ln \mathrm{EC}_{it} + \alpha_3 \ln \mathrm{URB}_{it} + \alpha_4 \ln \mathrm{SMD}_{it} + u_{it} \quad (3)$$

$$\ln \mathrm{EF}_{it} = \alpha_0 + \alpha_1 \ln \mathrm{GDP}_{it} + \alpha_2 \ln \mathrm{EC}_{it} + \alpha_3 \ln \mathrm{URB}_{it} + \alpha_4 \ln \mathrm{BND}_{it} + u_{it} \quad (4)$$

where ln EF is the natural log of ecological footprint which indicates environmental degradation, ln GDP is the natural log of real gross domestic product which indicates economic growth, ln EC is natural log of energy consumption, ln URB is natural log of urbanization, ln FD is natural log of overall financial development index, ln BAD is natural log of banking development index, ln SMD is natural log of stock market development index, and ln BND is natural log of bond market development index. In addition, i, t, and u_{it} refers to cross section, time period, and error terms, respectively.

The ecological footprint is measured in ecological footprint per capita, gross domestic product per capita is measured in constant 2010 US$, urbanization is measured in percentage of urban population in total population, and energy consumption is measured in kg of oil equivalent per capita. FD represents the financial development index which includes three sub-indices. The financial development index includes banking sector development index (BAD), stock market development index, (SMD) and bond market development index (BND). The banking sector development index is constructed with using deposit money bank assets to GDP, financial system deposit to GDP, liquid liabilities to GDP, and private credit by deposit money banks to GDP. The stock market development index covers the stock market capitalization to GDP, stock market turnover ratio, and stock market total value traded to GDP. The bond market development index includes the outstanding domestic private debt securities to GDP, the outstanding domestic public debt securities to GDP, the outstanding international private debt securities to GDP, and the outstanding international public debt securities to GDP. Following the studies of Tang and Tan [37], Shahbaz et al.

[34], Topcu and Payne [38] and Destek [8], the financial development index and the sub-indices are computed with principal component analysis (PCA).

3.2 Methodology

3.2.1 Panel Unit Root Test

The stationary properties of variables are examined with the panel unit root test of Pesaran [24] to consider the cross-sectional dependence. The test which is called as second-generation panel data methodologies is characterized by the rejection of cross-sectional independence hypothesis, and therefore, the tests is suitable for the panel data, where cross-sectional dependence is present. Since the CIPS unit root test is based on CADF test, first the computation of the cross-sectional ADF (CADF) regression can be shown as follows:

$$\Delta y_{it} = a_i + \rho_i y_{it-1} + \beta_i \bar{y}_{t-1} + \sum_{j=0}^{k} \gamma_{ij} \Delta \bar{y}_{it-1} + \sum_{j=0}^{k} \delta_{ij} y_{it-1} + \varepsilon_{it} \tag{5}$$

where a_i is deterministic term, k is the lag order, and $\bar{y}_t$ is the cross-sectional mean of time t. Following above equation, t-statistics are obtained with the computation of individual ADF statistics. Furthermore, CIPS is obtained from the average of CADF statistic for each i as follows:

$$\text{CIPS} = \left(\frac{1}{N}\right) \sum_{i=1}^{N} t_i(N, T) \tag{6}$$

The critical values of CIPS for different deterministic terms are given by Pesaran [24].

3.2.2 Common Correlated Effect Mean Group (CCE-MG) Estimator

In case of the existence of cross-sectional dependence, the impact of explanatory variables on the dependent variable should be examined with a second-generation panel data estimators. In this direction, this study utilizes the common correlated effect mean group (CCE-MG) estimator developed by Pesaran [26] to take into account the cross-sectional dependence. If we combined our main panel models as follows:

$$Y_{it} = \delta_0 + \delta_1 X_{it} + e_{it} \tag{7}$$

where Y_{it} is ecological footprint, $X_{i,t}$ is the vector of explanatory variables, and the residual term (e_{it}) is a multifactor residual term. The multifactor residual terms are constructed as follows:

$$e_{it} = \lambda_i' \mathrm{UF}_t + u_{it} \quad (8)$$

where UF_t is the $m \times 1$ vector of unobserved common factors. In addition, Pesaran [26] utilizes with cross-sectional averages, $\bar{y}_t = \frac{1}{N}\sum_{i=1}^{N} Y_{it}$ and $\bar{X}_t = \frac{1}{N}\sum_{i=1}^{N} X_{it}$ to deal with cross-sectional dependence of residuals as observable proxies for common factors. In the next step, slope coefficients and their cross-sectional averages are consistently regressed as follows:

$$Y_{it} = \delta_0 + \delta_1 X_{it} + a\bar{y}_t + c\bar{X}_t + \varepsilon_{it} \quad (9)$$

Pesaran [26] refers to the computed OLS estimator $\hat{B}_{i,\mathrm{CCE}}$ of the individual slope coefficients $B_i = (\delta_1, .., \delta_n)$ as the "Common Factor Correlated Effect" estimator:

$$\hat{B}_{i,\mathrm{CCE}} = \left(Z_i' \bar{D} Z_i\right) Z_i' \hat{D} Y_i, \quad (10)$$

where $Z_i = (z_{i1}, z_{i2}, \ldots, z_{iT})'$, $z_{it} = (X_{it})'$, $Y_i = (Y_{i1}, Y_{i2}, \ldots, Y_{it})'$, $\bar{D} = I_T - \bar{H}\left(\bar{H}'\bar{H}\right)^{-1}\bar{H}$, $\bar{H} = (h_1, h_2, \ldots, h_T)'$, $h_t = \left(1, \bar{Y}_t, \bar{X}_t\right)$ as the CCE estimators. The CCE-MG estimator is obtained with the average of the individual CCE estimators as follows:

$$\hat{B}_{\mathrm{CCEMG}} = \sum_{i=1}^{N} \hat{B}_{i,\mathrm{CCE}}. \quad (11)$$

3.2.3 Augmented Mean Group (AMG) Estimator

In panel data methodologies, in addition to the issue that cross-sectional dependence, one of the other problems is that assuming the homogeneous slope coefficient. Using the standard dynamic panel estimators may not be appropriate for macroeconomics panels since these estimators assume homogeneous slope coefficients across panels. In order to deal with this problem, Bond and Eberhardt [3] developed the augmented mean group (AMG hereafter) estimator which allows heterogeneity in slope coefficients and also allows for both cross-sectional dependence and non-stationary variables. The AMG estimator includes a common dynamic process which indicates unobservable common factors in the main model. To employ the AMG estimator, the main model of this study can be constructed as follows;

$$Y_{it} = \beta_{1i} X_{it} + \mu_{it} \quad (12)$$

where i and t indicate the cross section and the time period, respectively. The AMG testing procedure includes two stages. In first stage, first differenced form augmented with $T - 1$ year dummies of Eq. (12) is estimated with pooled OLS regression and the parameters of the year dummies are collected as follows;

$$\Delta Y_{it} = \beta_{1i} \Delta X_{it} + \sum_{t=2}^{T} p_t (\Delta D_t) + \mu_{it} \tag{13}$$

where (ΔD_t) represents differenced $T - 1$ year dummies and p_t indicates parameters of year dummies. Estimated parameters $\left(\hat{p}_t\right)$ are relabeled as $\hat{\gamma}_t$ which implies the evolution of common dynamic process. The second stage is as following;

$$\Delta Y_{it} = \beta_{1i} \Delta X_{it} + d_i \left(\hat{\gamma}_t\right) + \mu_{it} \tag{14}$$

$$\Delta Y_{it} - \hat{\gamma}_t = \beta_{1i} \Delta X_{it} + \mu_{it} \tag{15}$$

The group-specific regression model is augmented with $\hat{\gamma}_t$ as shown in Eq. (14) and finally, the group-specific model coefficients are averaged across the panel.

3.2.4 Panel Heterogeneous Causality Test

Investigating the causal relationship between variables is also crucial for empirical studies. Therefore, we employ the panel heterogeneous causality test of Dumitrescu and Hurlin [11] to determine the possible causal connections and the directions of the causalities. There are some advantages of using this procedure. First, this methodology gives consistent results in case of both small samples and cross-sectional dependence. Second, the test is suitable if all the variables are stationary at same level. Third, the test is appropriate for the unbalanced panels and panels with different lag order for each individual. The panel heterogeneous causality method is constructed as follows:

$$W_{N,T}^{\text{HNC}} = \frac{1}{N} \sum_{i=1}^{N} W_{i,t} \tag{16}$$

where $W_{i,t}$ is the Wald statistic for the country i, therefore the first statistic computed with the simple means of Wald statistic, individually. In addition, Dumitrescu and Hurlin [11] suggested another statistic with standardizing $W_{N,T}^{\text{HNC}}$ statistic by using estimated values of mean and variance of each Wald statistic with a small sample for T. The computation of this statistic is as following:

$$Z_{N,T}^{\mathrm{HNC}} = \frac{\sqrt{N}\left[W_{N,T}^{\mathrm{HNC}} - \sum_{i=1}^{N} E\left(W_{i,t}\right]\right.}{\sqrt{\sum_{i=1}^{N} \mathrm{Var}\left(W_{i,t}\right)}} \tag{17}$$

In testing procedure, the null of there is not a homogeneously causality in the panel is tested against the alternative hypothesis.

4 Institutional Background

In order to observe the global importance of emerging economies, some macroeconomic variables related to this study are observed within global indicators. The global significance of emerging economies can be seen in Table 1. The statistics show that the national income of emerging economies constituted 17.18% of global income in 1991 and this share has been increased to 26.54% in 2013. As a common result of this economic achievement, the share of energy usage of emerging economies has increased from 30.20% in 1991 to 40.18% in 2013 and the share of ecological footprint of emerging economies has increased from 33.13% in 1991 to 41.60% in 2013. Surprisingly, as a shown in Table 1, in contrast to rapid economic growth and rapid environmental degradation, the share of the population of these countries in the global population dropped from 39.53% in 1991 to 36.20% in 2013.

If the statistics are evaluated in terms of the growth rates, it seems the significance of the emerging economies in global income has increased by 54.45% and the energy consumption share of these countries in global energy consumption has increased by 33.04%. In addition, the responsibility of emerging economies for increasing environmental degradation has increased by 25.57% spanning the period from 1991 to 2013. Moreover, the share of the population of these countries has decreased by 8.42%. To sum up, if the emerging economies maintain their growth rates for mentioned variables, they will increase their economic importance for the global economy as well as they will be responsible for accelerating the environmental degradation in the near future. Based on this, the successful implementation of effective energy policies by these countries is crucial to the achievement of targets to reduce global environmental degradation.

Table 2 presents the mean values of observed variables as well as the summary statistics of emerging economies for the period of 1991–2013. It seems that there is a huge variation of per capita income among emerging economies with the highest 24,017 US dollars in Greece and the lowest 1767 US dollars in Philippines. In the similar direction, Greece, Czech Republic, and Russia have the highest ecological footprint while lowest ecological footprint values belong to Philippines, Indonesia, and Colombia. In addition, the most energy consumer countries are Russia and South Korea. In case of urbanization, the share of urban population in total population of emerging economies ranges from 35.92% in Thailand to 81.04% in Brazil.

Table 1 Trend of selected variables for emerging economies

Year	EF	GDP	EC	POP
1991	33.136	17.185	30.201	39.538
1992	33.255	17.003	29.898	39.438
1993	34.108	17.353	30.206	39.320
1994	33.521	17.449	29.719	39.207
1995	34.393	17.694	30.091	39.086
1996	34.557	17.956	30.182	38.972
1997	34.579	18.220	30.081	38.856
1998	33.766	17.872	29.665	38.735
1999	34.668	17.991	29.777	38.601
2000	34.721	18.357	30.009	38.449
2001	35.225	18.633	30.340	38.294
2002	35.507	19.195	30.766	38.131
2003	35.668	19.662	31.983	37.959
2004	36.437	20.146	33.001	37.782
2005	36.611	20.671	33.960	37.605
2006	37.425	21.358	34.880	37.425
2007	38.026	22.236	35.654	37.243
2008	38.764	23.060	36.097	37.061
2009	40.196	23.899	37.152	36.882
2010	40.371	24.612	38.033	36.704
2011	41.445	25.347	39.317	36.542
2012	41.898	25.949	39.841	36.374
2013	41.608	26.542	40.180	36.207

Note EF: percentage of global ecological footprint, GDP: percentage of global GDP, EC: percentage of global energy consumption, POP: percentage of global population

Table 2 Summary statistics of emerging economies

Countries	EF	GDP	EC	URB
Brazil	2.869	9433.569	1136.406	81.046
China	2.332	2578.151	1263.548	39.231
Colombia	1.956	5315.454	674.335	72.606
Czech Rep.	5.790	16,274.880	4173.430	73.947
Greece	5.432	24,017.380	2433.732	73.870
Hungary	3.697	11,228.220	2526.732	66.424
Indonesia	1.328	2492.328	737.819	42.827

(continued)

Table 2 (continued)

Countries	EF	GDP	EC	URB
S. Korea	5.206	16,503.360	4009.881	79.877
Malaysia	3.715	7451.526	2211.574	63.063
Mexico	2.819	8464.951	1521.742	75.376
Peru	1.934	3808.129	496.849	73.763
Poland	4.439	9265.527	2511.007	61.351
Philippines	1.147	1767.570	462.858	47.031
Russia	5.346	8297.668	4634.506	73.478
S. Africa	3.388	6441.304	2583.561	58.046
Thailand	2.116	4021.487	1335.426	35.922
Turkey	2.787	8992.756	1230.752	66.080
Descriptive statistics				
Mean	3.312	8609.074	1996.715	63.761
Median	3.049	7494.315	1622.965	69.311
Maximum	7.267	30,055.470	5861.144	85.171
Minimum	1.007	787.868	408.434	27.312
Std. Dev.	1.500	6031.888	1308.269	14.506

Note EF: ecological footprint per capita, GDP: GDP per capita in 2010 constant dollar, EC: energy consumption per capita, URB: the share of urban population in total population

5 Empirical Results

In order to investigate the effect of different financial development indicators on environmental degradation, we first examine the validity of cross-sectional dependence among emerging economies using with Lagrange multiplier (LM) test of Breusch and Pagan [5], cross-sectional dependence (CD) and Lagrange multiplier for cross-sectional dependence (CD_{LM}) test of Pesaran [23], and LM_{adj} test of Pesaran et al. [25]. As illustrated in Table 3, the null hypothesis of cross-sectional independence is rejected by all tests. Therefore, it is concluded that a shock in one of the emerging country may be easily transmitted to the other countries.

Although utilized coefficient estimators do not require pretesting procedures such as unit root and cointegration tests, the stationarity of the variables is examined by CIPS unit root test because the causality test to be used can be applied to stationary variables. The results from Table 4 shows that the null hypothesis of unit root is not rejected for the level form of all variables. However, in the first differenced form, the null hypothesis is strongly rejected and the variables have become stationary. This results mean that the variables are integrated of order one and denoted I(1).

The validity of cross-sectional dependence requires the second-generation panel data estimation method that allows cross-sectional dependence among countries. Hence, we first utilize with CCE-MG estimator and the results are shown in Table 5.

Table 3 Cross-sectional dependence test results

	ln EF	ln GDP	ln EC	ln URB	ln FD	ln BAD	ln SMD	ln BND
LM	647.819 [0.000]	2544.776 [0.000]	1036.885 [0.000]	2442.135 [0.000]	255.312 [0.000]	192.954 [0.001]	255.658 [0.000]	766.143 [0.000]
CD_{LM}	31.033 [0.000]	146.053 [0.000]	54.624 [0.000]	139.830 [0.000]	7.234 [0.000]	3.453 [0.000]	7.255 [0.000]	38.208 [0.000]
CD	30.647 [0.000]	145.667 [0.000]	54.237 [0.000]	139.443 [0.000]	6.847 [0.000]	3.067 [0.002]	6.868 [0.000]	37.821 [0.000]
LM_{adj}	10.899 [0.000]	50.094 [0.000]	14.969 [0.000]	24.332 [0.000]	−1.887 [0.059]	−2.643 [0.008]	−2.313 [0.020]	2.887 [0.003]

Note Numbers in brackets are *p*-values

Table 4 CIPS unit root test results

	ln EF	ln GDP	ln EC	ln URB	ln FD	ln BAD	ln SMD	ln BND
CIPS test (*L*)	−2.506	−2.064	−1.754	−2.295	−1.835	−2.558	−1.837	−1.746
CIPS test (Δ)	−4.907	−3.412	−4.176	−2.925	−3.366	−4.697	−3.366	−4.191

Note L and Δ indicates the level form and the first differenced form of variables. Critical values are 10%: −2.580, 5%: −2.670, 1%: −2.830

First of all, based on the results from all models, we found that increasing real income and energy consumption increases environmental degradation in emerging economies. A 1% increase in real income increases ecological footprint by 0.570–0.672% and a 1% increase in energy consumption increases ecological footprint by 0.390–0.401%. The findings that increasing real income increases ecological footprint is also found by Al-Mulali et al. [2], Ulucak and Bilgili [40], and Destek et al. [9]. This result means that observed countries pay more attention to the economic sustainability than environment. Moreover, the findings that ecological footprint increasing effect of energy consumption is also consistent with the study of Charfeddine [6]. This finding can be interpreted as the production activities of emerging economies have still depended on fossil fuel energy consumption. In addition, it seems that the coefficient of urbanization on environmental degradation is positive for all models while it is statistically significant only for Model II and Model III. In case of financial development, the result reveals that financial development reduces environmental degradation. All else is same, a 1% increase in overall financial development index reduces ecological footprint by 0.007%. The obtained evidence that financial development reduces ecological footprint is consistent with Uddin et al. [39]. In addition, our results show that only stock market development index is efficient to reduce environmental degradation among sub-indices of financial development. A 1% increase in stock market development index reduces ecological footprint by 0.005%. On the other hand, the coefficient of both banking development index is statistically insignificant.

Table 5 CCE mean group estimation results

	Model I	Model II	Model III	Model IV
ln GDP	0.581*** [0.155]	0.570*** [0.175]	0.583*** [0.150]	0.672*** [0.165]
ln EC	0.399*** [0.125]	0.401*** [0.123]	0.390*** [0.121]	0.399*** [0.137]
ln URB	1.093 [1.050]	1.650* [0.875]	0.935* [0.525]	1.180 [1.142]
ln FD	−0.007** [0.003]	–	–	–
ln BAD	–	0.002 [0.004]	–	–
ln SMD	–	–	−0.005** [0..002]	–
ln BND	–	–	–	0.002 [0.002]

Note *, ** and *** indicates statistically significance at 10, 5, and 1% level, respectively. The numbers in brackets are standard errors

We also use the AMG estimator to robustness check of the estimation results and present in Table 6. According to the AMG estimation, similar to the CCE estimation results, it is found that increasing real income and energy consumption increases environmental degradation. All else is same, a 1% increase in real income increases ecological footprint by 0.583–0.603% and a 1% increase in energy usage increases ecological footprint by 0.378–0.388%. Unlike the CCE-MG estimation, the coefficient of urbanization on ecological footprint is found as statistically insignificant. When the results are evaluated in terms of financial development, the result reveals a 1% increase in overall financial development index reduces ecological footprint by 0.005%. In the same way, as CCE-MG results, the AMG estimation results also show that only stock market development is efficient in reducing environmental degradation.

Next, the causal relationship between explanatory variables and ecological footprint is searched with Dumitrescu–Hurlin causality method and the results are shown in Table 7. According to the findings, there is bidirectional causal relationship between real income and ecological footprint. The bidirectional causality is also found between urbanization and ecological footprint. In addition, the unidirectional causal relationships are valid from energy consumption to ecological footprint, overall financial development index to ecological footprint, stock market development index to ecological footprint, and from ecological footprint to bond market development index. However, there is no causal connection between banking development index and ecological footprint.

To sum up, our results show that increasing real income and increasing energy usage are the main drivers of environmental degradation in emerging economies. In case of financial development, it seems that increasing overall financial development

Table 6 Augmented mean group estimation results

	Model I	Model II	Model III	Model IV
ln GDP	0.593*** [0.108]	0.603*** [0.111]	0.583*** [0.109]	0.598*** [0.106]
ln EC	0.382*** [0.117]	0.378*** [0.115]	0.386*** [0.117]	0.388*** [0.122]
ln URB	0.246 [0.386]	0.191 [0.426]	0.223 [0.381]	0.028 [0.428]
ln FD	−0.005* [0.003]	–	–	–
ln BAD	–	0.001 [0.003]	–	–
ln SMD	–	–	−0.005* [0.003]	–
ln BND	–	–	–	0.003 [0.002]

Note *, ** and *** indicates statistically significance at 10, 5, and 1% level, respectively. The numbers in brackets are standard errors

Table 7 Dumitrescu–Hurlin causality test results

Null hypothesis	*W*-stat.	Zbar-stat.	Prob.
ln GDP does not homogeneously cause ln EF	3.986	6.831	0.000
ln EF does not homogeneously cause ln GDP	4.859	8.909	0.000
ln EC does not homogeneously cause ln EF	2.891	4.223	0.000
ln EF does not homogeneously cause ln EC	1.647	1.261	0.207
ln URB does not homogeneously cause ln EF	3.972	6.797	0.000
ln EF does not homogeneously cause ln URB	8.985	18.734	0.000
ln FD does not homogeneously cause ln EF	2.008	2.121	0.034
ln EF does not homogeneously cause ln FD	0.684	−1.032	0.302
ln BAD does not homogeneously cause ln EF	0.770	−0.828	0.408
ln EF does not homogeneously cause ln BAD	0.761	−0.848	0.396
ln SMD does not homogeneously cause ln EF	2.008	2.121	0.034
ln EF does not homogeneously cause ln SMF	0.684	−1.032	0.302
ln BND does not homogeneously cause ln EF	1.015	−0.244	0.807
ln EF does not homogeneously cause ln BND	0.332	−1.871	0.061

index and stock market development reduces environmental degradation while bond market development and banking development have not statistically significant effect on environment.

6 Conclusions and Policy Implications

This chapter examined the impact of financial development with different dimensions (banking development, stock market development, and bond market development) on environmental degradation for the period from 1991 to 2013 in emerging economies. In doing so, as proxy of environmental degradation, we used the ecological footprint; and overall financial development index, banking development index, stock market development index, bond market development index, real income, energy consumption, and urbanization are included as explanatory variables to the empirical models and the associations between variables are estimated using with second-generation panel data methodologies to take into account possible cross-sectional dependence among countries.

Our empirical findings show strong evidence of cross-sectional dependence among emerging economies thus it is concluded that a shock in one of the emerging economies may be easily transmitted to the other countries. The results also indicate that increasing income level and increasing energy consumption are the main triggers of environmental degradation in observed countries. In case of finance sector, it is found that overall financial development and stock market development reduce the ecological footprint while banking development and bond market development have no significant effect on environmental degradation. We also search the causal connection between variables and causality test results reveal that there is bidirectional causal relationship between real income and ecological footprint. The bidirectional causality is also found between urbanization and ecological footprint. In addition, the unidirectional causal relationships are valid from energy consumption to ecological footprint, overall financial development index to ecological footprint, stock market development index to ecological footprint, and from ecological footprint to bond market development index. However, there is no causal connection between banking development index and ecological footprint.

The empirical findings of this study have many policy implications. The most remarkable of which is that although carbon emissions is one of the most important components of the ecological footprint, addressing only carbon emissions reduction goals and steering the funds in the financial system solely for this purpose does not reduce ecological footprint. In this direction, it is important that these countries should adopt policies and measures to reduce the excessive exploitation of natural resources and increase the effectiveness in resource use in order to reduce the gap between their biocapacity and ecological footprint.

Moreover, it is a well-known fact that in countries where the financial sector is developed, financial resources are obtained at a lower cost. In this direction, the funds needed for the purchase of technologies that provide efficiency in energy consumption and for eco-friendly and renewable energy technologies can be provided from finance sector. However, our empirical findings suggest that such funds are provided from only stock market; banking sector and bond market does not have any role on environment in emerging economies. In this regard, new instruments and regulations for the finance sector can be developed. Governments of these countries should monitor the financial resources allocation mechanism of the banking sector through central banks or banking regulation agencies and tighten the credit conditions of the firms that are involved in the environmental degradation activities. For instance, the interest rates can be increased in the loans allocated to the firms having environmental degradation enhancing activities. In addition, the governments should encourage banks to enhance funding for development projects that promote energy efficiency and environmental friendly technologies.

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Implications of Environmental Convergence: Continental Evidence Based on Ecological Footprint

Faik Bilgili, Recep Ulucak and Emrah Koçak

Abstract Recently seminal articles in the literature have been investigating the issues of air pollution and convergence in air pollution by following CO_2 emissions. These seminal works eventually suggest some prominent environmental policies. This paper aims at (i) following a new, more comprehensive ecological indicator than CO_2 indicator, which is called ecological footprint (EF), and, (ii) observing if countries of four continents converge in EF indicator. The continents are Asia, Africa, America and Europe, respectively. This work eventually suggests some relevant environmental policies. EF compares the demand side and supply side of the natural resources. The EF, on the demand side, calculates the amount of human's consumption of natural resources and amount of waste from the consumption of resources. The EF indicator, on the supply side, measures how quickly nature can absorb people's waste and how quickly new resources can be created by nature. EF considers the global warming in a broader framework by following effects of land use, deforestation carbon emissions on climate change. The CO_2, hence, the greenhouse gas, is accounted for in ecological footprint measurement. Ecological footprint (i) presents an aggregated indicator considering separately the indicators of carbon dioxide emissions, collapse of fisheries, change in land use, and, deforestation, and, (ii) tracks the human activities-driven pressures on ecosystems and biodiversity. Therefore, ecological footprint might be followed to understand, in an integrated manner, the environmental impacts of the humans' activities on the biosphere and its composing ecosystems. To this end, a bootstrap-based panel KPSS test with structural breaks is carried out to determine whether or not environmental convergence happens for 15 countries of each continent. The continents are Asia, Africa, America and Europe, respectively. Results show that convergence in EF is verified

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in Africa, America and Europe whereas null hypothesis of convergence is rejected in Asia. Following the panel estimations, this paper eventually aims at exploring some environmental policies regarding sustainable urbanization, efficient water usage and optimization in land and forest management.

Keywords Ecological footprint · Biocapacity · Urbanization · Convergence · Asia · Africa · America · Europe

1 Introduction

Since the industrial revolution, mid-eighteenth century, the nations have experienced an important development process. The world economies have grown rapidly, the population has increased, industrialization and urbanization process has advanced and the use of natural resources has broadened prominently. However, concerns about the environmental effects of the economic development process began to emerge gradually in the 1970s. In this context, the Roman club, founded in 1968, published a report entitled 'The Limits to Growth in 1972.' This report emphasized that if the current upward trend in population growth, industrialization, environmental pollution, food production and resource consumption continues, humanity may face the threat of extinction. The report also stated that it would be possible to provide conditions for sustainable ecological and economic stability [32]. The messages in this report provided a basis for new environmental movements and created a huge impact by finding a social response [18]. Thus, the first seeds of the idea of sustainable development at the global level have been laid. Later, the Brundtland report (1987) argued that if mankind has a common future, this future is only based on the protection and development of the environment. Similar concerns are expressed in the Rio Conference (1992), the Kyoto Protocol (1997), the World Summit on Sustainable Development (2002) and the Paris Agreement (2015), and other recent international meetings. The main theme of all these meetings/summits has always been sustainability [47].

Sustainability is, in the simplest sense, a way of life to continue without interruption. Sustainability seeks answers to the following questions for the ecological balance [34]: (1) How should the natural system work? (2) How should diversity be protected? (3) How should the production be? The potential answer(s) might include many criteria such as ecological, economic and social issues. The clearest answer to these questions regarding sustainability can be given as preserving the productivity of renewable resources and biological systems in the world. The ecological footprint (EF) is a concept that represents sustainability in this respect [51]. The EF basically calculates the biological areas required to provide renewable resources that people use. In this way, a new perspective emerges in order to investigate the relationship between human demands and human resources. Through this perspective, the human impact on the world/environment is clearly revealed [33, 36]. The capacity of the world to meet people's demand was first exceeded in the mid-1970s, after

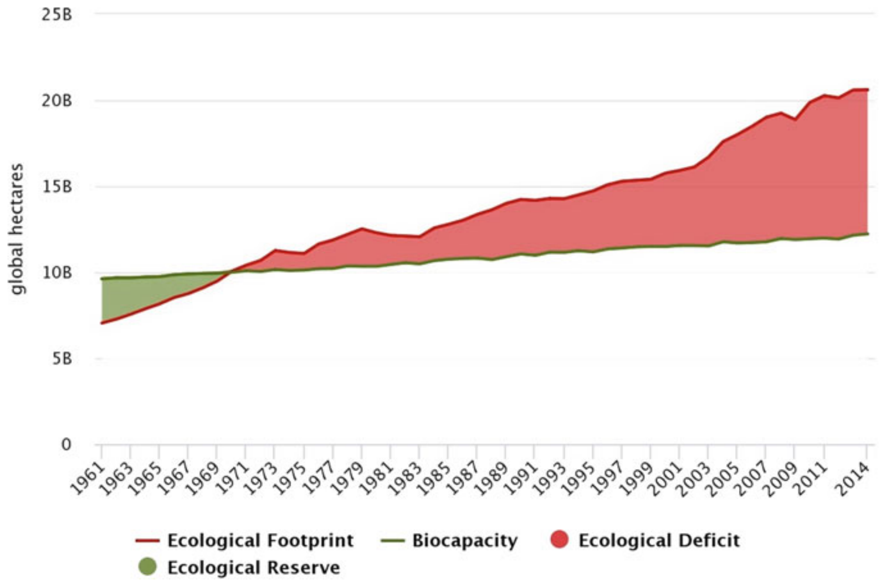

Fig. 1 Global ecological footprint and biocapacity 1961–2014

the ecological deficit increased continuously each year. In other words, while human consumption/EF has increased very rapidly with economic development and prosperity, the biological capacity of the world has developed very slowly (see Fig. 1). The change of this unsustainable situation or the elimination of the ecological deficit has become a necessity. Today, the sustainability and management of the planet's ecological existence has been a central problem for decision-makers. There is an urgent need to develop mechanisms, policies and strategies to address this issue [35]. For this reason, understanding of EF's stochastic behavior and its dynamic changes will make significant contributions to the design of sustainable policies. At this point, convergence studies on environmental indicators are of great importance in directing both national and international policies [14, 27].

Convergence hypothesis has attracted great interest in macroeconomic area especially with the pioneering work of Barro and Sala-i-Martin [8]. Convergence behavior between countries/regions is tested by many empirical methods such as time series, cross section and panel data. In the literature, economic growth and income convergence behaviors are frequently tested within the framework of neoclassical growth theory. Also, convergence behavior is being investigated for many different indicators such as commodity prices, education, health and military expenditures, financial and monetary variables, tourism and foreign trade [49]. Recently, global warming and climate change, environmental degradation and unsustainability of fossil energy consumption have paved the way for the investigation of environmental convergence behaviors.

In line with the importance of environmental convergence research, we will explore the ecological footprint convergence behavior for Asian, African, American and European continents for the period 1961–2014. The contribution of this paper is threefold:

(1) The average footprint of humanity causes a 50% global footprint. However, regional and national ecological footprint and biological capacity calculations in different parts of the world show different results. The ecological footprint of developed countries is much higher than that of developing countries [51]. Briefly, the environmental impact of people and their consumption varies from country to country and from region to region. Therefore, instead of revealing the global convergence behavior, we examine the convergence behavior of the continents. Thus, we aim to reach more specific results and offer more specific recommendations.

(2) When the current literature is evaluated, the following results are observed: (i) A large number of studies in the literature monitor CO_2 emissions as an indicator of the environment. (ii) The literature mainly supports the convergence hypothesis for the countries. (iii) There are few studies investigating the ecological footprint convergence hypothesis [44, 48]. Table 1 summarizes the literature testing the environmental convergence hypothesis.
It should be emphasized that the ecological footprint is a more satisfactory indicator than CO_2 emission. The ecological footprint is calculated by taking into consideration the CO_2 emissions as well as the indicators such as natural resources, soil, forest and mine stocks [48]. We use a more effective environmental indicator by testing the convergence hypothesis of the ecological footprint at the continents level. Thus, we aim to fill the gap in the literature by differentiating CO_2 emission from convergence studies.

(3) We will test the convergence hypothesis with the panel unit root test. Most studies using panel data method in energy economics literature assume that countries are homogeneous and there is no cross-sectional dependence between countries [9]. This paper follows the panel KPSS unit root test with structural breaks developed by Carrion-i-Silvestre et al. [15]. The reason why panel KPSS unit root method is preferred can be explained by the following advantages: (a) Economic, social and political shocks or structural changes may occur in countries within a certain period. These shocks/changes cause structural breaks in the time series and/or panel data. Therefore, unit root tests that do not consider structural breaks produce biased results. The panel KPSS unit root test takes structural breaks into account. (b) The panel KPSS unit root test considers the probability of heterogeneity and cross-sectional dependence of the countries. Because of these advantages, panel KPSS unit root method is expected to produce more effective and unbiased findings for convergence hypothesis.

Table 1 Summary of literature on environmental convergence

Paper	Period	Country	Environmental indicator	Methodology	Result
Strazicich and List [45]	1960–1997	21 industrial countries	Per capita CO_2	Panel unit root test and cross-sectional regressions	Convergence
Aldy [3]	1960–2000	23 OECD countries and 88 countries	Per capita CO_2	Traditional unit root test	Convergence in 20 OECD countries Convergence in 75 countries
Lee et al. [25]	1960–2000	21 OECD countries	Per capita CO_2	Unrelated regressions augmented Dickey—Fuller (SURADF) panel unit root test	Convergence in 7 countries Divergence in 14 countries
Criado and Grether [19]	1960–2002	166 countries	Per capita CO_2	Nonparametric distributional tests and Markov analysis	Mix results (convergence and divergence)
Christidou et al. [17]	1870–2006	36 countries	Per capita CO_2	Linear and non-linear panel unit root tests	Convergence
Li and Lin [27]	1971–2008	110 countries	Per capita CO_2	Panel generalized moments method (GMM)	Convergence
Solarin [43]	1960–2010	39 African countries	Per capita CO_2	Lagrange multiplier (LM) unit root tests	Convergence
Acaravci and Erdogan [1]	1960–2011	7 region	Per capita CO_2	Cross-sectionally augmented Dickey Fuller (CADF) and panel KPSS unit root tests	Convergence

(continued)

Table 1 (continued)

Paper	Period	Country	Environmental indicator	Methodology	Result
Ahmed et al. [2]	1960–2010	162 countries	Per capita CO_2	Wavelet-based unit root test	Divergence
Lin et al. [28]	1950–2013	G18 countries	Per capita CO_2	Quantile unit root test	Convergence in 5 countries Divergence in 13 countries
Ulucak and Apergis [48]	1961–2013	European Union countries	Ecological footprint per capita	Club clustering approach	Convergence
Solarin and Bello [44]	1961–2013	128 countries	Ecological footprint per capita	Linear and non-linear unit root tests	Divergence

2 Data, Methodology and Application Results

In order to investigate the environmental convergence hypothesis, the annual data of ecological footprint provided by Global Footprint Network has been observed for the period 1961–2014. 2014 has been the last year observed by the Global Footprint Network. Fifteen countries were selected from each continent in accordance with economic sizes and data availability for Asian, African, American and European continents. The stationarity analyses might be followed to specify which of these continents may jointly struggle with environmental threats. Analyzing the stationarity process is the common methodology to determine convergence based on stationarity properties of relevant series [24]. An important consideration is that individual effects changing from one country to another should be paid attention to test the convergence [16]. Accordingly, panel unit root tests may be more appropriate since the use of panel data enables such analyses to control for individual heterogeneities, as well as providing more information about data and more efficient results [6]. However, one might need to pay attention that, in case of cross-sectional dependence, more precisely, the existence of cross-correlation among the units of panel data leads to efficiency loss for least squares and invalidates conventional t-tests and F-tests which use standard variance–covariance estimators [5]. For this reason, cross-sectional dependence should previously be checked before proceeding panel unit root analyses. Breusch and Pagan [13] calculate a Lagrange multiplier (LM) statistic to check cross-equation error correlations via following Eq. 1.

$$\mathrm{CD\_LM} = T \sum_{i=1}^{N-1} \sum_{j=1+1}^{N} \hat{\rho}_{ij}^{2} \tag{1}$$

$\hat{\rho}_{ij}^2$ represents square of pair-wise correlation based on errors (e) of ordinary least squares estimation and $\hat{\rho}_{ij}$s are calculated through Eq. 2:

$$\hat{\rho}_{ij} = \frac{\sum_{t=1}^{T} e_{it} e_{jt}}{\left(\sum_{t=1}^{T} e_{it}^2\right)^{1/2} \left(\sum_{t=1}^{T} e_{jt}^2\right)^{1/2}} \tag{2}$$

CD_LM procedure is then tested under the null hypothesis of no cross-sectional dependence and it is not sensitive to orders of the sections in the panel. Additionally N should be relatively small while T is sufficiently large in order to reach reliable results [38].

The next step is to conduct unit root test to specify the possibility of convergence. However unit root tests tend to imply non-stationarity in case of series have structural breaks [37] and series may probably have structural breaks due to various policy changes and ignoring them may lead to inconsistent estimation and invalid inference [7]. Carrion-i-Silvestre et al. [15] propose a panel unit root test with multiple structural breaks based on the procedure of panel KPSS test developed by Hadri [22]. The structure of the panel KPSS test with structural breaks is determined by following Eqs. (3) and (4).

$$x_{it} = \psi_{it} + \delta_i t + v_{it} \tag{3}$$

$$\psi_{it} = \sum_{k=1}^{m_i} \zeta_{i,k} D\left(T_{b,k}^i\right)_t + \sum_{k=1}^{m_t} \beta_{i,k} DU_{i,k,t} + \psi_{i,t-1} + \epsilon_{i,t} \tag{4}$$

where $\epsilon_{it} \sim i \cdot i \cdot d \cdot \left(0, \sigma_\epsilon^2\right)$ and $k(k-1, \ldots m_i, m_i \geq 1)$ takes the place of break numbers. Breaks are captured by dummy variables in Eq. 4 and they are adjusted as: (i) $D(T_{b,k}^i)_t = 1$ for $t = (T_{b,k}^i)_t + 1$ and 0 elsewhere and (ii) $DU_{i,k,t} = 1$ for $t > T_{b,k}^i$ and =0 elsewhere. More precisely $T_{b,k}^i$ indicates kth break date as $k = 1, \ldots, m_i$, $m_i \geq 1$ for the relevant country, region or any unit in the panel data. Under the structural breaks, the null hypothesis implies stationarity (H_0: $\sigma_{\epsilon,i}^2 >$ for $i = \forall 1, \ldots N$).

Panel KPSS test statistic is calculated through Eq. 5 and is responsive to break dates.

$$\mathrm{LM}(\lambda) = \frac{1}{N} \sum_{i=1}^{N} \left(\hat{\vartheta}_i^{-2} T^{-2} \sum_{t-1}^{T} \hat{\Gamma}_{i,t}^2 \right) \tag{5}$$

where $\hat{\Gamma}_{i,t}^2 = \sum_{j=1}^{t} \hat{\varepsilon}_{i,j}$ and it denotes the partial sum process produced by least squares residuals and $\hat{\vartheta}_i^2$ denotes its long-run variance that allows the disturbances to be heteroscedastic. λ in Eq. 5 represents breaks and they are captured by following Bai and Perron [4]. Having determined the optimal number of breaks, the panel KPSS test is normalized by Eq. 6.

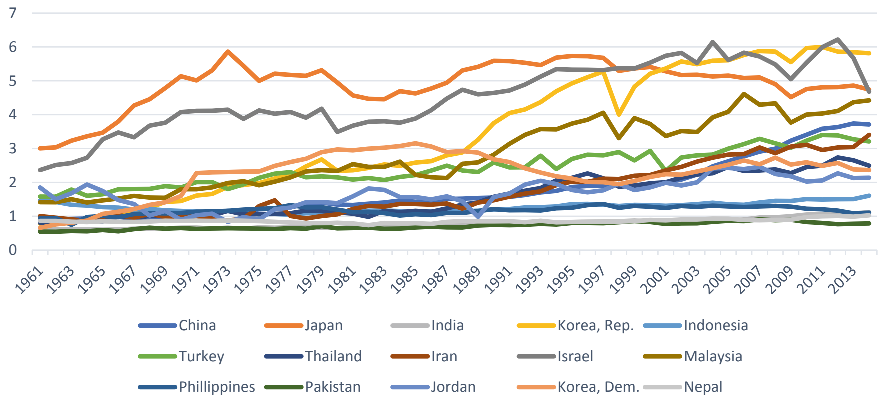

Fig. 2 EF per capita for panel Asian countries

$$Z(\lambda) = \frac{\sqrt{N}\left(\mathrm{LM}\left(\hat{\lambda}\right) - \overline{\Pi}\right)}{\overline{\Upsilon}} \tag{6}$$

since $\overline{\Pi}$ and $\overline{\Upsilon}$ represent individual mean and variance of $\left(\hat{\lambda}_i\right)$, the test statistic has the asymptotic standard normal distribution. However, the bootstrap critical values are calculated by following Maddala and Wu [31] so as to consider cross-sectional dependence.

Before proceeding for econometric analyses, general outlook and descriptive statistics of data sets for each continent might be useful for providing foresights about country conditions or their stochastic behaviors. Figure 2 shows EF per capita for Asian countries. Japan and Israel have the highest mean values of 4.90 and 4.53, respectively, among Asian countries although the footprint has started to decline post-1997 in Japan. Pakistan has the lowest mean value of 0.71. On the other hand, South Korea and Malaysia take attention by their sharp upward trends that are also most volatile with 1.808 and 1.009 standard deviations. Even though China is under the average footprint value of Asian countries, its footprint has been moving upside since the 1980s. When comparing the continents by their per capita footprint, environmental performances of Asian countries are better than American (Fig. 4) and European countries (Fig. 5) although their total average value has a considerable amount of magnitude and although each country follows different paths in general.

Tables 2, 3, 4 and 5 present the descriptive statistics for panel Asia, panel Africa, panel America and panel Europe, respectively. The individual standard deviations of panel Asia range from 0.0581 (Nepal) to 1.8086 (Korea, Rep.) as Japan and Pakistan take the highest (4.9032) and smallest (0.7140) mean values, respectively.

Table 2 Descriptive statistics for panel Asian EF per capita, 1961–2014

	Mean	Median	Max	Min	Std. dev.
China	1.777134	1.514521	3.740306	0.911248	0.817024
India	0.773162	0.732784	1.120083	0.601512	0.14221
Indonesia	1.267223	1.262796	1.60808	1.041957	0.139194
Iran	1.730371	1.389615	3.404048	0.863513	0.786125
Israel	4.531197	4.53849	6.220643	2.364574	0.997467
Japan	4.903279	5.090672	5.863017	3.006034	0.681461
Jordan	1.676949	1.727342	2.456897	0.834246	0.433207
Malaysia	2.834904	2.569168	4.610779	1.406502	1.009217
Nepal	0.860701	0.855494	1.026345	0.735419	0.058147
Pakistan	0.714023	0.699115	0.908394	0.539997	0.099871
Philippines	1.16594	1.178022	1.361023	0.744804	0.122274
Korea, Rep.	3.443711	2.841532	5.999868	0.785119	1.808657
Korea, Dem.	2.259043	2.374942	3.155416	0.659281	0.649812
Thailand	1.576391	1.28613	2.737383	0.803573	0.607944
Turkey	2.419266	2.342906	3.399018	1.576783	0.522233
Panel Asia	2.128886	1.566146	6.220643	0.539997	1.459365

Table 3 Descriptive statistics for panel African EF per capita, 1961–2014

	Mean	Median	Max	Min	Std. dev.
Algeria	1.394281	1.441636	2.481657	0.531819	0.519644
Cameroon	1.179335	1.213494	1.398999	0.936677	0.13811
Cote Divoire	1.343996	1.302175	1.73631	0.97146	0.237083
Dem. Congo	0.984146	0.968801	1.314642	0.801083	0.10679
Egypt	1.382061	1.425367	2.02399	0.801618	0.377092
Ghana	1.378641	1.268757	2.000574	1.027375	0.299546
Kenya	1.362386	1.383978	1.71598	1.011938	0.223728
Mali	1.437156	1.447551	1.694667	1.078113	0.143872
Morocco	1.261272	1.17823	1.864071	0.864421	0.271544
Nigeria	1.090063	1.077764	1.371521	0.899735	0.117504
S. Africa	3.434782	3.427024	4.082211	2.664184	0.317488
Senegal	1.453282	1.37737	1.932985	1.095052	0.231773
Tunisia	1.551662	1.555478	2.269033	0.835322	0.430931
Uganda	1.752415	1.7562	2.171523	1.186948	0.272033
Zimbabwe	1.479894	1.475072	1.8966	1.088133	0.20372
Panel Africa	1.499025	1.36137	4.082211	0.531819	0.6154

Table 4 Descriptive statistics for panel American EF per capita, 1961–2014

	Mean	Median	Max	Min	Std. dev.
Argentina	3.511932	3.443311	4.651935	2.88567	0.392291
Brazil	2.795351	2.883131	3.106045	2.319935	0.243544
Canada	8.977496	8.926791	10.29804	7.438794	0.681558
Chile	3.026316	2.754116	4.304463	2.035064	0.727018
Colombia	2.088666	2.116602	2.30351	1.893253	0.113986
Costa Rica	2.459988	2.476232	3.207513	2.159178	0.222313
Dom. Republic	1.309658	1.243746	1.723434	0.906343	0.233797
Ecuador	1.741758	1.807471	2.328995	1.159092	0.309163
Guatemala	1.501597	1.409756	1.897213	1.252192	0.190725
Mexico	2.491379	2.498674	3.847254	1.783703	0.42992
Panama	2.448627	2.401596	3.118889	1.870971	0.284138
Peru	2.109881	1.997618	2.78224	1.599638	0.355465
Uruguay	4.578503	4.630521	6.618398	2.69614	0.811316
USA	9.737091	9.877392	11.11268	8.053772	0.789855
Venezuela	2.912218	2.99203	3.856888	1.646523	0.567819
Panel America	3.446031	2.538405	11.11268	0.906343	2.498065

Table 5 Descriptive statistics for panel European EF per capita, 1961–2014

	Mean	Median	Max	Min	Std. dev.
Austria	5.205249	5.152496	6.460972	3.605339	0.749049
Belgium	7.109537	7.109774	7.962804	5.750656	0.502842
Denmark	8.177525	8.358249	9.529633	5.887291	0.958117
Finland	6.777509	6.788593	8.03115	5.309829	0.657349
France	5.370415	5.407772	6.338119	4.229499	0.44301
Germany	5.932819	5.760628	7.475371	4.272328	0.855997
Italy	4.662639	4.728441	5.862601	2.425363	0.87156
Netherlands	5.927342	6.122677	7.128325	3.531832	0.839234
Norway	8.034663	7.729492	11.60553	5.354713	1.764271
Poland	4.944499	4.688376	6.21647	3.973618	0.670866
Portugal	3.601521	3.638206	4.839404	2.327475	0.831254
Spain	4.195695	3.975788	5.984382	2.311148	0.975092
Sweden	6.918444	6.780914	8.717073	5.39684	0.852667
Switzerland	5.540226	5.594417	6.497769	4.396812	0.506963
UK	5.993968	5.966729	7.080254	4.799216	0.5555
Panel Europe	5.892803	5.812258	11.60553	2.311148	1.537128

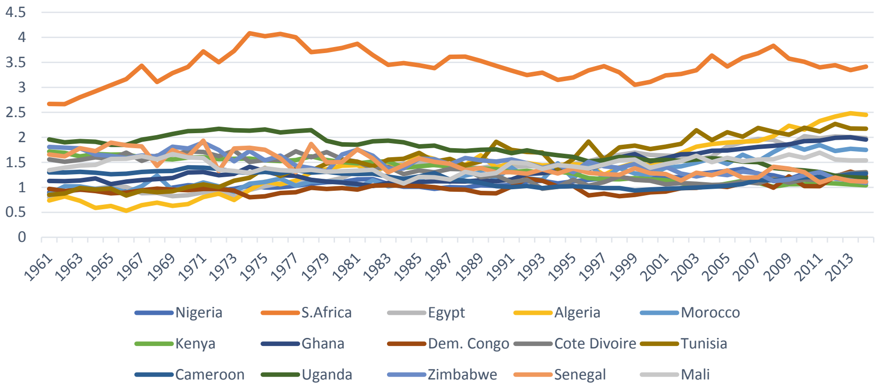

Fig. 3 EF per capita for African countries

The individual standard deviations of panel Africa seem to be smaller than those of Asia. They range from 0.1067 (De. Congo) to 0.5196 (Algeria) and panel mean value is 1.4990 which is less than the panel Asian mean (2.0817). Panel Europe and panel America have the highest and second highest mean values among four continents, respectively as the panel Africa has least mean value of 1.4990.

The outlook for African countries is displayed in Fig. 3 and they have less average per capita footprint value than the other continents in general. Almost all countries follow a horizontal trend with less volatility except South Africa that has the largest footprint value. On the other hand, Uganda has experienced commendable performance by decreasing its per capita footprint from 2.14 to 1.18 since 1978.

USA and Canada have the worst performance with average per capita values among either American countries or the others. As seen from descriptive statistics (Table 4), mean values are 9.73 and 8.97 for USA and Canada respectively. Uruguay, Argentina and Chile have also high averages with 4.57, 3.51 and 3.02 respectively though they have showed a falling tendency in recent years (see Fig. 4). Apart from them, most of the countries follow nearly horizontal and similar trends with less volatility in the continent.

When looking European countries' performance for the ecological footprint, common trends they have experienced since the 1980s are striking with downward tendency in recent years (Fig. 5). European continent exhibits however worst performance among the other continents with 5.89 panel average.

Having observed non-normal distribution for 12 out of 60 countries and the panels through Jarque-Bera statistics, logarithmic transformation was used to normalize the data, since log transformation is widely preferred to consider non-normality as one of the alternative approaches [21, 44]. Then, cross-sectional dependence is checked for each panel sample and results are depicted in Table 6.

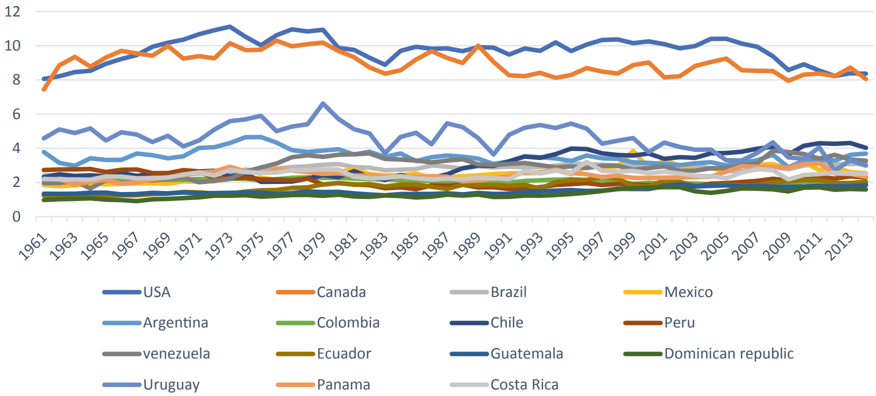

Fig. 4 EF per capita for American countries

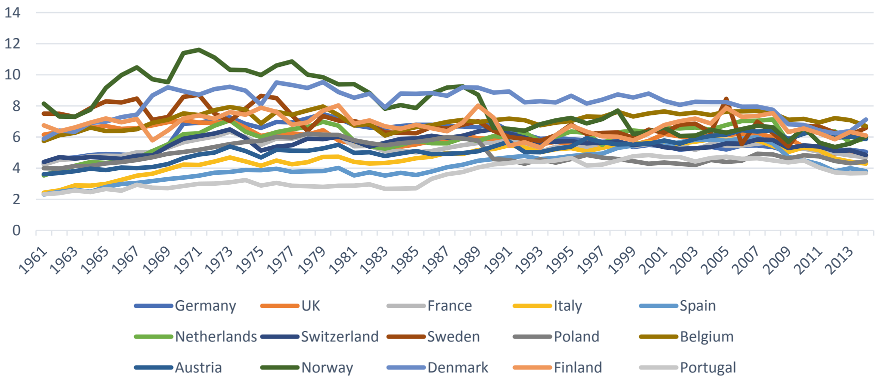

Fig. 5 EF per capita for European countries

Table 6 Test results for cross-sectional dependence

	Panel_Asia	Panel_Africa	Panel_America	Panel_Europe
CD-LM statistic	190.898	187.419	138.183	272.240
Probability	0.000	0.000	0.017	0.000

Table 6 shows that the null hypothesis of no cross-sectional dependence can be rejected strongly for all continents. Therefore, bootstrap critical values for panel KPSS test should be regarded. Tables 7, 8, 9 and 10 reveal the panel KPSS statistics, bootstrap critical values at 10, 5, 1% and break dates captured through Bai and Perron [4] procedure for both individual country and panel levels. Table 7 displays outputs of test results for Asian countries and the Asian panel. Individual test statistics reveal that the null hypothesis of stationarity is rejected for China, Korea (Rep.), Korea (Dem.), Turkey, Thailand, Israel, Malaysia and Jordan while stationarity is verified

Table 7 Panel KPSS test results for Asian Countries

		Bootstrap critical values			m	T_{b1}	T_{b2}
	Test statistics	10%	5%	1%			
China	0.322	0.110	0.139	0.205	2	1992	2002
Japan	0.116	0.096	0.128	0.201	2	1973	1987
India	0.123	0.097	0.126	0.187	2	1978	2001
Korea, Rep.	0.359	0.101	0.130	0.189	2	1989	1997
Indonesia	0.091	0.094	0.123	0.183	1	1975	–
Turkey	0.294	0.092	0.122	0.187	2	1979	2000
Thailand	0.238	0.103	0.131	0.194	2	1985	1997
Iran	0.031	0.101	0.132	0.190	1	1988	–
Israel	0.511	0.097	0.126	0.188	2	1979	2004
Malaysia	0.347	0.103	0.130	0.200	2	1984	1997
Philippines	0.049	0.093	0.121	0.197	2	1980	2004
Pakistan	0.048	0.099	0.131	0.199	1	1988	–
Jordan	0.176	0.095	0.124	0.180	1	1975	2003
Korea, Dem.	0.156	0.100	0.132	0.195	2	1982	1999
Nepal	0.035	0.091	0.116	0.184	2	1976	2006
Panel results							
Panel test[a]	7.582	4.320	5.074	6.659			
Panel test[b]	13.488	7.135	8.121	10.140			

Note: m is the number of structural breaks, T_{b1} and T_{b2} represent structural break dates of break 1 and break 2, respectively
[a]Refers to assumption of homogeneity of long-run variance
[b]Refers to assumption of heterogeneity of long-run variance

for the others. Panel results confirm non-stationarity for Asian panel, implying that convergence does not hold within Asian sample.

Results for African countries given in Table 8 support convergence at 1%, although panel test statistic under heterogeneity does not fall into the acceptance region at 5%. The null hypotheses are not rejected by 9 out of 15 countries. The null of stationarity is individually rejected for South Africa, Egypt, Algeria, Morocco, Senegal and Tunisia and these countries have already higher volatility than the others. Apart from them, each country in the panel has stationarity process for their ecological footprint series.

Table 9 presents the results for American countries. All countries have individually stationary process under the structural breaks except the USA that has the highest test statistic falling into the rejection area. Other countries follow rather small statistics which do not to reject the null hypothesis. Panel statistics under homogeneity and heterogeneity also fall into the acceptance region. Results for European countries in Table 10 strongly support the convergence. All countries have stationary process for their footprints under structural breaks. One of the important and striking output of

Table 8 Panel KPSS test results for African countries

		Bootstrap critical values			m	T_{b1}	T_{b2}
	Test statistics	10%	5%	1%			
Nigeria	0.037	0.129	0.157	0.263	2	1979	1995
S. Africa	0.410	0.181	0.224	0.328	2	1969	1982
Egypt	0.239	0.146	0.174	0.268	2	1979	2004
Algeria	0.311	0.158	0.191	0.289	2	1974	2002
Morocco	0.253	0.147	0.181	0.270	2	1985	2002
Kenya	0.109	0.141	0.176	0.266	2	1983	1995
Ghana	0.032	0.199	0.248	0.367	2	1994	2003
Congo	0.048	0.164	0.201	0.290	1	2005	–
C. Divoire	0.114	0.152	0.183	0.275	2	1981	1990
Tunisia	0.245	0.136	0.164	0.237	2	1974	1997
Cameroon	0.140	0.165	0.209	0.326	2	1987	2006
Uganda	0.053	0.158	0.192	0.295	2	1986	2006
Zimbabwe	0.066	0.144	0.178	0.259	2	1976	2001
Senegal	0.300	0.152	0.187	0.266	1	1987	–
Mali	0.123	0.144	0.175	0.249	2	1971	1990
Panel results							
Panel test[a]	2.874	2.599	3.238	4.402			
Panel test[b]	4.033	3.279	3.842	5.120			

Note: m is the number of structural breaks, T_{b1} and T_{b2} represent structural break dates of break 1 and break 2, respectively
[a]Refers to assumption of homogeneity of long-run variance
[b]Refers to assumption of heterogeneity of long-run variance

the table is that over half of the selected countries have the same structural break date (1968) captured by KPSS estimations. The break date of 1969 is detected for Poland and Austria. Therefore, 1968 and 1969 might be a turning point for European countries since environmental movements have started to evolve during those dates. For instance, German green movement became popular in the 1960s and was considered foundations of the green political acts emerged afterward. The Club of Rome was formed in 1968. The French Federation of Nature Protection Societies and the French branch of Friends of the Earth were founded in France, hydroelectric plans were protested in Sweden, pollution and environmental degradation started to be protested in the Netherlands and Denmark in 1968. Political ecology movements appeared prominently through the protests of students and workers during 1968–1969 in Italy [42].

Table 9 Panel KPSS test results for American countries

		Bootstrap critical values			m	T_{b1}	T_{b2}
	Test statistics	10%	5%	1%			
USA	0.376	0.225	0.248	0.294	2	1968	2006
Canada	0.100	0.858	0.949	1.131	1	1990	–
Brazil	0.052	0.492	0.558	0.671	1	1973	–
Mexico	0.133	0.477	0.559	0.701	2	1972	1995
Argentina	0.107	0.410	0.460	0.565	2	1970	1982
Colombia	0.072	0.431	0.484	0.595	2	1983	1998
Chile	0.061	0.544	0.595	0.734	2	1988	2005
Peru	0.086	0.344	0.398	0.477	2	1978	2005
Venezuela	0.096	0.503	0.570	0.679	1	1973	–
Ecuador	0.052	0.466	0.553	0.706	2	1974	1993
Guatemala	0.053	0.714	0.780	0.929	2	1992	2000
Dom. Rep.	0.071	0.576	0.629	0.752	2	1970	1995
Uruguay	0.062	0.615	0.710	0.847	1	1999	–
Panama	0.085	0.730	0.829	1.014	2	1968	2004
Costa Rica	0.178	0.371	0.469	0.732	0	–	–
Panel results							
Panel test[a]	0.494	16.571	17.424	19.157			
Panel test[b]	0.129	17.246	18.095	19.629			

Note: m is the number of structural breaks, T_{b1} and T_{b2} represent structural break dates of break 1 and break 2, respectively
[a]Refers to assumption of homogeneity of long-run variance
[b]Refers to assumption of heterogeneity of long-run variance

3 Empirical Facts Underpinning the Panel Estimation Outputs

The ecological footprint is closely associated with urbanization. Therefore, to understand better the continental divergence or convergence in EF, one might need to observe the urbanization process of the continents. The prominent demand for natural resources in urbanization areas with luxurious lifestyle results in consumption which is in general greater than the biocapacities of the regions. Hence the urbanization and high population intensity in urbanization will have great negative impact (stress) on the ecosystem [40]. Rashid et al. [40] indicate that, for instance, footprint values of two population-intensive regions in Pakistan (Bahria Town and Gulraiz Colony) are greater than average footprint value of Pakistan. The EF values of Bahria, Gulraiz and Pakistan are 8.6, 6.9 and 4.7 gha (global hectares), respectively. Luo et al. [30] also underline the serious damage of urbanization on the ecological environment and reveal that urbanization-induced ecological pressure in central region of China

Table 10 Panel KPSS test results for European countries

		Bootstrap critical values			m	T_{b1}	T_{b2}
	Test statistics	10%	5%	1%			
Germany	0.146	0.403	0.450	0.505	2	1968	1992
UK	0.010	0.206	0.254	0.368	1	1979	–
France	0.069	0.594	0.651	0.767	2	1968	1980
Italy	0.046	0.610	0.676	0.772	2	1968	1986
Spain	0.026	0.309	0.346	0.432	2	1968	1988
Netherlands	0.119	0.287	0.368	0.516	1	1968	–
Switzerland	0.046	0.646	0.712	0.827	2	1968	1998
Sweden	0.092	0.213	0.268	0.380	1	1977	–
Poland	0.051	0.263	0.297	0.385	2	1969	1989
Belgium	0.070	0.288	0.369	0.535	1	1968	–
Austria	0.099	0.599	0.660	0.751	2	1969	1995
Norway	0.078	0.186	0.221	0.325	1	1989	–
Denmark	0.207	0.615	0.726	1.021	2	1968	2006
Finland	0.054	0.234	0.253	0.297	2	1990	2000
Portugal	0.120	0.182	0.220	0.307	1	1986	–
Panel results							
Panel test[a]	1.727	11.386	12.759	15.406			
Panel test[b]	0.018	11.321	12.099	13.747			

Note: m is the number of structural breaks, T_{b1} and T_{b2} represent structural break dates of break 1 and break 2, respectively
[a]Refers to assumption of homogeneity of long-run variance
[b]Refers to assumption of heterogeneity of long-run variance

has the greatest eco-pressure among other regions of China due to its higher living standards. According to Luo et al. [30], on the other hand, the ecological pressure of Midwestern China has slightly increased greatly for the period 2005–2014 and is expected to increase till 2010. Li et al. [26] emphasize the increasing ecological deficit (the deficit between ecological footprint of a population and biocapacity of the region) in Nanchong city. According to Li et al. [26], the ecological deficit was 3.012 hm^2/person in 2012 due to urbanization process with high population growth, farmland shrinking and resource consumption such as water consumption, land use.

The correlations between urbanization, water scarcity, land use, forest area and farmland shrinking have been intensively studied by several seminal articles. For instance, among others, one might see the relevant seminal works of the nexus between ecological footprint and water footprint [23], water scarcity and water stress in, e.g., agricultural production-industry evaluation within water footprint framework [53], the urbanization and water shortage [20], the urbanization and water footprints of urban and rural areas [46], ecological footprint and land use [54], the environmental impacts related to greenhouse gas emissions, water use and land use [41], forest area, carbon emissions and carbon capacity [39].

Feng et al. [20] state that Zhangye city of China has been experiencing increasing water shortage during the rapid urbanization process over the past decades. Sun [46] yields that in Tianjin and Hebei (the greater capital region of China in 2010), consumption-based water footprints (WFs) of urban areas are 1.6 and 3.7 times the rural WFs. Xie et al. [52] also underline the fact that the water scarcity issues, together with the issues of energy consumption and CO2 emissions, have been great concern of environmental literature. Qi et al. [39] study the linkage between carbon footprints of some enterprises and forest area in China and yield that carbon footprints of some enterprises in China are far beyond the capacity of the local forest area. This deficit, in turn, causes several environmental problems such as an overloaded ecosystem and global climate change. Ridoutt et al. [41], by monitoring the agricultural and food products and relevant environmental impacts related to greenhouse gas emissions, water use and land use in southern Australia, indicate that land resources have been under stress through high world population with the increased demand for food, fiber and bio-energy. Yao et al. [54] also observe the linkage between urbanization, land resources and biocapacity in China. They reveal that, due to farmers' migration to metropolitan cities, e.g., to Wuhan city with higher income, the crop farming, biocapacity of arable land in Wuhan have reduced and are expected to decrease in the future.

This work observes the urbanization variable and several indicators to understand the change in environmental quality in panel continentals and to underpin the output of panel estimations. The urbanization refers to population intensity in urban areas (% of population). The other indicators are renewable internal freshwater resources per capita (m^3), arable land (% of land area), forest area (% of land area) and CO_2 emissions (metric tons per capita). These barometers might be considered as well the components of ecological footprints in general. According to World Bank, World Bank Indicators (World Bank Indicators 2018), renewable internal freshwater resource flows demonstrate internal river flows and groundwater from rainfall. Arable land refers to land under temporary crops, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Forest area denotes natural or planted stands of trees of at least 5 m in situ, and, carbon dioxide emissions are the emissions from consumption of solid, liquid, and gas fuels and gas flaring (World Bank 2018).

In Table 11, panel Asian data shows that urban population (% of population) and CO_2 emissions (metric tons per capita) have grown prominently as renewable freshwater resources per capita (cubic meters) have declined excessively. The positive change in arable land (% of land area) and negative change in forest area (% of land area) are relatively smaller.

The percentage changes in urban population, renewable freshwater resources, arable land, forest area and CO_2 emissions are 26.69, −65.62, 3.37, −6.53 and 435.25, respectively.

Table 11 Panel Asia

	Period/value		% change
	1990	2016	
Urban population (% of population)	49.2	62,333	26.6937
Renewable internal freshwater resources	1962	2014	
Per capita (m^3)	11163.91	3,847,974	−65.6235
	1961	2014	
Arable land (% of land area)	18,398	19,017	3.3676
	1990	2014	
Forest area (% of land area)	32,400	30,285	−6.526
	1960	2014	
CO_2 emissions (metric tons per capita)	0.89648	4.798441707	435,247

Source Calculated through World Bank Data (2018)

The panel data for Africa exhibited in Table 12 yields that, as in the case of Asia, urban population, arable land and CO_2 emissions have positive growth rates as renewable internal freshwater resources and forest area follow negative growth rates. The percentage changes in urban population, renewable freshwater resources, arable land, forest area and CO_2 emissions are 14.00, −73.67, 46.81, −16.00 and 146.62, respectively. The magnitudes of changes in renewable freshwater resources, arable land and forest area in Africa are greater than those in Asia.

The panel data for America in Table 13 demonstrates that, as in the cases of Asia and Africa, urban population, arable land and CO_2 emissions have increasing growth rates while renewable internal freshwater resources and forest area have decreasing growth rates. The percentage changes in urban population, renewable freshwater resources, arable land, forest area and CO_2 emissions are 15.60, −61.29, 7.85, −2.05 and 50.34, respectively.

In Table 14, panel European data explores different courses of arable land and forest area in Europe in comparison with corresponding variables' trends of other continents. The percentage changes in urban population, renewable freshwater resources, arable land, forest area and CO_2 emissions in Europe are 7.46, −25.40, −20.15, 5.99 and 20.45, respectively.

Figure 6 depicts column graph of urban population (% of population) variable for each Asian country in the panel. Figure 7 denotes the line graph of population variable to demonstrate better the clear discrepancies in urbanization between 1990 and 2016, and, seems to confirm the output of Table 7. Table 7 displays that Asian

Table 12 Panel Africa

	Period/value		% change
	1990	2016	
Urban population (% of population)	52.3381	59.66986	14.00846
Renewable internal freshwater resources	1962	2014	
per capita (m^3)	4645.136	1223.144	−73.6683
	1961	2015	
Arable land (% of land area)	9.690165	14.22662	46.81502
	1990	2015	
Forest area (% of land area)	25.21104	21.17702	−16.001
	1960	2014	
CO_2 emissions (metric tons per capita)	0.624314	1.539712	146.6247

Source Calculated through World Bank Data (2018)

Table 13 Panel America

	Period/value		% change
	1990	2016	
Urban population (% of population)	68.8	79.533	15.60029
Renewable internal freshwater resources	1962	2014	
per capita (m^3)	72986.66	28252.57	−61.2908
	1961	2015	
Arable land (% of land area)	7.552119	8.145281	7.854247
	1990	2015	
Forest area (% of land area)	41.75847	40.90136	−2.05254
	1960	2014	
CO_2 emissions (metric tons per capita)	3.065133	4.608158	50.3412

Source Calculated through World Bank Data (2018)

Table 14 Panel Europe

	Period/value		% change
	1990	2016	
Urban population (% of population)	73.26667	78.73333	7.461328
Renewable internal freshwater resources	1962	2014	
per capita (cubic meters)	12759.3	9518.747	−25.3976
	1961	2015	
Arable land (% of land area)	28.71464	22.92934	−20.1476
	1990	2015	
Forest area (% of land area)	32.25793	34.18997	5.989332
	1960	2014	
CO2 emissions (metric tons per capita)	5.528796	6.659245	20.44657

Source Calculated through World Bank Data (2018)

panel data does not converge in per capita ecological footprint. This statement might come from empirical evidence that urbanization with high population and resource consumption is the prominent determinant of ecological footprint and ecological deficit. Table 7 reveals as well that China, South Korea, North Korea, Turkey, Thailand, Israel, Malaysia, and, Jordan do not converge individually in EF indicator as other countries in panel Asia approach each other in terms of EF. Figures 8 and 9 show the urban populations of convergent countries (sub-panel Asia 1) and non-convergent countries (sub-panel Asia 2), respectively. 1990 and 2016 average urban populations of convergent countries are greater than those of non-convergent countries. The differences between population densities in urban areas of sub-panel Asia 1 and sub-panel Asia 2 might depict, to some extent, why null hypothesis of stationarity does not hold for China, South Korea, North Korea, Turkey, Thailand, Israel, Malaysia and Jordan as the null hypothesis is valid for India, Indonesia, Iran, Japan, Nepal, Pakistan, and, Philippines. This expression of course needs to be confirmed strongly by other empirical facts.

Figure 10 exhibits the column graph of urban population (% of population) variable for each African country in the panel. Figure 11 reveals the line graph of urban population variable for the years 1990 and 2016, and, might verify the output of stationarity of Table 8 which shows panel convergence in per capita ecological footprint. In comparison with Figs. 7 and 11, in terms of standard deviation in urban population (% of population) given in Table 15, African panel data has relatively much smaller standard deviation than the Asian panel has. Therefore, monitoring the urban population figures of Africa (Figs. 10 and 11), together with Table 15 output, one

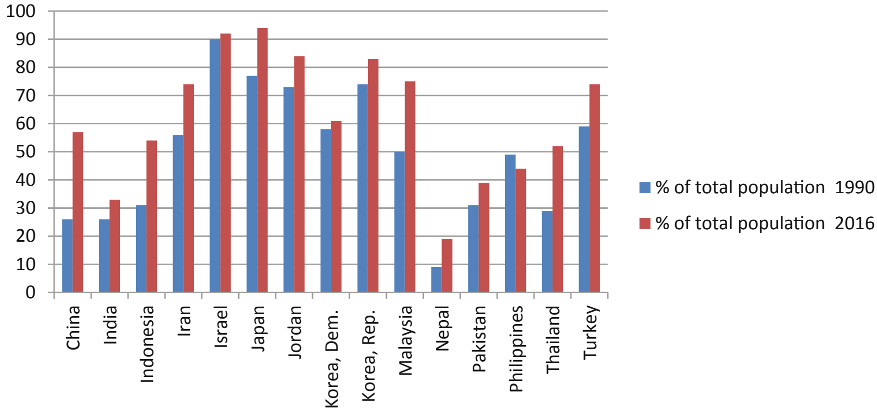

Fig. 6 Panel Asia-urbanization: column chart

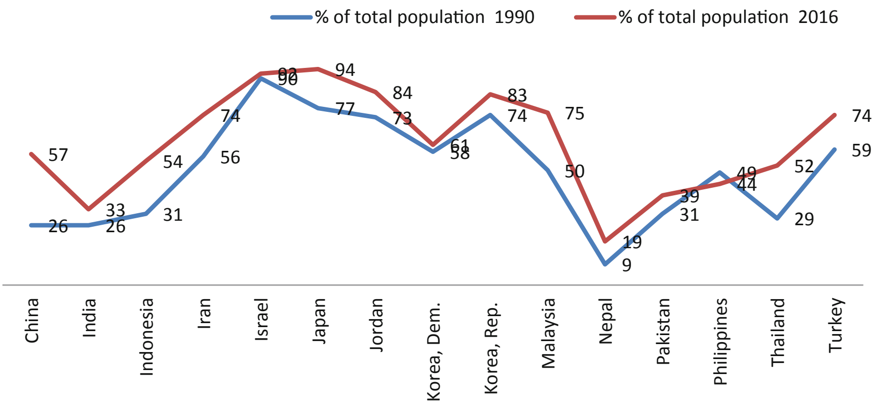

Fig. 7 Panel Asia-urbanization: line chart

Table 15 Standard deviation of urban population (% of population)

Period: 1990–2016	Asia	Africa	America	Europe
Standard deviation	9.812	6.264	6.902	6.093

might assert that the panel Africa has more probability of obtaining EF convergence than panel Asia. The standard deviations of Asia, Africa, America and Europe are 9.812, 6.264, 6.902 and 6.093, respectively. The relatively higher standard deviation of Asia results from the large urban population discrepancies of China, Indonesia and Thailand for the period 1990–2016 (Figs. 12 and 13).

Although American continent data has the second highest standard deviation within the group, the standard deviation of 15 countries in the America appears to be significantly less than that of 15 countries in Asia for 1990 and 2016. The outliers of American panel in terms of urban population density correspond to the relevant values

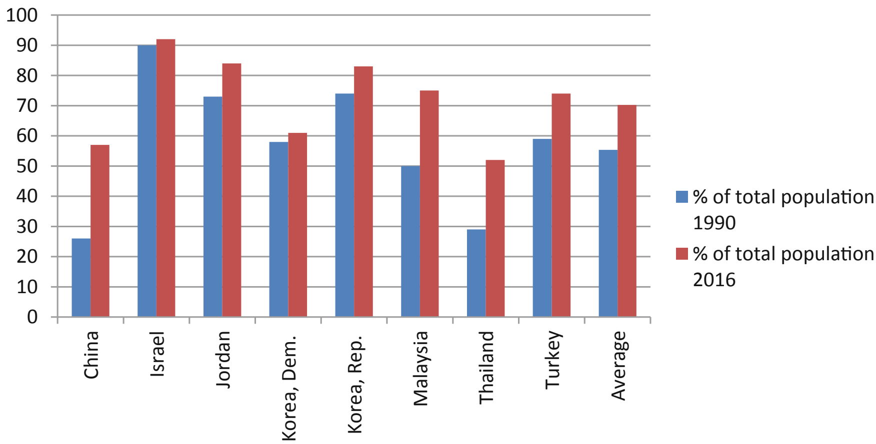

Fig. 8 Sub-panel Asia 1-urbanization

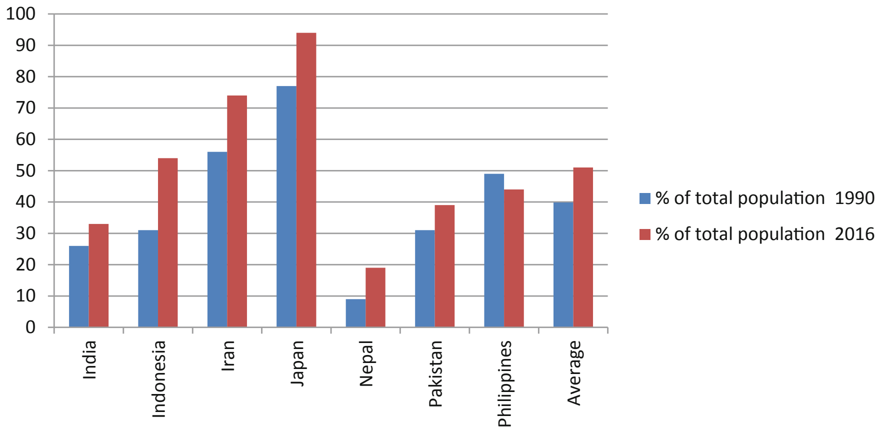

Fig. 9 Sub-panel Asia 2-urbanization

of Costa Rica and Dominican Republic for the same period. One might observe also from the table that the European continent follows the smallest standard deviation of urban population among other continents. Therefore, besides the possibility of convergence in African panel, the probability of convergence in urbanization might exist in Europe and America. This later probability might be supported by Figs. 14 and 15 of America, and Figs. 16 and 17 of Europe, and relevant results of Table 15.

Panel Figs. 18, 19, 20 and 21 demonstrate the population intensity in urban areas (% of population), renewable internal freshwater resources per capita (m^3), arable land (% of land area), forest area (% of land area) and CO_2 emissions (metric tons per capita) for Asia, Africa, America, and, Europe continents, respectively.

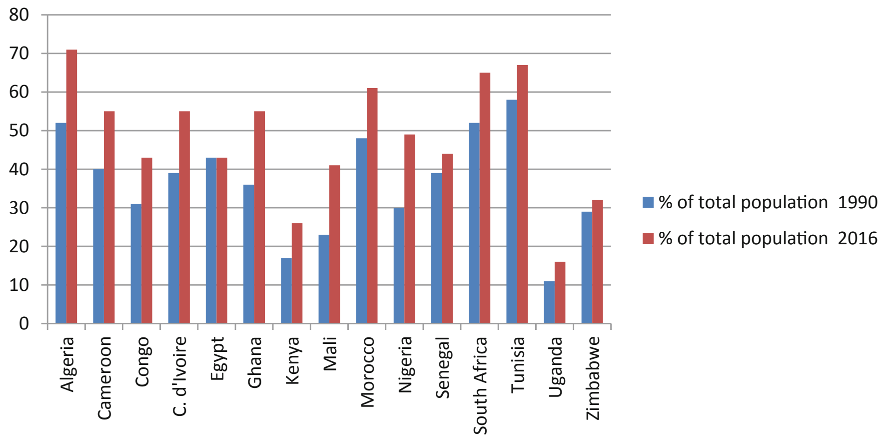

Fig. 10 Panel Africa-urbanization

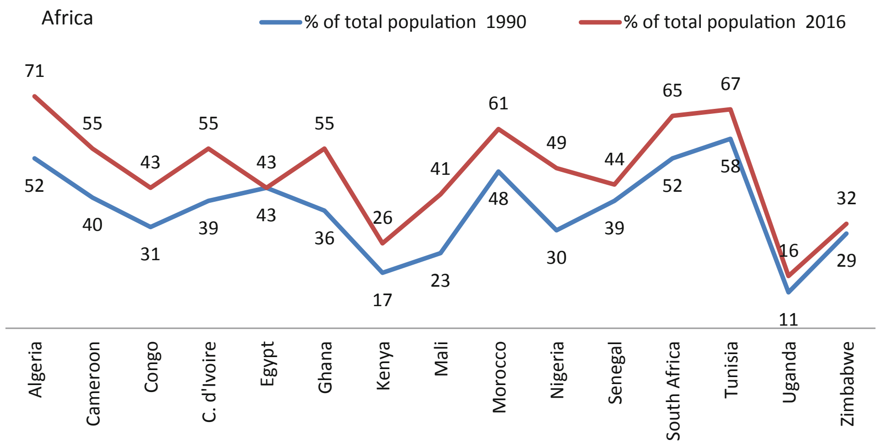

Fig. 11 Panel Africa-urbanization

In all panel figures, the renewable internal freshwater resources per capita decline while carbon emissions per capita increase (Figs. 18a–d, 19a–d, 20a–d, 21a–d). This output alone might explore that a noteworthy environmental degradation emerges in all continents and that urgent environmental policies should be implemented effectively to change the course of environmental quality from negative path to positive locus.

The variables of arable land (% of land area), forest area (% of land area) are given in Figs. 18b, c, 19b, c, 20b, c and 21b, c. The arable land in panel Asia first tends to increase until 1987 and later diminishes till 2010. It, thereafter, again seems to increase. The forest area in Asia declines at increasing rate until 2005 and, afterward, continues to diminish at decreasing rate. The arable land tends to increase as forest

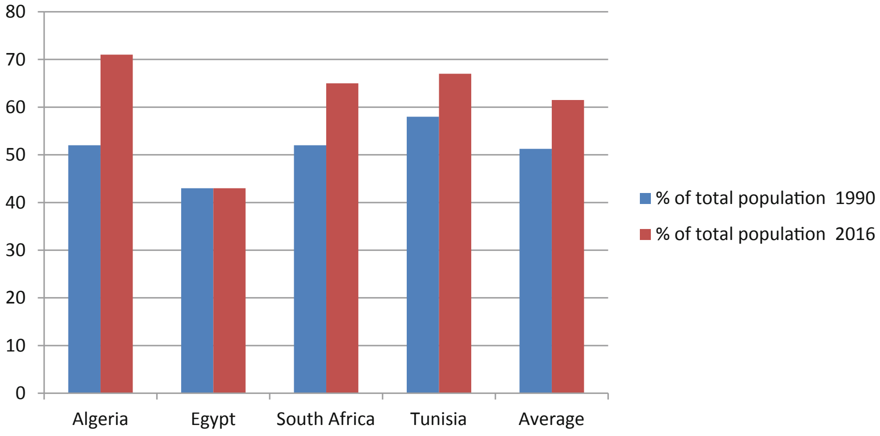

Fig. 12 Sub-panel Africa 1-urbanization

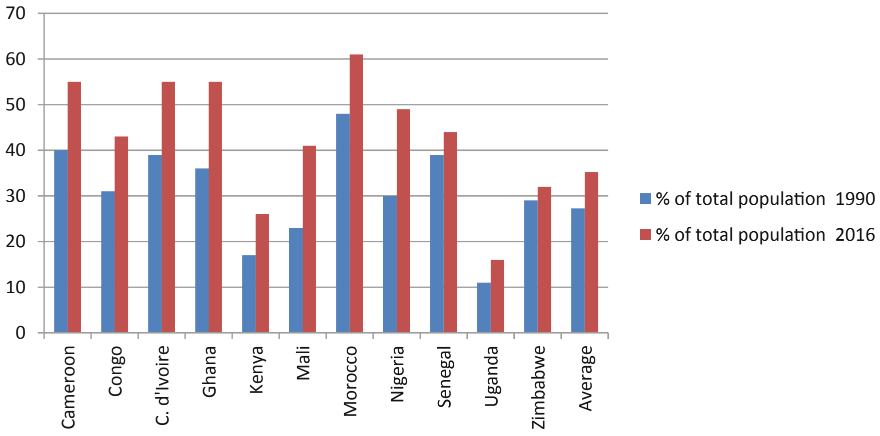

Fig. 13 Sub-panel Africa 2-urbanization

area decreases in Africa and America. The forest area in Europe has a positive growth rate of 5.98% from 1990 to 2015 while arable land reduces by 20.14% from 1960 to 2015.

4 Conclusion and Policy Recommendations

The human needs for commodities and services, especially in urban-metropolitan areas, with high living standards, cause harmful effects on ecosystems. This will create, in turn, the deficit between biocapacity and ecological footprint (EF) of the

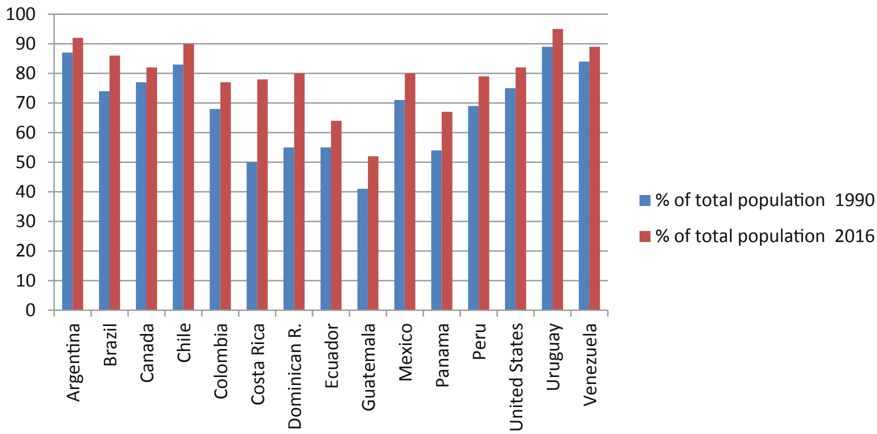

Fig. 14 Panel America-urbanization: column chart

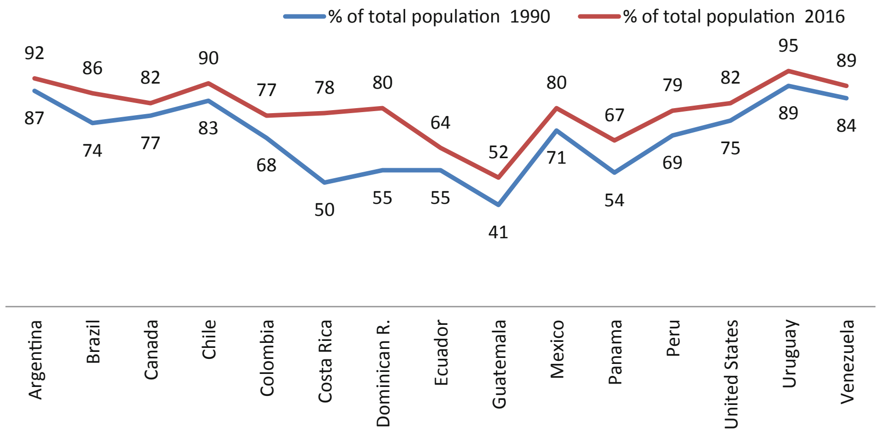

Fig. 15 Panel America-urbanization: line chart

regions. The policy makers and/or administrators should observe closely the EF data since it seems to be better indicator than other indicators such as carbon emissions to measure the level of environmental quality/degradation.

This work first underlines the significance of EF indicator, and, later, focuses mainly the convergence issue of EF since such possible EF convergence in countries might help countries' administrators launch common environmental policies to lower EF. Such common policies might increase the efficiency of current and future environmental regulations to reach more quality and sustainable intertemporal consumption/production patterns. Otherwise, the absence of convergence might yield different level of awareness of environmental deterioration within regions/countries.

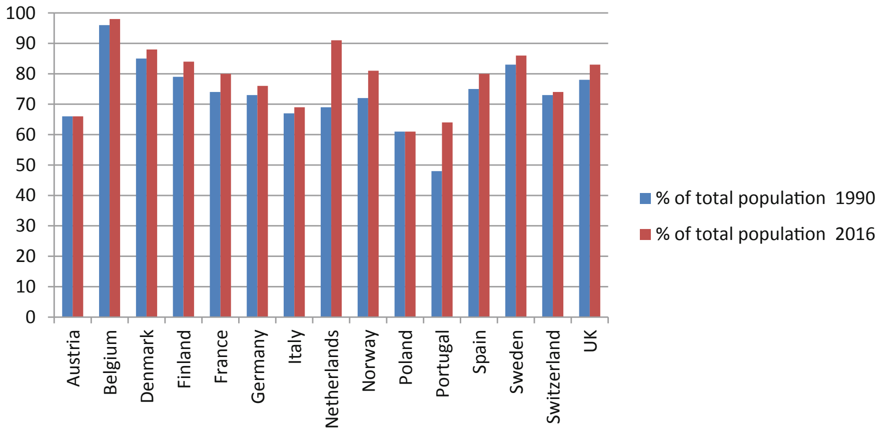

Fig. 16 Panel Europe-urbanization: column chart

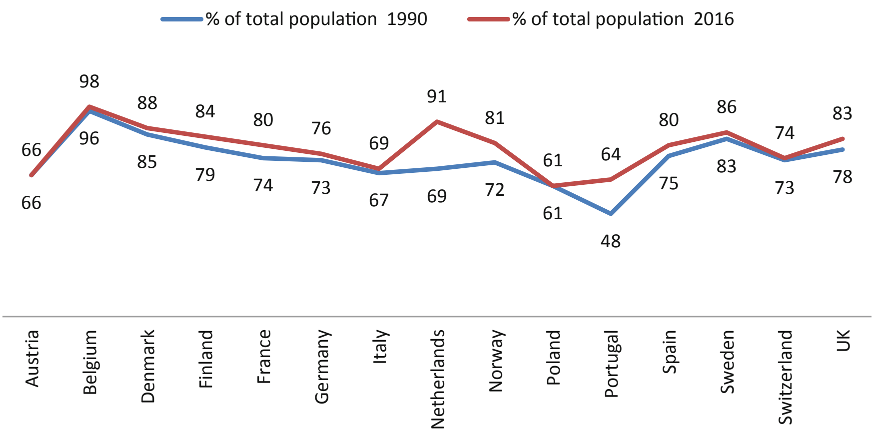

Fig. 17 Panel Europe-urbanization: line chart

To this end, by considering the continents of Asia, Africa, America and Europe, this work analyzes the EF data of 15 countries from each continent and observes if EF convergence appears in each continent. In result, panel KPSS estimations, considering structural breaks, support the evidence of convergence in Africa, America and Europe, but, do not verify the evidence that panel Asian countries approach each other in terms of their trends in EF.

This work, later, searches the possible reasons why null hypothesis of stationarity in EF is rejected in Asia as the stationarity output is hold in other continents. The results underline the significances of urbanization process, renewable freshwater resources, arable land area, forest area and CO_2 emissions of the continents to understand the possible convergence and divergence paths of EF.

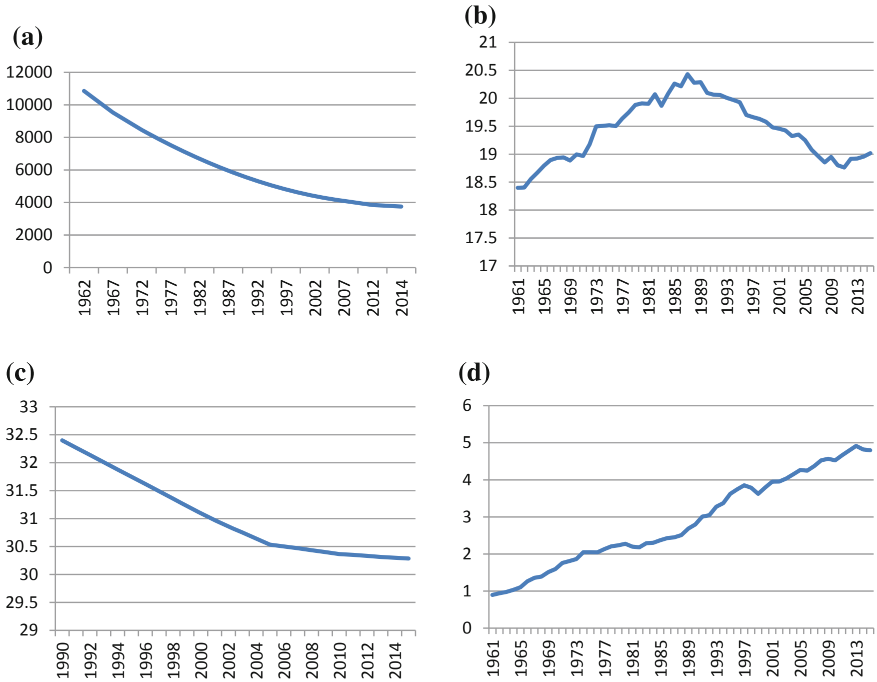

Fig. 18 **a** Panel Asia-renewable internal freshwater resources per capita (m^3), **b** panel Asia-arable land (% of land area), **c** panel Asia-forest area (% of land area), **d** panel Asia-CO_2 emissions (metric tons per capita)

The urbanization is a great contributor to stress on ecosystem hence EF. Eventually, one might claim that policy makers and/or administrators should follow the efficient policies to lower the stress on the ecology of each continent. Such policies need to include (a) the efficient use of natural resources [23, 40], (b) incentives to lower the migration to urban areas [30], (c) technological innovation and adjustments in demand structure to offset the water footprints of urban and rural areas [20, 46], (d) environmental awareness and improved market mechanism [29] and (e) improvement in the management irrigation systems, micro-irrigation systems [23].

A reduction in ecological footprint can be reached by maximum utilization of green resources and adaption of energy saving habits as immediate intervention measures [40]. Luo et al. [30] consider migration to urban areas a harmful factor on ecosystem since urbanization induces higher living standards and suggest that local government promote the return of migrated population to their hometowns. Feng et al. [20] suggest technological innovation and adjustment in demand structure to lower water footprint since increase of water footprints in urban and rural areas might be offset by technological and per capita scale effects. Sun [46] indicates that high standard consumption pattern of urbanization leads to increase in water footprint and claim that water use efficiency, sustainable water resource consumption under

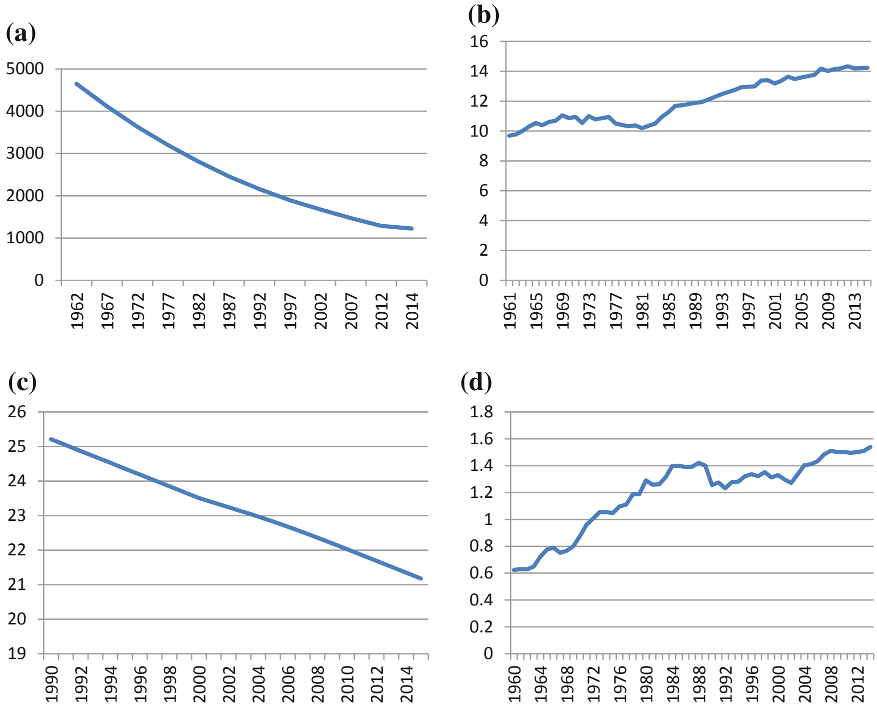

Fig. 19 **a** Panel Africa-renewable internal freshwater resources per capita (m^3), **b** panel Africa-arable land (% of land area), **c** panel Africa-forest area (% of land area), **d** panel Africa-CO_2 emissions (metric tons per capita)

the framework of the integrated/adjusted structures of production and consumption patterns might offset the water footprints of urban and rural areas. Hubacek et al. [23] recommend that administrators follow the polices of (i) water use efficiency in agriculture, (ii) improvement in the management irrigation systems, micro-irrigation systems by taking into account soil type, precipitation, crop needs and soil moisture retention.

Qi et al. [39] focusing the role of forest area in global warming state that improvement in forest areas and expanding the forest coverage might enhance the buffering capacity of climate change, especially in the provinces with high steel output. The improvement in forest area as well as improvement in arable land could help regions reduce the carbon footprints and ecological deficits as indicated in Yao et al. [54].

For the future possible studies on significant determinants of environmental degradation and relevant polices, this research suggests as well that impacts of fossil fuels and renewable resources on environmental deterioration should be analyzed explicitly through field studies and/or econometric methods. For instance, Ulucak and Bilgili [50], Bilgili et al. [9–12] emphasize the positive role of renewables on environmental quality in terms of carbon emissions. They suggest that renewables

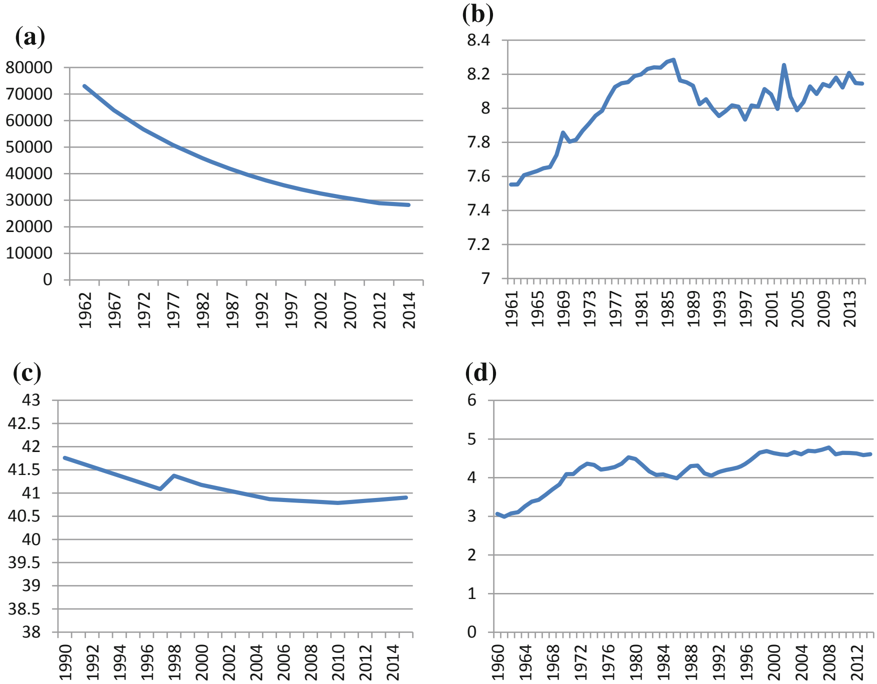

Fig. 20 **a** Panel America-renewable internal freshwater resources per capita (m^3), **b** panel America-arable land (% of land area), **c** panel America-forest area (% of land area), **d** panel America-CO_2 emissions (metric tons per capita)

should be promoted to lower the environmental degradation. Besides, the influences of traditional and non-traditional (e.g., shale gas) energy productions on ecological system need to be observed clearly. The possible significant impacts of shale gas revolution on climate change as well as the influence of shale on local and regional economies are ought to be investigated thoroughly. Eventually, future works might explore if renewables and/or shale gas can be better/worse than fuel oil in terms of environmental quality.

This work further may suggest that researchers conduct time series applications through models of wavelet coherency and/or Markov regime shifts in which estimated parameters are possibly subject to change from one period to another period or from one state (regime) to another state (regime). Such model estimations of course require high frequency data. To this end, Global Footprint Network and/or other research centers might measure ecological footprints monthly or quarterly.

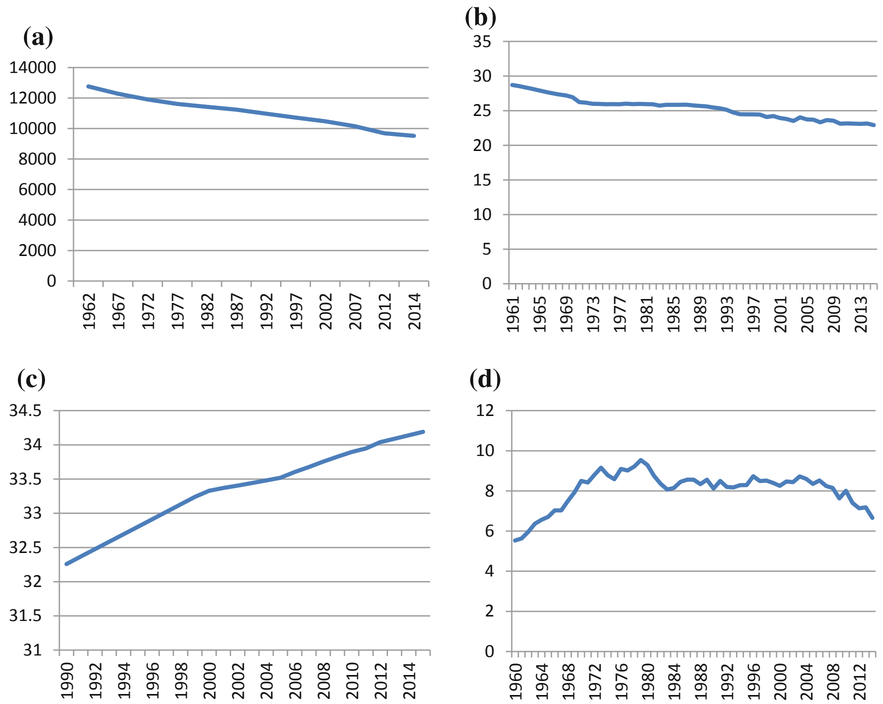

Fig. 21 **a** Panel Europe-renewable internal freshwater resources per capita (m^3), **b** panel Europe-arable land (% of land area), **c** panel Europe-forest area (% of land area), **d** panel Europe-CO_2 emissions (metric tons per capita)

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Impact of Trade Inequality on Environmental Quality: A Global Assessment

Avik Sinha

Abstract The interaction between environmental degradation and economic growth is a growing matter of interest among policymakers, and in the era of globalized economy, trade openness plays a significant role in determining the economic growth of nations. Given this context, this paper examines the impact of inequality in trade volume on CO_2 emissions, following environmental Kuznets curve (EKC) hypothesis, for 187 countries and over the period of 1990–2017. In terms of methodology, this study has employed Generalized Method of Moments (GMM) and Geweke (J Am Stat Assoc 77:304–313, [22]) causality analysis, while checking for the cross-sectional dependence. The study has been carried out on both aggregate and disaggregated dataset. Disaggregation of the dataset has been done based on the income levels (low, middle, and high) and continents (Asia, Europe, North America, South America, Oceania, and Africa). This study has found the evidence of N-shaped EKC for both the aggregate and disaggregated dataset. The impacts of inequality in trade volume and globalization differ in accordance with the level of development of the nations under consideration.

Keywords Inequality · Trade volume · Theil index · EKC hypothesis · CO_2

1 Introduction

In the wake of globalization and trade liberalization, it is quite obvious that the economic activities around the globe are majorly driven by the international trade of goods and services. Now, by means of trade, the level of development of a nation is determined, as the nature of trade has the potential to determine the developmental trajectory of a nation. Owing to this reason, trade, economic activity, and the development of a nation are closely associated with its environmental quality. For the developed nations, it has been observed that they try to dump their low-cost

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polluting technologies to developing nations, so that they can keep their ecological footprint intact [52]. On the other hand, it is necessary for the developing nations to traverse along the growth trajectory, and in doing so, the policymakers of these nations always prefer to achieve the growth at the cost of environmental quality. In this way, the developing nations gradually turn out to be the pollution haven for the developed nations, and this transformation is caused by the technology transfer via international trade [53]. On the other hand, if the underdeveloped nations are considered, then it can be observed that the trade portfolios of these nations mostly consist of the natural resources. In order to achieve growth, these nations trade their natural resources, and owing to this, their economic growth is hampered [42]. Through this discussion, it is quite evident that the environmental quality of any nation is largely dependent on volume and nature of international trade, economic activity, and the development.

When these aspects are considered together, then the discussion calls for the introduction of environmental Kuznets curve (EKC) hypothesis. While assessing the environmental impact of North American Free Trade Agreement (NAFTA), Grossman and Krueger [23] found that the environmental degradation in any nation is an increasing function of economic activity to a point, and beyond this point, higher-income levels lead to improve environmental quality. Owing to its resemblance with the inverted U-shaped curvilinear association between income inequality and economic growth found by Kuznets [29], this association was named as environmental Kuznets curve. This curvilinear association can be analyzed by considering three channels, through which economic growth affects the environment, i.e., scale effect, composition effect, and technique effect [54]. During the earliest phase of development, more emphasis on the extraction of natural resources and agricultural production results in faster depletion of natural resources. The gradual rise in the industrialization process adds to the depletion of natural resources and increase in non-biodegradable waste. This is when scale effect is predominant in the economy. With the rise in income, when the new technologies start to usher in the economy, the composition effect comes to pass. This effect results in gradual decrease in the environmental degradation process, led by gradual decrease in fossil fuel-based energy consumption. Lastly, during the advanced phase of development, further technological development in the economy leads to the rise of service industry, and this is where technique effect comes into picture. In this phase, continuous fall in fossil fuel consumption, introduction of less polluting technologies, and discovery of alternate sources of energy result in fall in environmental degradation with rise in economic growth. Now, in each of these three phases, international trade plays a major role. First, during the scale effect, when the economy is at the earliest phase of development, a country generates income by exporting the natural resources, and thereby causing the *Dutch disease*. Second, when the composition effect starts in any economy, developed economies try to dump their polluting technologies, as the developing economies can get those technologies at a lower cost. In this phase, international trade makes the developing economies the pollution haven for the developed economies. Third, by the international trade route, the developing nations can have the access to improved technologies, and this helps to exert technique effect on the economy. This aspect of technology transfer can be seen in terms of the emergence of service industry, as well as the advent of renewable energy solutions. These are the channels, through which international trade can impact the environmental quality of any nation.

Saying this, it is also needed to be remembered that the volume and nature of trade differ from one country to another, and it majorly depends on the nature of development in that country. The international trade between the nations creates an inequality in terms of the balance of payment of those nations, and it can have a direct impact on the environmental quality of those nations. The valuation of a currency is largely dependent on the global demand–supply considerations, which is again based on the international trade, and therefore, purchasing power parity (PPP) is determined by the inequality in trade among the trading countries. The PPP reflects the status of economic growth and development in any nation, and it can have a direct impact on the environmental quality, based on their position on the EKC. This inequality varies among the countries from different income levels and continents, and this divergence is reflected differently on their environmental quality. In this study, we analyze the impact of trade inequality on carbon dioxide (CO_2) emissions for 187 countries over the period of 1990–2017. For the purpose of analysis, we have considered GDP, fossil fuel energy consumption, renewable energy consumption, and globalization index as other explanatory variables. Using Theil index [56], inequality in trade has been calculated for all the countries together, for different income levels (low, middle, and high) and for different continents (Asia, Europe, North America, South America, Africa, and Oceania). The cubic specification of EKC has been chosen for the analysis, as it can demonstrate the inflection point in the curve, where the scale effect and composition effect are overcome by technique effect. Moreover, having an alternate specification (other than the quadratic specification, i.e., inverted U-shaped form) of EKC can help to formulate policy implications in a clearer way.

The results from prior studies indicate that certain research gaps exist. For example, we have not found a study that has considered the impact of inequality in trade volume on CO_2 emissions. This study contributes to existing literature on trade and globalization in three ways: (i) This study uses the EKC framework to investigate the associations among income, renewable energy consumption, non-renewable energy consumption, inequality in trade volume, globalization, and CO_2 emissions for a panel of 187 countries over the period of 1990–2017. (ii) We applied the generalized method of moments (GMM) to estimate the relationship between these variables. (iii) We also consider two different subpanel categorizations that are constructed based on income level (low, middle, and high) and continents (Asia, Europe, North America, South America, Africa, and Oceania). Our results demonstrate that an N-shaped environmental Kuznets curve exists for the sample countries and for the two categories of subpanels.

2 Literature Review

Over the years, researchers have looked into the association between CO_2 emissions, economic growth, and different forms of energy consumption. The literature of environmental and energy economics have studied this association in several contexts. Therefore, we will focus on the other model variables. In this study, we have brought forth the aspects of globalization and trade inequality. In the following subsections, we will limit our discussion on the impact of globalization and trade on CO_2 emissions. This will help us in retaining the focus of our study. In order to maintain the precision and relevance with the study, we have reviewed the recent literature of energy and environmental economics, and the beginning of review period has been chosen as 2014.

2.1 Globalization and CO_2 Emissions

Ideally, in the literature of energy and environmental economics, the impact of globalization has largely been captured through KOF index of globalization [13, 14]. Some of these studies are conducted following the EKC framework. A brief review of these studies has been provided in Table 17.

Following the EKC framework, studies by Nwani [33], Shahbaz et al. [46, 48], Khan and Khan [27], and You and Lv [58] have found the evidence in support of the existence of EKC, whereas the studies by Bu et al. [11], and Shahbaz et al. [45] have found the evidence against the existence of EKC. On the other hand, the studies by Leitão [31], Ahad and Khan [1], Bernard and Mandal [9], Shahbaz et al. [47], Audi and Ali [6], Mutascu [32], and Shahbaz et al. [49] have been conducted without following the EKC framework. These studies provide a mixed evidence regarding the impact of globalization on CO_2 emissions.

By far, apart from the study by Bu et al. [11], most of these studies have focused on the context as aggregate, and there is no evidence regarding the impact in case of disaggregated data. There lies the contribution of this study, as we have focused on aggregate as well as disaggregated data for studying the impact of globalization on CO_2 emissions.

2.2 Trade and CO_2 Emissions

In the literature of energy and environmental economics, trade plays a very important role in determining the impact of economic growth on environmental quality. Trade is the factor, which determines level of technological innovation in any nations, and therefore, the state of development in any nation largely depends on this aspect. For the studies focused on estimating the EKC for any given context, trade plays a major role. A brief review of these studies has been provided in Table 18.

Following the EKC framework, studies by Arouri et al. [4], Boutabba [10], Farhani et al. [19, 20], Kivyiro and Arminen [28], Lau et al. [30], Osabuohien et al. [34], Oshin and Ogundipe [35], Shahbaz et al. [43, 44], Akpan and Abang [2], Jebli et al. [26], Seker et al. [41], Tang and Tan [55], Al-Mulali and Ozturk [3], Dogan and Seker [15], Ertugrul et al. [18], Sinha and Sen [53], Dogan et al. [17], Ozatac et al. [36], Sapkota and Bastola [39], and several others have found the evidence in support of the existence of EKC, whereas the studies by Farhani and Ozturk [21], Ozturk and Al-Mulali [37], and Dogan and Turkekul [16] have found the evidence against the existence of EKC. These studies also have provided mixed evidence regarding the impact of trade on the environmental quality.

By far, we have not come across any study, which has considered the inequality in trade, while determining the impact of trade on environmental quality. There lies the contribution of this study, as we have focused on analyzing the impact of trade inequality on CO_2 emissions using aggregate as well as disaggregated data.

3 Empirical Model and Data

In order to find an N-shaped EKC for the sample countries, first we need to establish a long-run association between CO_2 emissions, GDP, renewable and fossil fuel energy consumption, globalization index, and inequality in trade volume. Let us start with a standard EKC model with cubic specification, as per the following:

$$C = \beta_0 + \beta_1 Y + \beta_2 Y^2 + \beta_3 Y^3 + \beta_Z Z + \epsilon \quad (1)$$

where C is per capita CO_2 emission, Y is per capita GDP, Z is the other explanatory variables, and ϵ is the error term.

From Eq. (1), we obtain the following specifications, which denote specific functional forms:

(a) $\beta_1 = \beta_2 = \beta_3 = 0$; no growth–pollution association
(b) $\beta_1 > 0$, $\beta_2 = \beta_3 = 0$; linearly increasing growth–pollution association
(c) $\beta_1 < 0$, $\beta_2 = \beta_3 = 0$; linearly decreasing growth–pollution association
(d) $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 = 0$; inverted U-shaped growth–pollution association
(e) $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 = 0$; U-shaped/ monotonically increasing growth–pollution association
(f) $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$; N-shaped growth–pollution association
(g) $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$; inverted N-shaped growth–pollution association

The necessary condition for the EKC to be N-shaped is that β_1, $\beta_3 > 0$ and $\beta_2 < 0$. Similarly, for the EKC to be inverted N-shaped, the necessary condition is β_1, $\beta_3 < 0$ and $\beta_2 > 0$. However, this condition is not sufficient for commenting on the nature of the EKC, as this condition does not reflect anything about the validity of the model. To check the validity of the model, the model should be differentiated to the first order. The first-order differential of Eq. (1) is given by

$$\frac{\mathrm{d}C}{\mathrm{d}Y} = \beta_1 + 2\beta_2 Y + 3\beta_3 Y^2 = 0 \tag{2}$$

For the EKC to be N-shaped or inverted N-shaped, Eq. (1) must have local maxima and minima at two distinct values of Y.[1] The condition for Eq. (1) having local maxima and minima is given by Eq. (3):

$$\beta_2^2 - 3\beta_1\beta_3 > 0 \tag{3}$$

To find the values of the maxima and minima, arriving at the second-order condition is required. The second-order condition, derived from Eq. (2), takes the following form:

$$\frac{\mathrm{d}^2C}{\mathrm{d}Y^2} = 2\beta_2 + 6\beta_3 Y = \pm\sqrt{4\beta_2^2 - 12\beta_1\beta_3} \tag{4}$$

The validity of the second-order condition is also given by Eq. (3). Therefore, it can be stated that Eq. (3) is the sufficient condition for an N-shaped or an inverted N-shaped EKC to be valid.[2]

For estimation purpose, we will be using the following system of equations:

$$\begin{aligned}\log C_{it} = {} & \beta_0 + \beta_1 \log Y_{it} + \beta_2(\log Y_{it})^2 + \beta_3(\log Y_{it})^3 + \beta_4 \log \mathrm{REN}_{it} + \beta_5 \log E_{it} \\ & + \beta_6 \log \mathrm{GLOB}_{it} + \beta_7 \log \mathrm{INEQ}_{it} + \epsilon_{it}\end{aligned} \tag{5}$$

where C_{it} denotes the per capita CO_2 emissions, Y_{it} is real GDP per capita, REN_{it} is the per capita renewable energy consumption, E_{it} is per capita fossil fuel energy consumption, GLOB_{it} is the KOF index of overall globalization, INEQ_{it} is the inequality in trade volume, ϵ_{it} is the error term, t is the time period ($t = 1, 2, \ldots, T$), and i is the cross section ($i = 1, 2, \ldots, N$).

Now, let us look at the expected sign of the coefficients of other explanatory variables. As renewable energy consumption will exert no negative ecological pressure, the sign of β_4 is expected to be negative. On the contrary, fossil fuel consumption is expected to have a negative impact on environmental quality, and therefore, the sign of β_5 is expected to be positive. For the emerging economies, globalization is largely associated with access to improved resources, which might have a positive impact on environmental quality. Therefore, the sign of β_6 is expected to be negative. The

[1]The local maxima and minima can be found at $Y = \left(-2\beta_2 \pm \sqrt{4\beta_2^2 - 12\beta_1\beta_3}\right)/6\beta_3$, or $Y = \left(-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_1\beta_3}\right)/3\beta_3$. These are derived by solving the first-order condition given in Eq. (2).

[2]$Y_{\text{maxima}} > Y_{\text{minima}}$: EKC is N-shaped.
$Y_{\text{maxima}} < Y_{\text{minima}}$: EKC is inverted N-shaped.

impact of inequality in trade volume on environmental quality is dependent on the level of development of the nation. Owing to this reason, the sign of β_7 is can be either positive or negative.

In this study, we have used the data of sample countries over the period of 1990–2017. We collected the annual data for per capita CO_2 emissions (in kt), per capita GDP (constant 2010 US$), per capita renewable energy consumption (in kt), per capita fossil fuel energy consumption (in kt) from World Bank indicators, and KOF index of globalization from Dreher [13] and Dreher et al. [14]. The inequality in trade volume has been calculated using Theil [56] index, which is also commonly known as Theil's second measure. Taking a cue from the information entropy measure demonstrated by Shannon [50], Theil's index can take the following form of entropy:

$$\mathrm{INEQ} = -k \sum_{1}^{N} (p_i \log p_i) \tag{6}$$

where p_i is the probability of having a balance of payment t_i of a nation among N number of nations, and the total balance of payment of the group of countries can be given by N_t, $\bar{t}$ being the average balance of payment of the nations under consideration, and k is a positive definite scalar. Therefore, the Theil's index is given by:

$$\mathrm{INEQ} = \sum_{1}^{N} \left(\frac{t_i}{N_t} \log \frac{N_t}{t_i} \right) \tag{7}$$

If the homogeneity among the nations is considered, then $p_i = 1/N$. Therefore, Eq. (7) can be represented as:

$$\mathrm{INEQ} = \frac{1}{N} \sum_{1}^{N} \left(\log \frac{N_t}{t_i} \right) \tag{8}$$

The limiting condition applied to Theil's basic measure brings out the Theil's second measure, and at the limit condition of the scalar multiplier s to be zero [51], we obtain the following form of entropy:

$$\mathrm{INEQ} = \lim_{s \to 0} \left[\frac{1}{N} \frac{1}{s(s-1)} \sum_{1}^{N} \left\{ \left(\frac{t_i}{N_t} \right)^{s} - 1 \right\} \right] = \frac{1}{N} \sum_{1}^{N} \left(\frac{N_t}{t_i} \right) \tag{9}$$

This form is generally referred to as the Atkinson's index [5, 40], and this is also the form, which is by and large referred to as Theil's second measure. Given by the probabilistic functional form as mentioned by Theil [56], Theil's second measure can be ranged as (0, 1), where values zero can be signified as perfect equality, and one as perfect inequality. Disintegration of INEQ in the subgroup inequality components can be carried out in the following manner:

$$\text{INEQ} = \text{INEQ}_{\text{wg}} + \text{INEQ}_{\text{bg}} = \sum_{1=1}^{g} p_g \left(\log \frac{\bar{t}}{t_i} \right) \tag{10}$$

where INEQ_{wg} refers to the within-group inequality, INEQ_{bg} refers to the between-group inequality, and p_g stands for percentage balance of payment by group g.

4 Results and Discussion

Before applying the unit root tests, we need to check for the applicability of the first or second-generation unit root tests, and in this pursuit, we have to check the possibility of cross-sectional dependence in the data. In order to achieve this, we have applied Chudik and Pesaran [12] weak cross-sectional dependence test. Null hypothesis of this test is that the cross sections of the panel data are weakly dependent on each other, and the results of this test are reported in Tables 1, 2 and 3. The results signify that the cross-sectional dependence is significantly present among the model variables. Based on this result, we can now proceed for the second-generation unit root tests.

For checking the order of integration among the variables, we have applied the cross-sectional Im–Pesaran–Shin (CIPS) and cross-sectionally augmented Dickey—Fuller (CADF) unit root tests devised by Pesaran [38]. These tests are second-generation unit root tests, which assume the cross-sectional dependence in a panel dataset. CIPS test is an extension of the Im–Pesaran–Shin (IPS) [24] with a single factor with heterogeneous loading across the cross sections. It is a cross-sectionally augmented IPS Dickey Fuller type test, which takes account of cross-sectional means of the level and lagged differences to the IPS-type regression. In this test, the p value of the Breusch–Godfrey Lagrange multiplier test of each specific regression is reported. Here, the null hypothesis of homogeneous non-stationary is tested against the alternate hypothesis of heterogeneous alternatives. On the other hand, CADF test is based on the mean of the augmented Dickey–Fuller (ADF) t-statistic of every panel mem-

Table 1 Results of Chudik and Pesaran [12] weak cross-sectional dependence test (all countries)

Variables	Test statistic	p value	Variables	Test statistic	p value
C	8.1132	0.0000	GLOB	7.2646	0.0000
Y	8.2396	0.0000	E	3.2123	0.0013
Y^2	8.3194	0.0000	REN	8.0321	0.0000
Y^3	8.4756	0.0000	INEQ	2.2754	0.0229

Table 2 Results of Chudik and Pesaran [12] weak cross-sectional dependence test (countries segregated by income)

Segment	Variables	Test statistic	*p* value	Variables	Test statistic	*p* value
Low income	C	7.5244	0.0000	GLOB	1.6451	0.0000
	Y	4.1736	0.0000	E	5.4664	0.0046
	Y^2	4.1681	0.0000	REN	4.6565	0.0000
	Y^3	4.1772	0.0000	INEQ	7.8750	0.0000
Middle income	C	2.6708	0.0000	GLOB	6.6495	0.0000
	Y	3.0035	0.0000	E	4.7179	0.0370
	Y^2	2.0804	0.0000	REN	9.9121	0.0000
	Y^3	1.2018	0.0000	INEQ	7.7147	0.0000
High income	C	2.9423	0.0000	GLOB	3.8119	0.0000
	Y	4.6099	0.0000	E	3.9537	0.0000
	Y^2	4.7492	0.0000	REN	9.4719	0.0000
	Y^3	4.8826	0.0000	INEQ	5.5974	0.0000

ber. Null hypothesis of this test is that all of the series in the panel are non-stationary, against the alternate hypothesis of only a section of the series are stationary.

The results of these tests are recorded in Table 4, and it visible from the results that the variables are free from unit roots after first differentiation. Therefore, it can be concluded that the variables are integrated to order one; i.e., the variables are I(1) in nature. With this result, we can proceed for the cointegration tests.

For checking the cointegrating association among the variables, we have employed Westerlund and Edgerton [57] test and continuously updated FMOLS test [7]. These cointegration tests are conducted in the presence of the cross-sectional dependence in the panel data. The results of Westerlund and Edgerton [57] test are reported in Table 3, and they show the significant cointegrating association among the variables. However, the unobserved nonlinearity is not considered in this test, which is covered by continuously updated FMOLS approach. Results of this test are reported in Tables 5, 6, 7, 8, 9, and 10. In order to show the robustness of the results, least square dummy variable (LSDV) and Bai and Ng [8] two-step fully modified estimator results are also shown. The results show that the cointegrating association among the variables is significant. They also show the long-run equilibrium among the model variables for the period of 1990–2017 in the sample countries.

After the confirmation of cointegrating association, we can now proceed with testing the model in Eq. (5). In order to test the model, we have applied generalized method of moments (GMM), and results of the test are reported in Tables 11, 12, and 13. The coefficients of income (Y), squared income (Y^2), and cubic income (Y^3) are positive, negative, and positive for the panel of all sample countries and the two subpanels. This piece of evidence demonstrates the presence of N-shaped EKC, and the validity conditions stated in Eqs. (3) and (4) are fulfilled. Now, for an N-shaped EKC, there are two turnaround points, and these turnaround points divulge

Table 3 Results of Chudik and Pesaran [12] weak cross-sectional dependence test (countries segregated by continents)

Segment	Variables	Test statistic	*p* value	Variables	Test statistic	*p* value
Asia	C	2.3356	0.0000	GLOB	4.1942	0.0000
	Y	−2.4219	0.0154	E	−1.9627	0.0497
	Y^2	−2.4501	0.0143	REN	5.2738	0.0000
	Y^3	−2.4675	0.0136	INEQ	−1.8172	0.0692
Europe	C	5.2393	0.0000	GLOB	3.7426	0.0000
	Y	−3.3230	0.0009	E	2.0479	0.0406
	Y^2	−3.2877	0.0010	REN	7.3080	0.0000
	Y^3	−3.2383	0.0012	INEQ	5.3582	0.0000
North America	C	3.0387	0.0024	GLOB	3.3619	0.0000
	Y	−2.3894	0.0168	E	2.6154	0.0089
	Y^2	−2.4828	0.0130	REN	2.1335	0.0329
	Y^3	−2.6029	0.0092	INEQ	−3.3410	0.0008
South America	C	3.3177	0.0009	GLOB	7.6752	0.0000
	Y	−2.9217	0.0035	E	−2.2695	0.0232
	Y^2	−2.8516	0.0043	REN	2.2956	0.0217
	Y^3	−2.7557	0.0059	INEQ	6.7028	0.0000
Africa	C	8.0774	0.0000	GLOB	8.9876	0.0000
	Y	3.5966	0.0003	E	2.0669	0.0836
	Y^2	3.3425	0.0008	REN	2.1209	0.0339
	Y^3	3.0752	0.0021	INEQ	7.8479	0.0000
Oceania	C	−2.0081	0.0446	GLOB	2.1025	0.0722
	Y	−2.1812	0.0292	E	−2.7053	0.0068
	Y^2	−2.1783	0.0294	REN	2.5595	0.0108
	Y^3	−2.2071	0.0273	INEQ	−2.8349	0.0046

Table 4 Results of second-generation unit root tests

Variables	CIPS		CADF	
	Level	First diff.	Level	First diff.
C	−1.480	-5.237^a	−1.191	-3.741^a
Y	−1.602	-4.571^a	−1.511	-3.618^a
Y^2	−1.570	-4.549^a	−1.490	-3.591^a
Y^3	−1.535	-4.526^a	−1.469	-3.562^a
GLOB	−1.503	-4.899^a	−1.269	-3.489^a
E	−1.952	-5.071^a	−1.733	-4.043^a
REN	−1.898	-4.961^a	-2.001^c	-3.588^a
INEQ	−1.683	-5.466^a	−1.184	-4.446^a

Note [a]Significant value at 1%; [c]significant value at 10%

Table 5 Results of Westerlund and Edgerton [57] cointegration test (aggregate data)

	Test statistic (1)	*p* value	Test statistic (2)	*p* value	Test statistic (3)	*p* value
LM_τ	−6.940	0.000	−8.745	0.000	−4.315	0.000
LM_ϕ	−12.176	0.000	−8.019	0.000	−3.772	0.000

Note Model (1): model with a maximum number of ten factors and no shift. Model (2): model with a maximum number of ten factors and level shift. Model (3): model with a maximum number of ten factors and regime shift

Table 6 Results of Westerlund and Edgerton [57] cointegration test (countries segregated by income)

	Test statistic (1)	*p* value	Test statistic (2)	*p* value	Test statistic (3)	*p* value
Low income						
LM_τ	−7.356	0.000	−5.249	0.000	−7.504	0.000
LM_ϕ	−9.668	0.000	−4.527	0.000	−8.940	0.000
Middle income						
LM_τ	−1.713	0.043	−5.904	0.000	−4.204	0.000
LM_ϕ	−1.515	0.065	−2.857	0.002	−2.805	0.003
High income						
LM_τ	−9.404	0.000	−5.887	0.000	−5.636	0.000
LM_ϕ	−14.627	0.000	−5.039	0.000	−7.777	0.000

Note Model (1): model with a maximum number of ten factors and no shift; Model (2): model with a maximum number of ten factors and level shift; Model (3): model with a maximum number of ten factors and regime shift

significant insights about the level of development in the nations. When we look at the turnaround points for all the countries together, they demonstrate a wholesome carbon reduction effort, as both the turnaround points are well within the sample range. This result is in line with Jaforullah and King [25] for seven countries and Sinha et al. [54] for N11 countries. However, they do not tell us about the possible divergence in developmental efforts in different nations. This aspect comes to pass, when we look into the turnaround points for the two subpanels. Let us begin with the subpanel, with the income-level categorization. The first turnaround point is lowest for the high-income category, followed by low income and middle income, whereas the second turnaround point is lowest for the high-income category, followed by middle income and low income. It is evident from that the countries under highest income category have shown highest level of development, in terms of the carbon reduction effort, whereas countries under the middle- and low-income categories have failed to demonstrate this. This might give an indication that the high-income countries have made the low- and middle-income countries as pollution havens, and as the property rights and environmental protection measures are poor in low-income countries, they have achieved the highest second turnaround point, which is nearly

Table 7 Results of Westerlund and Edgerton [57] cointegration test (countries segregated by continents)

	Test statistic (1)	*p* value	Test statistic (2)	*p* value	Test statistic (3)	*p* value
Asia						
LM_τ	−4.548	0.000	−2.543	0.006	−4.373	0.000
LM_ϕ	−7.441	0.000	−2.765	0.003	−6.156	0.000
Europe						
LM_τ	−3.603	0.000	−2.019	0.022	−1.508	0.034
LM_ϕ	−7.201	0.000	−5.758	0.000	−4.105	0.000
North America						
LM_τ	−5.088	0.000	−5.925	0.000	−2.394	0.008
LM_ϕ	−5.818	0.000	−6.176	0.000	−2.176	0.015
South America						
LM_τ	−2.044	0.020	−7.034	0.000	−2.908	0.002
LM_ϕ	−3.013	0.001	−5.698	0.000	−3.381	0.000
Africa						
LM_τ	−6.306	0.000	−1.922	0.027	−1.777	0.038
LM_ϕ	−14.118	0.000	−4.713	0.000	−3.586	0.000
Oceania						
LM_τ	−2.886	0.002	−2.562	0.005	−2.070	0.019
LM_ϕ	−3.650	0.000	−3.096	0.001	−2.288	0.011

Note Model (1): model with a maximum number of ten factors and no shift; Model (2): model with a maximum number of ten factors and level shift; Model (3): model with a maximum number of ten factors and regime shift

two times higher than that of the middle-income countries and nearly 26 times higher than that of the high-income countries.

Now, if we look at the second subpanel with continent-level categorization, then we can see that Oceanian countries have reported lowest second turnaround point, whereas South American has reported highest second turnaround point. For Asian, European, and North American countries, the second turnaround points are moderately high, thereby showing the sturdiness of the development process in these nations. On the flipside, if we look at the second turnaround points of African and South American countries, then we can see that they are very high and well outside the sample space, thereby, implying the ineffectiveness of the development process.

These scenarios can be elaborated in a better way, when the impact of globalization will be analyzed. Though the impact of globalization on CO_2 emissions for the entire panel is negative, as expected, this impact differs for the two subpanel members. Let us begin with the subpanel with income-level categorization. For the countries with high- and medium-income level, the impact is negative, whereas for the low-income countries, the impact is positive. Opening up if the economy has

Table 8 Results of continuously updated FMOLS test (aggregate data)

Variables	LSDV	Bai-FM	CUP-FM	CUP-BC
C	2.010837[a]	2.008943[a]	2.009385[a]	2.010738[a]
	[257.883076]	[432.804391]	[437.914089]	[438.775748]
Y	2.007486[a]	2.006017[a]	2.006311[a]	2.006429[a]
	[258.159098]	[427.987235]	[432.962889]	[433.309846]
Y^2	2.001872[a]	2.002007[a]	2.001929[a]	2.001709[a]
	[273.912763]	[462.300401]	[467.576410]	[467.780740]
Y^3	2.000682[a]	1.989107[a]	1.991419[a]	1.990122[a]
	[254.316850]	[405.936486]	[410.899885]	[410.884303]
GLOB	1.999118[a]	2.000744[a]	2.000051[a]	2.000031[a]
	[241.602984]	[391.057904]	[395.377049]	[395.649956]
E	2.003301[a]	2.005404[a]	2.005181[a]	2.005300[a]
	[261.887510]	[441.748614]	[446.744359]	[447.029467]
REN	1.992860[a]	1.993828[a]	1.993755[a]	1.993920[a]
	[264.531346]	[458.809870]	[464.193322]	[464.300161]
INEQ	1.988146[a]	2.002951[a]	1.999923[a]	1.999926[a]
	[266.589141]	[446.191909]	[450.714456]	[450.747377]

Note [a]Significant value at 1%; *t* statistics are within [ ] parentheses

hurt the environmental quality of the low-income countries the most among the three groups of countries, as the high and emerging middle-income countries, might have made the low-income countries as pollution havens. Moreover, movement of natural resources outside the low-income countries has further worsened their environmental quality. Though some of the middle-income countries faced this issue, emerging economies under this category exerted the expected impact. On the flipside, for the high-income countries, the impact of globalization has been positive, and one of the major reasons behind this is the diffusion of clean technologies, which is reflected in their trade portfolio. This scenario is presumably predominant also in case of the emerging middle-income countries. The geographical dispersion of this aspect can be seen in the results for the subpanel with continent-level categorization. For Asian, European, North American, and Oceanian countries, the impact of globalization on CO_2 emissions is found to be negative, whereas for South American and African countries, this impact is found to be positive. These impacts can be described in terms of the level of development in these continents. In terms of average per capita income, European countries lead the chart table, followed by Oceanian, North American, Asian, South American, and African countries, and thereby, developmental progress in these continents can be visible. For the developed countries, the impact of globalization has been found to be negative, as the nature of globalization in these countries is more prone toward the diffusion of cleaner technologies, and therefore, the impact of globalization on CO_2 emissions in these countries is perceived to be

Table 9 Results of continuously updated FMOLS test (countries segregated by income)

Segment	Variables	LSDV	Bai-FM	CUP-FM	CUP-BC
Low income	C	1.985186[a]	1.977037[a]	1.975273[a]	1.972570[a]
		[148.866019]	[265.163554]	[273.208332]	[279.420544]
	Y	2.011956[a]	1.992656[a]	1.999038[a]	1.996584[a]
		[151.895854]	[250.875679]	[259.560583]	[265.676494]
	Y^2	1.985052[a]	1.980215[a]	1.984249[a]	1.985591[a]
		[143.623563]	[237.861522]	[245.476472]	[251.065960]
	Y^3	1.997561[a]	2.017499[a]	2.014644[a]	2.013946[a]
		[144.649535]	[248.611628]	[256.292313]	[262.157760]
	GLOB	2.014682[a]	2.023792[a]	2.023888[a]	2.024783[a]
		[154.000186]	[259.072854]	[266.648488]	[272.864935]
	E	2.013796[a]	2.010594[a]	2.012575[a]	2.011248[a]
		[149.569129]	[263.208807]	[272.196810]	[277.701736]
	REN	1.972424[a]	1.979483[a]	1.978873[a]	1.978539[a]
		[142.374544]	[231.382909]	[238.753679]	[243.989715]
	INEQ	2.011567[a]	1.996752[a]	1.996344[a]	2.000657[a]
		[156.596869]	[284.022579]	[292.886914]	[300.297940]
Middle income	C	2.005347[a]	1.995296[a]	1.997603[a]	1.998613[a]
		[149.067650]	[280.292830]	[293.695978]	[295.930958]
	Y	1.992101[a]	1.991448[a]	1.992081[a]	1.992487[a]
		[151.946611]	[242.552762]	[253.495625]	[255.255993]
	Y^2	1.993373[a]	2.006590[a]	2.005137[a]	2.005422[a]
		[145.245785]	[271.388516]	[283.732627]	[285.749905]
	Y^3	1.990942[a]	1.989477[a]	1.992842[a]	1.991844[a]
		[137.383776]	[244.458640]	[256.234865]	[257.941447]
	GLOB	1.997534[a]	2.017913[a]	2.013505[a]	2.012347a
		[165.279456]	[304.783092]	[318.189019]	[320.186109]
	E	1.988282[a]	1.994749[a]	1.991260[a]	1.990256[a]
		[155.608026]	[256.692265]	[267.856973]	[269.628852]
	REN	2.014785[a]	1.996859[a]	2.002477[a]	2.003668[a]
		[163.345643]	[290.383276]	[304.555764]	[306.844702]
	INEQ	2.014577[a]	1.999152[a]	2.000166[a]	1.999929[a]
		[155.884156]	[297.631384]	[311.802864]	[313.912942]
High income	C	1.988934[a]	1.984397[a]	1.983650[a]	1.983972[a]
		[147.881644]	[294.686362]	[310.528958]	[309.764375]
	Y	2.008307[a]	2.004298[a]	2.008110[a]	2.008683[a]
		[143.435845]	[273.514413]	[288.768762]	[288.176314]

(continued)

Table 9 (continued)

Segment	Variables	LSDV	Bai-FM	CUP-FM	CUP-BC
	Y^2	2.035062[a]	2.007101[a]	2.010344[a]	2.010766[a]
		[128.652110]	[245.460250]	[258.520996]	[258.004485]
	Y^3	1.969944[a]	1.986728[a]	1.983234[a]	1.982078[a]
		[136.578122]	[260.416177]	[273.085443]	[272.311632]
	GLOB	1.995691[a]	1.995718[a]	1.995706[a]	1.997170[a]
		[143.330134]	[264.308020]	[277.869904]	[277.690696]
	E	1.983289[a]	2.008963[a]	2.002522[a]	2.001674[a]
		[146.046182]	[261.664175]	[273.576986]	[272.914278]
	REN	1.997742[a]	1.996117[a]	1.998761[a]	1.998420[a]
		[120.301122]	[219.423715]	[230.978623]	[230.466044]
	INEQ	2.000898[a]	2.015363[a]	2.010966[a]	2.011972[a]
		[140.451615]	[250.461304]	[262.483881]	[262.286798]

Note [a]Significant value at 1%; *t* statistics are within [ ] parentheses

negative. This is reflected in the lower second turnaround points compared to the countries with less developmental prospect. On the other hand, for the countries with less developmental prospect, the impact of globalization has been found to be positive, as the nature of globalization in these countries is more prone toward the trade of polluting technologies and natural resources, and therefore, the impact of globalization on CO_2 emissions in these countries is perceived to be positive. The trade pattern in these countries has made them pollution haven for the developed nations, and it is further reflected in the second turnaround points of their EKCs, which are higher compared to those of the developed nations.

Along with the impact of globalization, we should also analyze the impact of the trade inequality, which is the prime focus of this study. The trade inequality has been calculated based on the balance of payment of the nations under each category for the two subpanels and the entire panel. When we look at the aggregate data, then we can see that trade inequality has a positive impact on CO_2 emissions. It signifies that the volume of trade across the nations is disproportionate, and this can affect the environmental quality adversely. In order to dig deeper into the issue, we will analyze the results for the subpanel with income-level categorization. It is evident that the impact of trade inequality on CO_2 emissions for high and medium-income countries is negative, whereas the same is positive for low-income countries. The trade inequality in low-income areas occurs mainly due to the divergence in development processes, which is in turn reflected in their trade portfolio, trade balance, and thereafter balance of payment. Ineffective diffusion of technology is a major problem in these countries, which is also characterized by this trade inequality, and owing to this, innovations are not replicated among these countries. Moreover, the resource curse problem is also evident in their trade portfolio, and by the outward movement of one of the major factors of production, these countries end up importing substitute factors

Table 10 Results of continuously updated FMOLS test (countries segregated by continents)

Segment	Variables	LSDV	Bai-FM	CUP-FM	CUP-BC
Asia	C	1.996036[a]	2.000710[a]	2.000217[a]	1.999962[a]
		[116.307188]	[205.482873]	[205.29207]	[206.613254]
	Y	2.013340[a]	1.985345[a]	1.985145[a]	1.983843[a]
		[120.87796]	[223.283295]	[222.207415]	[223.374756]
	Y^2	2.026169[a]	1.999578[a]	2.004974[a]	2.004005[a]
		[131.360476]	[264.507146]	[266.134725]	[267.872182]
	Y^3	1.999375[a]	1.992512[a]	1.990911[a]	1.990220[a]
		[113.224889]	[226.488739]	[229.132988]	[230.911774]
	GLOB	1.992819[a]	1.994255[a]	1.998921[a]	1.998633[a]
		[129.806684]	[241.06858]	[241.355029]	[242.931837]
	E	2.007266[a]	2.002321[a]	2.003650[a]	2.004014[a]
		[120.238711]	[232.362161]	[234.780933]	[236.622647]
	REN	1.981237[a]	1.996242[a]	1.995419[a]	1.996442[a]
		[127.524215]	[250.460936]	[250.747587]	[252.637998]
	INEQ	1.992369[a]	2.011490[a]	2.005609[a]	2.006390[a]
		[139.463685]	[260.604946]	[260.22035]	[262.260047]
Europe	C	1.996036[a]	2.000710[a]	2.000217[a]	1.999962[a]
		[116.307188]	[205.482873]	[205.292070]	[206.613254]
	Y	2.013340[a]	1.985345[a]	1.985145[a]	1.983843[a]
		[120.877960]	[223.283295]	[222.207415]	[223.374756]
	Y^2	2.026169[a]	1.999578[a]	2.004974[a]	2.004005[a]
		[131.360476]	[264.507146]	[266.134725]	[267.872182]
	Y^3	1.999375[a]	1.992512[a]	1.990911[a]	1.990220[a]
		[113.224889]	[226.488739]	[229.132988]	[230.911774]
	GLOB	1.992819[a]	1.994255[a]	1.998921[a]	1.998633[a]
		[129.806684]	[241.068580]	[241.355029]	[242.931837]
	E	2.007266[a]	2.002321[a]	2.003650[a]	2.004014[a]
		[120.238711]	[232.362161]	[234.780933]	[236.622647]
	REN	1.981237[a]	1.996242[a]	1.995419[a]	1.996442[a]
		[127.524215]	[250.460936]	[250.747587]	[252.637998]
	INEQ	1.992369[a]	2.011490[a]	2.005609[a]	2.006390[a]
		[139.463685]	[260.604946]	[260.220350]	[262.260047]
North America	C	2.053495[b]	2.034961[a]	2.026223[a]	2.025425[a]
		[74.206327]	[114.649632]	[133.470693]	[135.037915]
	Y	2.025911[b]	2.019765[a]	2.031695[a]	2.029744[a]
		[88.793961]	[145.618674]	[167.837979]	[170.457111]

(continued)

Table 10 (continued)

Segment	Variables	LSDV	Bai-FM	CUP-FM	CUP-BC
	Y^2	1.973148[b]	2.005215[a]	1.997659[a]	1.995584[a]
		[82.337227]	[136.074717]	[151.605188]	[153.824203]
	Y^3	1.992242[b]	1.951552[a]	1.962763[a]	1.959703[a]
		[99.194290]	[152.649022]	[174.679979]	[176.674485]
	GLOB	1.968401[b]	1.997005[b]	2.007077[a]	2.005624[a]
		[68.308426]	[98.093561]	[106.725097]	[107.627234]
	E	1.967571[b]	1.993635[a]	2.023725[a]	2.023168[a]
		[84.094911]	[149.746836]	[176.589467]	[178.987856]
	REN	1.983530[b]	2.003376[a]	1.980879[a]	1.982962[a]
		[67.182070]	[138.036397]	[163.311930]	[166.175730]
	INEQ	2.030518[b]	2.013412[a]	1.985915[a]	1.993661[a]
		[88.517768]	[158.162029]	[185.467468]	[189.114574]
South America	*C*	1.992353[b]	1.978911[b]	1.930592[b]	1.984556[a]
		[51.310868]	[84.070199]	[98.337909]	[123.925959]
	Y	1.949098[c]	2.030542[b]	2.125192[a]	2.032825[a]
		[47.445680]	[89.994760]	[111.582811]	[135.646971]
	Y^2	2.055137[b]	1.998263[b]	1.896869[a]	1.974110[a]
		[54.051929]	[86.790563]	[103.689017]	[127.367428]
	Y^3	1.956922[b]	1.981059[a]	2.007154[a]	1.971018[a]
		[67.708907]	[137.069860]	[148.091572]	[196.265598]
	GLOB	1.972142[b]	1.978966[b]	1.991915[a]	2.008504[a]
		[68.955888]	[99.548123]	[125.259064]	[146.703206]
	E	1.948333[b]	1.971896[a]	2.041256[a]	1.982004[a]
		[58.675624]	[120.485029]	[137.083191]	[181.919196]
	REN	2.084611[b]	2.043767[a]	2.071870[a]	2.039393[a]
		[80.537902]	[156.753741]	[173.048724]	[227.739666]
	INEQ	1.969989[b]	1.996361[a]	1.983981[a]	2.006925[a]
		[57.168124]	[112.825411]	[131.303557]	[171.665504]
Africa	*C*	1.982151[a]	1.993347[a]	1.993215[a]	1.991291[a]
		[136.455316]	[223.332291]	[246.820980]	[248.600652]
	Y	1.992797[a]	1.998041[a]	1.995971[a]	1.998376[a]
		[130.563497]	[223.315771]	[247.496539]	[249.815948]
	Y^2	2.002433[a]	1.98243[a]	1.986885[a]	1.985913[a]
		[125.244524]	[217.993992]	[242.252026]	[244.148198]
	Y^3	1.998458[a]	2.001626[a]	1.999013[a]	1.999595[a]
		[129.149623]	[225.576201]	[249.802124]	[251.900626]
	GLOB	1.965683[a]	1.999632[a]	1.996057[a]	1.996558[a]
		[124.550145]	[251.098972]	[278.964837]	[281.361061]

(continued)

Table 10 (continued)

Segment	Variables	LSDV	Bai-FM	CUP-FM	CUP-BC
	E	2.025951[a]	1.995997[a]	2.001877[a]	2.003080[a]
		[120.321368]	[212.401483]	[236.379000]	[238.666162]
	REN	2.003431[a]	2.024638[a]	2.015846[a]	2.015989[a]
		[244.510095]	[270.302129]	[272.562799]	[130.407804]
	INEQ	2.004375[a]	2.008150[a]	2.008761[a]	2.008555[a]
		[137.103798]	[226.011055]	[250.114599]	[252.163428]
Oceania	*C*	1.992353[b]	1.978911[b]	1.930592[b]	1.984556[a]
		[51.310868]	[84.070199]	[98.337909]	[123.925959]
	Y	1.949098[c]	2.030542[b]	2.125192[a]	2.032825[a]
		[47.44568]	[89.99476]	[111.582811]	[135.646971]
	Y^2	2.055137[b]	1.998263[b]	1.896869[a]	1.97411[a]
		[54.051929]	[86.790563]	[103.689017]	[127.367428]
	Y^3	1.956922[b]	1.981059[a]	2.007154[a]	1.971018[a]
		[67.708907]	[137.06986]	[148.091572]	[196.265598]
	GLOB	1.972142[b]	1.978966[b]	1.991915[a]	2.008504[a]
		[68.955888]	[99.548123]	[125.259064]	[146.703206]
	E	1.948333[b]	1.971896[a]	2.041256[a]	1.982004[a]
		[58.675624]	[120.485029]	[137.083191]	[181.919196]
	REN	2.084611[b]	2.043767[a]	2.07187[a]	2.039393[a]
		[80.537902]	[156.753741]	[173.048724]	[227.739666]
	INEQ	1.969989[b]	1.996361[a]	1.983981[a]	2.006925[a]
		[57.168124]	[112.825411]	[131.303557]	[171.665504]

Note [a]Significant value at 1%; [b]significant value at 5%; [c]significant value at 10%. *t* statistics are within [ ] parentheses

of production, i.e., fossil fuel. Therefore, this inequality in trade volume results in the negative impact on environmental quality by giving rise to CO_2 emissions. Though this feature can be seen in some of the middle-income countries, this impact is offset by the emerging middle countries. Similar to the high-income countries, these countries are characterized by technology diffusion and gradual substitution of fossil fuel import. Moreover, these countries are leaning toward clean technology solutions, and owing to the high price of these solutions, the inequality in the balance of payment among these countries arises. Therefore, the impact of trade inequality on CO_2 emissions in these two groups of countries has been found to be negative.

This scenario behind this impact becomes clearer, when we look at the results for the other subpanels with continent-level categorization. It is evident that the impact of trade inequality on CO_2 emissions for Asian, European, North American, and Oceanian countries is negative, whereas the same is positive for South American and African countries. In this particular context, the results might be associated with the

Table 11 Results of GMM test (all countries)

Independent variables	Dependent variable = C
Y	1.3016[c]
Y^2	−0.1171[c]
Y^3	0.0034[b]
GLOB	−0.0029[a]
E	1.0248[a]
REN	−0.1182[a]
INEQ	0.9303[a]
Constant	−2.3325[a]
Hansen's J statistics	0.9934
DWH test statistics	8.6860[a]
Shape of EKC	N-shaped
Turnaround points	a. 12,494.73 b. 749,920.41

Note [a]Significant value at 1%; [b]significant value at 5%; [c]significant value at 10%

Table 12 Results of GMM test (countries segregated by income)

Independent variables	Dependent variable = C		
	Low income	Middle income	High income
Y	0.7142[c]	1.5644[a]	0.8090[a]
Y^2	−0.0510[c]	−0.1243[a]	−0.0810[a]
Y^3	0.0012[c]	0.0032[a]	0.0026[a]
GLOB	0.0048[b]	−0.0120[a]	−0.0005[c]
E	1.1551[a]	0.8404[a]	0.9827[a]
REN	−0.0489[a]	−0.2832[a]	−0.2226[a]
INEQ	0.6563[a]	−1.4184[a]	−0.6376[a]
Constant	−9.9659[c]	−16.5807[a]	−10.3995[a]
Hansen's J statistics	0.1075	0.3747	0.6745
DWH test statistics	2.6767[a]	4.9676[b]	8.3255[a]
Shape of EKC	N-shaped	N-shaped	N-shaped
Turnaround points	a. 311,221.78 b. 6,485,453.24	a. 48,157.24 b. 3,662,316.95	a. 4248.30 b. 246,460.55

Note [a]Significant value at 1%; [b]significant value at 5%; [c]significant value at 10%

Table 13 Results of GMM test (countries segregated by continents)

Independent variables	Dependent variable = *C*					
	Asia	Europe	North America	South America	Africa	Oceania
Y	3.4178[a]	1.3997[a]	14.2027[a]	2.3799[b]	1.7310[a]	0.6493[b]
Y^2	−0.4052[a]	−0.4376[a]	−2.0018[a]	−0.2071[c]	−0.1787[b]	−0.0653[b]
Y^3	0.0139[a]	0.0191[a]	0.0753[a]	0.0057[b]	0.0055[b]	0.0021[c]
GLOB	−0.0038[c]	−0.0169[a]	−0.0403[a]	0.0096[a]	0.0041[b]	−0.0466[a]
E	0.7894[a]	0.8396[a]	1.5357[a]	1.0436[a]	0.9944[a]	0.6333[a]
REN	−0.1874[a]	−0.3361[a]	−0.0149[b]	−0.1827[a]	−0.1327[a]	−0.4814[a]
INEQ	−3.5798[a]	−16.3303[a]	−1.6471[a]	1.0601[b]	1.3786[a]	−9.8365[a]
Constant	−18.7969[a]	−13.4609[a]	−5.0272[a]	−14.2155[c]	−6.5795[c]	−15.6294[c]
Hansen's *J* statistics	0.3492	0.2642	0.4406	0.1447	0.9994	0.7583
DWH test statistics	8.9091[a]	8.2773[a]	9.4211[a]	4.1267[a]	8.5492[a]	3.3786[a]
Shape of EKC	N-shaped	N-shaped	N-shaped	N-shaped	N-shaped	N-shaped
Turnaround points	a. 468.53 b. 566,228.58	a. 9.81 b. 438,254.32	a. 134.96 b. 368,759.45	a. 11,752.79 b. 2,814,728.30	a. 1496.49 b. 1,706,117.61	a. 3921.76 b. 256,751.37

Note [a]Significant value at 1%; [b]significant value at 5%; [c]significant value at 10%

level of development in these nations. The continents with a high or moderately high level of development are showing the impact of trade inequality to be positive on environmental quality, whereas the continents with a comparatively lower level of the development are showing the impact to be negative.

The last segment of results shows the impacts of fossil fuel-based energy consumption and renewable energy consumption of CO_2 emissions, as expected. For the aggregate data and the two subpanels, the impact of fossil fuel-based energy consumption on CO_2 emissions has been found to be positive, and the impact of renewable energy consumption has been found to be negative. This shows that, irrespective of the geographical area or level of development, fossil fuel-based energy consumption adds to the rise in CO_2 emissions, whereas renewable energy consumption results in a reduction in CO_2 emissions.

In order to examine the causal association among the model parameters, we have employed the Geweke [22] causality test, and the empirical results are provided in Tables 14, 15 and 16. The results for the aggregate data show bidirectional causal associations between economic growth and CO_2 emissions, fossil fuel-based energy consumption and CO_2 emissions, renewable energy consumption and CO_2 emissions, economic growth and globalization, fossil fuel-based energy consumption and economic growth, renewable energy consumption and economic growth, eco-

Table 14 Results of Geweke causality tests (all countries)

Variables	Test statistics
C and *Y*	14.4959[a]
C and GLOB	0.3330
C and *E*	14.6795[a]
C and REN	19.4857[a]
C and INEQ	0.2433
Y and GLOB	10.0150[a]
Y and *E*	15.7883[a]
Y and REN	12.4538[a]
Y and INEQ	22.8638[a]
GLOB and *E*	1.1455
GLOB and REN	0.3466
GLOB and INEQ	0.4378
E and REN	35.0710[a]
E and INEQ	0.0301
REN and INEQ	0.9657

Note [a]Significant value at 1%

Table 15 Results of Geweke causality tests (countries segregated by income)

Variables	Low income	Middle income	High income
C and *Y*	2.2254	12.9273[a]	1.6845
C and GLOB	0.4361	0.6589	0.0581
C and *E*	18.4893[a]	28.4252[a]	39.8036[a]
C and REN	20.8565[a]	31.3469[a]	27.0613[a]
C and INEQ	0.6486	0.7970	0.2224
Y and GLOB	9.3357[b]	0.5801	12.0813[a]
Y and *E*	13.7482[a]	3.5194[c]	0.6544
Y and REN	8.4878[a]	4.5791[b]	0.4528
Y and INEQ	12.0007[a]	46.3921[a]	24.9575[a]
GLOB and *E*	3.4675[c]	1.2159	1.0035
GLOB and REN	2.0381	0.0156	3.3950[c]
GLOB and INEQ	0.6516	0.3255	0.9852
E and REN	37.0151[a]	27.7722[a]	17.2543[a]
E and INEQ	0.1345	0.0234	0.0042
REN and INEQ	0.0074	1.8557	0.0269

Note [a]Significant value at 1%; [b]significant value at 5%; [c]significant value at 10%

Table 16 Results of Geweke causality tests (countries segregated by continents)

Variables	Asia	Europe	North America	South America	Africa	Oceania
C and *Y*	8.3132[a]	0.9285	0.0602	0.5287	10.4648[a]	0.3550
C and GLOB	0.1115	0.1883	1.7137	2.8254[c]	1.5686	0.1797
C and *E*	41.1051[a]	60.7925[a]	26.8958[a]	14.6253[a]	39.7576[a]	35.2643[a]
C and REN	25.0706[a]	15.1907[a]	3.6796[c]	10.2772[a]	64.3811[a]	18.0164[a]
C and INEQ	0.8328	0.3558	0.2701	1.5295	1.5441	0.8828
Y and GLOB	7.7476[a]	0.1309	0.4626	0.3012	7.5110[a]	2.2968
Y and *E*	0.6796	0.0150	2.8594[c]	1.2353	11.4799[a]	10.9620[a]
Y and REN	1.0860	1.5954	0.0710	3.4864[c]	9.4316[a]	2.1928
Y and INEQ	19.7182[a]	14.8562[a]	0.9020	26.2596[a]	23.3020[a]	0.6681
GLOB and *E*	0.1645	0.7292	0.1832	5.5794[b]	1.8223	2.9648[c]
GLOB and REN	1.1093	0.0493	0.0880	0.0884	0.9025	0.7857
GLOB and INEQ	2.0947	0.4048	0.2507	0.5479	0.9044	0.9531
E and REN	43.2558[a]	1.1648	13.0985[a]	39.7528[a]	72.7078[a]	10.0164[a]
E and INEQ	0.2159	0.1013	0.0164	2.3482	0.1006	0.3301
REN and INEQ	0.2088	0.1410	0.7884	0.6290	1.5577	0.1235

Note [a]Significant value at 1%; [b]significant value at 5%; [c]significant value at 10%

nomic growth and trade inequality, and fossil fuel-based energy consumption and renewable energy consumption. However, for the two subpanels, these results vary based on their contextual settings.

5 Conclusion

By far, we have analyzed the impact of income, trade inequality, globalization, fossil fuel, and renewable energy consumption on CO_2 emissions for 187 countries over the period of 1990–2017. The analysis has been carried out at both the aggregate and disaggregate levels, while considering the cross-sectional dependence among the panel and subpanel member nations. In methodological terms, we have employed linear and nonlinear panel cointegration techniques with cross-sectional dependence and GMM to estimate the impact of income, trade inequality, globalization, fossil fuel, and renewable energy consumption on CO_2 emissions. We have found the evidence of N-shaped EKC for both the aggregate and the disaggregated datasets.

One of the main contributions of this study is to introduce the concept of inequality in trade volume, expressed by the implementation of Theil index on balance of payment. This is a new variable in the literature of energy and environmental economics. Subsequently, we have analyzed the impact of this variable on the CO_2 emissions, in the background of globalization. We have seen how the level of development can catalyze the impact of trade inequality on CO_2 emissions. The existing disparity in developmental process across the nations is reflected in this impact only. In order to combat this situation, the less developed nations or low-income countries should start developing renewable energy solutions endogenously. This not only will help them in sustaining the economic growth, but also will help them in reducing the level of CO_2 emissions and in import substitution for fossil fuels. The respective governments in these countries should also intervene in protecting the rights for public goods, so that the nations can protect the pool of natural resources and, consequently, can catalyze the economic growth endogenously.

In such a situation, implementing the nation-wide renewable energy solutions for the less developed and low-income countries might not be a good initiative, as this might hamper the economic growth owing to the cost of renewable energy solutions. Therefore, this implementation can be carried out in a phase-wise manner, in which the existing fossil fuel resources will be gradually replaced with the renewable energy solutions. Firstly, the industrial consumers will be targeted, and they will be provided the solutions at the prescribed rate of government. For enforcing this, the banks can provide loans at subsidized rate. Then, the revenue received from this phase will be used to provide the solutions to the small-scale sector and households at a rental basis. They will be provided the solution free for a fixed period of time, and after that, they will be charged at a lower price, compared to the industrial counterpart. In this way, the gradual phase-wise shifting will take place without causing much damage to the economic growth pattern, and the sustainable development will be ensured in parallel.

Once these solutions are in place, then the increased growth rate in these countries will allow them to procure clean technology solutions from the developed nations, and the negative impact on environmental quality will be decreased gradually. This will also gradually reduce the trade inequality across the countries, as the technological diffusion will be smoother, and the flow of natural resources will come down. This will have an overall positive impact on the environmental quality, in the background of globalization. Simultaneously, the rise in the technological diffusion across the less developed and low-income nations not only will create a wide number of vocational opportunities, but also will ensure the social security in the economic system by ensuring better access to education, health, and ecological facilities.

Appendix

See Tables 17 and 18.

Table 17 Literature on globalization and CO_2 emissions

Author(s)	Context	Method	EKC supported	Verdict
Leitão [31]	Portugal (1970–2010)	GMM, VECM	Not tested	Globalization reduces CO_2 emissions
Ahad and Khan [1]	Bangladesh (1972–2015)	ARDL bounds, VECM	Not tested	Globalization increases CO_2 emissions
Bernard and Mandal [9]	60 countries (2002–2012)	GMM	Not tested	Globalization reduces CO_2 emissions
Bu et al. [11]	166 countries (1990–2009)	2SLS	No	Globalization increases CO_2 emissions
Nwani [33]	Ecuador (1971–2013)	ARDL bounds, TY procedure	Yes	Globalization increases CO_2 emissions
Shahbaz et al. [45]	Australia (1970–2012)	ARDL bounds, VECM	No	Globalization reduces CO_2 emissions
Shahbaz et al. [46]	China (1970–2012)	ARDL bounds, VECM	Yes	Globalization reduces CO_2 emissions
Shahbaz et al. [47]	Japan (1970–2014)	Threshold NARDL	Not tested	Globalization increases CO_2 emissions
Audi and Ali [6]	MENA countries (1980–2013)	ARDL bounds, Granger causality	Not tested	Globalization increases CO_2 emissions
Khan and Khan [27]	American countries (1990–2014)	Panel regression, 2SLS	Yes	Globalization increases CO_2 emissions
Mutascu [32]	France (1960–2013)	Wavelet analysis	Not tested	Mixed evidence
Shahbaz et al. [48]	G7 countries (1980–2014)	GMM	Yes	Globalization increases CO_2 emissions
Shahbaz et al. [49]	UAE (1975–2014)	ARDL bounds, TY procedure	Not tested	Globalization reduces CO_2 emissions
You and Lv [58]	83 countries (1985–2013)	Spatial model	Yes	Globalization reduces CO_2 emissions

Table 18 Literature on trade and CO_2 emissions

Author(s)	Context	Method	EKC supported	Verdict
Arouri et al. [4]	Thailand (1971–2010)	ARDL bounds	Yes	Trade increases CO_2 emissions
Boutabba [10]	India (1970–2008)	ARDL bounds	Yes	Trade increases CO_2 emissions
Farhani et al. [19]	Tunisia (1971–2008)	ARDL bounds	Yes	Trade increases CO_2 emissions
Farhani et al. [20]	10 MENA countries (1990–2010)	FMOLS, DOLS	Yes	Trade increases CO_2 emissions
Kivyiro and Arminen [28]	6 African countries (1971–2009)	ARDL bounds	Yes	Mixed evidence
Lau et al. [30]	Malaysia (1970–2008)	ARDL bounds	Yes	Trade increases CO_2 emissions
Osabuohien et al. [34]	50 African countries (1995–2010)	PDOLS	Yes	Trade decreases CO_2 emissions
Oshin and Ogundipe [35]	West Africa (1995–2010)	Panel regression	Yes	Trade increases CO_2 emissions
Shahbaz et al. [43]	Tunisia (1971–2010)	ARDL bounds	Yes	Trade increases CO_2 emissions
Shahbaz et al. [44]	The UAE (1975–2011)	ARDL bounds	Yes	Trade decreases CO_2 emissions
Akpan and Abang [2]	47 countries (1970–2008)	2SLS	Yes	Trade decreases CO_2 emissions
Jebli et al. [26]	24 African countries (1980–2010)	FMOLS	Yes	Trade increases CO_2 emissions
Farhani and Ozturk [21]	Tunisia (1971–2010)	ARDL bounds	No	Trade increases CO_2 emissions
Ozturk and Al-Mulali [37]	Cambodia (1996–2012)	2SLS	No	Trade increases CO_2 emissions
Seker et al. [41]	Turkey (1974–2010)	ARDL bounds	Yes	Trade decreases CO_2 emissions
Tang and Tan [55]	Vietnam (1976–2009)	FMOLS	Yes	Trade decreases CO_2 emissions
Al-Mulali and Ozturk [3]	27 countries (1990–2012)	Panel cointegration	Yes	Trade decreases CO_2 emissions

(continued)

Table 18 (continued)

Author(s)	Context	Method	EKC supported	Verdict
Dogan and Seker [15]	23 countries (1985–2011)	DOLS, FMOLS	Yes	Trade decreases CO_2 emissions
Dogan and Turkekul [16]	The USA (1960–2010)	ARDL bounds	No	Trade decreases CO_2 emissions
Ertugrul et al. [18]	10 countries (1971–2011)	ARDL bounds	Yes	Mixed evidence
Sinha and Sen [53]	BRIC countries (1980–2013)	GMM	Yes	Mixed evidence
Dogan et al. [17]	OECD countries (1995–2010)	PDOLS	Yes	Trade decreases CO_2 emissions
Ozatac et al. [36]	Turkey (1960–2013)	ARDL bounds	Yes	Trade increases CO_2 emissions
Sapkota and Bastola [39]	14 Latin American countries (1980–2010)	Panel regression	Yes	Trade increases CO_2 emissions

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How Total Factor Productivity Drives Long-Run Energy Consumption in Saudi Arabia

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Abstract In this study, we investigate how total factor productivity (TFP), alongside income, price, and population, shapes energy consumption in the long-run in Saudi Arabia, the world's number one oil exporter. To do so, we first estimate a production function and construct the associated TFP series, and then assess TFP's impact on energy consumption. To take into consideration the stochastic properties of the variables, we employ unit root and cointegration methods. We also correct estimations and test results for potential small sample bias. Our main finding is that TFP has a statistically significant impact on energy consumption in the long-run. The main contribution of our research is that to the best of our knowledge this is the first study that estimates energy consumption effects of TFP for Saudi Arabia. We believe that our research would be useful for Saudi Arabian policymakers in understanding how TFP, a representation of technological progress, institutional development, innovations, openness, and R&D development, influences energy consumption over time. Saudi Vision 2030, the strategic road map of Saudi Arabian development, implies

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rational behavior and lowering the pace of energy consumption in the country. Thus, TFP improvement is a sustainable way to attain these goals.

Keywords TFP · Growth accounting · Energy consumption · Cointegration · Saudi Arabia

1 Introduction

The study of productivity is a very important topic in the applied literature, as the analysis of productivity is crucial to an understanding of the economy and how it changes. The pursuit of productivity growth and productivity stimulation is also one of the central goals that emerging countries are pursuing in the face of globalization. In the past, changes in gross domestic product per capita were used as a simple measure of output growth and productivity growth. The more recent sophistication of the empirical analysis of productivity has highlighted the importance of the developments in production technology and the efficiency whose dynamics can be represented by total factor productivity (TFP). Among the many lines of analysis, there is the analysis of the role of energy in the economic growth of many developing countries, pioneered by the study of Kraft and Kraft [1], who unveiled the causal relation between energy consumption and economic growth. In addition, the new environmental awareness has highlighted that economic development may create a conflict with environmental sustainability, addressing the issue of enhancing productivity to mitigate the impact of energy consumption on economic growth through deterioration of the quality of the environment. Most of the recent literature has continued to investigate the impact of energy consumption on TFP ([2–4] inter alia). At the same time, one can think that TFP as a representative of technological progress and efficiency measures may also have certain implications in lowering energy consumption. Theoretically, it can be derived from the production function framework and empirically; some studies (e.g., see [4–6]) have found the causality running from TFP to energy consumption. However, to the best of our knowledge, there has not been a comprehensive investigation of the impact of TFP on energy consumption.

In this study, we conduct an econometric analysis of how TFP alongside income, price, and population shapes energy consumption in Saudi Arabia, the world's number one oil exporter. We believe that there is a value in conducting this analysis for developed, developing, and less-developed countries. For Saudi Arabia, it would be additionally useful because of the following two reasons. First, there is a policy willing to stimulate rational consumption of energy as highlighted in the Fiscal Balance Program of Saudi Vision 2030 [7]. Second, a number of studies show that domestic energy consumption in Saudi Arabia is considerably high compared to other similar countries, which can lead to some consequences [8–12]. Both of these would imply lowering the pace of domestic energy consumption, for which TFP can be considered as one of the sustainable factors. We first estimate the production function, construct the TFP series, and then explore its impact on energy consumption over the period 1989–2015.

The key finding of this study is that TFP has a statistically significant negative effect on energy consumption in the long-run, which is theoretically expected and empirically explainable. We also find that income and population have a positive impact on energy consumption while energy price is negatively associated with energy consumption. To the best of our knowledge, this is the first study that estimates the long-run energy consumption effects of TFP in the case of Saudi Arabia and, thus, intends to fill this gap in the literature. This is the main contribution of this research. Another contribution is that the study employs different unit root and cointegration methods in testing and estimating the long-run elasticities to get robust results. Also, it applies a small sample bias correction to the obtained estimations and test results. We believe that our research would be useful for Saudi Arabian policymakers to understand how TFP as a representation of factors such as technological progress, institutional development, innovations, openness, and R&D development can shape energy consumption over time in Saudi Arabia. This understanding can be helpful particularly in implementating policy measures aimed at achieving some targets in Saudi Vision 2030 related to energy efficiency and lowering the pace of energy consumption in the country. Policymakers may also wish to consider how and which factors can be improved to lower energy consumption.

The remainder of the study is organized as follows. Section 2 reviews the related literature. Section 3 presents the theoretical framework, while Sect. 4 discusses the econometric methodology. The data used in the study is documented in Sect. 5. Section 6 conducts an empirical analysis for the production function and TFP calculation, while Sect. 7 analyzes energy consumption. Section 8 discusses the results of the empirical analyses. Section 9 concludes the paper.

2 Literature Review

There is a vast literature devoted to the (potential) causal relationship between energy consumption and economic growth. Ozturk [13], Smyth and Narayan [14], and Hasanov et al. [15] reviewed many of these papers. Unlike the energy consumption-economic growth nexus, few papers investigate the relationship between energy consumption and TFP. In addition, the existing studies mainly focused on causality; only a few investigated the impact of energy consumption on TFP. Again, the first (and main) strand of the existing literature examines the causality between aggregate/disaggregated energy consumption and TFP. Since the main focus of our study is not investigating causality but rather estimating TFP elasticity of energy consumption, we will shortly mention some of the causality-related studies. Tugcu and Tiwari [16] investigate the direction of the causal relationship between different types of energy consumption and TFP growth in the BRICS countries from 1992 to 2012 using the panel bootstrap Granger causality test. The Granger causality and dynamic panel estimation technique is also used in Al-Iriani [17], Costantini and Martini [18], Ladu and Meleddu [6] to examine the long-run relationship between TFP and energy consumption. Jorgenson [19], Kelly et al. [20], and Boyd and Pang [5] investigated the causality impacts between TFP and energy consumption for the

US, while Adenikinju [21] did the same for Nigeria, and Sahu and Narayanan [22] for did the same for India. Moreover, Worrell et al. [23] reviewed more than 70 studies examining the effects of energy efficiency on TFP in the case of US industry.

The second strand of the literature is devoted to investigating the impact of energy consumption (aggregate or disaggregated) on TFP. Hisnanick and Kymn [2] studied the impact of petroleum and non-petroleum energy consumption on TFP growth in the US manufacturing sector using data from 1958 to 1985. Using the relationship as described by Eq. (7), and disaggregating energy consumption to petroleum and non-petroleum types, Hisnanick and Kymn [2] investigated the productivity slowdown, analyzing the simple growth rates of manufacturing output and relevant factor inputs. The study concluded that the decline in productivity is mainly influenced by disaggregated energy components, namely petroleum and non-petroleum energy consumption. Likewise, Moghaddasi and Pour [3] studied the impact of energy consumption on agricultural TFP in the case of Iran, using data from 1974 to 2012. The study first estimated the respective elasticities of input factors using the Cobb–Douglas production function and then calculated TFP using the Solow residuals approach. After calculating TFP, the study estimated TFP growth as a function of agricultural energy consumption and concluded that a 1% increase in the sector's energy consumption leads to a 0.56% decrease in TFP growth. Tugcu [4] studied the impact of three types of energy consumption, namely alternative, fossil, and renewable energy consumption on TFP for the Turkish economy, employing the autoregressive distributed lag (ARDL) bound testing approach to data ranging from 1970 to 2011. The study concludes that renewable energy consumption has a positive impact on TFP, while other two types of energy consumption have a negative impact on TFP. The study calculated TFP using the Cobb–Douglas production function with two factors. In addition, the estimated long-run and short-run elasticities of alternative, fossil, and renewable energy consumption were −0.29, −2.1, and 0.8; −0.24, −1.7, and 0.7, respectively. Furthermore, the study concludes that there are bidirectional causalities between TFP and these types of energy consumption. Ladu and Meleddu [6] examined the causality relationship between energy consumption and TFP for the regions of Italy, applying the dynamic panel estimation technique to the data from 1996 to 2008, and found that there is a bidirectional relationship between the variables. Furthermore, the study concluded that in the short-run, TFP has a negative impact on energy consumption, while its impact is positive in the long-run. The study employed the Cobb–Douglas production function with two inputs in order to calculate TFP.

An interesting stream of this literature focuses on energy productivity. Haider and Ganaie [24] investigated the impact of energy productivity (GDP per unit of energy use), trade openness, and CO_2 emissions on TFP employing a vector error correction model (VECM) to Indian data from 1971 to 2013. The study used TFP data from Penn World Table version 8.1 and concluded that energy productivity has a negative impact on TFP. In addition, Haider and Ganaie [24] found that there is one-directional causality from energy productivity to TFP. The long-run energy productivity elasticity of TFP is found to be −0.8. One of the conclusions from the reviewed studies above is that there is causality running from TFP to energy consumption ([4–6] inter alia). In addition, from a theoretical point of view, TFP as a representation of factors like improvements in applied equipment and machinery, technological progress, and increases in research and development (R&D) would be expected to reduce energy consumption through efficiency gains—something that could be tested empirically. However, as can be seen from the reviewed literature, there is no study that explicitly estimates the impact of TFP on energy consumption, either in aggregate or in disaggregated form. This is the gap in the existing literature that our study addresses.

3 Theoretical Framework

3.1 TFP Calculation

As detailed in Diewert [25, 26], TFP can be calculated using either direct or indirect methods. Direct methods involve the calculation of an aggregated index as representative of all inputs used in production. Here TFP is approximated as a ratio of output quantity to the aggregated input index. There are two widely used direct TFP calculation methods: the model proposed by Kendrick [27] and the one proposed by Divisia [28] (see Diewert [25] inter alia for detailed information). The indirect methods involve estimating an appropriate production function, from which TFP is calculated. As in direct methods case, there are two often used approaches: Solow residual method and Solow model [29–31]. Since we used the Solow residual method, only this method is described here. In this approach, first the logarithm expression of the Cobb–Douglas-type production function in the case of two inputs is estimated econometrically [32, 33][1]:

$$\ln Q_t = \alpha_0 + \alpha_1 \ln L_t + \alpha_2 \ln K_t + lnA_t \tag{1}$$

where Q, L, and K are output, labor, and capital, respectively. α_1 and α_2 are the elasticities of output with respect to labor and capital, respectively. ln represents the natural logarithm, and t denotes time. If we take derivatives of both sides of (1) with respect to time, and consider that

$$\Delta Y_t \approx \mathrm{d}Y_t = Y_t' \mathrm{d}t = Y_t' \Delta t \tag{2}$$

and

$$\Delta t = t - (t-1) = 1 \tag{3}$$

[1] At the beginning of the study, we also included energy as a factor of production in (1). However, with the short sample represented by the available data, we could not find any significant impact of energy on production in the empirical analysis. Hence, we excluded it from the empirical analysis.

here Δ is difference operator and '$\prime$' stands for derivative, then we get:

$$Y_t' = \Delta Y_t \tag{4}$$

Considering (4) in the expression for derivative, we obtain the below equation:

$$\frac{\Delta Q_t}{Q_t} = \frac{\Delta A_t}{A_t} + \alpha_1 \frac{\Delta L_t}{L_t} + \alpha_2 \frac{\Delta K_t}{K_t} \tag{5}$$

Here the TFP growth can be found solving (5) for $\frac{\Delta A}{A}$:

$$\frac{\Delta A_t}{A_t} = \frac{\Delta Q_t}{Q_t} - \alpha_1 \frac{\Delta L_t}{L_t} - \alpha_2 \frac{\Delta K_t}{K_t} \tag{6}$$

With new notations, (6) can be written in the below form:

$$\dot{\text{tfp}}_t = \dot{Q}_t - \alpha_1 \dot{L}_t - \alpha_2 \dot{K}_t \tag{7}$$

where $\dot{\text{tfp}}_t = \frac{\Delta A_t}{A_t}$ is TFP growth, $\dot{Q}_t$ is output growth and $\dot{L}_t$ and $\dot{K}_t$ are growth values of inputs, respectively. From (7), it can be interpreted that growth in TFP is a part of production growth which cannot be explained by the inputs' growth. $\dot{\text{tfp}}_t$ is called the 'Solow residual.'

3.2 Energy Consumption Modeling

The conventional energy demand equation can be written as a function of income, *Y*, and price, *P*, as follows (see [34, 35] inter alia):

$$\text{EC} = f(Y, P) \tag{8}$$

As discussed in Beenstock and Dalziel [36] and recently in Hasanov [37], among other studies, demographic factors, such as population, POP, or population age group, can be considered as drivers of energy consumption [38–42]. Thus, (8) can be augmented to (9):

$$\text{EC} = f(Y, P, \text{POP}) \tag{9}$$

Finally, (9) can be extended with TFP following the functional specification similar to the one in Nordhaus [34]. Actually, it is not difficult to see how TFP can be included in the energy demand equation in the production function framework (theoretical derivations of this extension are provided in Mikayilov and Hasanov [43]).

$$\text{EC} = f(Y, P, \text{POP}, \text{TFP}) \tag{10}$$

Evidently, (10) differs from the conventional energy demand equation as it has TFP as an individual independent variable in the modeling framework. For the econometric estimation purposes of our study here, (10) can be re-written as the following explicit functional form:

$$\text{ec}_t = b_0 + b_1\,\text{tfp}_t + b_2\,\text{gdp}_t + b_3\,\text{ep}_t + b_4\,\text{pop}_t + e_t \tag{11}$$

where ec, tfp, gdp, ep, and pop stand for energy consumption, TFP, gross domestic product, energy price, and population, respectively; e is the error term; $b_0, \ldots, b_4$ are the coefficients to be estimated econometrically. It is expected that $b_1 < 0$ and $b_3 < 0$, while $b_2 > 0$ and $b_4 > 0$. All variables are in the natural logarithmic form.

4 Econometric Methodology

We begin the investigation by testing the employed variables for unit root. To examine the unit root properties of variables, the augmented Dickey–Fuller (ADF, [44]) and Phillips–Perron (PP, [45]) unit root tests are applied. We also conduct unit root tests with structural breaks, namely the ADF with structural breaks (ADFBP hereafter), which is advanced by Perron [46], Perron and Vogelsang [47, 48], and Vogelsang and Perron [49]. Once the integration order of the variables is identified, the existence of a long-run relationship among the variables should be tested. We employed a bound test for cointegration proposed by Pesaran and Shin [50], and Pesaran et al. [51] as a principal tool in our cointegration analysis. In addition, as a robustness check of the existence of long-run comovement, the Johansen and Juselius [52] and Johansen [53] cointegration test is also used. We select the Johansen test over other cointegration tests given that this is only the test that can deal with more than one cointegrating relationship if more than one explanatory variable is involved in the analysis. Unlike the Johansen method, other cointegration tests assume only one cointegrating relationship between the variables regardless of the number of explanatory variables in the analysis. Obviously, this can lead to improper analysis and inferencing. Also note that we apply the small sample bias correction developed by Reinsel and Ahn [54] and Reimers [55] to the Johansen test results to get more robust conclusions. After determining the cointegration relationship among the variables, the long-run relationship/coefficients need to be estimated. In empirical estimations, the autoregressive distributed lag (ARDL) [50, 51] is used as the main estimation method, since it outperforms other cointegration techniques in the small sample case. As with the cointegration exercise, in empirical estimations of the long-run relationship, we also employed the VECM [52, 53] approach. As the employed unit root tests and cointegration techniques are commonly used methods, they are not described here. Instead, interested readers can refer to Dickey and Fuller [44], Phillips and Perron

[45], Enders [56], Stock and Watson [57], and Dolado et al. [58], for the unit root tests, and Pesaran and Shin [50], Pesaran et al. [51], Johansen and Juselius [52], and Johansen [53], for the cointegration tests and techniques.

5 Data

The study uses annual data for Saudi Arabia from 1989 to 2015. The description of the variables is as follows:

GDP is real gross domestic product at 2010 prices, measured in million riyals, and used as a proxy for income variable. This data is taken from the General Authority for Statistics of the Kingdom of Saudi Arabia [59].
CS is the real total economy capital stock, in million riyals, 2010 prices, calculated based on the perpetual inventory method using the investment data taken from GASTAT [59]. Initial capital output ratio and depreciation rate were set to 1.5 and 5%, respectively, following the related studies for the Saudi Arabian economy ([60, 61] inter alia). This variable is used to measure the capital input.
ET is total employment in thousand persons and is taken from GASTAT [59]. This variable is used as a measure for labor input.
EC is demand for energy in the total economy, in million tons of oil equivalent (MTOE). It is calculated as the sum of sectorial energy consumption based on IEA data [62]. This is our dependent variable in energy demand specification.
POP is the total domestic population, in thousand persons, taken from the United Nations [63] database. POP is used in energy consumption specification as one of the main drivers of energy consumption.
EP is the real domestic crude oil price, in riyals per ton of oil equivalent. Nominal price values are collected from different royal decrees and publically available documents of the related government institutions. Then it is deflated by the GDP deflator, 2010 = 100, to get real values. We use the domestic price of crude as a measure for energy prices, since the domestic prices of other energy types in Saudi Arabia are mainly determined by the domestic price of crude.
TFP is calculated based on the production function estimation results using the growth accounting framework. Details of the calculation are provided in Sect. 6.3.

The graphs of the variables, in logarithmic forms, are given in Fig. 1, while descriptive statistics are presented in Table 1.

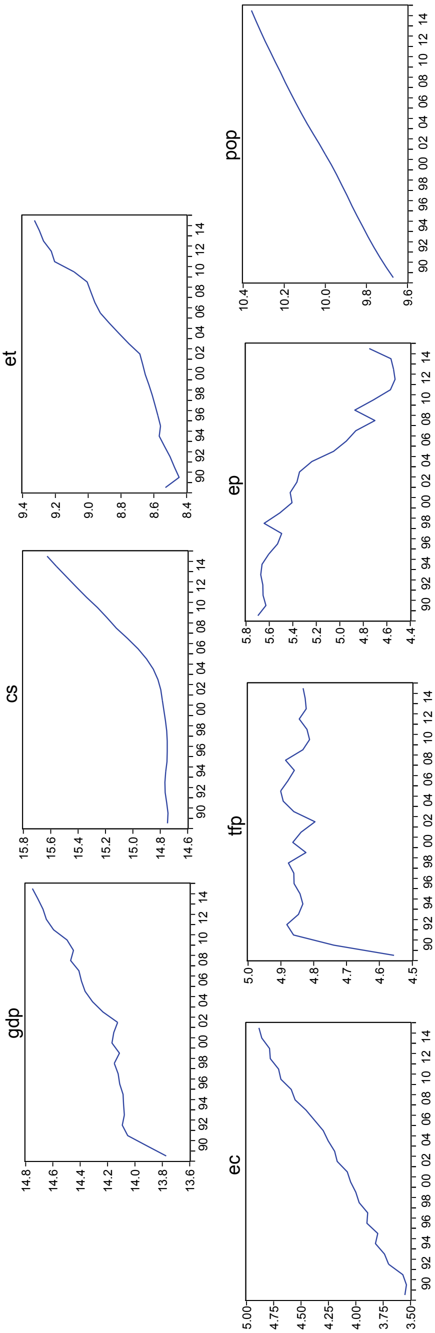

Fig. 1 Graphical illustration of the variables

Table 1 Descriptive statistics of the variables

	GDP	CS	ET	TFP	EC	EP	POP
min	95.69	252.59	46.50	95.15	34.38	92.66	158.13
mean	164.06	331.54	69.39	126.08	72.32	198.40	231.38
max	254.52	611.42	112.30	134.38	132.49	298.39	315.40
st. dev.	43.20	110.35	20.96	7.48	31.25	75.84	48.42
CoV (%)	26	33	30	6	43	38	21

Notes min = minimum, max = maximum, st. dev. = standard deviation, CoV = coefficient of variation. GDP and CS in ten billion riyals, ET and POP persons in hundred thousand, EC in MTOE, EP in riyals per TOE. The Saudi riyal is the domestic currency, 1 USD = 3.75 Riyals

6 Empirical Analysis

This section documents the results of the unit root tests, cointegration tests, and long- and short-run estimations.

6.1 The Unit Root Test Results

Table 2 reports the results of the ADF and PP unit root tests.

It is straightforward that the null hypothesis of unit root cannot be rejected for the log levels of the variables according to both the ADF and PP test results as the upper part of the table presents. Regarding the first differences of the log levels, i.e., growth rates of the variables, again the ADF and PP test results decidedly indicate stationarity for all the variables except for cs. Also pop does not seem to be the first difference stationary according to the PP test statistic. The graphical illustration of cs shows something like a gradual break in its development trend since 2004. Therefore, we apply the ADF test with structural breaks, i.e., ADFBP to cs and Δcs. For cs, we set an intercept and a trend in the test equation and allow a break in trend. Then we specify three lags as a maximum and use the Schwarz selection criteria to determine the optimal lag. Finally, we select innovative break type as the break happens gradually and specify 2004 as the first year of the new regime. The estimated sample ADFBP statistic is −3.49, while the critical values are −4.56, −3.96, and −3.67 at the 1%, 5%, and 10% significance levels. These suggest that cs has a unit root with the structural break. In other words, the variable is non-stationary. If there is a break in the trend of a variable, then there should be a shift in the first difference of it (e.g., see [64, 65]). This implies that Δcs has a shift in its level starting in 2004. In testing Δcs, we include an intercept and a trend in the test equation and allow a break in the intercept. The rest of the setup is the same as for cs. Now, the estimated sample ADFBP statistic is −4.35, while the critical values are −4.37, −3.76, and −3.46 at the 1%, 5%, and 10% significance levels. This implies that Δcs

Table 2 Results of the unit root tests

Variable	ADF test					PP test			
	Test value	*C*	*t*	None	*k*	Test value	*C*	*t*	None
gdp	−1.52	x	x		0	−1.34	x	x	
cs	−1.74	x	x		2	−0.29	x	x	
et	−1.35	x	x		0	−1.35	x	x	
tfp	−3.15	x	x		0	−3.19	x	x	
ec	−1.05	x	x		3	−2.73	x	x	
ep	−1.95	x	x		0	−1.95	x	x	
pop	1.10	x	x		2	−0.44	x	x	
Δgdp	−5.18***	x			0	−5.18***	x		
Δcs	−2.868	x	x		1	−1.95	x	x	
Δet	−3.21**	x			0	−3.21**	x		
Δtfp	−6.45***			x	1	−15.24***			x
Δec	−5.31***	x			2	−8.46***	x		
Δep	−4.28***	x			0	−4.27***	x		
Δpop	−3.92**	x	x		1	−2.02	x	x	

Notes ADF and PP denote the augmented Dickey–Fuller and Phillips–Perron tests, respectively. The maximum lag order is set to three, and the optimal lag order (k) is selected based on the Schwarz criterion; *** and ** indicate rejection of the null hypotheses of having unit root at the 1% and 5% significance levels, respectively; the critical values for the tests are taken from MacKinnon [73]. None means neither the intercept nor the trend is included in the test equation. Note that the final unit root test equation can include one of the three: intercept (C), intercept and trend (t), and none of them (None). x indicates that the corresponding option is selected in the final unit root test equation.

is stationary at the 5% significance level. Thus, our conclusion for cs is that it is non-stationary at the level but stationary when the first difference is considered both in the presence of the structural break. As for pop variable, the ADF suggests that the variable is I(1) process, i.e., non-stationary in levels but stationary in first differences. Moreover, conventional wisdom and the findings of the earlier studies also indicate that the variable is I(1). Hence, we consider population as an I(1) process. Thus, our conclusion for the unit root test exercise is that all the variables are non-stationary in their levels but are stationary when they are first-differenced, i.e., all the variables follow I(1) processes.

6.2 The Results from the Cointegration Tests and Long-Run Estimations

The conclusion about the integration orders of the variables makes it reasonable for us to test whether our variables are cointegrated. As mentioned in Sect. 4, the ARDL is our main cointegration test and long-run estimation method as we have a small sample size. At the same time, in order to make more proper inferences about the long-run relationship among the variables, we also use the Johansen cointegration tests for robustness.

6.2.1 The Results from ARDL Method

In the ARDL estimation of Eq. (1), we set the maximum lag order to be three and use the Schwarz information criterion to select the optimal lag length following the seminal studies by Pesaran and Shin [50] and Pesaran et al. [51].[2] The results are reported in Table 3.

Table 3 shows that the selected specification, ARDL (1, 0, 3), successfully passes the serial correlation, ARCH, heteroscedasticity, normality, and mis-specification tests. Besides, the sample value of *F*-statistic from the Wald test strongly suggests a

Table 3 ARDL estimation and test results

Selected specification: *ARDL*(1, 0, 3)						
Panel A: Residual diagnostics, mis-specification, and cointegration						
Test	$F_{SC}(2)$	$F_{ARCH}(2)$	F_{HETR}	JB_N	F_{FF}	F_W
Value	0.74	0.77	1.10	1.03	1.89	25.10^A
Prob.	0.50	0.48	0.41	0.60	0.19	
Panel B: Estimated long-run elasticities						
Coefficient	α_0	α_1	α_2			
Value	5.44***	0.60***	0.24***			
Std. error	0.44	0.08	0.06			

Notes gdp is the dependent variable; F_{SC}, F_{ARCH}, F_{HETR}, F_{FF} and F_W denote *F*-statistics to test the null hypotheses of no serial correlation, no autoregressive conditioned heteroscedasticity, no heteroscedasticity in the residuals, no functional form mis-specification, and no cointegration in the Wald test, respectively; JB_N indicates the Jarque–Bera statistic to test the null hypotheses of normal distribution of the residuals. ^{A}Indicates that the sample statistic is greater than the upper bound of the critical value of Narayan [74] at the 1% significance level in the given combination of the regressors, the number of observations and intercept is included in the long-run equation. ***denotes rejection of null hypothesis at the 1% significance level.

[2] We include two pulse dummy variables to capture the 1999 and 2002 crises in the ARDLBT estimations. Also note that our estimation and testing period here and hereafter is 1992–2015 as our data starts in 1989 and three lags are considered as a maximum.

cointegrating relationship among the variables even after a small sample adjustment. The estimated long-run coefficients of labor and capital have theoretically expected signs and magnitudes, and they are statistically significant.

6.2.2 The Results from Johansen Method

First, we construct a VAR specification for Eq. (1). Intercept and time trend are included in the VAR as exogenous variables. Then, we specify three lags as a maximum order as we did in the ARDL analysis. The Schwarz information criterion, which is more relevant in small samples, suggests two lags as optimum. Additionally, the lag exclusion test shows that two lags should not be reduced to one. Hence, we specify two lags as the optimum which provides non-correlated residuals as tabulated in Panel A of Table 4. The table also reports other diagnostics and also cointegration test results.

Table 4 Results of the Johansen method

Panel A: Serial correlation LM test[a]				**Panel D**: VAR stability test			
Lags	LM-statistic	*P*-value		#	Root	Modulus	
1	7.69	0.57		1	$0.93 - 0.18i$	0.94	
2	14.31	0.11		2	$0.93 + 0.18i$	0.94	
3	5.95	0.75		3	$0.38 - 0.60i$	0.71	
Panel B: Normality test[b]				**Panel E**: Johansen cointegration test results			
Statistic	χ^2	d.f.	*P*-value	Null hypothesis	$r = 0$	$r \leq 1$	$r \leq 2$
Skewness	5.85	3	0.12				
Kurtosis	1.99	3	0.57	λ^{a}_{Trace}	30.41**	11.15	0.36
Jarque–Bera	7.84	6	0.25	λ^{a}_{Max}	19.27*	10.79	0.36
Panel C: Heteroscedasticity test[c]				**Panel F**: Estimated long-run elasticities			
White	χ^2	d.f.	*P*-value	Coefficient	α_0	α_1	α_2
				Value	6.11***	0.56**	0.22**
Statistic	91.45	84	0.27	Std. error	0.32	0.06	0.04

Notes [a]The null hypothesis in the serial correlation LM test is that there is no serial correlation at lag order h of the residuals; [b]System normality test (square root of correlation) with the null hypothesis of the residuals is multivariate normal; [c]White heteroscedasticity test takes the null hypothesis of no cross-term heteroscedasticity in the residuals; χ^2 is chi-squared; d.f. means degree of freedom; r is rank of Π matrix, i.e., number of cointegrated equations; λ_{Trace} and λ_{Max} are the Trace and Max-Eigenvalue statistics, while λ^{a}_{Trace} and λ^{a}_{Max} are adjusted versions of them; *** and **denote rejection of null hypothesis at the 1% and 5% significance levels; critical values for the cointegration test are taken from MacKinnon et al. [75]

Evidently, the residuals of the VAR successfully pass normality and heteroscedasticity tests, and it is stable as no root lies outside the unit circle. The cointegration test option that we employ includes an intercept but not a trend. We select this option as none of the other options provides economically meaningful and statistically significant results.[3] The adjusted Trace and Max-eigenvalue statistics show that there is only one cointegrating relationship among the variables at the 5% and 10% significance levels, respectively. Since we find a cointegration among the variables, it would be meaningful to estimate this long-run relationship for gdp, although the small sample span here would not allow us to rely on these estimates. Nonetheless, we reported them in Panel F just for comparison purposes. The main message of Sect. 6.2.1 is that the ARDL findings, that there is one cointegrating relationship among the variables, are supported by the Johansen method. Additionally, the estimated long-run elasticities from the methods are quite close to each other.

6.3 Constructing TFP Series

In this section, we first calculate the TFP growth following the growth accounting approach, i.e., using Eq. (7). We use labor and capital elasticities of output estimated using ARDL method reported in Table 3.[4] Then, we construct the TFP level as we will investigate whether it has an impact on energy consumption in the long-run. The second graph in the second row of Fig. 1 above illustrates the level values of the constructed TFP series. Finally, we compare our constructed TFP growth series with the one retrieved from the Penn World Table [66] for a robustness check. In order to make the TFPs comparable, we re-scaled the PWT TFP from 1 to 100 scale and then take the difference. Figure 2 illustrates both TFPs' growth patterns.

The time profiles of both series are quite similar. We will not discuss the profiles here, but it is worth mentioning that such a similar pattern would indicate that our estimations and calculations seem quite reasonable.

Our main conclusions from Sect. 6 can be summarized as follows:

- Our variables can be considered I(1) processes. In other words, they are non-stationary at their log levels and stationary at their growth rates.
- There is a long-run relationship between output, labor, and capital. This estimated relationship is consistent with production function theory, given both the capital and labor elasticities are positive and the latter is greater than the former.

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[3]The test results on the other cases can be obtained from the authors under request. Also note that we include the pulse dummy variables in the VAR as we did in the ARDL estimations, but we exclude them when we perform the cointegration test.

[4]We prefer the labor and capital elasticities estimated using ARDL to those from the VEC in constructing the TFP because it is well known that the former provides more reliable estimates in the small samples. VEC estimation-based TFP construction can be obtained from the authors in the case of interest. Note that the VEC-based TFP is very similar to the ARDL-based TFP since the estimated numerical values from the methods are quite close to each other.

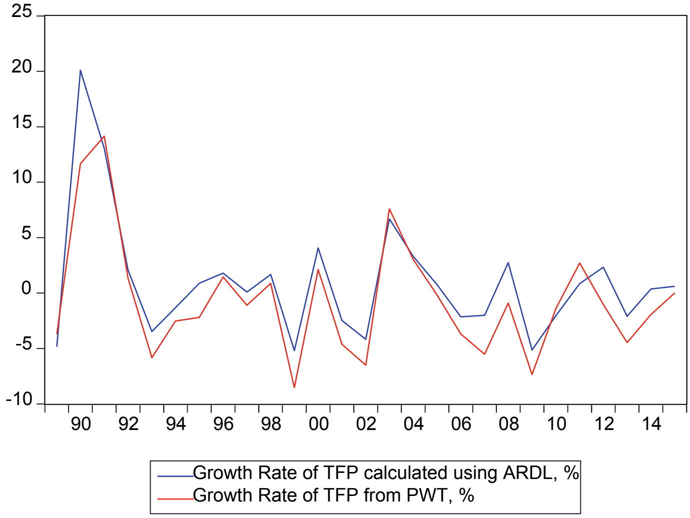

Fig. 2 Calculated TFP and PWT-based TFP, 1989–2015

- The calculated TFP and given TFP from PWT follow a very similar pattern over the period considered.

7 An Empirical Analysis of Energy Consumption

This section first tests the existence of cointegration between energy consumption and the considered factors in Eq. (11), and then estimates the long-run relationship between them.[5] Our main cointegration test and long-run estimation tool is the ARDL, and the Johansen method is used for a robustness check as we did in Sect. 6.

7.1 The Results from ARDL Method

The number of explanatory variables in Eq. (11) is twice that of Eq. (1). Besides, we have a small number of observations. Therefore, we set the maximum lag number to one to avoid over-parameterization and save some degree of freedom in the estimations.[6] If this lag order of one is not sufficient to remove the serial correlation from the

[5]Note that we do not analyze the short-run effects of the TFP and other factors on energy consumption, but this could be considered in future research.

[6]We include a pulse dummy in the ARDL estimation as a deterministic regressor to capture an increase in the energy consumption in 2008 which is caused by the boom in the Saudi Arabian

Table 5 ARDL estimations and test results

Selected specification: *ARDL*(1, 0, 1, 1, 1)						
Panel A: Residual diagnostics, mis-specification, and cointegration						
Test	$F_{SC}(2)$	$F_{ARCH}(2)$	F_{HETR}	JB_N	F_{FF}	F_W
Value	0.20	0.33	1.11	1.51	0.55	9.40^A
Prob.	0.82	0.72	0.42	0.47	0.47	
Panel B: Estimated long-run elasticities						
Coefficient	b_0	b_1	b_2	b_3	b_4	
Value	−8.64***	−0.90***	0.20***	−0.11***	1.49***	
Std. error	1.16	0.11	0.07	0.03	0.05	

Notes ec is the dependent variable; F_{SC}, F_{ARCH}, F_{HETR}, F_{FF} and F_W denote *F*-statistics to test the null hypotheses of no serial correlation, no autoregressive conditioned heteroscedasticity, no heteroscedasticity in the residuals, no functional form mis-specification, and no cointegration in the Wald test, respectively; JB_N indicates the Jarque–Bera statistic to test the null hypotheses of normal distribution of the residuals; ^{A}Indicates that the sample statistic is greater than the upper bound of the critical value of Narayan [74] at the 1% significance level in the given combination of the regressors, number of observations and intercept is included in the long-run equation; ***denotes a rejection of the null hypothesis at the 1% significance level.

residuals of the ARDL estimation, then we will increase the lag order to two or three until we will have serially uncorrelated residuals in our estimations. Fortunately, the estimated ARDL specification, with a maximum lag order of one, does not have any issue with the residuals' serial correlation. Moreover, it successfully passes all the other post-estimation tests as Table 5 documents.

The sample values of the *F*-statistic from the Wald tests strongly suggest a cointegrating relationship between energy consumption and the explanatory variables after small sample adjustments. The estimated long-run coefficients of the explanatory variables have the theoretically expected signs and are statistically significant.

7.2 The Results from the Johansen Method

We construct VAR specifications for Eq. (11). Regarding exogenous variables, we included only an intercept since including a time trend leads to instability in the VAR.[7] Then, we set one lag maximum, as we did in the ARDL analysis, because of the number of variables and small sample size. The Schwarz information criterion,

economy in the same year as it is not fully captured by GDP. The dummy variable appears statistically significant. However, we do not include it in the long-run estimation.

[7]We include a pulse dummy in the estimations as a deterministic exogenous regressor for the same reason as we did in the ARDL estimation (see footnote 5). However, we do not include it in the cointegration test although the inclusion of it does not change the results at all. Details can be obtained from the authors under request.

Table 6 Results of the Johansen method

Panel A: Serial correlation LM test[a]				**Panel D**: VAR stability test					
Lags	LM-statistic	*P*-value		#	Root	Modulus			
1	33.03	0.13		1	0.97	0.97			
2	24.82	0.47		2	$0.85 - 0.03i$	0.85			
3	25.51	0.43		3	$0.85 + 0.03i$	0.85			
Panel B: Normality test[b]				**Panel E:** Johansen cointegration test results					
Statistic	χ^2	d.f.	*P*-value	Null hypothesis	$r = 0$	$r \leq 1$	$r \leq 2$	$r \leq 3$	$r \leq 4$
Skewness	8.33	5	0.14						
Kurtosis	7.55	5	0.18	λ^a_{Trace}	80.32***	36.87	16.75	8.10	1.25
Jarque–Bera	15.88	10	0.10	λ^a_{Max}	43.44***	20.12	8.64	6.86	1.25
Panel C: Heteroscedasticity test[c]				**Panel F**: Estimated long-run elasticities					
White	χ^2	d.f.	*P*-value	Coefficient	b_0	b_1	b_2	b_3	b_4
				Value	−8.52**	*−0.93****	*0.16***	*−0.09***	*1.54****
Statistic	150.98	150	0.46	Std. error	1.66	0.09	0.06	0.03	0.05

Notes [a]The null hypothesis in the serial correlation LM test is that there is no serial correlation at lag order h of the residuals; [b]System normality test (square root of correlation) with the null hypothesis of the residuals are multivariate normal; [c]White heteroscedasticity test takes the null hypothesis of no cross-term heteroscedasticity in the residuals; χ^2 is chi-squared; d.f. means the degree of freedom; r is rank of Π matrix, i.e., number of cointegrated equations; λ_{Trace} and λ_{Max} are the Trace and Max-Eigenvalue statistics, while λ^a_{Trace} and λ^a_{Max} are adjusted versions of them; *** and ** denote rejection of null hypothesis at the 1% and 5% significance levels; critical values for the cointegration test are taken from MacKinnon et al. [75]

which is more relevant in small samples, as well as the lag exclusion test and lag selection criteria all indicate that one lag is optimal. One lag provides non-correlated residuals as documented in Panel A of Table 6.

Additionally, the estimated VAR is well-behaved in terms of residual diagnostics and stability tests. We employ the cointegration option of intercept but not trend in the test equation. We select this option since none of the other options provide economically meaningful and statistically significant results.[8] Panel E in the table reports that the adjusted Trace and Max-eigenvalue statistics reject the null hypothesis of no cointegration in favor of the alternative hypothesis of at most one cointegrating relationship among the variables in Eq. (11) at the 1% significance level. We can estimate the numerical values of the long-run relationships for ec as we find that there is a cointegrating relationship among the variables in Eq. (11). However, the sample size that we have does not allow us to rely on these estimates. Nonetheless, we report them in Panel F of the tables just to compare them to the long-run relationships estimated by the ARDL method in Table 5. The finding of the Johansen method supports that of the ARDL, i.e., there is one cointegrating relationship between the variables. Additionally, the estimated long-run elasticities of all the variables from ARDL and the VEC specifications are quite close to each other in magnitude.

8 Discussion

8.1 Unit Root and Cointegration

We concluded that our variables are I(1) processes, i.e., the log level of the variables is non-stationary, but their growth rates are stationary. Non-stationarity implies that impacts to the log level of the variables can result in permanent changes. Such impacts can be internal, as a result of policy, or external, such as fluctuations in oil and other commodity prices or movements in international labor or financial markets. Hence, the (log) levels of the variables should not be used for predicting future trends because of their non-stationarity. Unlike non-stationarity, stationarity implies that any impacts to the variables can create only temporary changes. Therefore, mean, variance, and covariance values of the stationary variables do not change over time as they 'dance' around their mean value.[9] Since we found that the levels of our variables are non-stationary, there is the possibility that the relationship among such variables is meaningless or spurious, unless a theoretically articulated/predicted relationship can be established. Two different tests were used to determine the cointegration properties of our variables. The test results presented in Table 3 and Table 4 indicated that the level relationship between output, labor, and capital is not spurious and it is in line

[8] The test results on the other cases can be obtained from the authors on request.

[9] Socioeconomic variables follow weak stationarity but not strong stationarity, as their mean, variance, and covariance are not strictly constant over time. Strong stationarity is the case in the natural sciences. A detailed discussion of this can be found in econometrics textbooks (e.g., [56]).

with the theory of production function for the Saudi Arabian economy. The theory of production function simply articulates that labor and capital are the main drivers of economic growth (see, [32, 33]). Likewise, the test results reported in Tables 5 and 6 showed that the level of energy consumption moves together with the levels of income, price, population, and TFP in the long-run. In other words, the variables established a long-run relationship, which can be explained theoretically. Indeed, the theory of consumption predicts that income and price are its main determinants.

8.2 Production Function, TFP Calculation, and Growth Accounting

Again, we found a long-run relationship between output, labor, and capital in the Saudi Arabian economy, which is consistent with the theory of production. The results of the long-run estimations using ARDL reported in Table 3 and those obtained from the Johansen method reported in Table 4 are quite close to each other, which would be an indication of robustness. According to the results, a **1%** increase in employment is associated with a **0.6%** increase in GDP in the long-run *ceteris paribus*. Likewise, the Saudi Arabian economy grows by **0.2%** if the capital stock increases by **1%** in the long-run if other factors are constant. Both findings are, again, in line with the theory of production and therefore, we think that they do not need any detailed explanation. However, some findings are worth mentioning. It appears that labor has a greater role than capital in the production of goods and services in the Saudi Arabian economy during the period 1989–2015. This finding is in line with the theory of production and economic growth (see, [32, 33, 29–31]). We are only aware of one study, Aljebrin [67], that estimates the elasticities of output with respect to labor and capital coefficients of production inputs, being 0.57 and 0.67, respectively. The labor elasticity is very close to ours, while that of the capital stock is higher than what we find. Additionally, Aljebrin [67] finds an increasing return to scale for the Saudi Arabian economy, which would be difficult to justify as its is a developing economy.

The estimations suggest that there are decreasing returns to scale, as the sum of the elasticities is slightly smaller than unity, in the economy during the period considered. A constant return to scale (i.e., the sum of the elasticities equal to one) was rejected statistically. So, there is not a strict one-to-one relationship between production and its inputs. In other words, if both labor and capital increased by 1%, then GDP will increase by 0.84%. We do not conduct a detailed investigation for this as it is beyond the scope of our main focus, which is the relationship between energy consumption and TFP. But it could be an interesting area for future research.

We calculated TFP using growth accounting, and Fig. 1 and 2 illustrate the level and growth rates of TFP, respectively. Overall, the TFP level has an upward trend if we consider the entire period 1989–2015. However, if we ignore the first three years, in which the TFP level has a huge jump, and only consider the remaining period, we observe that its overall trend declines until 2002, then moves upward up to 2008, then declines again, and finally trends up from 2010. This pattern can be associated, among other things, with the dynamics of the international oil price, a factor that plays a significant role in the Saudi Arabian economy. The IMF [68] and Mitra et al. [69], among others, also find a similar association for the TFP in Saudi Arabia. In addition, there is another association between the TFP level and the budget spending since the economy, in particular its fiscal stance, relies on oil exports and thereby oil revenues, which are significantly shaped by the international price of oil. Figure 3 illustrates the TFP level, the price of Arabian Light, and the budget spending on a normalized scale to make them comparable.

Evidently, from the graph, the TFP level follows the dynamics of the oil price and budget spending. This might show that TFP improvements in the Saudi Arabian economy are mainly driven by government support among other determinants such as openness and institutional development.

Finally, we very briefly did a growth accounting to determine how the factors of production contribute to Saudi Arabia's economic growth over time. Table 7 presents the results for sub-periods.

Some findings from this growth accounting are worth mentioning. It seems that the labor contribution was the main driver of economic growth in Saudi Arabia in all periods except for 1989–1994. Also, labor has a growing contribution over time. The capital contribution increases over time, indicating a growing role for capital in economic development. The TFP contribution to economic growth can be characterized as 'on' and 'off.' We think this is simply because TFP developed with ups and downs as discussed above. Our conclusion from this accounting exercise is that the role of the non-oil sector in economic growth outweighs that of the oil sector. This is because the oil sector is not labor intensive (as is well known). In contrast,

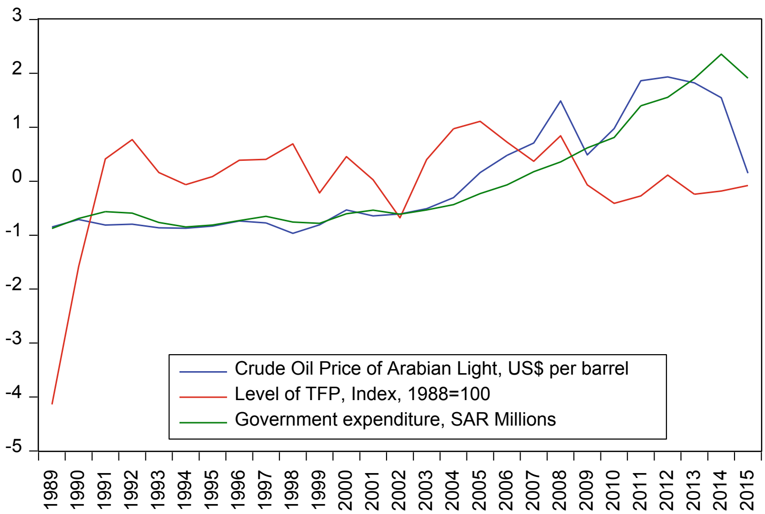

Fig. 3 TFP level, the price of Arabian Light, and budget spending

Table 7 Contributions to GDP growth, 1989–2015

Period	GDP growth	Capital contribution	Labor contribution	TFP contribution
1989–1994	5.48	0.00	1.22	4.26
1995–1999	0.62	0.01	0.76	−0.15
2000–2004	4.16	0.43	2.25	1.48
2005–2009	2.88	1.67	2.37	−1.16
2010–2015	5.15	1.82	3.33	0.00

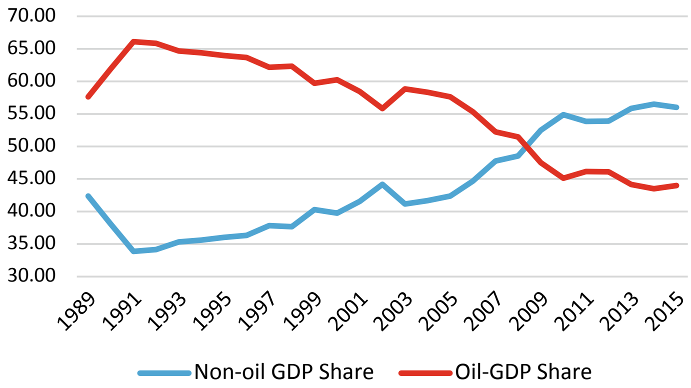

Fig. 4 Sector contributions to GDP, %

the non-oil sector is labor and capital intensive. In fact, Fig. 4 illustrates the growing share of the non-oil sector in the overall economy.

We compare our findings with those of earlier studies on the Saudi Arabian economy. Our findings are similar in terms of magnitude of calculated TFP for Saudi Arabia to the results of Alkhareif et al. [70], Algarani [71], Mousa [61]. Moreover, Dubey et al. [72] also mentioned that Saudi Arabia experienced slightly positive TFP growth in the non-oil sector.

8.3 Energy Consumption and TFP

Finally, we estimated the impact of the TFP level on energy consumption in the long-run alongside income, price, and population. For robustness, we used two different approaches, namely the ARDL and Johansen methods. The estimation results from these two methods are documented in Tables 5 and 6, respectively, and are very close to each other. According to the results, a **1%** increase in TFP level leads to a **0.9%** decrease in energy consumption in the long-run, keeping other factors unchanged. Theoretically, the negative energy consumption effects of TFP can be derived from the production function framework. One explanation for this negative association is that theoretically, TFP is representative of technological progress, institutional development, R&D development, awareness, and the use of efficient technology, which would all lead to efficiency gains and thereby result in less energy consumption. Figure 5 portrays the Saudi Arabian data on energy intensity and TFP on a normalized scale.

Evidently from the figure, any increases in TFP coincide with lowering energy intensity and vice versa over the period. One can easily see an empirical negative association between energy consumption and TFP here for the Saudi Arabian economy. Another observation from the figure is that energy intensity has two significant downward level shifts in its path: one since 2003 and another since 2011. The last development not only caused a level downshift but also formed a flatter slope of the energy intensity trend. These developments in energy intensity might be related to the above-mentioned elements of TFP improvements.

Estimation results also show that a **1%** increase in income and population cause a **0.2%** and **1.5%** rise in energy consumption in the long-run, respectively. Besides, the results indicate that energy consumption can be reduced by **0.1%** if the energy price is raised by **1%**. Since our main interest in this study is TFP, we do not discuss the impacts of income, price, and population in detail. However, the findings are in line with the theoretical expectations and the findings of prior empirical studies of the Saudi Arabian economy, although there are not enough studies using total energy consumption. For example, 0.27 was estimated for the GDP elasticity of total energy consumption both in per capita term by Gazder [11].[10]

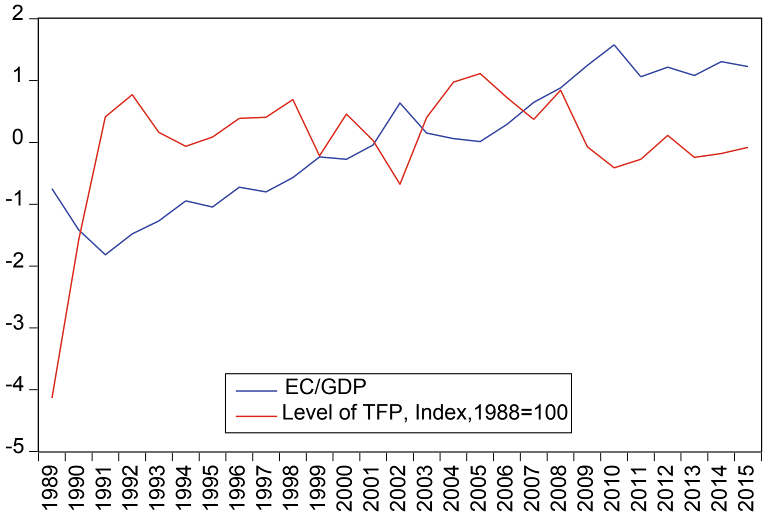

Fig. 5 Energy intensity and TFP

[10]Gazder [11] does not report the estimation period. Our guess from Table 4 of the study is that the estimation period is 1990–2011.

9 Conclusions and Policy Insights

As stated in the introduction, the analysis of TFP is very important, and existing studies either estimate the impact of energy consumption on TFP or test for Granger causality between the two. However, to the best of our knowledge, none of the earlier studies examined the impact of TFP on energy consumption, although it is theoretically straightforward and empirically useful to do so. This motivated us to estimate the long-run energy consumption effects of TFP in the Saudi Arabian economy. In the cointegration analysis framework, we first estimated a production function and constructed the associated TFP series. Then we assessed how TFP, alongside income, price, and population, shapes energy consumption in Saudi Arabia, the world's number one oil exporter. The key finding of this study was that TFP has a statistically significant negative effect on energy consumption in the long-run. We additionally found that income and population have positive impacts on energy consumption, while the energy price has a negative impact.

We believe that our research would be useful in helping Saudi Arabian policymakers to understand how TFP can lower energy consumption in the long-run. Usually, TFP is thought to reflect factors like technological progress, institutional development, innovations, openness and R&D development. In this regard, policymakers could consider how and which of those mentioned factors might be improved, while also considering the stylized facts of the economy, in order to lower the pace of energy consumption. Saudi Vision 2030—the strategic roadmap of Saudi Arabia's development—implies greater energy efficiency and a lower pace of energy consumption in the country. Thus, TFP improvement would be a sustainable way to obtain these goals.

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Ecological Innovation Efforts and Performances: An Empirical Analysis

Ferit Kula and Fatma Ünlü

Abstract The negative effects caused by global warming and climate change have increased the need for production technologies in decreasing environmental costs. This need has brought up the eco-innovation concept. Eco-innovation policies are the main priority of the European Union in ensuring a sustainable development and in the process of cyclical economy transformation. This chapter aims to investigate the relative eco-innovation efforts and performances of the European Union countries. In order to measure the eco-innovation performances of community members by the European Union, "eco-innovation index" has been published by calculating eco-innovation scoreboard since 2010. The 16 indicators gathered from different data sources are grouped into five thematic areas (eco-innovation inputs, eco-innovation activities, eco-innovation outputs, resource efficiency outputs and socioeconomic outputs). These variables indicate the efforts and performances of the European Union countries in terms of eco-innovation. In other words, eco-innovation inputs and eco-innovation activities are used as a proxy for eco-innovation efforts. Eco-innovation outputs, resource efficiency outputs and socioeconomic outputs are used as a proxy eco-innovation performance. Cluster analysis and discriminant analysis were used to determine the relative eco-innovation efforts and performances of the European Union countries. The results show that EU countries have different performance levels in terms of eco-innovation efforts.

1 Introduction

The negative effects caused by global warming and climate change have increased the need for production technologies in decreasing environmental costs. This need has brought up the eco-innovation concept. This is often used synonymously with the concepts of "sustainable innovation," "green innovation" and "environmental innovation" in the literature. Eco-innovation refers to the process of uncovering new or

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significantly improved products, processes, systems and services that reduce environmental costs by minimizing resource use and waste disposal. It is expected that the use of environmental technologies providing productivity in resource utilization will directly contribute to competitiveness with the formation of new business areas and new industries. For this reason, various studies are carried out on the production and use of environmental technologies, especially in developed countries. For example, eco-innovation policies are the main priority of the European Union in ensuring a sustainable development and in the process of cyclical economy transformation. The EU offers a variety of funding programs to achieve the goals related to eco-innovation. These funding programs are Horizon 2020, LIFE, COSME and ESIF. Therefore, it is important to investigate the experiences of European Union countries in terms of eco-innovation.

Although there are many micro-level studies [4, 6, 10, 11, 15, 16, 45, 50, etc.] about eco-innovation in the literature, the number of macro-level studies [26, 48] is limited. The micro-level studies predominantly measure eco-innovation activities of the firms. No studies, which performed macro-level analysis using variables in the European Union Eco-Innovation Scoreboard, were found. The other original contributions of this study are the classification of these variables as eco-innovation efforts and eco-innovation performances and their application as such.

The aim of this chapter is to investigate the relative eco-innovation efforts and performances of the European Union countries. In order to measure the eco-innovation performances of community members by the European Union, "eco-innovation index" has been published by calculating eco-innovation scoreboard since 2010. Sixteen indicators gathered from different data sources are grouped into five thematic areas (eco-innovation inputs, eco-innovation activities, eco-innovation outputs, resource efficiency outputs and socioeconomic outputs). These variables indicate the efforts and performances of the European Union countries in terms of eco-innovation. In other words, eco-innovation inputs and eco-innovation activities are used as a proxy for eco-innovation efforts. Eco-innovation outputs, resource efficiency outputs and socioeconomic outputs are used as a proxy for eco-innovation performance. Cluster analysis and discriminant analysis were used to determine the relative eco-innovation efforts and performances of the European Union countries. These analyses were applied separately in exploring eco-innovation efforts and eco-innovation performances. Sixteen indicators from 2016 have been included in the empirical analysis in order to determine the relative eco-innovation performance of European Union countries. The indicators have been obtained from the Eurostat database.

The chapter will be divided into four sections. After the introduction, Sect. 2 explains the theoretical framework of eco-innovation. In this section, the literature review and the eco-innovation policies in EU will also be dealt with. Section 3 provides the methodology and data used in the empirical analysis. Section 4 contains the conclusion.

2 Theoretical Background

2.1 Definition and Types of Eco-innovation

The eco-innovation concept first appeared in the book "Driving Eco-innovation: A Breakthrough Discipline for Innovation and Sustainability" written by C. Fussler and P. James in 1996. They defined eco-innovation as "new products and processes that provide customer and business value while significantly decreasing environmental impacts" [36, 37]. Eco-innovation refers to the process of uncovering new or significantly improved products, processes, systems and services that reduce environmental costs by minimizing resource use and waste disposal.

According to Rennings [41], eco-innovation is that politicians, non-governmental organizations, private sector and households reduce environmental costs by developing new ways of thinking, behaviors, products and processes. Also, there are four types of eco-innovation: technological, organizational, social and institutional eco-innovation. Chen et al. [11] define green innovation as software and hardware innovations related to green products or green processes involving energy saving, pollution prevention, waste recycling and green product designs or corporate environmental management. According to this definition, eco-innovation can be grouped into three types: green product innovation, green process innovation and corporate environmental management. Based on the OECD definition of innovation, Kemp and Pearson [28] defined the term eco-innovation as follows: creation, adaptation or use of new products, processes, services and management techniques reducing the environmental risks, pollution and other negative effects of resource use compared to relevant alternatives. The authors define eco-innovator as companies adopting a good, service, production process management or business method with environmental benefits. These companies are classified in terms of their behavior related to eco-innovation as follows:

- Strategic eco-innovators operating in environmental equipment and service sector develop environmental innovations to sell to other firms.
- Strategic eco-adopters intentionally implement environmental innovations both developed in house and acquired from other companies.
- Passive eco-innovators develop process, organizational, product innovations which result in environmental benefits, but there is no specific strategy related to eco-innovation.
- Non-eco-innovators develop no activities for eco-innovation.

Reid and Miedzinski [40] define eco-innovation broadly as "the creation of novel and competitively priced goods, processes, systems, services and procedures designed to satisfy human needs and provide a better quality of life for everyone with a whole-life-cycle minimal use of natural resources (materials including energy and surface area) per unit output, and a minimal release of toxic substances."

Halila and Rundquist [22] define eco-innovation as innovations that contribute to a sustainable environment through the development of ecological improvements.

According to the authors, support for the diffusion and development of environmentally harmonized products, processes, organizational models and systems can improve living conditions for both present and future generations.

Based on the above definitions, we can define eco-innovation as an interactive process through which new products, processes, services and organizational techniques reduce negative environmental impacts. This definition focuses on two issues: First is to reduce negative environmental impacts. Second is to implement it through the new technologies. Firms implementing eco-innovation have many purposes as maintaining or increasing the current market share, entering new markets, saving energy, reducing or disposing waste, minimizing labor costs and creating awareness about environmental protection [14]. In addition, legal arrangements about establishing environmental awareness and using environmental technologies in the manufacturing process are a compelling force for firms. Eco-innovations not only provide diffusion of innovation, but also reduce the cost of negative environmental externalities.

Eco-innovation is classified in different ways by different authors [3, 23, 24, 30, 40, 42, etc.]. For example, Klassen and Whybark [30] claim that environmental technologies can be grouped into three main categories: pollution prevention technologies, management systems and pollution control technologies. Pollution prevention technologies point out structural investments in activities involving fundamental changes to basic product or process. These technologies are characterized as product adaptation and process adaptation. First includes all investments that enable the modification of existing product design to reduce negative environmental impacts in any stage of the production process. Second involves fundamental changes to the production process to reduce negative environmental impacts during raw material acquisition, production or delivery. The environmental technologies called management systems refer to infrastructure investments that include efforts to develop new practices enhancing cooperation between the departments, to establish a new environmental department, to train employees about reduction and elimination of waste, to provide outside stakeholder participation in management activities and to formalize procedures for assessing environmental impacts during capital decision budgeting. Pollution control technologies are structural investments like pollution prevention technologies. However, in contrast to pollution prevention technologies, these technologies treat or dispose of pollutants at the end of the production process. The original process does not change because it is applied at the end of the existing manufacturing processes. Therefore, these technologies are known as end-of-pipe controls.

Reid and Miedzinski [40] grouped eco-innovation types into four categories as product, process, organizational and marketing eco-innovation according to the innovation classification in Oslo Manual published by OECD in 2005. A product innovation is the introduction of a good or service that is new or significantly improved. Significant improvements have to be made in technical specifications of the product, used materials, software, user convenience and other functions. Product eco-innovations include any novel and significantly improved product or service produced in a way that its overall impact on environment is minimized. Process innovation is the implementation of production or delivery method that is new or significantly improved.

This includes significant changes in techniques, equipment and software. Process eco-innovation refers to applications called environmental technologies. Marketing innovation is the implementation of a new marketing method involving important changes in product design or packaging, placement, promoting and pricing. Marketing innovations are very important from the point of view of eco-innovation. The activities include environmental aspects in the product promotion, franchising and licensing as well as pricing. Organizational innovation is the implementation of a new organizational method in the firm's business practices, workplace organization or external relations. Organizational eco-innovations represent environmental management system (EMS) and other specific environmental management tools such as process control tools and environmental audits.

Rennings et al. [42] grouped types of eco-innovation similar to eco-innovation classification of Reid and Miedzinski [40]. Eco-innovation types are gathered in three groups: environmental product innovations, environmental process innovations and environmental organizational innovations. Environmental process innovations are grouped into two categories: innovations in end-of-pipe technologies and innovations in cleaner production technologies. While waste disposal, water protection, noise abatement and air quality control are typical examples of end-of-pipe technologies, the recirculation of materials, the use of environmentally friendly materials and the modification of the combustion chamber design are the most common examples of clean production technologies. Hawkins et al. [23] evaluated eco-innovation in three main categories: product, process and system innovations. The authors have defined product and process eco-innovations similar to those in the literature. They draw attention to the fact that not only system innovations are technological systems, but they also include radical and destructive technologies that change market conditions as well as all system changes such as industrial, social and behavioral changes. Authority [3] grouped eco-innovation types into three categories: incremental eco-innovation, disruptive eco-innovation and radical eco-innovation. Incremental eco-innovations modify and improve existing technologies or processes to raise the efficiency of resource and energy use. These innovations do not change the core of technologies. Disruptive eco-innovations change how things are done or specific functions are fulfilled, but they do not change the technological regime itself. Radical eco-innovations involve a shift in the technological regime of an economy.

Hofstra and Huisingh [24] have defined four types of eco-innovation: exploitative or degenerative eco-innovations, restorative eco-innovations, cyclical eco-innovations and regenerative eco-innovations. Exploitative or degenerative eco-innovations do not take into account the environmental impacts of the product design and subsequent processes. These innovations are usually designed to meet legal requirements based on minimizing cost analyses to increase market share. Although restorative eco-innovations are called "green," these eco-innovations do not change existing business models. They focus on generally maximizing eco-efficiency processes to minimize energy use, pollution and waste, instead of trying to change consumption patterns. Cyclical eco-innovations consider the connectivity of humans to their social and cultural structures. In the case of regenerative eco-innovations, it is essential that the power of the ecosystem is used to create added value for man and nature.

2.2 Economics Approaches to Eco-innovation

The eco-innovation concept which appeared in the 1990s refers to the environmental dimension of innovation. The concept is derived from both environmental economics and innovation economics. While environmental economics tells how environmental policy instruments are used, innovation economics examines the factors affecting innovation decisions [41].

The environmental economics literature is concerned with the identification of optimal policy instruments to stimulate environmental innovation. Market-based instruments such as taxes and tradable permits have been used as environmental policy instruments with the highest dynamic efficiency. In contrast to regulatory regimes established by technical standards, these instruments continuously provide incentives to reduce emissions [14]. In terms of innovation economics, eco-innovation refers to "double externality" problem. First, innovation process inherently has a spillover effect. This means that when a firm realizes innovation activities, this promotes other firms. Second externality is created by new products and processes. The natural result of the double externality problem is sub-optimal investment. Hence, the regulatory legal framework becomes integral in solving the problem of externality. Innovation economics mainly have discussed whether technological innovation is determined by technological development or demand factors. Due to the externality problem of eco-innovations, this traditional discussion has been extended to the influence of the regulatory framework [14].

According to Andersen [2], who deals with the problem of externality of eco-innovations in terms of evolutionary economics, these externalities are the result of new technologies. In other words, economic and technological developments will cause new environmental externalities and new institutional and organizational structures will be developed to challenge these externalities. Innovation system theory within evolutionary economics has been applied to environmental area, and efforts identifying systemic features of eco-innovation process have been increased [2]. According to the theory of evolutionary economics, the production of environment-friendly technologies (greening of markets) has begun to increase over time. It is seen that increase in production of environment-friendly technologies is the result of the techno-economic paradigm shift as the theory tells us that knowledge and learning capacity play a key role in terms of global competitive advantage. The integration of environmental issues into economic processes has been evaluated in stages because greening of markets has occurred in the historical process. Gradually, new green firms enter and seek to compete with the dominating firms on environmental innovations in the process of greening of markets. The industries and firms which do not produce environmental technologies are eliminated in this process. As the number of green markets increases, nongreen sectors and all technologies are at risk.

Figure 1 illustrates the five stages of the greening of markets. The first long stage began in the 1950s and has prevailed for over 30–50 years. The agenda about environmental sensitivity had been tried to be established, but firms perceived environmental costs as a burden. The transition period between phase 1 and phase 2 took place toward the end of the 1980s. More applications (such as clean technology support programs) driven by environmental policies and efforts to create environmental strategies were observed among the leading firms in the market. The process between phase 2 and phase 3 is critical. Because the green markets take off in this process. It is argued that this process started 10 years ago and it is not over yet. In addition, the transition to phase 4 and phase 5 of existing market has been quite difficult. The main purpose of the innovation activities carried out by the firms in the first two phases is to respond to policy initiatives, i.e., to fulfill the legal obligations or to take advantage of incentives. The lack of capabilities and the related institutions in the market causes that the leading eco-innovators are faced with very high friction to developing and marketing eco-innovations. As markets start to turn green, technology tends to produce environment-friendly products. At this phase, green transaction costs are very high for firms in the market. At phase 4, costs start to decline and eco-innovations become easier to engage in the market; however, the economic returns may be below expectations. The last phase is called *learning green economy*. At this phase, the eco-innovation has become the easy-innovation. So, environmental technology has transformed into a natural process rather than a legal obligation for eco-innovators. On the other hand, eco-innovative goods which are seen as luxury goods for consumers have become normal goods. At this phase of eco-innovation becoming easy-innovation, there are four characteristics of the economy [2]:

- High eco-innovative capacity,
- Selection environment,
- Efficient organization of green production and learning across actors,
- Strong green knowledge base.

If an economy has these characteristics, integrating eco-innovation for companies and information agencies (universities, research centers, etc.) is easy and attractive. Because at the last phase, innovation has become a natural innovation and market conditions are very suitable.

2.3 Literature Review

There are many studies which aim to evaluate eco-innovation phenomenon from different aspects and different levels such as firm, sector or country. In these studies, different methods such as survey, statistical and econometric techniques (structural equation model, cluster analysis, factor analysis, logit, probit, panel regression models, etc.) have been used to evaluate the phenomenon of eco-innovation. However, the empirical literature about eco-innovation has focused more on the determinants of eco-innovation.

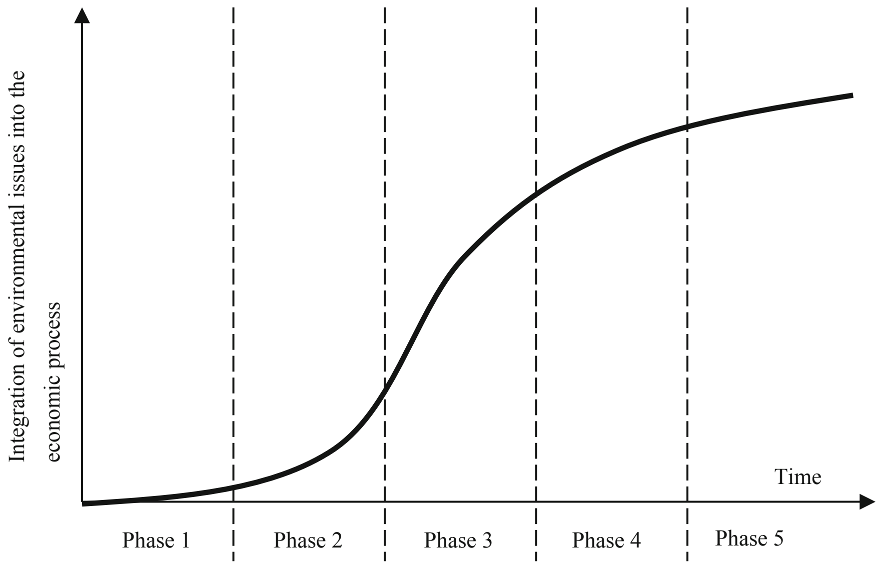

Fig. 1 Greening of markets [2]

Table 1 illustrates the classification of the determinants of eco-innovation by Horbach [25]. Horbach's approach is similar to Rennings' [41] classification, but there are certain differences. Unlike Rennings [41], who evaluated supply side in terms of efficiency and technology, Horbach [25] included the market structure. On the demand side, Horbach [25], who prioritizes social awareness for the use of environment-friendly products, takes into account the existence of innovation networks in terms of regulatory framework and the flow diagram of knowledge within this network system. Rennings [41] emphasized the importance of only regulating environmental legislation within the regulatory framework. Reid and Miedzinski [40] added some factors by revising the classification Horbach did. For example, cost, demand, taxation policy, competition conditions and sociocultural factors are also among the forces driving eco-innovation. Jang et al. [27] examined the determinants of eco-innovation in four groups in light of the literature: supply, market and society; governments; knowledge; and cooperation. The authors' classification is basically similar to the classification made by Rennings [41] and Horbach [25]. Differently, the importance of R&D role in eco-innovation process in terms of knowledge and cooperation is emphasized clearly. There are basically three elements determining eco-innovation. The eco-innovation, which is the product of a process of the interaction between supply, demand and environmental regulations, is also influenced by sociocultural factors. An increase in demand for eco-friendly products will reveal clean production processes by instigating supply-side factors in the current market structure and technological capabilities. Therefore, environmental regulations and standards will be needed. On the other hand, the creation of environmental regulations and standards

Table 1 Determinants of eco-innovation [25]

Supply side	Technological capabilities Appropriation problem and market characteristics
Demand side	Expected market demand Social awareness of the need for clean production; environmental consciousness and preference for environmentally friendly products
Institutional and political influences	Environmental policy (incentive-based instruments or regulatory approaches) Institutional structure: e.g., political opportunities of environmentally oriented groups, organization of information flow, existence of innovation networks

may be compelling for companies. In this respect, the existence of regulations and practices aimed at promoting eco-innovation is important. Many driving forces play a role in the process when firms are carrying out eco-innovation activities. For example, incentives can be encouraging, such as support programs, whereas legal regulations may be a pressure tool. In addition, the efforts of civil society organizations are more efficient in the early process to raise public awareness about use of eco-friendly products and to increase in demand for eco-innovative goods and services. In this process, the firms have cost advantage since high added value which is created by new technologies encourages productivity in resource utilization. Nevertheless, the positive effects of environmental technologies on production and consumption lead to reduce negative environmental externalities. According to the literature about the determinants of eco-innovation, there are three main determinants of eco-innovation [25, 41]: technology push (supply side), demand pull (demand side) and regulatory pull (institutional and political influences).

Regulatory Push (Institutional and Political Influences)
According to Rennings [41], the regulatory framework, in particular the environmental policy, has a strong influence on eco-innovation. Regulatory support is needed because eco-innovations do not have a self-enhancing process like other types of innovation and supply and demand factors alone are inadequate. Rennings [41] suggests that environmental policy and innovation policy should be coordinated in the eco-innovation process. While innovation policies can help to cut the costs, e.g., technological, institutional and social innovation, the environmental policies are responsible for internalizing external. Also, externality problem reduces the incentives for firms about eco-innovations. In other words, firms are not very willing to invest in eco-innovation. At this point, the existence and coordination of these policies contribute to the solution of the problem. According to Horbach [25], environmental innovations are less market-driven than other innovations, despite the negative external effects. Hence, *environmental policy* is the main determinant of eco-innovation. He outlines that environmental regulation may lead to a win-win situation through reduced pollution and increased profits.

There are many studies that support the theoretical arguments of Rennings [41] and Horbach [25] in this issue. For example, Pickman [38] investigated whether there is a relationship between environmental innovation and environmental regulation in the US manufacturing industry. The results estimated by OLS showed that environmental regulation and innovation have a positive correlation. Brunnermeier and Cohen [10] estimated by using panel data model how environmental innovations responded to the changes in pollution abatement pressures in 146 US manufacturing industries for the 1983–1992 period. The findings showed that increasing monitoring and enforcement activities related to available regulations did not provide any additional incentive to innovate, while environmental innovations responded to increases in pollution abatement expenditures. Qi et al. [39] examined the factors influencing contractors and the role of the government managers in the adoption of green construction practices in the Chinese construction industry. They claimed that the most important drivers for the adoption of green practices are managerial concerns and government environmental regulations. Belin et al. [5] investigated the determinants of eco-innovations in Germany and France by employing probit regression analysis. The results illustrated that cost savings and environmental regulations are important drivers of eco-innovation in both countries. Kesidou and Demirel [29] examined the drivers of eco-innovations for 1566 firms in UK. In the analysis, the authors applied two methods: Heckman selection model and quantile regression analysis. According to the results of these analyses, environmental regulations affect eco-innovation as firms respond to stricter environmental regulations with higher levels of eco-innovations. Triguero et al. [46] examined the drivers of different types of eco-innovation for SMEs which operate in 27 European countries. The results showed that existing regulations form eco-product and eco-organizational innovations while expected regulations have no significant effect on the decision of firms. Constantini et al. [16] aimed to identify the drivers of the innovation activity; they employed Poisson regression model (PRM) and the negative binomial regression model (NBRM) by using data for OECD members and some non-OECD countries between 1990 and 2010. Econometric estimates confirmed that technological capabilities and environmental regulations incented innovative activities in the sector. Horbach [26] analyzed the determinants of eco-innovation activities for comparing 19 different European countries. This analysis was employed separately for the two groups: Eastern and Western European countries. The findings indicated that environmental regulation activities and environmentally related subsidies were more important for the Eastern countries than Western European countries. On the other hand, environmental regulations and cost savings are the most important determinants of eco-innovation activities. Chen et al. [12] investigated factors influencing regional eco-innovation by employing panel data analysis for the 2000–2014 period in 30 Chinese provinces. The results showed that environmental regulation (pollution discharge fee) has a positive impact on eco-innovation. However, these factors have differentiated impacts on eco-innovation in different regions. Rio and Penasco [43] investigated the main determinants influencing different types of eco-innovations and eco-innovators in Spain, based on dichotomous probit model. The sample consisted of 3341 firms in Spain. They grouped two types of eco-innovations as follows: process versus product and new-to-the-market (NTM) versus new-to-the-firm (NTF). In addition, they grouped two different types of eco-innovators as large versus small and old versus new firms. They found that compliance with environment regulation and cost savings are the main determinants of NTF eco-innovations. Tsai and Liao [47] claimed that government subsidies positively moderate the relationship between environmental strategy and eco-innovation.

Technology Push (Supply Side)
According to Rennings [41], technological push factors refer to the supply side and include factors such as raw material efficiency, product quality, energy efficiency. According to Horbach [25], supply side points out both *technological capabilities* and *market characteristics*. Technological capabilities implicate the physical and knowledge capital stock of firms to develop new products and processes. Inputs such as R&D investment or human capital are very important because such a capital stock can only be created in this way. On the other hand, the existing technological capabilities of a firm determine the success of future innovations. The market structure also influences investment decisions of firms for eco-innovation. For example, small-size firms in competitive markets are forced to compete with their rivals for developing new products and process, but it is not valid for large monopolistic firms.

Empirically, relationship between supply factors and eco-innovation has been evaluated by different authors. Triguero et al. [46] found that the most important drivers of environmental processes and organizational innovations are supply-side factors, but this is not valid for environmental product innovations. Constantini et al. [16] expressed that technology-push factors are an important driver of innovation. Chen et al. [12] reached the results supporting the theory, which factors such as technology push (R&D and foreign direct investment) have a positive eco-innovation. Also, Bossle et al. [7] analyzed the production and consumption for eco-innovative food in Brazil. The results showed that firm strategies are important drivers for the adoption of eco-innovations.

Market Pull (Demand Side)
According to Rennings [41], market pull factors refer to demand side and include factors such as market share, competition, new markets, consumer demand, image, labor costs. Regulatory factors include the available regulations and standards related to environment. According to Horbach [25], demand side emphasizes the use of eco-friendly products and social awareness about this issue. For example, an increase in demand for eco-friendly products will stimulate firms in market, so it may increase investments in eco-innovations.

Empirically, relationship between demand factors and eco-innovation has been evaluated by different authors. For example, Horbach [25] confirmed the validity of the Demand Pull Hypothesis. Similarly, Lin et al. [31], Triguero et al. [46], Constantini et al. [16], Chen et al. [12] and Tsai and Liao [47] reached the conclusion that market demand was positively correlated with the eco-innovation activities. However, Kesidou and Demirel [29] claimed that demand factors do not affect the level of investment in eco-innovation. On the other hand, Bossle et al. [7] examined demand side to investigate consumer behaviors toward eco-innovative food and found that consumers tended to show positive attitudes toward environment and technological progress to buy eco-innovative food. Also, Tsai and Liao [47] point out that market demand positively moderates the relationship between environmental strategy and eco-innovation.

Other Studies

Chen et al. [11] explored the effects of the green innovations (green product innovation and green process innovation) on competitiveness by using questionnaire survey method and regression analysis for 203 firms which operate in the information and electronics industries in Taiwan. The data obtained from the questionnaires were used in the regression analysis. The results showed that green product innovation and green process innovation were positively correlated with the competitive advantage of the firms. Rennings et al. [42] analyzed the effects of different characteristics of EMAS on technical environmental innovations and economic performance. The data obtained from 1277 German EMAS-validated manufacturing facilities were used in the binary probit model. The results showed that: (i) The maturity of environmental management systems has a positive impact on environmental process innovations. (ii) Both learning processes and environmental process innovations have a positive impact on economic performance. (iii) The presence of specific departments such as the R&D department in the further development of EMAS is an important determinant of environmental process. Cheng and Shiu [13] proposed an instrument that measures eco-innovation activities. They suppose that eco-innovation activities or implementations cannot be measured through a single variable because of their complex structure. Data are obtained from 298 senior managers who carried out successful eco-innovation projects employed in the principal component analysis which is one of the statistical analysis techniques. The results of the analysis show that there are 17 items that are instrumental for measuring eco-innovation. These items consist of eco-organization, eco-process and eco-product implementations.

Bocken et al. [6] investigated the initial phase of the eco-innovation process (front end of eco-innovation—FEEI) for 42 SME eco-innovators in the Netherlands by using survey method. The findings indicate that SMEs take into account informal, systematic and open innovation approaches at the FEEI. Teams engaged in the FEEI are multidisciplinary and have creativity skills. In addition to this, essential element for the success of the team is environmental knowledge. Also, it is important that eco-innovations are generated in house by R&D departments, while SMEs engage with external stakeholders to generate new ideas. Ding [17] explored the inner mechanism of supply chain collaboration toward eco-innovation by taking the role of the mediation and moderation effect into account by using survey data. This data were obtained from 276 high-technology firms in Wuhan City of Hubei Province. The empirical results based on SEM analysis showed that supply chain collaboration has a significant impact on eco-innovation performance and the interaction between two variables is partially through collaborative innovation capability. Marin [33] evaluated drivers and productivity effects of environmental innovations for Italy by applied CDM model, which is an empirical structural econometric model. The author investigated the drivers of environmental innovations by using mainly administrative data

(AIDA by Bureau van Dijk and patent data from PATSTAT) of Italian manufacturing firms. The results show that innovation efforts of polluting firms are significantly biased toward environmental innovations. Environmental innovations differ from other innovations in terms of their effects on firm productivity. Also, environmental innovations crowd out other innovations which are more expensive.

Marin et al. [34] proposed a classification of EU SMEs in terms of barriers to eco-innovation. They examined how SMEs differ in terms of barriers and environmental innovation activities. In the analysis survey, data from the Flash Eurobarometer on "Attitudes of European Entrepreneurs Towards Eco-Innovation," conducted by the Gallup Organization on behalf of the DG Environment of the European Commission, were used. Choosing manufacturing and related environmental industries, 2308 firms were included in empirical analysis. They classified the barriers of eco-innovation for SMEs in EU by applying average linkage method which is one of the cluster analysis techniques. The results indicated that there were six clusters of SMEs. These clusters included firms facing revealed barrier, deterring barriers, cost deterred firms, market deterred firms, non-eco-innovators and green champion. Brasil et al. [8] investigated the relationship between process, product and organizational eco-innovations. Additionally, they examined the effects of three types of eco-innovation on business performance by employing a structural equation model. Data used in the analysis consisted of 70 firms gathered from textile industry in Brazil. The results of the empirical analysis showed that organizational and product eco-innovations had a direct impact on the performance of firms. There are significant relationships between organizational and process eco-innovations, organizational and product eco-innovations and process and product eco-innovations.

2.4 Eco-innovation Policies in European Union

In the European Union, the idea is that prosperity of the member countries and the life quality are linked to the natural environment. Indeed, it is expected that renewable energy, global demand and resource-efficient solutions will play an active role in economic growth and the creation of new jobs in the future. So, eco-innovation and green technologies, which are at the core of EU policies, are seen as a key element of the EU's future. Today, the market value of eco-industry is about €1 trillion and expected to increase in the coming years. So, the environment industry sector grew by more than 50% between 2000 and 2011. More than 3 million people are employed in eco-industries. Additionally, Europe has a third of the global market for green technologies. Eco-innovation therefore has great potential as a driver of new jobs and growth. The most important priority of the European Commission is that Europe again will become a growing economy and create new jobs. To achieve this aim, member states are offered supports such as investment plans and funding programs. Especially within the scope of investment plans, it is also aimed to determine obstacles in front of investments, to remove these obstacles and to make smarter use of both existing and new financial resources. Funds provided by the European Union support strategic investments in infrastructure, education, research and innovation [20].

Demographic changes occurring in Europe, aging population, increasing unemployment rates and global issues such as climate changes have raised the need for economic and social reform in the European Union (EU). In this context, the European Union firstly adopted the Lisbon Strategy and then the Europe 2020 Strategy. The main targets of the strategy are as follows [20]:

- 75% of people aged 20–64 to be in work,
- 3% of the EU's GDP to be invested in R&D,
- Greenhouse gas emissions 20% lower than 1990 levels,
- 20% of energy coming from renewables,
- 20% increase in energy efficiency,
- Rates of early school leavers below 10%,
- At least 40% of people aged 30–34 having completed higher education,
- At least 20 million fewer people in—or at risk of—poverty/social exclusion.

The three main priorities of the European 2020 Strategy are set out as follows: The first is *smart growth* by developing an economy based on knowledge and innovation. Second is a *sustainable growth*. Accordingly, it is aimed to provide a sustainable economy by using low carbon and low resource and enhancing competition. The third one is *inclusive growth* which promotes employment with social and regional integration. Thus, the main objective of the 2020 Strategy is eco-innovation. The EU's 7th Environment Action Programme (7EAP) is assessed within the European Union's eco-innovation policy. The vision of this action program as "*living well within the limits of the planet*" means that the EU needs to transform into a resource-efficient, green, competitive and low-carbon economy by 2050.

The European Commission prepared the Eco-innovation Action Plan (EcoAP) in 2011, based on the above-mentioned reasons. Seven activities have been identified in this plan, in which the European Union seeks to underline the determinants and obstacles to eco-innovation in the member countries. The commission will foster key drivers for the market uptake of eco-innovation by [18]:

- Using environmental policy and legislation to promote eco-innovation,
- Supporting demonstration projects and partnering to bring promising, smart and ambitious operational technologies to the market that have been suffering from low uptake,
- Developing new standards boosting eco-innovation,
- Mobilizing financial instruments and support services for SMEs,
- Promoting international cooperation,
- Supporting the development of emerging skills and jobs and related training programs to match the labor market needs,
- Promoting eco-innovation through the European Innovation Partnerships foreseen under the Innovation Union.

Looking at the activities and targets in the Eco-innovation Action Plan, it is seen that the elements in the foreground are public–private partnership on eco-innovation, national and international collaborations, legal regulations, financial support especially for SMEs and qualified labor force. In other words, the Eco-innovation Action Plan is a key to the union's policies for sustainable production and consumption. Eco-innovation is an opportunity for business in a circular economy. Eco-innovation is a key to delivering many aspects of the circular economy: industrial symbiosis or ecologies, cradle-to-cradle design and new and innovative business models. Within the framework of eco-innovation policies, the European Commission published *Circular Economy Strategy* in 2015. The strategy aims to transform Europe into a more competitive resource-efficient economy. Additionally, it acknowledges the key role of eco-innovation in the context of job creation, growth and competitiveness with environmental protection. According to this, eco-innovation is a powerful tool that positively affects the economy and society and reduces the negative environmental impacts. It also leads companies to reduce their costs and improve their existing capacity to take advantage of new growth opportunities. Cooperation and interaction between actors such as producers and consumers will perform a key role in the process of cyclical economy at local, national and international levels.

With this strategy, it is expected that cyclical economy will boost the competitiveness of the EU by [19]:

- Protecting businesses against scarcity of resources and volatile prices,
- Helping to create new business opportunities and innovative,
- Creating local jobs at all skills levels and opportunities for social integration and cohesion,
- Improving energy efficiency,
- Preventing water, air and soil pollution and contributing to biodiversity.

This strategy has various targets for sustainable production, and consumption is a tool for Sustainable Development Goals in EU. The objectives of the strategy include areas such as product design, production process, consumption, waste management, secondary raw materials, priority sectors, innovation and investment [19: 3–21]. In this process, it draws attention to recycle food and construction material waste, together with environmentally innovative solutions, especially in the design of electronic products. European Union has different funding programs for eco-innovation. These are Horizon 2020 (the EU Framework Programme for Research and Innovation), LIFE (EU funding instrument for the environment and climate action), COSME (program for the Competitiveness of Enterprises and Small and Medium-sized Enterprises) and ESIF (European Structural and Investment Funds) and investment plan. *Horizon 2020* is the biggest EU research and innovation program ever with nearly €80 billion and is a financial tool for implementing the European 2020 Strategy.

LIFE is a financial tool by which the EU has supported approximately 4306 projects since 1992. It supports the projects in the areas of especially environmental nature and climate change problems. The main aim of this funding program is to contribute to transformation of the EU into a resource-efficient, low-carbon and climate-resilient economy. The main funding tools are grants, public procurement contracts and contribution to financial tools. In general, grants make a financial contribution of 60% to the projects during the first multi-annual work program. *COSME* is the funding program of the EU as part of eco-innovation. The budget allocated by the EU for the 2014–2020 period for this program, which aims to increase the competitiveness of SMEs, is €2.3 billion. This program aims to improve access to finance and market for SMEs, to improve their competitiveness and sustainability, and to support and promote entrepreneurship and entrepreneurial culture. *ESIF* is an important tool for the EU inclusive policy implementation. These policies focus on the economic and social dimension of a sustainable development by providing social integration with growth, competitiveness and employment. Environmental technologies, which are priority areas of regional development policy with climate change and sustainability-related projects, are supported in this context. So, the EU supports investments in areas such as eco-innovation, energy efficiency and renewable energies within the scope of the *European Regional Development Fund* (ERDF).

The latest support program of the EU for eco-innovation is the *investment plan.* This plan focuses on removing obstacles to investment, providing technical assistance to investment projects and using new and existing financial resources smartly. To achieve these targets, the plan is active in three areas: mobilizing investments of at least €315 billion in three years, supporting investment and creating an investment-friendly environment. Projects such as strategic infrastructure (digital and energy investments), transport infrastructure in industrial centers, investments that increase youth employment especially in SMEs and environment-friendly sustainable projects have priority. The EU carries out its vision of being the world's most competitive economy through a smart, sustainable, inclusive and innovative growth strategy. While determining the policies and targets for this purpose, the EU also offers various funding programs to achieve these goals. Therefore, eco-innovation policies are the main priority of the EU in providing a sustainable development and in the process of cyclical economy transformation.

3 Empirical Analysis

3.1 Methodology and Data

Eco-innovation and green technologies are at the core of EU policies, and they are seen as a key element of the EU's future. Therefore, the EU publishes eco-innovation index since 2010, which is seen as a tool to evaluate and show eco-innovation performance of the member states. This index is a composite index developed by the Eco-Innovation Observatory. Additionally, it aims to capture the different aspects of eco-innovation by applying 16 indicators grouped into five thematic areas:

- Eco-innovation inputs,
- Eco-innovation activities,
- Eco-innovation outputs,
- Resource efficiency outcomes,
- Socioeconomic outcomes.

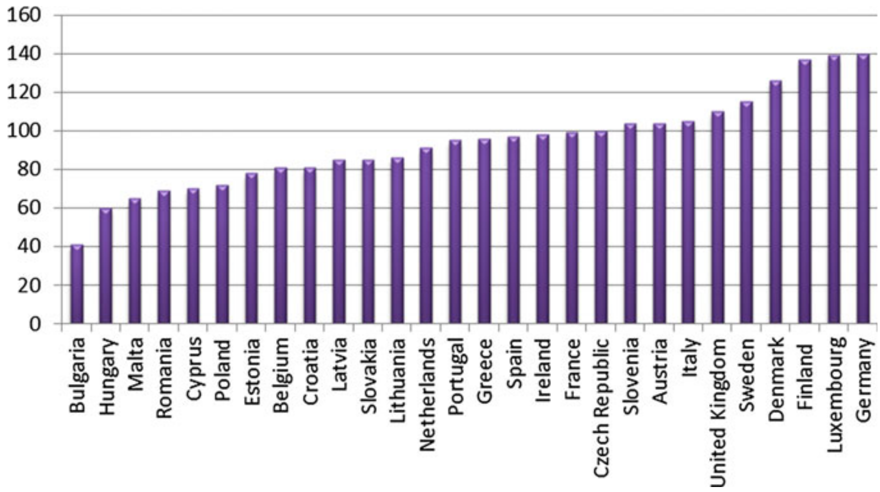

Fig. 2 Eco-innovation index 2016, EU countries [21]

In this index, eco-innovation inputs and eco-innovation activities are used as a proxy for *eco-innovation efforts*. Eco-innovation outputs, resource efficiency outputs and socioeconomic outputs are used as a proxy *eco-innovation performance.* Figure 2 shows eco-innovation index of 2016. According to eco-innovation index, the EU countries were classified into three groups: eco-innovation leaders (with scores higher than the EU average), average eco-innovation performers (with scores around the EU average) and countries catching up in eco-innovation (with around 85% or less performance compared to the EU average) [21]. Eco-innovation leaders are Germany (140), Luxembourg (139), Finland (137), Denmark (126), Sweden (115) and the UK (110). There are ten member countries called average eco-innovation performers. These countries are Italy (105), Austria (104), Slovenia 104), Czech Republic (100), France (99), Ireland (98), Spain (97), Greece (96), Portugal (95) and the Netherlands (91). Belgium (81) and the member countries joined the European Union after 2005 were clustered in the group called countries catching up in eco-innovation. They are Lithuania (86), Latvia (85), Slovakia (85), Croatia (81), Estonia (78), Poland (71), Cyprus (70), Romania (69), Malta (65), Hungary (60) and Bulgaria (41).

In this study, two methods of analysis were used to determine the relative eco-innovation efforts and performances of the European Union countries. They are cluster analysis and discriminant analysis. These analyses were applied separately in exploring eco-innovation efforts and eco-innovation performances. Sixteen indicators from 2016 were included in the empirical analysis, and they were obtained from the Eurostat database. These indicators can be seen in Table 2.

Table 2 Indicators included in the analysis

Eco-innovation inputs
Governments' environmental and energy R&D appropriations and outlays
Total R&D personnel and researchers
Total value of green early stage investments
Eco-innovation activities
Enterprises that introduced an innovation with environmental benefits obtained within the enterprise
Enterprises that introduced an innovation with environmental benefits obtained by the end user
ISO 14001 registered organizations
Eco-innovation outputs
Eco-innovation-related patents
Eco-innovation-related academic publications
Eco-innovation-related media coverage
Resource efficiency outcomes
Material productivity (GDP/domestic material consumption)
Water productivity (GDP/water footprint)
Energy productivity (GDP/gross inland energy consumption)
GHG emission intensity (CO_2/GDP)
Socioeconomic outcomes
Exports of products from eco-industries (% of total exports)
Employment in eco-industries and circular economy (% of total employment across all companies)
Revenue in eco-industries and circular economy (% of total revenue across all companies)

3.1.1 Cluster Analysis

Cluster analysis is a multivariate statistical technique for identifying homogenous groups of cases, objects or observations called clusters, which is used in many fields [32, 44]. Cluster analysis refers to the process of grouping similar objects into different groups. Observations in the cluster have similar characteristics, but are dissimilar to the observations belonging to other clusters [32]. Therefore, the purpose of cluster analysis is to maximize intra-cluster homogeneity and inter-cluster heterogeneity [35]. While high heterogeneity means that observations in different clusters are far from each other, high homogeneity means that and observations in the same cluster are close to each other. In cluster analysis, observations are grouped on the basis of similarities or dissimilarities. The distance between observations is calculated by the Euclidean distance. A Euclidean distance is a geometric distance between two observations. The formula of this distance is as follows [49]:

$$deij = \sqrt{\sum_{k=1}^{n}(Xik - Xjk)^2} \quad (1)$$

In the formulation, *Xik* is the measurement of *i*th cases on *k*th variable; *Xjk* is the measurement of *j*th cases on *k*th variable; and *n* is the number of variables. If Euclidean distance is smaller, the cases are more similar. If Euclidean distance is greater, the cases are more dissimilar. There are three types of cluster analyses. They are hierarchical, non-hierarchical and two-step cluster analyses [44]. If the researcher does not have preliminary information about the number of clusters, hierarchical cluster analysis is preferred [35]. Due to lack of preliminary information on the number of clusters, the hierarchical cluster analysis is preferred in this study. In hierarchical analysis, observations are grouped into a hierarchical structure. In other words, observations are grouped into a tree of clusters by using the distance matrix. In hierarchical cluster analysis, different methods are used to form the clusters. In this study, Ward method was applied. In this method, clusters are formed if the variation within the two clusters is least. Therefore, this method is known as minimum variance method. In cluster analysis, in order to decide the number of clusters, the agglomeration schedule and the dendrogram are observed. According to Verma [49], cluster analysis can be applied to any type of data. However, the data need to be standardized if the range or scale of measurement of one variable is different from others.

3.1.2 Discriminant Analysis

Discriminant analysis is one of the multivariate statistical methods. It aims to estimate the relationship between categorical dependent variables and metric independent variables. In the discriminant analysis, the independent variables are metric, but dependent variables are categorical. The main aim of this analysis is to estimate group membership based on a linear combination of the predictive variables. The second aim is to identify the relationship between group membership and the variables used to predict group membership, which provides information about the relative importance of independent variables in predicting group membership. Also this analysis tests whether cases are classified as predicted [1, 49].

Discriminant analysis involves the determination of a linear equation that will predict which group the case belongs to. The form of the function is as follows [1]:

$$D = v1X1 + v2X2 + v3X3 + \cdots + viXi + a \quad (2)$$

In the function, *D* refers to discriminate function; *v* is the discriminant coefficient or weight for that variable; *X* is respondent's score for that variable; *a* is constant; and *i* is the number of predictor variables. The discriminant function is calculated by using an existing set of data, and then observations are classified. A classification table is created after the analysis, which illustrates whether the cases are correctly classified in accordance with the original groups. To determine the relative importance of independent variables in predicting group membership, it is taken into account the results of tests of equality of group means [9].

3.2 Results

3.2.1 Eco-innovation Efforts

The aim of this study is to analyze the relative eco-innovation efforts and performances of the European Union countries. To this end, multivariate statistical techniques of cluster analysis and discriminant analysis were used. Firstly, the eco-innovation efforts of the countries were analyzed by using hierarchical cluster analysis and discriminant analysis. Then, two analyses were repeated for eco-innovation performance. Using Ward method, cluster analysis was performed. To decide the number of the clusters, the agglomeration schedule and the dendrogram were observed.

Agglomeration schedule is presented in Table 3. The first column in the schedule shows at which stage the countries create single cluster. The first row constitutes the first stage of the analysis. The nearest two observations which are in the first cluster and in the second cluster can be shown in cluster combined. For example, at the first stage the eighteenth observation (Austria) in the first cluster and the twenty-second observation (Lithuania) in the second cluster are the nearest two observations. The information about the distance between observations is in the coefficient column, and it is called the "squared Euclidean distance." For instance, the distance between Belgium and the Netherlands is 0,124. The columns, called the *stage cluster first appears*, show the step at which each of the two clusters that are being joined first appears. For example, at stage four, when cluster 12 and 20 are combined, cluster 12 was firstly formed at stage 4 and cluster 20 is a single case and the resulting cluster (known as 12) will see action again at stage 13. In the first row, it can be observed that the next stage is stage 14. This process continues until the stage 27. At this stage, the distance between two cases is quite far.

When the number of clusters is determined through the agglomeration schedule, the increase in the coefficients should be considered. The largest increases in the coefficients are identified to decide the number of the clusters. According to Table 3, there are high increases in the coefficients after stage 23. While the coefficient at stage 23 was 56,465, it increased to 70,396 at stage 24. As there are five jumps in coefficients in the following stages, it can be decided that there are five clusters. In other words, the EU countries can be classified under five groups according to their eco-innovation efforts. If we want a visual representation of the distance at which clusters are combined, we can look at a display called the dendrogram, shown in Fig. 3. The dendrogram is read from up to down. The results of the dendrogram support the results from agglomeration schedule. According to these results, Cluster 1 contains Belgium, the Netherlands, Greece, Luxembourg, Slovenia, Austria, France and

Table 3 Agglomeration schedule by using input indicators

Stage	Cluster combined		Coefficients	Stage cluster first appears		Next stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	18	22	0.124	0	0	6
2	12	23	0.263	0	0	4
3	21	28	0.470	0	0	14
4	12	20	0.792	2	0	13
5	3	25	1.126	0	0	15
6	18	19	1.929	1	0	19
7	2	11	2.746	0	0	14
8	14	16	3.606	0	0	9
9	14	17	4.850	8	0	19
10	10	27	6.111	0	0	13
11	1	9	7.694	0	0	20
12	24	26	9.578	0	0	18
13	10	12	12.146	10	4	18
14	2	21	14.782	7	3	21
15	3	13	17.557	5	0	23
16	4	15	20.783	0	0	22
17	6	8	24.665	0	0	21
18	10	24	28.845	13	12	25
19	14	18	33.382	9	6	22
20	1	7	38.420	11	0	24
21	2	6	44.083	14	17	25
22	4	14	50.225	16	19	26
23	3	5	56.465	15	0	24
24	1	3	70.396	20	23	26
25	2	10	84.485	21	18	27
26	1	4	102.408	24	22	27
27	1	2	162.000	26	25	0

Portugal. All countries in this cluster are called as average eco-innovation performers, with the exception of Belgium and the Netherlands. Cluster 2 contains Finland, Sweden and Germany, which are the best performance countries in the European Union. Cluster 3 contains Spain, UK, Ireland and Denmark. This cluster consists of countries called as eco-innovation leaders and average eco-innovation performers. Cluster 4 and Cluster 5 contain countries that joined the European Union after 2005, with the exception of Italy. These are the countries catching up in eco-innovation. These results show that cluster analysis of eco-innovation efforts generally supports

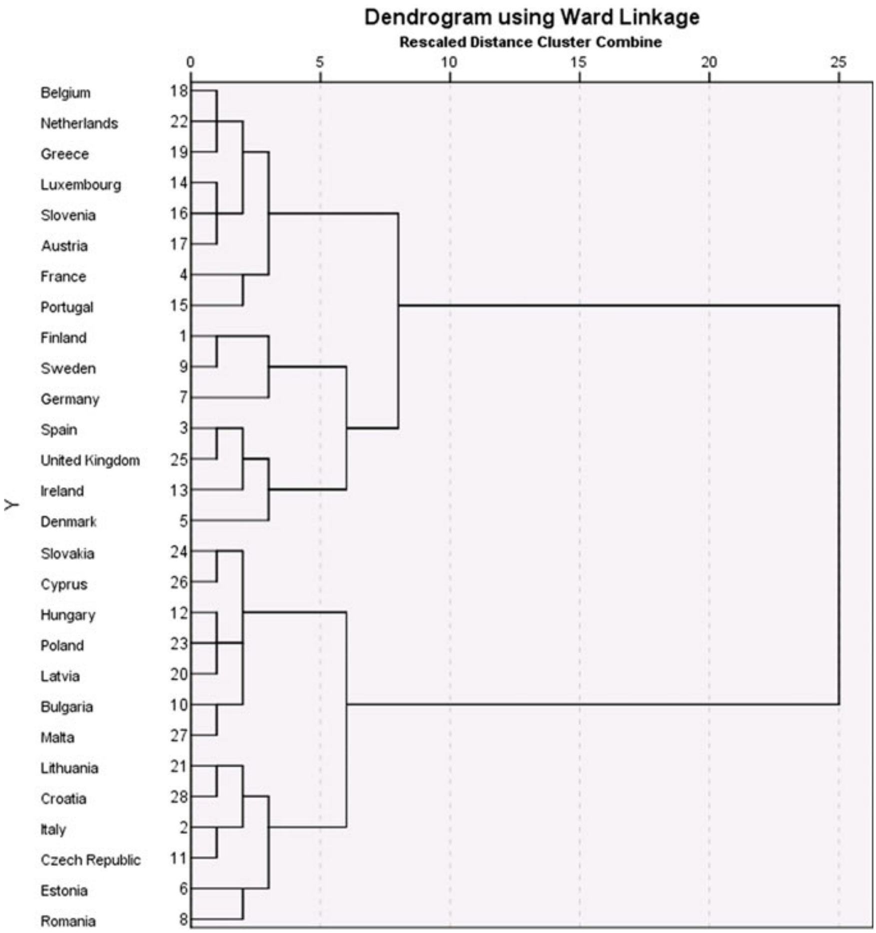

Fig. 3 Dendrogram (efforts)

eco-innovation index results. Cluster 1 contains mostly countries called as average eco-innovation performers, while Cluster 2 includes eco-innovation leaders and Cluster 4 and Cluster 5 contain countries that are called countries catching up in eco-innovation. However, Cluster 3 has a heterogeneous appearance. These results show that the EU countries do not have similar levels of eco-innovation efforts.

The discriminant analysis was used to verify the results of the cluster analysis and to determine the variables that are most effective in explaining the differences between the clusters. The results of discriminant analysis are shown in Tables 4 and 5.

Classification matrix in Table 4 shows whether the cases are correctly classified according to the original groups. As it correctly classifies 100% of the cases, the

Table 4 Classification results for inputs

K			Predicted group membership[a]					Total
			1	2	3	4	5	
Original	Count	1	3	0	0	0	0	3
		2	0	6	0	0	0	6
		3	0	0	4	0	0	4
		4	0	0	0	8	0	8
		5	0	0	0	0	7	7
	%	1	100.0	0.0	0.0	0.0	0.0	100.0
		2	0.0	100.0	0.0	0.0	0.0	100.0
		3	0.0	0.0	100.0	0.0	0.0	100.0
		4	0.0	0.0	0.0	100.0	0.0	100.0
		5	0.0	0.0	0.0	0.0	100.0	100.0

[a] 100.0% of original grouped cases correctly classified

Table 5 Tests of equality of group means

	Wilks' lambda	*F*	*df* 1	*df* 2	Sig.
Governments' environmental and energy R&D appropriations and outlays	0.527	5.162	4	23	0.004
Total R&D personnel and researchers	0.334	11.474	4	23	0.000
Total value of green early stage investments	0.200	23.051	4	23	0.000
Enterprises that introduced an innovation with environmental benefits obtained within the enterprise	0.287	14.274	4	23	0.000
Enterprises that introduced an innovation with environmental benefits obtained by the end user	0.219	20.514	4	23	0.000
ISO 14001 registered organizations	0.525	5.206	4	23	0.004

model is valid. So, the cluster analysis is valid in terms of both number of clusters and cluster memberships.

The most important variables in terms of eco-innovation efforts were also identified with the study. Table 5 illustrates the results of tests of equality of group means. This table is called the ANOVA table. The variable that has the smaller Wilks' lambda is the most important independent variable to the discriminant function. Wilks' lambda is significant by the F test for all independent variables. According to this, the variables that cause countries to be divided into different groups in terms of eco-innovation efforts are as follows: total value of green early stage investments (0.200), enterprises that introduced an innovation with environmental benefits obtained by the end user (0.219), enterprises that introduced an innovation with environmental benefits obtained within the enterprise (0.287), total R&D personnel and researchers (0.334), ISO 14001 registered organizations (0.525) and governments' environmental and energy R&D appropriations and outlays (0.527). So, the eco-innovation efforts of the countries are determined by investments in eco-innovation areas, environmental standards, governments' environmental and energy R&D outlays and innovation activities aiming at a reduction of material and energy input per unit output.

3.2.2 Eco-innovation Performances

The eco-innovation performances of the countries were analyzed by using hierarchical cluster analysis and discriminant analysis. Firstly, cluster analysis was performed by using Ward method. The results obtained from the analysis are shown in agglomeration schedule and dendrogram.

According to Table 6, there are high increases in the coefficients after stage 24. While the coefficient at stage 24 was 157,206, it increased to 182,160 at stage 25. As there are five jumps in coefficients in the following stages, it can be decided that there are four clusters. In other words, the EU countries can be classified under four groups according to their eco-innovation performances. The results of the dendrogram in Fig. 4 support the results from agglomeration schedule. According to these results, Cluster 1 contains Romania, Lithuania, Estonia, Ireland, Portugal, Hungary, Slovenia, Croatia, Czech Republic, Poland, Slovakia, Greece, Cyprus and Bulgaria. This cluster has two characteristics: First, it is the largest cluster in terms of number of countries with 14 members. Second, it contains mostly the average eco-innovation performers. Cluster 2 includes countries that are eco-innovation leaders (Finland and Sweden), except for Latvia. Similarly, Cluster 3 contains eco-innovation leaders (UK, Luxembourg and Denmark), except for Malta. The last cluster contains Belgium, the Netherlands, Italy, Spain, France, Austria and Germany. Cluster 4 contains countries with different levels of eco-innovation. According to the findings, the EU has different levels of eco-innovation performances. These results show that cluster analysis with eco-innovation performances generally supports eco-innovation index results. But the clusters have a more heterogeneous appearance in comparison with the clusters obtained from the previous analysis.

The results of discriminant analysis about eco-innovation performances are illustrated in Tables 7 and 8.

Table 7 shows the classification results from the discriminant analysis. According to the table, cases are correctly classified to originally grouped (100%). Therefore, cluster analysis is valid in terms of both number of clusters and cluster memberships.

Table 8 shows the result tests of equality of group means. All variables, except eco-innovation-related media coverage, are statistically significant at the 0.05 level (p

Table 6 Agglomeration schedule by using output indicators

Stage	Cluster combined		Coefficients	Stage cluster first appears		Next stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	8	21	1.127	0	0	5
2	18	22	2.671	0	0	12
3	12	16	4.768	0	0	9
4	4	17	6.929	0	0	14
5	6	8	9.118	0	1	15
6	2	3	11.330	0	0	12
7	1	9	13.575	0	0	17
8	13	15	15.874	0	0	15
9	12	28	18.935	3	0	19
10	25	27	22.483	0	0	20
11	19	26	26.077	0	0	16
12	2	18	29.746	6	2	23
13	11	23	33.437	0	0	18
14	4	7	37.686	4	0	23
15	6	13	43.693	5	8	19
16	10	19	51.095	0	11	24
17	1	20	58.566	7	0	26
18	11	24	68.102	13	0	22
19	6	12	77.658	15	9	22
20	14	25	90.143	0	10	21
21	5	14	103.380	0	20	25
22	6	11	118.474	19	18	24
23	2	4	136.362	12	14	25
24	6	10	157.206	22	16	26
25	2	5	182.160	23	21	27
26	1	6	207.638	17	24	27
27	1	2	270.000	26	25	0

< 0.05). The most significant variables that cause countries to be divided into different groups in terms of eco-innovation performance are as follows: water productivity (0.299), material productivity (0.399), eco-innovation-related academic publications (0.493), revenue in eco-industries and circular economy (0.503), energy productivity (0.599) and eco-innovation-related patents (0.606). According to cluster analysis, the results related to eco-innovation efforts are consistent with the EU eco-innovation index, but findings obtained from analysis related to eco-innovation performance show the homogeneity of the clusters. This situation shows that there is an incon-

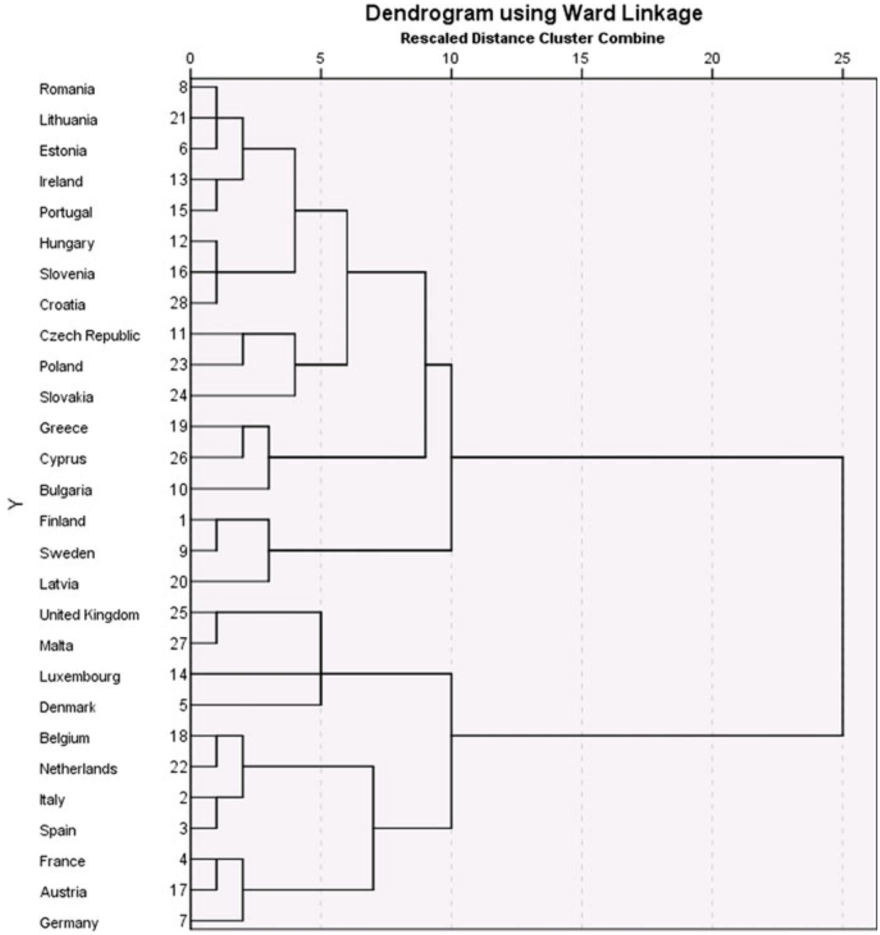

Fig. 4 Dendrogram (performances)

sistency between eco-innovation efforts of the countries and their performances and points out the *inefficiency problem* in terms of eco-innovation.

4 Conclusions

Environmental technologies are seen as a key element of a sustainable economy. Because of the rapid depletion of natural resources, environmental problems have gained a global dimension. Thus, the need for production technologies reducing environmental costs while meeting the needs of today's generations without jeopardizing the needs of future generations is increasing day by day. This need has brought

Table 7 Classification results for outputs

K			Predicted group membership[a]				Total
			1	2	3	4	
Original	Count	1	3	0	0	0	3
		2	0	7	0	0	7
		3	0	0	4	0	4
		4	0	0	0	14	14
	%	1	100.0	0.0	0.0	0.0	100.0
		2	0.0	100.0	0.0	0.0	100.0
		3	0.0	0.0	100.0	0.0	100.0
		4	0.0	0.0	0.0	100.0	100.0

[a] 100.0% of original grouped cases correctly classified

Table 8 Tests of equality of group means

	Wilks' lambda	*F*	*df* 1	*df* 2	Sig.
Eco-innovation-related patents	0.606	5.206	3	24	0.007
Eco-innovation-related academic publications	0.493	8.239	3	24	0.001
Eco-innovation-related media coverage	0.935	0.557	3	24	0.648
Material productivity	0.399	12.064	3	24	0.000
Water productivity	0.299	18.748	3	24	0.000
Energy productivity	0.599	5.354	3	24	0.006
GHG emission intensity	0.685	3.677	3	24	0.026
Exports of products from eco-industries	0.677	3.808	3	24	0.023
Employment in eco-industries and circular economy	0.626	4.775	3	24	0.010
Revenue in eco-industries and circular economy	0.503	7.891	3	24	0.001

up the concept of eco-innovation, which indicates the processes in which innovation encapsulates environmental dimension and has especially led the developed countries to focus on environmental technologies. It is accepted that sustainable and quality life in the European Union is linked to the environment and eco-innovation plays a key role in economic growth and development. The EU has been struggling to achieve its 2020 targets by implementing various tools and funding programs related to eco-innovation policy.

In this chapter, the relative eco-innovation efforts and performances of the European Union countries were analyzed. The most important variables in terms of eco-innovation efforts and eco-innovation performance were also tried to be determined. To this end, cluster and discriminant analyses were used. Findings of the analyses can be summarized as follows:

- The EU countries can be classified under five groups according to their eco-innovation efforts. It shows that EU has different performance levels in terms of eco-innovation efforts.
- The results related to eco-innovation efforts are consistent with the EU eco-innovation index.
- The EU countries can be classified under four groups according to their eco-innovation performances.
- Although these results support eco-innovation index, the clusters have a more heterogeneous appearance than the cluster obtained from the previous analysis.
- According to discriminant analysis, while the eco-innovation efforts of the countries are mostly determined by investments in eco-innovation areas, the eco-innovation performances are determined by water and material productivity.

In sum, the EU countries have different levels of development in terms of eco-innovation. If the EU wants to achieve a sustainable development in line with the 2020 targets and to transform into a resource-efficient cyclical economy, especially the new member states should make more efforts. The lack of direct policies related to eco-innovation in these countries and the integration of existing policies with other policies are seen as the main problems of eco-innovation. Therefore, solving these problems requires new implementations, such as increasing eco-innovation investments that are important for eco-innovation performance.

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Globalization and CO_2 Emissions: Addressing an Old Question with New Techniques

Victor Troster and Muhammad Shahbaz

Abstract This chapter uncovers the dynamics between CO_2 emissions, globalization, energy use, and economic growth in the US over the period 1970–2014. As an aftermath of the recent global financial crisis, it is important to assess the effects of globalization on CO_2 emissions. We extend the analyses of previous studies to evaluate causal relationship across the quantiles that allows us to examine asymmetric causal patterns associated with different CO_2 emissions regimes (normal, bad, and good). We find bidirectional causality between changes in the globalization index and changes in CO_2 emissions. Besides, very large decreases in energy use contribute to reductions in CO_2 emissions in the US, although linear tests find no relationship between them. Further, both linear and quantile-causality tests fail to support the environmental Kuznets curve hypothesis in the US. Our results call for policies for promoting the efficiency in energy use and for importing technologies that reduce the level of CO_2 emissions in the US.

Keywords CO_2 emissions · Globalization · Energy use · Granger-causality · Quantile regression · Environmental Kuznets curve

JEL Classification C32 · F18 · Q53 · Q56

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1 Introduction

As an aftermath of the recent global financial crisis, it is important to consider the effects of globalization on CO_2 emissions. Whereas globalization has significant economic impacts on employment and gross domestic product (GDP) *per capita*, it also affects the environmental quality of the countries (see, e.g., [50, 72, 75, 83]). Globalization may influence the environmental quality of a country by expanding the scale of economic activity [29, 53], by creating technological changes toward cleaner energies [30], and by modifying the composition of the economic activity or the comparative advantage of a country [41, 52]. Hence, the globalization effects on environment of a country rely on its income level, environmental regulation, and comparative advantage with its trade partners.

The US is the world's richest economy and the world's largest consumer of energy use *per capita* (in kg of oil equivalent), with an annual consumption of 6.797 thousands of kg of oil equivalent *per capita* in 2015 (http://www.data.worldbank.org). The US also has the world's largest number of CO_2 emissions *per capita*, with an annual amount of 16.491 metrics of ton *per capita* as of 2014 (http://www.data.worldbank.org). Besides, the US is a highly globalized economy with an annual revisited KOF globalization index [22, 64] of 79.95 (out of 100) in 2015, which is larger than the world's average KOF globalization index of 60.94 (http://www.kof.ethz.ch). Therefore, it is important to study the dynamics between globalization, CO_2 emissions, energy use, and economic growth *per capita* in the US to formulate sustainable energy policies that affect the environmental quality of the whole planet.

In this chapter, we study the dynamics between CO_2 emissions, globalization, energy use, and economic growth in the US over the period 1970–2014. We consider linear and nonlinear causal relationships between these variables. Besides, we extend the analyses of previous studies to evaluate causal relationship at each quantile of the distribution. This approach allows us to analyze asymmetric causal relationship associated with different CO_2 emissions regimes (normal, bad, and good). We employ a significance test on the estimated coefficient of the causing variable of a linear quantile regression developed by Koenker and Bassett [44] and Koenker and Xiao [45]. For comparison, we also implement the semi-parametric quantile-causality test proposed by Troster [80].

Our results indicate significant bidirectional linear causality between variations in the globalization index and changes in CO_2 emissions. Moreover, the quantile-causality test results show that increases in trade openness negatively affect CO_2 emissions in the US at an upper-tail quantile of $\tau = 0.70$. Conversely, we find weak evidence supporting causality from variations of the globalization index to changes in the GDP *per capita* in the US. Finally, changes in the globalization index negatively alter the energy use at the quantiles $\tau = \{0.45, 0.95\}$. Very large decreases in energy use contribute to reductions in CO_2 emissions in the US, although linear tests ignore tail dependence between them. Further, both linear and quantile-causality tests fail to support the environmental Kuznets curve (EKC) as economic growth does not significantly help reduce the level of CO_2 emissions in the US. Conversely, we find that changes in CO_2 emissions positively affect economic growth at the quantiles $\tau = \{0.35, 0.85\}$. We also find that reductions in energy use lead to economic growth in the US. Nevertheless, changes in the GDP *per capita* are not followed by changes in energy use in the US.

Therefore, our findings indicate that changes in globalization (trade openness) and in energy use are important for the dynamics of CO_2 emissions in the US. We find that economic growth does not significantly contribute to environmental deterioration in the US. Thus, our results fail to support the EKC in the US. Our results have relevant implications for policymakers in the US to consider both trade openness (globalization) and energy use as influential variables for promoting sustainable environment policies.

The rest of the chapter is arranged as follows: In Sect. 2, we review the literature on the dynamics between economic growth, globalization, trade openness (globalization), and carbon emissions. Section 3 outlines the methodology used in the chapter. Section 4 examines our empirical results. Finally, Sect. 5 concludes the chapter.

2 Literature Review

This chapter stands in the literature that analyzes the dynamics among trade openness, CO_2 emissions, and economic growth. Kraft and Kraft [47] reported significant causal effects of economic growth to energy use that led to increased carbon emissions in the US from 1947 to 1974. Grossman and Krueger [29] elaborated an environmental inverted U-shaped relation between economic growth and carbon emissions, the EKC, to evaluate the effects of the North American Free Trade Agreement on the US carbon emissions. Beckerman [8] demonstrated that high *per capita* income may decrease environmental deterioration. Bhagwati [9] suggested economic growth as a requirement for the enhancement of the environment. Selden and Song [65] reported an inverted U relationship between GDP *per capita* and carbon emissions *per capita* across a panel of countries. Besides, Grossman and Krueger [31] found support of an EKC between *per capita* income and urban air pollution using panel data of many countries.

Since trade openness helps promote economic growth, certain papers analyzed the dynamics between trade and environmental deterioration. Birdsall and Wheeler [10] found no causal relation between trade openness and environmental degradation in Latin America. Lee and Roland-Hoist [49] also showed that trade does not necessarily entail negative effects on the environment. Nevertheless, some studies argue that the structural change in production in developed economies, due to international trade, is not followed by structural changes in consumption. Then, the environmental Kuznets curve contributes to a rearrangement of polluting industries to poor countries with less strict environmental laws, the so-called displacement hypothesis [6, 17, 24, 61, 62, 76, 79]. Jänicke et al. [37], Suri and Chapman [77], and Agras and Chapman [1] showed that rich countries may improve their environment by importing more goods from dirty industries, worsening the environmental quality in less-developed countries. Antweiler et al. [4] showed that the net environmental effect of trade is good. Conversely, Liddle [51] provided evidence that the pollution level is generally greater under free trade than under autarky; besides, his results fail to provide evidence of the pollution haven hypothesis (PHH) that highly polluting firms shift their production to countries with less strict environmental regulations. Jaffe et al. [36] and Mani and Wheeler [56] also questioned the PHH; they argue that increasing capital outflows of polluting firms, because of severe environmental regulations in developed countries, compelled governments of developed countries to reduce their environmental protection laws. This race-to-bottom scenario straightened the EKC to a greater pollution level. On the other hand, Cole and Elliott [14], Cole [13], and Copeland and Taylor [15] found evidence of the PHH by analyzing North–South trade flows for dirty industry products. Managi et al. [55] also showed that trade improves the quality of the environment of OECD countries, although it involves adverse outcomes on the level of CO_2 emissions of non-OECD countries.

Some studies indicate that globalization can help improve environmental quality by increasing income and employment in less-developed countries [18, 60]. Nevertheless, Tisdell [78] argued that the environmental effect of globalization depends on whether important conditions are satisfied or not. Copeland and Taylor [16] remarked that the effect of globalization on pollution varies across countries, relying on their environmental regulations. Frankel and Rose [26] showed that trade openness is negatively associated with concentrations of SO_2 and NO_2. On the other hand, Kellenberg and Mobarak [43] found heterogeneous results on the relation between trade and concentrations of SO_2, CO_2, and NO_2. Kearsley and Riddel [42] provided little evidence that the PHH helps improve the environmental quality of developed countries. Baek et al. [7] and Wiebe et al. [82] reported that the trade effect on the quality of environment relies on the income level of the countries, because of the different economic policies, environmental regulations, and trade openness among them. Grossman and Krueger [29] proposed three distinct outcomes of trade on environmental quality: the scale, the technique, and the composition effects. The scale effect is the increase in environmental degradation because of the expansion of the scale of the economic activity due to trade liberalization [53]. Trade improves environmental quality since it engenders technological changes toward cleaner energies and better environmental practices, the so-called technique effect [30]. The composition effect is the change in the composition of the economic activity caused by trade openness; its impact relies on the income level, the environmental regulations, and the comparative advantage of a country [41]. Therefore, trade openness affects the environmental quality of a country according to its income level and its environmental regulation. Kozul-Wright and Fortunato [46] showed that the technique effect of trade significantly reduces the level of carbon emissions by providing cleaner energies. Nevertheless, carbon emissions increase with economic growth if it is mostly induced by trade openness [57, 58, 71]. Wiebe et al. [82] argued that the technique effect offsets the negative scale effect of trade as the preferences of individuals evolve.

Globalization also affects the environmental quality of a country by changing the comparative advantages of its trade partners, the so-called comparative advantage effect [52, 81]. Besides, globalization allows governments to reduce barriers to import clean energy technologies [12, 70]. Le et al. [48] investigated the relation between carbon emissions and trade liberalization across 98 countries. Their results indicate that trade liberalization worsens the environment of the countries, and the authors found evidence of the PHH. Dogan and Turkekul [21] analyzed the dynamics between trade openness and CO_2 emissions in the US from 1960 to 2010. The authors reported no causality between trade openness and CO_2 emissions in the US. Certain papers applied the globalization index proposed by Dreher [22] that incorporates economic, social, and political aspects of globalization. Using this globalization index, Shahbaz et al. [73] showed that globalization helped decrease the level of CO_2 emissions in Turkey from 1970 to 2010. Shahbaz et al. [66, 68] found that globalization improved the environmental quality in Australia and China, respectively, from 1970 to 2012. Nevertheless, Shahbaz et al. [67, 69] reported that globalization increases CO_2 emissions of Indonesia and India, respectively, over the period of 1975–2012. Further, Shahbaz et al. [74] showed that globalization worsened the quality of the environment in Japan from 1970 to 2014.

Lee and Min [50] reported that globalization helped reduce CO_2 emissions across 225 countries for the period 1980–2011. Conversely, Shahbaz et al. [72] documented that globalization augments the level of carbon emissions across 105 countries. Shahbaz et al. [75] also provided evidence that globalization helps increase carbon emissions across 25 developed countries from 1970 to 2014. Recently, You and Lv [83] used a spatial panel procedure to verify the relation between globalization and CO_2 emissions across 83 countries over the period 1985–2013. They found that globalization significantly reduces CO_2 emissions so that globalization improves environmental quality of the countries. Nevertheless, Haseeb et al. [33] reported that globalization has an insignificant effect on carbon emissions across BRICS economies from 1995 to 2014.

3 Econometric Methodology

In this section, we discuss the econometric approach used in the chapter. We apply bivariate linear Granger-causality tests. Further, we employ quantile-causality tests. Following Granger [27, 28], there is Granger-causality from X_t to Y_t if:

$$F_Y\left(y|\mathcal{F}_{t-1}^Y, \mathcal{F}_{t-1}^X\right) = F_Y\left(y|\mathcal{F}_{t-1}^Y\right), \text{ for all } y \in \mathbb{R}, \tag{1}$$

where $\mathcal{F}_{t-1}^Y$ and $\mathcal{F}_{t-1}^X$ are the past information sets up to time $t-1$ of Y_t and X_t, respectively, and $F_Y\left(\cdot|\mathcal{F}_{t-1}^Y\right)$ is the conditional distribution function of Y_t conditioned on $\mathcal{F}_{t-1}^Y$. Then, if Eq. (1) is satisfied, we have that:

$$E\left(Y_t|\mathcal{F}_{t-1}^Y, \mathcal{F}_{t-1}^X\right) = E\left(Y_t|\mathcal{F}_{t-1}^Y\right), \text{a.s.}, \tag{2}$$

where $E\left(Y_t|\mathcal{F}_{t-1}^Y\right)$ is the mean of $F_Y\left(\cdot|\mathcal{F}_{t-1}^Y\right)$. Hence, we carry out a Granger-causality-in-mean test of Eq. (2) by applying a F-test on $H_0 : \beta_{1j}^X = 0$, for all j, in a vector autoregressive (VAR) model as follows:

$$Y_t = \sum_{j=1}^{q} \beta_{1j}^Y Y_{t-j} + \sum_{j=1}^{q} \beta_{1j}^X X_{t-j} + \varepsilon_t,$$

$$X_t = \sum_{j=1}^{q} \beta_{2j}^Y Y_{t-j} + \sum_{j=1}^{q} \beta_{2j}^X X_{t-j} + \eta_t,$$

where ε_t and η_t are errors that follow a white noise process. We select the lag length q that minimizes the Bayesian information criterion (BIC), considering a lag length up to 10. We apply a robust heteroscedasticity-consistent covariance matrix estimator (HCCME) of the residuals of the VAR model proposed by MacKinnon and White [54]. We also apply the serial correlation test of Edgerton and Shukur [23] to verify whether the residuals of each VAR are uncorrelated.

We also employ the cointegration test of Johansen [39, 40] in bivariate vector error correction models (VECM):

$$Y_t = \alpha + \beta X_t + \sum_{j=1}^{q} \Upsilon_j Y_{t-j} + \sum_{j=1}^{q} \Gamma_j X_{t-j} + \nu_t,$$

where Y_t and X_t are non-stationary, and ν_t is a stationary error term. We also apply the cointegration test to a multivariate VECM including all the series, using the lag length that minimizes the BIC.

We apply the BDS test of Broock et al. [11] to verify whether the residuals of the VAR model are i.i.d. In addition, we employ the parameter-stability tests on the estimated parameters of the VAR model proposed by Andrews [2], Andrews and Ploberger [3], and Hansen [32].

We also consider nonlinear tests of mean-causality. We implement the nonlinear tests of Hiemstra and Jones [34] and Diks and Panchenko [20] on the standardized residuals of the VAR models. Although both procedures are similar, only the approach of Diks and Panchenko [20] provides a correct asymptotic size.

We further consider Granger-causality across the quantiles since mean-causality overlooks tail dependence or causality at other moments of the conditional distribution. Let $Q_\tau\left(\cdot|\mathcal{F}_{t-1}^Y\right)$ denote the τ-quantile of $F_Y\left(\cdot|\mathcal{F}_{t-1}^Y\right)$. Since the quantiles completely characterize the distribution, we can rewrite Eq. (1) as:

$$Q_\tau\left(Y_t|\mathcal{F}_{t-1}^Y, \mathcal{F}_{t-1}^X\right) = Q_\tau\left(Y_t|\mathcal{F}_{t-1}^Y\right), \text{ a.s., for all } \tau \in \mathcal{T}, \quad (3)$$

where $\mathcal{T} \subset (0, 1)$ is a closed subset of $(0, 1)$. Then, we can test the null hypothesis in Eq. (3) by applying a Wald test on $H_0 : \beta_j(\tau) = 0, \quad j = 1, \ldots, q,$ for all $\tau \in \mathcal{T}$, in a quantile autoregressive model as follows:

$$Q_\tau\left(Y_t|\mathcal{F}_{t-1}^{Y}, \mathcal{F}_{t-1}^{X}\right) = \alpha(\tau) + \sum_{j=1}^{q} \beta_j(\tau) X_{t-j} + \sum_{j=1}^{q} \gamma_j(\tau) Y_{t-j}, \quad (4)$$

where the parameters are estimated by the quantile approach proposed by Koenker and Bassett [44] and Koenker and Xiao [45]. For comparison, we also apply the semi-parametric test of quantile-causality proposed by Troster [80]. Given an indicator function $1[Y_t \leq y]$, we have that $\Pr\left\{Y_t \leq Q_\tau\left(Y_t\middle|\mathcal{F}_{t-1}^{Y}\right)\middle|\mathcal{F}_{t-1}^{Y}\right\} = E\left\{1\left[Y_t \leq Q_\tau\left(Y_t\middle|\mathcal{F}_{t-1}^{Y}\right)\right]\middle|\mathcal{F}_{t-1}^{Y}\right\}$. Then, Troster [80] suggests restating the null hypothesis in Eq. (1) as:

$$H_0^{GCQ} : E\left\{1\left[\mathrm{Y_t} \leq M\left(\mathcal{F}_{t-1}^{Y}, \theta_0(\tau)\right)\right]|\mathcal{F}_{t-1}^{Y}, \mathcal{F}_{t-1}^{X}\right\} = \tau, \text{ for all } \tau \in \mathcal{T}, \quad (5)$$

where $M\left(\mathcal{F}_{t-1}^{Y}, \theta_0(\tau)\right)$ is a parametric specification of the conditional quantile of Y_t, $Q_\tau\left(\cdot|\mathcal{F}_{t-1}^{Y}\right)$, with $M \in \mathcal{M} = \{M(\cdot, \theta(\tau))|\theta(\cdot) : \tau \mapsto \theta(\tau) \in \Theta \subset \mathbb{R}^q, \text{ for } \tau \in \mathcal{T}\}$. Assuming a correct specification of the quantile model in H_0^{GCQ} in Eq. (5), Troster [80] proposes the following test of quantile-causality:

$$E\left\{\left[1\left(Y_t - M\left(\mathcal{F}_{t-1}^{Y}, \theta_0(\tau)\right) \leq 0\right) - \tau\right]\exp\left(i\boldsymbol{\omega}'\mathcal{F}_{t-1}\right)\right\} = 0, \text{ for all } \tau \in \mathcal{T}, \quad (6)$$

where $i = \sqrt{-1}$, and $\exp\left(i\boldsymbol{\omega}'\mathcal{F}_{t-1}\right)$ is a weighting function satisfying $\exp(i\boldsymbol{\omega}'\mathcal{F}_{t-1}) := \exp[i(\omega_1(Y_{t-1}, X_{t-1})' + \cdots + \omega_s(Y_{t-s}, X_{t-s})')]$, for all $\boldsymbol{\omega} \in \mathbb{R}^s$ with $s \leq q$. Let $\hat{\theta}_N(.)$ be a consistent estimator of $\theta_0(\tau)$, for all $\tau \in \mathcal{T}$. We implement the following test of Troster [80]:

$$s_N(\boldsymbol{\omega}, \tau) := \frac{1}{\sqrt{N}} \sum_{t=1}^{N} \left[1\left(Y_t - M\left(\mathcal{F}_{t-1}^{Y}, \hat{\theta}_N(\tau)\right) \leq 0\right) - \tau\right]\exp(i\boldsymbol{\omega}'\mathcal{F}_{t-1}). \quad (7)$$

Troster [80] shows that $s_N(\boldsymbol{\omega}, \tau)$ converges to a zero-mean Gaussian process as N goes to infinity. Then, for testing the null hypothesis in Eq. (6), we apply the Cramér von-Mises functional norm of $s_N(\boldsymbol{\omega}, \tau)$ proposed by Troster [80]:

$$S_N \equiv \int_{\mathcal{T}} \int_{\mathcal{W}} |s_N(\boldsymbol{\omega}, \tau)|^2 \mathrm{d}W_{\boldsymbol{\omega}}(\boldsymbol{\omega})\mathrm{d}F_\tau(\tau), \quad (8)$$

where $W_\omega(\cdot)$ and $F_\tau(\cdot)$ are the weighting and quantile distributions, respectively. We reject the null hypothesis in Eq. (6) when S_N in Eq. (8) is sufficiently large. We apply the subsampling method of Troster [80] to estimate the p-values of S_N in Eq. (8). Since subsampling procedures rely on the subsample size, we use the method of Sakov and Bickel [63] to select the subsample size. Then, our subsamples have a size of $b = \left[\mathrm{kN}^{2/5}\right]$, where $[\cdot]$ is the floor function. We apply linear quantile autoregressive (QAR) models that control for other series under the null hypothesis in Eq. (6). Let Z_t and W_t be other series, we specify the QAR model under H_0 of Eq. (6) as:

$$M\left(\mathcal{F}_{t-1}^{Y}, \mathcal{F}_{t-1}^{Z}, \mathcal{F}_{t-1}^{W}, \theta(\tau)\right) = \alpha(\tau) + \sum_{j=1}^{q} \gamma_j(\tau) Y_{t-j} + \sum_{j=1}^{q} \delta_j(\tau) Z_{t-j} + \sum_{j=1}^{q} \phi_j(\tau) W_{t-j}. \quad (9)$$

4 Empirical Results

We study the dynamics between the globalization index (G_t), CO_2 emissions in thousands of metric tons (C_t), energy use in kg of oil equivalent *per capita* (E_t), and real GDP *per capita* (Y_t) of the US from 1970 to 2014. We chose this sample period because of the data availability. We use the annual revisited KOF globalization index of the US, developed by Savina et al. [64] and proposed by Dreher [22], obtained from the Web site http://www.kof.ethz.ch. This index encompasses the

Table 1 Summary statistics and unit root tests

	G_t	C_t	E_t	Y_t
Mean	4.27	8.52	8.94	9.18
Median	4.28	8.51	8.96	9.18
Min	4.09	8.37	8.83	8.51
Max	4.39	8.66	9.04	9.74
S.D.	0.10	0.09	0.05	0.39
Skewness	−0.28	0.02	−0.55	−0.13
Kurtosis	−1.51	−1.29	−0.14	−1.40
JB	4.53	2.76	2.41	3.42
Prob.	0.06	0.12	0.16	0.08
ADF level	−0.10	−0.93	−1.45	−1.89
ADF first diff	**−4.79**	**−5.42**	**−6.34**	**−4.14**
ADF-GLS level	−0.55	−2.36	−2.63	−2.03
ADF-GLS first diff	**−4.53**	**−5.49**	**−5.32**	**−4.90**
PP level	−0.08	−1.70	−2.07	−0.99
PP first diff	**−7.11**	**−4.69**	**−4.78**	**−4.70**

Notes We present the descriptive statistics of the logarithms of the revisited KOF globalization index (G_t), CO_2 emissions in thousands of metric tons (C_t), energy use in kg of oil equivalent per capita (E_t), and real GDP per capita (Y_t) of the US from 1970 to 2014. Our annual data span from 1970 to 2014. JB is the normality test of Jarque and Bera [38], where Prob. denotes its p-value. ADF is the unit root test of Dickey and Fuller [19]. ADF-GLS is the unit root test of Elliott et al. [25], and PP is the unit root test of Phillips and Perron [59]. We perform unit root tests for the level and for the first difference of the series. Boldface values indicate rejection of H_0 at the 5% level

Table 2 Cointegration tests

VAR	Trace H_0: No CE (15.49)	Maximum eigenvalue H_0: No CE (14.26)
G_t, C_t	9.74	7.97
G_t, E_t	8.37	6.07
G_t, Y_t	12.67	8.92
C_t, E_t	6.60	6.53
C_t, Y_t	8.16	6.11
E_t, Y_t	10.62	8.39
Multivariate VAR	Trace H_0 : No CE (47.86)	Maximum eigenvalue H_0 : No CE (27.58)
G_t, C_t, E_t, Y_t	41.81	16.62

Notes We report the results of the cointegration test proposed by Johansen [39, 40]. We selected an optimal lag order of one that minimized the BIC for all estimated VAR models. The 5%-critical values are in parentheses close to H_0: No CE (no cointegration)

economic, social, and political aspects of globalization. We gather annual data on CO_2 emissions (C_t) and energy use *per capita* (E_t) of the US from the World Development Indicators' Web site http://www.data.worldbank.org. Finally, we obtain the real GDP *per capita* (Y_t) of the US from the Federal Reserve Bank of St. Louis, http://www.fred.stlouisfed.org. Table 1 reports summary statistics and unit root tests of the logarithm of the series. All series display low volatilities and negative kurtosis values. We cannot reject the null hypothesis of a unit root process for each one of the series at the 5% level. Conversely, all the differences of the logarithm of the series are stationary.

Next, we implement the test for cointegration proposed by Johansen [39, 40] since all series are non-stationary in level. We selected a lag order of one that minimized the BIC for the bivariate and multivariate VECM. Table 2 displays the cointegration tests on the logarithm of the series. We find no evidence of cointegration between the logarithm of the globalization index, CO_2 emissions, energy use, and real GDP *per capita* at the 5% level. Therefore, we work with the logarithm of the difference of the series in our analysis.

We first perform Granger-causality-in-mean tests between changes in the logarithms of G_t, C_t, E_t, and Y_t. We selected an optimal lag order of one that minimized the BIC for all estimated VAR models. Table 3 presents the results of the linear Granger-causality F-tests. The serial correlation test results indicate that the residuals of all VAR models are not serially correlated at the 5% level. Table 3 reports bidirectional linear causality between ΔC_t and ΔG_t at the 5% level. In addition, economic growth (ΔY_t) affects changes in the globalization index (ΔG_t) at the 1% level. There is also $\Delta G_t - \Delta E_t$ linear causality at the 5% significance level. We verify whether the residuals of the estimated VAR models are i.i.d. by applying the

Table 3 Linear F-test for Granger-causality

H_0	F-test p-value	ES test p-value
$\Delta C_t \nRightarrow \Delta G_t$	0.022*	0.667
$\Delta E_t \nRightarrow \Delta G_t$	0.051	0.876
$\Delta Y_t \nRightarrow \Delta G_t$	0.003**	0.846
$\Delta G_t \nRightarrow \Delta C_t$	0.047*	0.667
$\Delta E_t \nRightarrow \Delta C_t$	0.105	0.844
$\Delta Y_t \nRightarrow \Delta C_t$	0.866	0.422
$\Delta G_t \nRightarrow \Delta E_t$	0.043*	0.876
$\Delta C_t \nRightarrow \Delta E_t$	0.188	0.844
$\Delta Y_t \nRightarrow \Delta E_t$	0.582	0.369
$\Delta G_t \nRightarrow \Delta Y_t$	0.298	0.846
$\Delta C_t \nRightarrow \Delta Y_t$	0.431	0.422
$\Delta E_t \nRightarrow \Delta Y_t$	0.326	0.369

Notes We calculate the F-test p-values on $H_0 : \beta_{1j}^X = 0$, for all j, in a VAR model under H_0 that X_t does not Granger-cause Y_t. We employ the heteroscedasticity-consistent covariance matrix estimator (HCCME) of MacKinnon and White [54], where * and ** indicate rejection of H_0 at the 5% and 1% levels, respectively. We selected an optimal lag order of one that minimized the BIC for all estimated VAR models. ES test is the p-value of the test for serial correlation of the residuals of the VAR model developed by Edgerton and Shukur [23]

test proposed by Broock et al. [11] (BDS). We also employ the stability tests on the estimated parameters of the VAR models proposed by Andrews [2], Andrews and Ploberger [3], and Hansen [32]. Table 4 presents the nonlinearity and parameter-stability test results. We find no significant evidence of nonlinearity in the data for the VAR models where ΔG_t is the dependent variable. Nevertheless, we reject the null hypothesis of parameter stability of the VAR model from ΔG_t to ΔC_t at the 5% level. We also reject the null hypothesis that the residuals of the VAR model from ΔY_t to ΔC_t are i.i.d. at the 1% level. The residuals of the three VAR models where ΔE_t is the dependent variable are nonlinear at the 5% level; besides, we reject the null hypothesis of parameter stability of the VAR model from ΔG_t to ΔE_t at the 5% significance level. Finally, we reject that the residuals of the VAR models, from ΔG_t to ΔY_t and from ΔC_t to ΔY_t, are i.i.d. at the 5% level. Therefore, there are nonlinearities and structural breaks in the VAR models, indicating that linear causality tests are unable to cover nonlinear or tail causal relations between certain variables.

Table 5 reports the nonlinear Granger-causality tests on standardized residuals of the VAR models. The p-values of the tests of Hiemstra and Jones [34] and Diks and Panchenko [20] fail to find significant nonlinear causality-in-mean between the changes in the variables at the 5% significance level.

Next, we carry out linear tests for Granger-causality in quantiles. We first apply the Wald test on the estimated lagged coefficients of quantile regression models of Eq. (4). We specify one lag for each causing variable since all VAR models presented in Table 3 selected a lag order of one. Figure 1 in Appendix reports the estimated quantile regression coefficients of the causing variable together with their 95% confidence interval. We find positive Granger-causality from ΔC_t and ΔE_t to ΔG_t for very low and very high quantiles at the 5% level. In line with the mean-causality test results, there is positive Granger-causality from ΔY_t to ΔG_t at almost all quantiles at the 5% level. Figure 1 reports negative causality from changes in the globalization index to changes in CO_2 emissions only at the quantile $\tau = 0.40$, at the 5% level. Nevertheless, the quantile-causality test uncovers a pattern of positive causality from variations in energy use to changes in CO_2 emissions at certain lower-tail quantiles of the distribution. This implies that large reductions in energy use lead to significant decreases in CO_2 emissions. Consistent with the linear tests findings displayed in Table 3, there is no causality from ΔY_t to ΔC_t across all quantiles.

The quantile-causality tests also report negative Granger-causality from ΔG_t to ΔE_t at the quantiles $\tau = \{0.45, 0.95\}$, at the 5% level. Besides, we find no causality from ΔC_t and ΔY_t to ΔE_t at all quantiles of the distribution, consistent with the linear tests displayed in Table 3. Finally, Fig. 1 reports positive Granger-causality from ΔC_t and ΔE_t to ΔY_t at certain lower-tail quantiles and at the median quantile of the distribution. Conversely, there is no significant causality from ΔG_t to ΔY_t at

Table 4 Nonlinearity and parameter-stability tests

VAR	BDS ($m = 2$)	BDS ($m = 3$)	BDS ($m = 4$)	SupF	AveF	ExpF
$\Delta G_t,\ \Delta C_t$	0.467	0.068	0.060	0.344	0.172	0.210
$\Delta G_t,\ \Delta E_t$	0.647	0.151	0.169	0.088	0.069	0.073
$\Delta G_t, \Delta Y_t$	0.313	0.898	0.787	0.165	0.136	0.119
$\Delta C_t,\ \Delta G_t$	0.246	0.439	0.000^{**}	0.001^{**}	0.019^{*}	0.001^{**}
$\Delta C_t,\ \Delta E_t$	0.184	0.014^{*}	0.834	0.218	0.202	0.182
$\Delta C_t, \Delta Y_t$	0.003^{**}	0.000^{**}	0.000^{**}	0.559	0.357	0.438
$\Delta E_t, \Delta G_t$	0.000^{**}	0.447	0.004^{**}	0.001^{**}	0.038^{*}	0.000^{**}
$\Delta E_t, \Delta C_t$	0.004^{**}	0.000^{**}	0.000^{**}	0.123	0.338	0.106
$\Delta E_t, \Delta Y_t$	0.159	0.000^{**}	0.000^{**}	0.115	0.322	0.116
$\Delta Y_t, \Delta G_t$	0.036^{*}	0.047^{*}	0.019^{*}	0.026^{**}	0.086	0.021^{*}
$\Delta Y_t, \Delta C_t$	0.047^{*}	0.003^{**}	0.001^{**}	0.637	0.572	0.576
$\Delta Y_t, \Delta E_t$	0.081	0.036^{*}	0.407	0.203	0.403	0.213

Notes We calculate the p-values of the BDS test of Broock et al. [11] where the residuals of the estimated VAR model are i.i.d. under the null hypothesis, for different embedded dimensions (m) of the test. The SupF, AveF, and ExpF are the parameter-stability tests proposed by Andrews [2], Andrews and Ploberger [3], and Hansen [32]; we test whether the estimated parameters of the VAR model are stable under the null hypothesis, where * and ** indicate rejection of H_0 at the 5% and 1% levels, respectively

Table 5 Nonlinear causality-in-mean tests

H_0	HJ test p-value	DP p-value
$\Delta C_t \nRightarrow \Delta G_t$	0.830	0.246
$\Delta E_t \nRightarrow \Delta G_t$	0.767	0.666
$\Delta Y_t \nRightarrow \Delta G_t$	0.995	0.793
$\Delta G_t \nRightarrow \Delta C_t$	0.874	0.192
$\Delta E_t \nRightarrow \Delta C_t$	0.793	0.739
$\Delta Y_t \nRightarrow \Delta C_t$	0.876	0.806
$\Delta G_t \nRightarrow \Delta E_t$	0.775	0.824
$\Delta C_t \nRightarrow \Delta E_t$	0.768	0.281
$\Delta Y_t \nRightarrow \Delta E_t$	0.531	0.393
$\Delta G_t \nRightarrow \Delta Y_t$	0.590	0.698
$\Delta C_t \nRightarrow \Delta Y_t$	0.775	0.760
$\Delta E_t \nRightarrow \Delta Y_t$	0.775	0.760

Notes HJ and DP test p-values denote the p-values of the nonlinear Granger-causality tests proposed by Hiemstra and Jones [34] and Diks and Panchenko [20], respectively. We used a lag order of one and a bandwidth parameter $\epsilon = 1.5$ for calculating both test statistics

all quantiles of the distribution. For comparison, we also employ the semi-parametric test for Granger-causality in quantiles of Eq. (8). Since we selected a lag order of one for all VAR models presented in Table 3, we specify a lag order of one under H_0 in Eq. (9). Table 6 presents the semi-parametric test results of causality in quantiles to ΔG_t and ΔC_t. In line with the results displayed in Fig. 1, we find causality from ΔC_t and ΔE_t to ΔG_t at the upper-tail quantiles of $\tau = \{0.85, 0.90\}$, at the 5% level. We also find that economic growth significantly contributes to ΔG_t at the quantiles of $\tau = \{0.15, 0.85\}$ at the 5% level. Table 6 also shows that there is Granger-causality from ΔG_t to ΔC_t at an upper-tail quantile of $\tau = 0.70$, at the 5% significance level. However, we find no causality from ΔE_t and ΔY_t to ΔC_t at all quantiles of the distribution. This implies that economic growth does not affect changes in CO_2 emissions.

Table 7 displays the results of the semi-parametric test of causality in quantiles to ΔE_t and ΔY_t. We find that ΔC_t and ΔY_t lead to ΔE_t at an upper-tail quantile of $\tau = 0.80$, at the 5% level. In contrast to the results reported in Fig. 1, we find a significant pattern of causality from ΔC_t and ΔY_t to ΔE_t at a certain upper-tail quantile. Nevertheless, there is no $\Delta G_t - \Delta E_t$ causality at the 5% significance level. Table 7 reports Granger-causality from ΔG_t to ΔY_t at the quantiles $\tau = \{0.35, 0.45, 0.85\}$, at the 5% level, in contrast to the linear tests and the Wald tests for the quantile regression model, as we find significant causality from variations in the globalization index to changes in the real GDP *per capita* at certain quantiles of the distribution. Besides, ΔC_t and ΔE_t lead to economic growth at the 5% level, if we consider all quantiles. There is also causality from ΔC_t to ΔY_t at $\tau = \{0.35,\ 0.85\}$ and from ΔE_t to ΔY_t at $\tau\ = \{0.35,\ 0.40\}$, at the 5% level.

Overall, we find bidirectional linear causality between ΔC_t and ΔG_t at the 5% level. The linear quantile-causality test results confirm these findings as ΔC_t positively affects ΔG_t, whereas changes in trade openness lead to negative changes in CO_2 emissions in the US at certain quantiles. Moreover, both linear and quantile-test results indicate that economic growth (ΔY_t) positively affects changes in the globalization index (ΔG_t). On the other hand, we find weak evidence supporting causal effects from ΔG_t to $\Delta \mathrm{Y}_t$ in the US. Although linear tests fail to uncover Granger-causality from ΔE_t to ΔG_t, quantile-causality tests report positive causality from ΔE_t to ΔG_t at two certain upper-tail quantiles. Finally, we find linear causality from ΔG_t to ΔE_t, and changes in the globalization index negatively alter variations in energy use at the quantiles of $\tau = \{0.45,\ 0.95\}$.

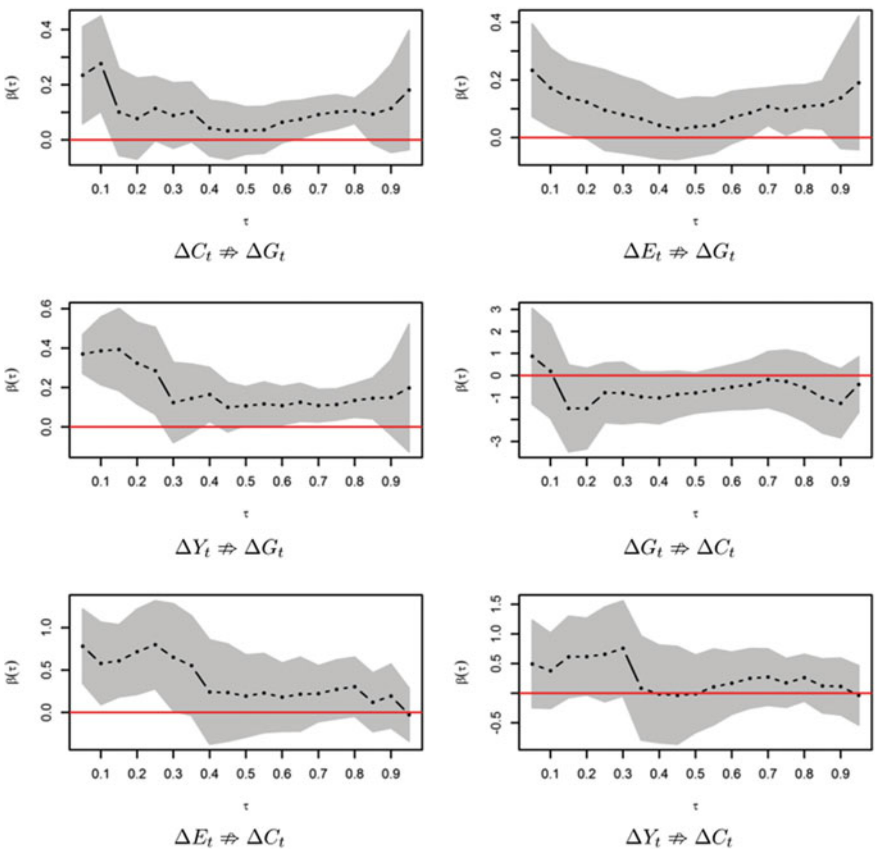

Fig. 1 Estimated quantile regression coefficients, $\beta(\tau)$, of the lagged causing variables

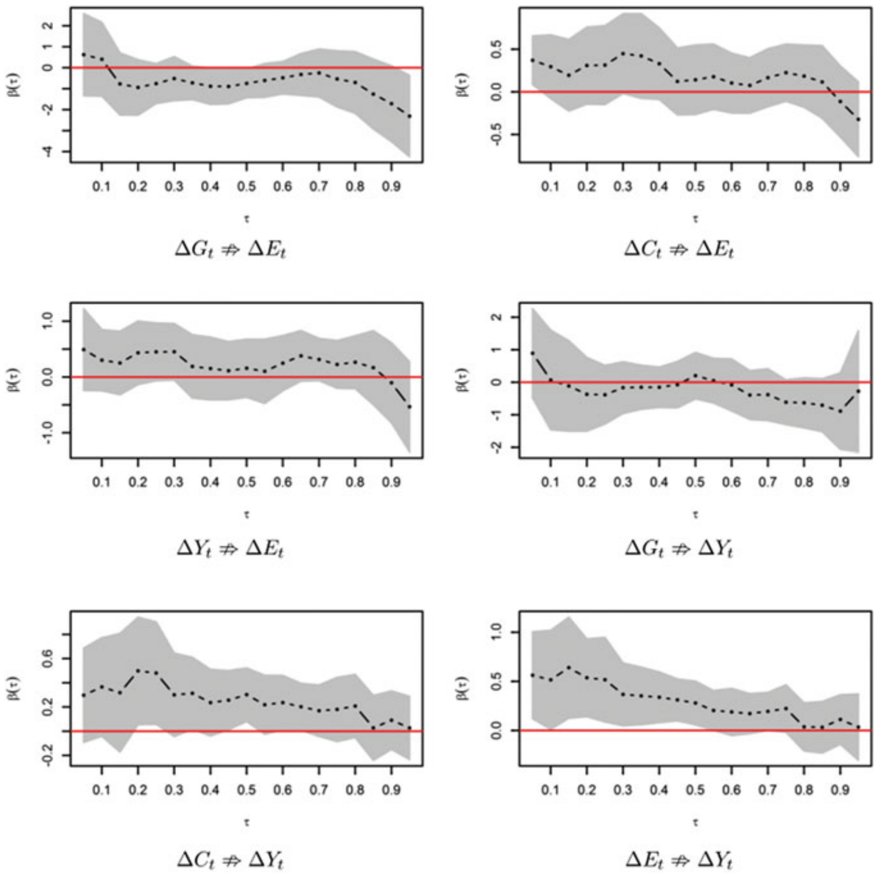

Fig. 1 (continued)

Our findings indicate that only very large decreases in energy use contribute to reductions in CO_2 emissions in the US, although linear tests ignore tail dependence between ΔE_t and ΔC_t. Besides, very large increases in CO_2 emissions (at an upper-tail quantile of $\tau = 0.80$) positively affect changes in energy use. Further, both linear and quantile-causality tests fail to support the EKC as economic growth does not significantly affect changes in CO_2 emissions in the US. Conversely, we find that changes in CO_2 emissions positively affect economic growth at the quantiles $\tau = \{0.35, 0.85\}$. We also find that reductions in energy use positively affect economic growth in the US. However, there are no significant causal effects of economic growth to changes in energy use in the US.

Table 6 Semi-parametric test of quantile-causality: ΔG_t and ΔC_t

τ	$\Delta C_t \nRightarrow \Delta G_t$	$\Delta E_t \nRightarrow \Delta G_t$	$\Delta Y_t \nRightarrow \Delta G_t$	$\Delta G_t \nRightarrow \Delta C_t$	$\Delta E_t \nRightarrow \Delta C_t$	$\Delta Y_t \nRightarrow \Delta C_t$
[0.05; 0.95]	0.364	0.727	0.318	0.136	0.136	0.318
0.05	0.545	0.545	0.500	0.727	1.000	0.636
0.10	0.591	0.409	0.273	0.318	0.864	0.500
0.15	0.318	0.182	**0.045**	0.091	0.409	0.182
0.20	0.318	0.545	0.364	0.091	0.318	0.318
0.25	0.136	0.136	0.318	1.000	1.000	1.000
0.30	0.591	1.000	0.227	1.000	0.682	1.000
0.35	0.682	0.773	0.636	0.955	0.818	1.000
0.40	0.182	0.455	1.000	0.182	1.000	0.591
0.45	0.318	0.227	0.273	0.455	0.455	0.409
0.50	0.273	1.000	1.000	0.227	0.091	0.591
0.55	0.500	1.000	0.636	0.136	0.091	0.545
0.60	0.409	0.273	0.682	0.273	0.182	0.409
0.65	0.591	0.864	0.273	0.091	0.727	0.273
0.70	0.773	0.727	1.000	**0.045**	1.000	0.091
0.75	0.727	0.727	0.273	0.409	0.136	0.091
0.80	0.182	0.182	0.318	0.409	0.455	1.000
0.85	**0.045**	**0.045**	**0.045**	0.318	0.091	0.409
0.90	**0.045**	**0.045**	0.091	1.000	0.182	0.182
0.95	1.000	1.000	1.000	0.500	0.455	1.000

Notes We calculate the p-values of the semi-parametric quantile-causality test S_N in Eq. (8), where boldface values indicate rejection of H_0 in Eq. (6) at the 5% level. We estimate a quantile regression model $M(\mathcal{F}_{t-1}^{Y}, \mathcal{F}_{t-1}^{Z}, \mathcal{F}_{t-1}^{W}, \theta(\tau)) = \alpha(\tau) + \gamma_1(\tau)Y_{t-1} + \delta_1(\tau)Z_{t-1} + \phi_1(\tau)W_{t-1}$, under H_0 that X_t does not Granger-cause Y_t in Eq. (6)

5 Concluding Remarks

This chapter uncovers the dynamics between globalization, economic growth, energy use, and CO_2 emissions in the US over the period of 1970–2014. We analyze the relationship between globalization and CO_2 emissions across the entire conditional distribution. We consider nonlinear and causal relationships in the tails as they may be ignored by linear causality tests. Our proposed method presents a more accurate pattern of causality associated with different CO_2 emission regimes (normal, bad, and good).

Our results indicate significant bidirectional linear causality between variations in the globalization index and changes in CO_2 emissions at the 5% level. The quantile-causality test results show that increases in trade openness negatively affect changes

Table 7 Semi-parametric test of quantile-causality: ΔE_t and ΔY_t

τ	$\Delta G_t \nRightarrow \Delta E_t$	$\Delta C_t \nRightarrow \Delta E_t$	$\Delta Y_t \nRightarrow \Delta E_t$	$\Delta G_t \nRightarrow \Delta Y_t$	$\Delta C_t \nRightarrow \Delta Y_t$	$\Delta E_t \nRightarrow \Delta Y_t$
[0.05; 0.95]	1.000	0.591	0.455	0.182	**0.045**	**0.045**
0.05	1.000	0.364	1.000	0.682	0.636	0.727
0.10	0.273	0.455	1.000	0.773	0.864	0.864
0.15	1.000	1.000	0.136	0.136	1.000	1.000
0.20	1.000	1.000	0.727	0.864	1.000	0.818
0.25	1.000	0.136	0.136	0.409	0.591	0.318
0.30	0.955	1.000	0.500	0.136	0.227	0.136
0.35	0.955	0.318	1.000	**0.045**	**0.045**	**0.045**
0.40	0.682	0.318	1.000	0.227	0.091	**0.045**
0.45	0.636	0.227	0.682	**0.045**	0.273	0.773
0.50	0.136	1.000	1.000	0.636	1.000	1.000
0.55	0.818	1.000	0.682	0.818	1.000	0.273
0.60	0.909	0.227	0.727	1.000	0.864	0.227
0.65	0.818	0.909	0.773	0.682	0.636	0.545
0.70	1.000	0.500	0.636	1.000	0.864	0.364
0.75	1.000	0.682	0.318	0.909	0.773	0.409
0.80	0.545	**0.045**	**0.045**	1.000	0.136	0.091
0.85	0.455	0.091	0.545	**0.045**	**0.045**	0.909
0.90	0.273	1.000	0.318	0.409	0.636	0.500
0.95	0.955	0.955	0.682	1.000	0.318	0.364

Notes We calculate the p-values of the semi-parametric quantile-causality test S_N in Eq. (8), where boldface values indicate rejection of H_0 in Eq. (6) at the 5% level. We estimate a quantile regression model $M(\mathcal{F}^Y_{t-1}, \mathcal{F}^Z_{t-1}, \mathcal{F}^W_{t-1}, \theta(\tau)) = \alpha(\tau) + \gamma_1(\tau)Y_{t-1} + \delta_1(\tau)Z_{t-1} + \phi_1(\tau)W_{t-1}$, under H_0 that X_t does not Granger-cause Y_t in Eq. (6)

in CO_2 emissions in the US at an upper-tail quantile of $\tau = 0.70$. Conversely, we find weak evidence supporting causality from variations of the globalization index to changes in the GDP *per capita* in the US. Although linear tests fail to uncover Granger-causality from ΔE_t to ΔG_t, quantile-causality tests report positive causality from ΔE_t to ΔG_t at two certain upper-tail quantiles. Finally, we find linear causality from ΔG_t to ΔE_t, and changes in the globalization index negatively alter changes in energy use at the quantiles of $\tau = \{0.45, 0.95\}$.

Very large decreases in energy use contribute to reductions in CO_2 emissions in the US, although linear tests ignore tail dependence between ΔE_t and ΔC_t. Besides, very large increases in CO_2 emissions (at an upper-tail quantile of $\tau = 0.80$) positively affect changes in energy use. Further, both linear and quantile-causality tests fail to support the EKC as economic growth does not significantly affect changes in CO_2 emissions in the US. Conversely, we find that changes in CO_2 emissions positively affect economic growth at the quantiles of $\tau = \{0.35, \ 0.85\}$. We also find that reductions in energy use positively affect the economic growth of the US. Nevertheless, changes in the GDP *per capita* are not followed by changes in energy use in the US.

Therefore, changes in globalization (trade openness) and in energy use are important for the dynamics of CO_2 emissions in the US. We find that economic growth does not significantly contribute to the environmental deterioration in the US. Thus, our results fail to support the EKC in the US. Our findings have relevant implications for policymakers in the US to consider both trade openness (globalization) and energy use as influential variables for promoting sustainable environment policies. The observed causality, from changes in the globalization index and changes in energy use to changes in CO_2 emissions, calls for policies for promoting the efficiency in energy use and for importing technologies that reduce the level of CO_2 emissions in the US. For example, Hirschl [35] and Apergis and Payne [5], among others, suggest fostering markets of certificates of tradeable renewable energy and to share information on technologies across countries. In addition, the improvement of a renewable energy market in the US may help decrease their reliance on polluting energies like oil, enabling the US to improve their environmental quality by reducing the level of CO_2 emissions.

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Appendix

See Fig. 1.

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The Role of Energy Innovation and Corruption in Carbon Emissions: Evidence Based on the EKC Hypothesis

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Abstract This study investigates how energy innovations and corruption affect carbon emissions. To this end, a panel data model of 16 selected OECD countries is employed, spanning the period of 1995–2016. The empirical framework falls within the hypothesis of the environmental Kuznets curve (EKC), which explores the relationship between the economic growth and carbon emissions. The empirical results show that when economic systems interact with corruption, positive effects that energy innovations have on environmental quality are reduced. Furthermore, the amount of economic growth needed to limit environmental pollution levels is also distorted. Corruption seems to be pernicious for the environment in the long term, as it limits the stage at which decontamination occurs; i.e., corruption reduces the positive effect generated by measures focused on energy innovation in terms of reducing environmental pollution. These findings are expected to be significant in terms of implementing anti-corruption measures and effective environmental policies, and they call for appropriate policy measures that might limit the effects of corruption on environmental quality.

Keywords Corruption · Energy innovations · Environmental Kuznets curve

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1 Introduction

The effects of economic growth of sustainability and environment degradation have been examined since the 1970s [76]. Increased levels of economic activity require more input and produce more waste, which in turn compromises environmental quality. This focus shifted in the 1990s to the theoretical and empirical study of the environmental effects of economic growth [40, 41, 85, 103]. Currently, the relationship between environmental degradation and economic activity is a central key for understanding the global climate change and for controlling greenhouse gas (GHG) emissions [4]. Over the last decades, many studies have explored the nexus between economic growth and environmental degradation. The link between economic growth and environmental degradation has become a priority of sustainable economic growth. Many studies have explored this relationship by employing the environmental Kuznets curve (EKC) framework. Furthermore, concern with greenhouse gas emissions, which have doubled over the last three decades, and with constant fluctuations in the price of fossil fuels has encouraged several countries to increase investments in energy innovation processes ([14, 4]).

Various studies consider corruption to be a central factor that affects environmental quality [71, 119], where corruption and environmental problems have been great challenges to sustainable economic development [120, 124, 125]. Corruption is understood as "*the abuse of public roles or resources for private benefit*" [56]. Corruption can appear in different forms and takes on different meanings in different contexts, through which it reflects the decline of contextual and sectoral challenges [115].[1] In contrast, the presence of corruption reduces social and economic costs of breaking rules previously established, while private benefits are prioritized at the expense of socially optimal outcomes [33, 121]. This behavior increases awareness of the economic value of climate initiatives, which highlight the awkward economic incentives that drive corruption [94, 95, 65, 99]. Several methodologies have emerged over the past decades to specify the levels of corruption aiming to increase awareness regarding its presence and to monitor the success of anti-corruption initiatives [59]. Positive steps that many governments, intergovernmental organizations, nongovernmental organizations, and businesses have taken are also being recognized. Across all sectors of environmental governance, successful anti-corruption initiatives have resulted in reforming the decision-making mechanisms to increase the levels of accountability and transparency and in new regulatory frameworks [114]. When policy-makers implement regulatory measures concerning energy research development and demonstration (RD&D), the presence of corruption limits the levels of expected effectiveness, efficiency, and equity [61]. Previous literature has given marginal attention to the connection between the levels of governance quality and

[1] The 2012 United Nations Conference on Sustainable Development (or the Rio+20 Conference) recognised corruption as an impediment to effective environmental stewardship: "Corruption is a serious barrier to effective resource mobilization and allocation and diverts resources away from activities that are vital for poverty eradication, the fight against hunger and sustainable development" [114].

energy innovations. Precisely, to explore the role of public regulations over innovations, it is required to comprehend how institutions and political factors influence the results of innovation. Our study focuses on analyzing the energy–environmental area, where the public intervention is motivated by the existence of environmental and innovations externalities (connected with private and social returns to innovation). We assume that energy R&D entails large-scale projects, where it is necessary to consider the existence of a public support [6].

Taking the above into account, the aim of this study is to explore the effects of corruption and energy innovations on carbon emissions. To this end, a panel data model is used to incorporate a dampening variable containing the interaction between public expenses dedicated to RD&D and corruption. The study also treats additional variables applied in the modeling approach that are linked to electricity consumption to explore how they affect environmental quality. Although the environmental Kuznets curve (EKC) scheme has been widely examined, a number of studies have noted the limits of the EKC hypothesis in terms of reaching unanimous results. This study represents, to the best of our knowledge, a first attempt to determine the interactions between energy innovation and corruption in terms of carbon emissions function. Our research underlines the significance of analyzing the impact corruption might have over public expenses for energy RD&D activities and how it affects the relationship between greenhouse gas per capita emissions (GHGpc) and per capita income (GDPpc). This indirect effect is justified by the fact that economic growth may not directly lead to higher levels of environmental quality, although strong pressures to apply effective environmental policies may help [41]. In other words, given that corruption mitigates the negative effects of innovations on carbon emissions, it seems that by integrating active anti-corruption policies improvements in environmental quality would be experienced. Hence, the study also considers indirect effects of corruption on per capita income and carbon emissions.

The rest of this study is organized as follows. Section 2 presents a brief description of relevant literature on the link between corruption, economic growth, and environmental degradation. Section 3 provides the description of the methodology and the model employed, the empirical approach is presented in Sect. 4, and Sect. 5 provides the empirical results with a discussion. Finally, Sect. 6 concludes and provides some policy recommendations and lines for future research.

2 Literature Review

We divide our literature review based on two lines of research focused on (i) the corruption–emissions nexus and (ii) the energy innovation–emissions nexus. For the first strand, previous research on the impacts of corruption on emissions can be divided into two areas, i.e., direct and indirect effects [9, 20, 22, 23, 83, 95, 125]. The first part of this literature review focuses on the damaging effects of corruption on economic growth and environment, where some studies consider the direct effects of corruption on carbon emissions [24, 83, 20]. On the other hand, a number of studies prove that corruption has negative impacts on the economic growth while it negatively affects competitiveness and results in imbalanced expenditures, misguides market incentives, and poor allocations of national resources [3, 75, 78]. These studies show indirect effects of corruption on carbon emissions [22, 43, 63, 9], where corruption may limit economic development [125]. Others highlight that corruption decreases private investments, which in turn decrease the efficiency of public investment expenditures and slow down economic growth [42, 79]. As a result, corruption seems to play a significant role by limiting growth and investment, and by leading to inefficient public investments. Others consider the positive effects of corruption on economic growth in that corruption intensifies the organizational efficiency of administration authorities while decreasing transaction costs, which positively influence economic growth, with political bribery leading to shortened political processes where optimal levels of corruption may be relatively low, while anti-corruption efforts place costs on the system and on society [2, 72]. Similarly, Fredriksson et al. [33] affirm that corruption, as reflected by a government's willingness to allow lobby groups to influence the determination of energy policies, can reduce the rigidity of energy policies. Therefore, the role of corruption in environmental degradation emerges as a complex issue due to different measures of corruption and different levels of economic development on one hand and of emissions on the other [125].

By contrast, corruption is linked to environmental quality in several ways. In particular, the improved quality of institutions may benefit not only environmental quality levels but also economic growth, thus creating a double dividend of improved societal welfare where any discrepancy in environmental policies could be explained by corruption itself. Therefore, low levels of institutional quality could imply lower environmental standards [18, 85–95]. Corruption can also affect the levels of environmental pollution through direct and indirect channels. In terms of direct channels, corruption leads to environmental degradation; i.e., corruption levels increase and spurs the delayed development and implementation of environmental policies because of bribes accepted by corrupted officials; consequently, carbon emissions levels increase, which in turn deteriorates environment quality. Therefore, corruption creates barriers to the application of improved management and protection schemes, distorting the designed structure of economic incentives and leading to an unfair allocation of benefits derived from RD&D activities. Regarding indirect channels, a negative relationship exists between corruption and carbon emissions, which shows that economies reduce their pollution levels by decreasing productivity levels due to the presence of high levels of corruption [9, 22, 75, 117]. Aparicio et al. [9] demonstrated that the control of corruption is fundamental to generating incentives for entrepreneurship opportunities and has positive impacts on economic growth. In addition, any decrease in corruption levels is expected to lead to high growth rates, which also improve environmental policies [23, 24, 65]. Concerning the effects of corruption, this study analyzes how corruption slows economic growth by mitigating net effects on energy innovations in regard to environmental pollution [24, 34, 35]. Hakkala et al. [43] concluded that corruption reduces the probability of a firm investing in a country. In addition, good governance is essential to improving the quality of the environment, which can be achieved by increasing the quality of public and civil services, independence from political pressures, and the quality of policy development and implementation [83].

A second strand of literature on which our research is based highlights the impacts of energy innovations on carbon emissions [64, 67, 110]. Technical progress refers to any improvements made to the production process that result in the less intensive use of inputs and/or in the adoption of less polluting technologies, while others define this variable as a fundamental driving force [26, 45]. A wealthy society can afford to spend more on energy RD&D, as, in such a society, technological progress occurs in conjunction with economic growth [61]. Technical effects suggest that certain improvements in technology allow for the use of fewer inputs per unit of output or for the adoption of cleaner technologies in place of obsolescent polluting ones. These innovation measures offer an additional explanation backed by endogenous theory that changes in the income/environment nexus which could be attributed to improvements in the production process supported by technological changes [17, 39, 7]. If it is assumed that environmental pollution is a negative externality, then the empirical evidence suggests the existence of a relationship between low-carbon technological innovations and the reduction of environmental pollution levels [15, 46]. Andreoni and Levinson [7] showed that decontamination processes are mainly dependent on investments made in energy innovation processes that help reduce levels of environmental pollution. Technical innovations improve levels of environmental quality at lower incomes levels, such that reforms and institutional changes are necessary [12, 116]. According to this premise, numerous studies have analyzed the positive effects of energy innovations on carbon emissions [8, 14, 111]; ([7], among others). In addition, some extended versions of the EKC have considered that technological impacts are essential for environmental correction process [5, 13, 44, 48]. He and Jiang [44] and Álvarez et al. [5] found a positive relationship between technical innovations and environmental quality. Huang [48] analyzed the relationship between the Porter Hypothesis[2] and the EKC and concluded that the evolution of the Porter hypothesis is also dependent on economic growth, which is compatible with the EKC. Baiardi [13] investigated the long-term influence of innovation on EKC and found that innovation influences the EKC directly and indirectly in close relation to economic growth. In addition, we also consider in our analysis the impact that the corruption perception index exerts over energy innovation processes. Some studies find that innovation is conditioned by policy-maker decisions and the quality of the organizations' governance [6, 36, 49]. Moreover, the institutional quality is affecting by the regulations and government policies [107]. The efforts in new technologies are shaped by the incentives and regulations managed by policy-makers [69].

Finally, this study is also relevant to the strand of the literature that considers the role of electricity consumption. It is widely accepted that the elevated share of fossil energy sources in the energy mix directly increases carbon emissions [53, 106]. Several studies show that high levels of economic growth led by energy consumption

[2]Porter and van der Linde [98] suggest that strict environmental regulation triggers the innovation and introduction of cleaner technologies and environmental improvements through the innovation effect, rendering production processes and products more efficient.

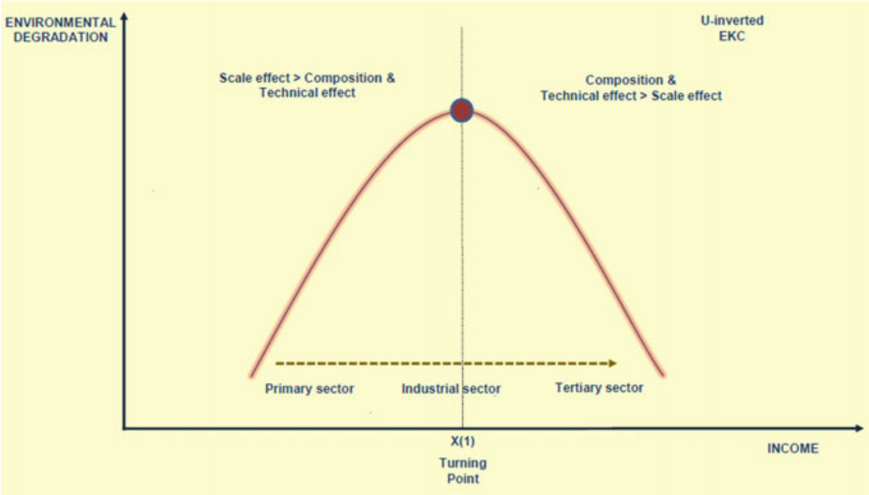

Fig. 1 The EKC Inverted-U relationship: the scale, the composition and the technical effect. *Source* Own elaboration based on Grossman and Krueger [40]. This figure illustrates how economic growth affects the quality of the environment based on three different channels: scale, composition, and technical effects

can facilitate the development of very high levels of carbon emissions [47, 82, 87]. Other researchers underline that economic growth that leads to a rise in demand for energy consumption also contributes to environmental pollution and deterioration [1, 10, 11, 29, 54, 58, 84, 105].

The pioneer work of Grossman and Krueger [40] analyzes the relationship between economic growth and environmental degradation based on what is generally known as the environmental Kuznets curve (EKC) hypothesis.[3] This hypothesis states that an initial increase in per capita income ends up in the degradation of the environment by increasing emissions [41, 85, 100, 102]. With higher growth rates in the economy overtime, when income levels are sufficiently high, society demands a cleaner and healthier environment, which decreases environmental degradation. Thus, an inverted-U shaped curve known as environmental Kuznets curve (Fig. 1) is produced.

The first stage of development corresponds to an early stage of economic growth, whereby environmental degradation increases when the structure of the economy changes from rural to urban or from agricultural to industrial. This phase is typ-

[3] The first set of empirical EKC studies appeared independently in three working papers: an NBER working paper as part of a study on the environmental impacts of NAFTA [40], the World Bank's 1992 World Development Report [103], and a Development Discussion paper as part of a study developed for the International Labour Organization [85]. Kuznets' name was attached to the inverted U-relationship between pollution and economic development later on due to its resemblance to Kuznets' [62] inverted-U relationship between income inequality and economic development. However, Panayotou [85] first coined it as the environmental Kuznets curve.

ical for developing countries with high growth rates. During this stage, the economy increases its output requirements with more natural resources being used during the production process. In other words, the economic growth exhibits a *scale effect* that has a negative impact on environment, as extra outputs imply the development of more waste and emissions reducing environmental quality. After this initial stage of growth, new and cleaner technologies replace their polluting and obsolete counterparts. This new scenario improves both the levels of environmental quality and growth rates, which in turn has a positive impact on environmental quality via *composition* and *technical* effects. At this stage, structural changes regarding the development of technological-intensive industries and services take place, linked to increased levels of environmental awareness, the enforcement of environmental regulations, the development of advanced technologies, and the application of higher environmental expenditures, resulting in the gradual decline of environmental degradation. In addition, structural changes involve a transition phase from a focus on production-intensive industries to services, the latest being less polluting [85]. Any strategy that seeks to reduce contamination levels must assume increasing returns to scale. Andreoni and Levinson (1998) propose that decontamination processes depend mainly on technological factors; as consumption implies contamination, energy innovation budgets linked to decontamination should lead to reductions in such contamination levels. Selden and Song [100] admit that better-executed measures for environmental correction lower levels of income are needed to improve environmental quality. Consequently, EKC-stylized facts suggest the presence of negative impacts on environmental quality when scale effects prevail during initial stages of economic growth, but these impacts are eventually outweighed by the positive impacts of the composition and technical effects of lower emissions [5, 118].

Figure 2 shows an N-shaped EKC's behavioral pattern. With the increase in income levels, in early stages of economic growth, pollution levels also rise. Once they reach the first turning point, they begin to experience corrections in their emissions. In a second stage, a reduction in pollution levels is present, while incomes are also increasing.

Balsalobre and Álvarez-Herranz [14] pointed out an additional long-term effect defined as the *technical obsolesce effect* (Fig. 2). This effect appears when innovation activities are limited or when they do not take place at the level they should, leading to the development of a new stage, wherein scale effects overcome composition and technical effects. To address this limitation, energy innovation efforts should be intensified to avoid this new path toward increased contamination levels. This behavior is sustained until the second turning phase where the pollution is increasing again. Hence, a long-term relationship between economic growth and environmental degradation is depicted by the EKC hypothesis.

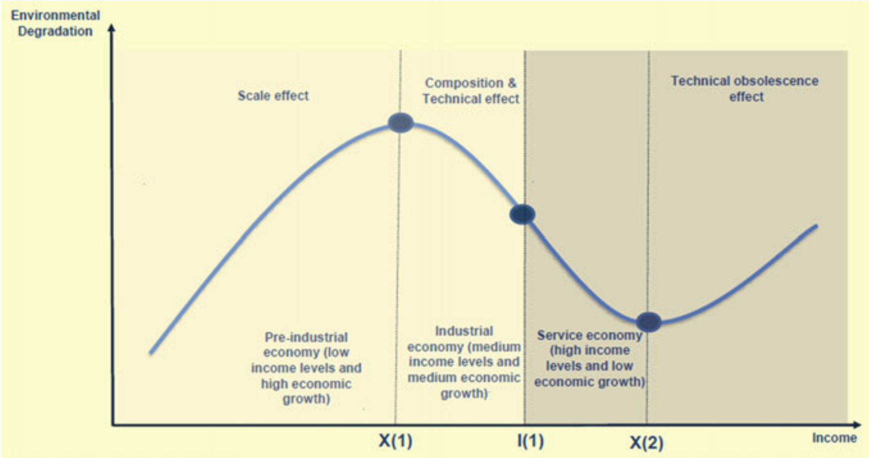

Fig. 2 Technical obsolescence effect of the N- shaped EKC model. *Source* Own elaboration

3 Empirical Model

This study employs the reduced form of the EKC model (Eq. 1) to test the presence of any potential relationship between economic growth and environmental degradation:

$$\mathrm{ED}_{it} = \alpha_{it} + \beta_1 \mathrm{GDPpc}_{it} + \beta_2 \mathrm{GDPpc}_{it}^2 + \beta_3 \mathrm{GDPpc}_{it}^3 + \beta_4 Z_{it} + \varepsilon_{it}, \tag{1}$$

where *ED* refers to environmental degradation, GDPpc is per capita income, and Z_{it} denotes a vector defining other factors that can potentially drive environmental degradation. Coefficient α denotes the average levels of environmental degradation measured when income has no special relevance to environmental quality, while coefficient β represents the relative importance of exogenous variables; e_{it} is the error term, which is normally distributed with a zero mean and with constant variance. Sub-index *i* denotes country *i*, and *t* denotes the time dimension. The relationship between income and a measure of environmental quality is not monotonic and may present different shapes. Many studies that consider the link between economic growth and environmental degradation recommend the use of an inverted-U relationship (Fig. 1) [40, 100, 102]; (Panayotou 1997). The EKC model can identify different relationships between income and environmental degradation depending on the values of β_1, β_2, and β_3 coefficients.[4] The EKC may not hold even in the long run [26]. The so-

[4] $\beta_1 = \beta_2 = \beta_3 = 0$ denotes a flat pattern or no relationship between *x* and *y*. $\beta_1 > 0$, $\beta_2 = \beta_3 = 0$ denotes a monotonic increasing relationship or a linear relationship between *x* and *y*. $\beta_1 < 0$, $\beta_2 = \beta_3 = 0$ denotes a monotonic decreasing relationship between *x* and *y*. $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 = 0$ denotes an inverted-U relationship, i.e., EKC. $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 = 0$ supports a U-shaped relationship, while $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$ denotes a N-shaped curve. Finally, $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$ supports an inverted-N relationship.

called N-shaped curve, as illustrated by Fig. 2, the initial inverted-U curve, but beyond a certain income level, the relationship between environmental degradation and income becomes positive once again, suggesting that the re-linking hypothesis may be plausible [27, 101].

The EKC's N-shaped behavior illustrates how an economy that reaches a certain income level (i.e., first turning point) also experiences a decrease in its environmental pollution levels with continued growth in income. Among the different shapes of the EKC, this study focuses on the N-shaped relationship between economic growth and environmental degradation [41, 68, 111]. This N-shaped pattern considers the fact that technological improvements are very expensive, with net environmental degradation resulting from increased incomes. An adequate environmental regulation policy could effectively accelerate technological changes capable of decreasing contamination levels [5, 111].

Equation (1) also shows that the EKC model can integrate additional variables, Z_{it}. Conventionally, these additional variables help explaining environmental pollution levels. In this study, such additional variables are linked to corruption, energy consumption, and energy innovation (see appendix). These variables are measured by the corruption perception index (CPI), electricity consumption (EC), and public energy RD&D expenses (E_RDD) as described by Eqs. (2)–(5). Hence, the main goal of the empirical analysis is to validate interactions between corruption and energy RD&D (Eqs. 4 and 5) and between corruption and GDPpc (Eq. 5). The results allow us to confirm the negative effects of corruption on environmental quality given the reduction of positive impacts of energy innovations on carbon emissions.

A *fixed effect panel data* model based on data from 16 OECD countries[5] for 1995–2015 is employed (Table 1). Fixed effects *panel data* are adequate when non-observable heterogeneities are present in any specific country or during a particular time period. This non-observed heterogeneity is associated with each country (errors are deterministic) and does not behave randomly. To demonstrate that corruption reduces positive effects of energy innovations on environmental quality, Eq. (2) has to omit the variable CPI to isolate the effect of corruption over the N-shaped relationship between economic growth and environmental degradation:

$$\mathrm{GHG}_{it} = \alpha_{it} + \beta_1 \mathrm{GDP}_{it} + \beta_2 \mathrm{GDP}_{it}^2 + \beta_3 \mathrm{GDP}_{it}^3 + \beta_4 \mathrm{E\_RDD}_{it} + \beta_5 \mathrm{EC}_{it} + \varepsilon_{it} \tag{2}$$

Equation (3) omits the variables that reflect the interaction between CPI and energy innovations (CPI * E_RDD) and CPI and economic growth (CPI * GDPpc), while Eq. (4) omits the interaction between economic growth and CPI:

$$\begin{aligned}\mathrm{GHG}_{it} = \alpha_{it} + \beta_1 \mathrm{GDP}_{it} + \beta_2 \mathrm{GDP}_{it}^2 + \beta_3 \mathrm{GDP}_{it}^3 \\ + \beta_4 \mathrm{E\_RDD}_{it} + \beta_5 \mathrm{EC}_{it} + \beta_6 \mathrm{CPI}_{it} + \beta_7 \mathrm{CPI}_{it}^2 + \varepsilon_{it}\end{aligned} \tag{3}$$

[5]Austria, Canada, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the UK, and the USA.

Table 1 Main statistics and Correlation matrix

	GHG	GDP	EC	E_RDD	CPI
Main statistics					
Mean	11.61820	32,271.75	9017.727	670.6688	70.07867
Median	10.77100	31,526.25	7025.834	149.8620	70.40000
Maximum	25.62500	66,954.32	25,590.69	10,635.12	82.60000
Minimum	4.126000	8608.417	1227.328	1.935000	50.60000
Std. dev.	4.89874	10,884.86	5486.633	1321.207	6.689786
Skewness	1.26732	0.388776	1.325447	3.210920	−0.193176
Kurtosis	4.200436	3.296405	4.149958	15.77281	2.374096
Jarque–Bera	118.3097	10.41549	125.5926	3074.2870	8.137915
Probability	0.000000	0.005474	0.000000	0.000000	0.017095
Correlation matrix					
GHG	1.000000				
GDP	0.259272	1.000000			
EC	0.247637	0.402085	1.000000		
E_RDD	0.429336	0.228630	−0.114577	1.000000	
CPI	0.481035	0.630236	0.262186	0.209241	1.000000

$$\begin{aligned}\mathrm{GHG}_{it} &= \alpha_{it} + \beta_1\mathrm{GDP}_{it} + \beta_2\mathrm{GDP}_{it}^2 + \beta_3\mathrm{GDP}_{it}^3 + \beta_4\mathrm{E\_RDD}_{it}\\ &\quad + \beta_5\mathrm{EC}_{it} + \beta_6\mathrm{CPI}_{it} + \beta_7\mathrm{CPI}_{it}^2 + \beta_8\mathrm{CPI}_{i*}\mathrm{E\_RDD}_{it} + \varepsilon_{it}\end{aligned} \tag{4}$$

As main model, Eq. (5) contains both the interaction between corruption (CPI) and energy innovations [38, 80] and the interaction between CPI and economic growth (CPI * GDPpc):

$$\begin{aligned}\mathrm{GHG}_{it} &= \alpha_{it} + \beta_1\mathrm{GDP}_{it} + \beta_2\mathrm{GDP}_{it}^2 + \beta_3\mathrm{GDP}_{it}^3 + \beta_4\mathrm{E\_RDD}_{it} + \beta_5\mathrm{EC}_{it}\\ &\quad + \beta_6\mathrm{CPI}_{it} + \beta_7\mathrm{CPI}_{it}^2 + \beta_8\mathrm{CPI}_{i*}\mathrm{E\_RDD}_{it} + \beta_9\mathrm{CPI}_{i*}\mathrm{GDP} + \varepsilon_{it}\end{aligned} \tag{5}$$

Some studies prove that corruption contributes to the development of environmentally damaging policies and practices and to the unfair allocation of environmental resources so that corruption inspires harmful practices [122]. In addition, corruption may render environmental policies difficult to carry out and may then affect CO_2 emissions [125].

Coefficient β_9 in Eq. (5) measures the interaction effect of CPI_{it} on GPDpc_{it} and moderating effects on GHGpc_{it}. We now consider potential two-way causality between GDPpc and environmental degradation [108, 121].

The main hypothesis to be tested is as follows:

H_0: Corruption diminishes the positive effects of energy innovation on carbon emissions.
H_1: Corruption diminishes the economic growth, affecting indirectly to GHG emissions.

4 Empirical Approach

To validate our main hypotheses, a four-step empirical methodology is employed. First, we examine the stationarity properties of the series in panel dataset through (Levin et al. [66]; (LLC), Im et al. [52]; IPS) unit root tests in order to evaluate the stationary of the variables. Second, the Pedroni [92], Kao [57], and Johansen's [55] Fisher panel cointegration is applied to scrutinize the long-run relationship among variables [74]. The third step involves using a fully modify ordinary least square (FMOLS) as convenient long-run estimation, to solve endogeneity problem. Finally, to check the relationship among selected variables, the Dumitrescu–Hurlin panel causality tests are used.

To check stationarity among variables, we consider a panel unit root test, as follows:

$$\Delta y_{it} = \varphi_{it\beta_{i,t-1}} + \rho * y_{i,t-1} + \sum_{j=1}^{ni} \varphi_{ij} \Delta y_{i,t-j} + \varepsilon_{it} \tag{6}$$

If results confirm that the variables are $I(1)$, according to the *p values* (Table 2), all the series are non-stationary at levels, and thus, the null hypothesis is accepted, stating that all the series hold a panel unit root and are stationary. In advance, we reject the null hypothesis, at their first difference, which stands for the integration at $I(1)$. Once we have confirmed that all variables are $I(1)$, to validate the long-run relationships among the variables, the proposed panel cointegration test is applied. Table 3 presents the results obtained from Pedroni [88], Kao [57], and Johansen's [55] Fisher cointegration tests. Pedroni [88, 92] and Kao [57] extend the Engle–Granger framework to tests involving panel data.[6] Equation (7) represents Pedroni [88] cointegration tests, which tolerates for heterogeneous intercepts and trend coefficients within cross sections, through the following regression:

$$y_{it} = \alpha_{it} + \delta_{it} + \beta_{1i} X_{1,it} + \beta_{2i} X_{2,it} + \cdots + \beta_{Mi} X_{M,it} + \varepsilon_{it} \tag{7}$$

[6]The Engle–Granger (1987) cointegration test is based on an examination of the residuals of a spurious regression performed using $I(1)$ variables. If the variables are cointegrated, then the residuals should be $I(0)$. On the other hand, if the variables are not cointegrated, then the residuals will be $I(1)$.

Table 2 Unit root test analysis

	(A) Null: unit root (assumes common unit root process)		(B) Null: unit root (assumes individual unit root process)					
	Levin, Lin, and Chu t		Im, Pesaran, and Shin W-stat		ADF–Fisher chi-square		PP–Fisher chi-square	
	t-statistic	*P* value	*t*-statistic	*P* value	*t*-statistic	*P* value	*t*-statistic	*P* value
GHG	4.4298	(1.0000)	6.4116	(1.0000)	12.0689	(1.0000)	6.8009	(1.0000)
GDP	−0.2669	(0.3948)	5.0119	(1.0000)	10.2019	(1.0000)	9.6241	(1.0000)
E_RDD	0.6524	(0.7429)	1.5352	(0.9376)	27.2762	(0.9373)	38.5535	(0.5354)
EC	−3.0891*	(0.0010)	0.0484	(0.5193)	44.0316	(0.3049)	44.0316	(0.3049)
CPI	−4.0409*	(0.0000)	−2.0482*	(0.0203)	55.2695**	(0.0547)	58.8218**	(0.0277)
ΔGHG	−4.7787*	(0.0000)	−6.6798*	(0.0000)	121.9410*	(0.0000)	288.9820*	(0.0000)
ΔGDP	−5.3681*	(0.0000)	−6.3712*	(0.0000)	111.7080*	(0.0000)	181.3803*	(0.0000)
ΔE_RDD	−8.2201*	(0.0000)	−8.4767*	(0.0000)	145.7600*	(0.0000)	377.2780*	(0.0000)
ΔEC	−3.5452*	(0.0002)	−4.5984*	(0.0000)	94.1289*	(0.0000)	232.0510*	(0.0000)
ΔCPI	−3.8046*	(0.0001)	−5.60062*	(0.0000)	100.7670*	(0.0000)	217.6030*	(0.0000)

Notes *, **, and *** significance at 1%, 5%, and 10%

Table 3 Cointegration test results: Kao [57], Pedroni [88], and Johansen Fisher

Series: GHG GDP CPI E_RDD EC				
Within-dimension		*t*-statistic	*P value*	
(a) Pedroni residual cointegration test. Newey–West automatic bandwidth selection and Bartlett kernel				
Panel v-statistic		0.0251	(0.4900)	
Panel rho-statistic		0.9541	(0.8300)	
Panel PP-statistic		−3.0343*	(0.0012)	
Panel ADF-statistic		−2.1162*	(0.0172)	
Weighted		*t*-statistic	Prob.	
Panel v-statistic		0.0780	(0.4689)	
Panel rho-statistic		0.8585	(0.8047)	
Panel PP-statistic		−3.6296*	(0.0001)	
Panel ADF-statistic		−1.6878**	(0.0457)	
AR coefs. (between-dimension)		*t*-statistic	*P value*	
Group rho-statistic		2.7240	(0.9968)	
Group PP-statistic		−6.0167*	(0.0000)	
Group ADF-statistic		−0.9830	(0.1628)	
(b) Kao residual cointegration test. Newey–West automatic bandwidth selection and Bartlett kernel				
ADF		−1.7296**	(0.0418)	
Residual variance		0.1874		
HAC variance		0.1481		
(c) Johansen fisher panel cointegration test				
	Hypothesized No. of CE(s) Fisher stat.* (from trace test)	*P value*	Hypothesized No. of CE(s) Fisher stat.* (from max-eigen test)	*P value*
None	395.70*	(0.0000)	260.00*	(0.0000)
At most 1	215.70*	(0.0000)	153.50*	(0.0000)
At most 2	118.60*	(0.0000)	81.31*	(0.0000)
At most 3	88.12*	(0.0000)	70.35*	(0.0001)
At most 4	64.40*	(0.0006)	64.40*	(0.0006)

Note The null hypothesis is no cointegration against the alternative of presence of cointegration for $t = 1, \ldots, T$; $i = 1, \ldots, N$, $m = 1, \ldots, M$, where y and x are expected to be integrated of order 1, e.g., $I(1)$. The parameters α_{it} and δ_{it} reflect the individual and trend effects. The aim is to find residuals from Eq. (7) to test whether residuals are $I(1)$ though the auxiliary regression:

$$\varepsilon_{it} = \rho_i \varepsilon_{i,t-1} + u_{it} \quad (8)$$

$$\varepsilon_{it} = \rho_i \varepsilon_{i,t-1} + \sum_{j=1}^{\rho} \varphi_{ij} \Delta \varepsilon_{i,t-j} + v_{it} \quad (9)$$

for each cross section. Pedroni [88] proposes several methodologies to build statistics to check the null hypothesis of no cointegration ($\rho_i = 1$). Pedroni [88] presents two alternative hypotheses: (a) the homogenous alternative, where $(\rho_i = \rho) < 1$ for all i (the within-dimension test or panel statistics test), and (b) the heterogeneous alternative, $\rho_i < 1$ for all i (the between-dimension or group statistics test). This process also contemplates seven different statistic test, four based on pooling the residuals of the regression along the within-dimension of the panel and the other three based on pooling the residuals along the between-dimension of the panel.

Kao [57] cointegration follows the same methodology but specifies cross-sectional intercepts and homogeneous coefficients on the first-stage regressors. In the bivariate case described in Kao [57], we have:

$$y_{i,t} = \alpha_i + \beta_{1i} X_{1,t} + \varepsilon_{it} \quad (10)$$

or

$$y_{i,t} = y_{1,t-1} + u_{i,t} \quad (11)$$

$$x_{i,t} = x_{1,t-1} + \varepsilon_{i,t} \quad (12)$$

for $t = 1, \ldots, T$; $i = 1, \ldots, N$. More generally, we may consider running the first stage regression (Eq. 7), lacking the α_i to be heterogeneous, β_i to be homogeneous through cross sections and setting all the trend coefficients ρ_i to zero. Kao [57] then runs either the pooled auxiliary regression as follows:

$$\varepsilon_{it} = \rho_i \varepsilon_{i,t-1} + u_{it} \quad (13)$$

or the augmented version of the pooled specification:

$$\varepsilon_{it} = \hat{\rho}_i \varepsilon_{i,t-1} + \sum_{j=1}^{\rho} \varphi_{ij} \Delta \varepsilon_{i,t-j} + v_{it} \quad (14)$$

Under the null of no cointegration, Kao [57] presents that the augmented version ADF test statistic for $\rho > 0$ is:

$$\text{ADF} = \frac{\tau\text{ADF} + \frac{\sqrt{N}\widehat{6\sigma_v}}{2\hat{\sigma}_{0v}}}{\sqrt{\frac{\sigma_{0v}^2}{\widehat{2\sigma_v^2}} + \frac{3\sigma_{vv}^2}{\widehat{10\sigma_{0v}^2}}}} \tag{15}$$

which converges to $N(0, 1)$ asymptotically.

Finally, Johansen-Fisher, combined individual tests, apply Fisher's (1932) result as an alternative approach for testing cointegration, connecting tests from individual cross sections. If Π_i is the *p value* from an individual cointegration test for cross section *i,* then under the null hypothesis for the panel:

$$-2\sum_{i=1}^{N}\log(\Pi_i) \rightarrow \chi^2 2N \tag{16}$$

χ^2 values based on MacKinnon-Haug-Michelis [73] *p* values for Johansen-Fisher's cointegration trace and maximum eigenvalue tests are reported.

In a third step, FMOLS econometric estimation methodology is applied to solve the endogeneity[7] issues, obtaining coefficients simultaneity bias and non-stationary. The FMOLS estimation is a nonparametric approach that provides optimal results from cointegrating regressions [97]. Additionally, it adjusts serial correlation and endogeneity due to the presence of cointegrating relationships [96]. Hence, the following equation was considered:

$$W_{i,t} = \alpha_i + \beta_i X_{i,t} + \varepsilon_{i,t} \quad \forall_t = 1, \ldots, T, \; i = 1, \ldots, N \tag{17}$$

allowing for W_i, and $X_{i,t}$ are cointegrated with slopes β_i.

where

$$W_{i,t} = \alpha_i + \beta_i X_{i,t} + \sum_{k=-K_i}^{K_i} \gamma_{i,k}\Delta X_{i,t-k} + \varepsilon_{i,t} \quad \forall t = 1, 2, \ldots, T, \; i = 1, \ldots, N \tag{18}$$

We assume $\xi_{i,t} = \left(\hat{\varepsilon}_{i,t}, \Delta X_{i,t}\right)$ and $\Omega_{i,t} = \lim_{T\to\infty} E\left[\frac{1}{T}\left(\sum_{i=1}^{T}\xi_{i,t}\right)\left(\sum_{i=1}^{T}\xi_{i,t}\right)\right]$.

The long covariance is divided into $\Omega_i = \Omega_i^0 + \Gamma_i + \Gamma_i'$, where Ω_i^0 is the simultaneous covariance and $+\Gamma_i'$ is a weighted sum of autocovariance. We obtain the FMOLS as:

[7] The problems related to endogeneity between regressors could be solved by using FMOLS [90, 91].

$$\hat{\beta}^*_{\text{FMOLS}} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\sum_{i=1}^{T}(X_{i,t}-\bar{X}_i)^2\right)^{-1}\left(\sum_{i=1}^{T}(X_{i,t}-\bar{X}_i)W^*_{i,t}-T_{\hat{\gamma}_i}\right)\right] \tag{19}$$

where

$$W^*_{i,t} = W^*_{i,t} - \bar{W}_i - \frac{\hat{\Omega}_{2,1,i}}{\hat{\Omega}_{2,2,i}}\Delta X_{i,t} \text{ and } \hat{\gamma}_i = \hat{\Gamma}_{2,1,i} + \hat{\Omega}^0_{2,1,i} - \frac{\hat{\Omega}_{2,1,i}}{\hat{\Omega}_{2,2,i}}\left(\hat{\Gamma}_{2,2,i} + \hat{\Omega}^0_{2,2,i}\right). \tag{20}$$

Finally, for obtaining efficient results also for unbalanced panels, Dumitrescu–Hurlin [30] test is applied as it considers cross-sectional dependence. The heterogeneity of both the regression model and the causal relation is considered in the homogeneous non-causality (*HNC*) hypothesis. The null hypothesis in this case is defined as follows:

$$H_0 : \beta_i = 0; \quad \forall_i = 1, 2, \ldots, N$$

where $\beta_i = \left(\beta_i^{(1)}, \beta_i^{(2)}, \ldots, \beta_i^{(k)}\right)$. The non-causality assumption means some of the individual vectors $\beta_i = 0$. The null hypothesis implies there are $N_1 < N$ individual processes with no causality from x to y. The alternative would be the following:

$$\begin{aligned} H_1 : \beta_i = 0; \ \forall i = 1, 2, \ldots, N_1 \\ \beta_i \neq 0; \quad \forall i = N_1 + 1, \ldots, N \end{aligned}$$

$0 \leq N_1/N < 1$ and N_1 is unknown. When $N_1 = N$ and N_1/N is inevitably less than 1, there is no causality for any of the individuals in the panel. Contrariwise, for $N_1 = 0$, causality is detected for all the individuals in the panel. On the other hand, when the null hypothesis is rejected, and $N_1 = 0$, X Granger causes Y for all the panel. To test null hypothesis, Wald statistics ($W_{i,T}$) are estimated for each of the cross sections and then averaged for each individual aiming at finding out panel Wald statistic $\left(W^{\text{HNC}}_{N,T}\right)$. Dumitrescu and Hurlin [30] also apply $Z^{\text{HNC}}_{N,T}$ statistic. When $T > N$ and use Z^{HNC}_{N} statistic when $T < N$.

$$Z^{\text{HNC}}_{N,T} = \sqrt{\frac{N}{2K}\left(W^{\text{HNC}}_{N,T} - K\right)} \tag{21}$$

$$Z^{\text{HNC}}_{N} = \frac{\sqrt{N\left[W^{\text{HNC}}_{N,T} - N^{-1}\sum_{i=1}^{N} E\left(W_{i,T}\right)\right]}}{\sqrt{N^{-1}\sum_{i=1}^{N}\text{Var}\left(W_{i,T}\right)}} \tag{22}$$

Therefore, by using Dumitrescu and Hurlin [30] test, two variables are examined and the expected results are whether unidirectional causality ($X \rightarrow Y$, or $Y \rightarrow X$), bidirectional causality ($X \leftrightarrow Y$), or no causality ($X \neq Y$).

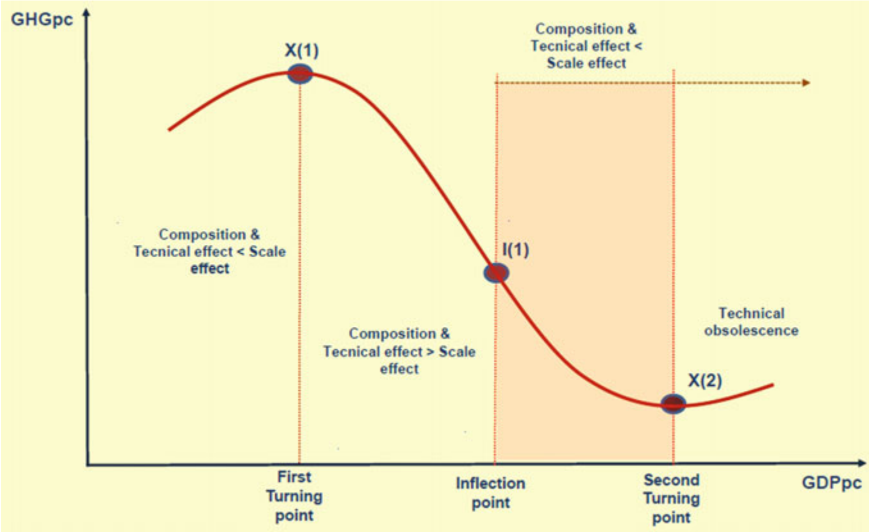

Fig. 3 Inflection point in an N-shaped EKC pattern. *Source* Based in Balsalobre-Lorente et al. [16]

5 Empirical Results

Though Levin, Lin & Chu (LLC), Im, Pesaran, and Shin (IPS), ADF—Fisher (ADF) and PP-Fisher unit root tests, we present in Table 2 evidence of stationarity of variables. The applied tests do not reject the null hypothesis of non-stationarity of selected variables (all variables are integrated of order 1, e.g., $I(1)$. However, the proposed Pedroni [88], Kao [57], and Johansen's [55] Fisher panel cointegration tests (Table 3) validate the long-run relationship among variables.

Table 4 presents the FMOLS econometric estimation results, confirming the existence of an N-shaped EKC's relationship between economic growth and environmental degradation. The coefficients obtained from the equations proposed (Eqs. 2–5) are significant and confirm an N-shaped EKC's pattern in line with Grossman and Krueger [41], de Bruyn and Opschoor [27], Sengupta [101], Diao et al. [28], Balsalobre and Álvarez-Herranz [14], or Khan et al. [60].

The EKC's N-shaped behavior corresponds with coefficients $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$, which assume that during the first stage of economic growth, carbon emissions increase to the first turning point ($X1$). Below this first turning point, a decrease in the emissions levels of the countries analyzed are experienced $X(2)$. Generally, in developed economies, growth rates are lower than in developing systems, where technical obsolescence is near to overcome the technical effect [16]. This situation suggests that is essential to increase innovation's efforts to keep a market economy on a socially optimal path. Figure 3 reflects this deceleration of economic growth and the transition to technical obsolescence through the inflection point [16].

Table 4 Panel fully modified least squares (FMOLS) estimation

Dependent variable: GHGPC				
Variable	Equation (2)	Equation (3)	Equation (4)	Equation (5)
GDPPC	0.00065*	0.000811*	0.000794*	0.000897*
	[7.032]	[9.255]	[9.879]	[12.413]
$GDPPC^2$	−2.12E−08*	−2.60E−08*	−2.56E−08*	−2.20E−08*
	[−9.534]	[−12.327]	[−13.234]	[−12.165]
$GDPPC^3$	1.70E−13*	2.08E−13*	2.06E−13*	1.85E−13*
	[9.7111]	[12.548]	[13.542	[13.631]
E_RDD	−0.000627*	−0.000558*	−0.001993*	−0.001771*
	[−14.795]	[−14.231]	[−5.084]	[−5.250]
EC	0.000889*	0.000919*	0.000920*	0.000923*
	[19.771]	[22.621]	[24.726]	[29.270]
CPI		−0.381839*	−0.316641*	−0.541990*
		[−5.021]	[−4.444]	[−6.809]
CPI^2		0.003039*	0.002480*	0.005164*
		[5.497]	[4.740]	[6.854]
CPI * E_RDD		–	1.91E−05*	1.66E−05*
		–	[3.700]	[3.764]
CPI * GDPPC		–	–	−4.07E−06*
		–		[−4.548]
R-squared	0.9764	0.9770	0.9771	0.9773
Adjusted *R*-squared	0.9746	0.9750	0.9751	0.9752
S.E. of regression	0.7817	0.7752	0.7738	0.7723
Long-run variance	0.1129	0.0901	0.0753	0.05391
Mean dependent var	11.5945	11.5945	11.5945	11.5945
S.D. dependent var	4.9118	4.9118	4.91187	4.9118
Sum squared resid	190.6499	186.3370	185.0615	183.7274

Notes *, **, and *** significance at 1%, 5%, and 10%

Figures 2 and 3 illustrate how, in the long run, scale effect overcomes composition and technical effect. This process contributes to explain the technical obsolescence, and how without a suitable policy regulation economic system can reach a new stage of ascending emission levels. The inflection point (Fig. 3) reveals the level of income where economic systems need to increase innovation measures to delay scale effect and in addition the technical obsolescence [16]. In other words, when scale effect overcomes composition and technical effects, the environmental degradation emerges again, via technical obsolescence. The stage between the first and the second turning point is characterized by decreasing per capita emissions, while societies are experiencing a reduction in growth rates, (inflection point X'), which is enlarged till

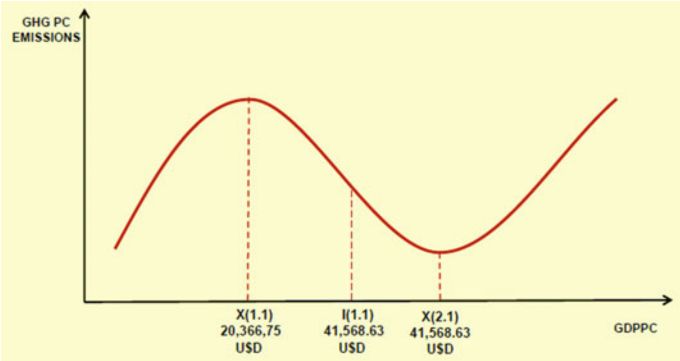

Fig. 4 Cubic shape of the EKC for Model 1 including turning points. *Notes* Coefficients $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$ denote a cubic polynomial in an N-shaped EKC. The first turning point is found for per capita income $X(1)$; the EKC returns to a path of increasing contamination at a per capita income of $X(2)$

these economies reach the second turning point ($X2$). Beyond the second turning point, however, per capita emissions rise again (Fig. 4).

This N-shaped relationship shows that efficient technologies are exhausted, appearing technical obsolescence which implies that further income growth, hence enabling a net environmental degradation [26]. It is thus necessary to improve innovations, environmental policies, and institutional arrangements that help flatten the EKC curve [111, 15]. Moreover, the negative sign of the coefficient $\beta_4 < 0$ (from the models proposed in Eqs. 2–5) reveals that an increase in public expenditures on energy innovations (E_RDD_{it}) reduces carbon emissions. This negative relationship confirms that energy innovation activities reduce carbon pollution. These findings are in line with those reached in previous literature focused on improvements associated with energy technologies that allow for higher levels of environmental quality using less contaminating energy sources and more efficient energy technologies [21, 109]. In addition, E_RDD_{it} clarifies the interaction between *scale* and *technical effects*. In rapidly growing developing countries, the scale effect dominates time-related effects, which captures technological changes occurring in relation to inputs and outputs. By contrast, in developed economies, technological changes overcome the scale effect [106]. Moreover, the N-shaped model is consistent with the presence of *technical obsolescence* [14, 104] as income increases in the long run, in turn increasing levels of environmental degradation. A long-term solution to the scale effect could involve the promotion of energy innovation measures [111]. It is thus necessary adopting more energy policies that might improve technological innovations and which can in turn delay the presence of scale effects.

Additionally, all proposed models also include a variable linked to energy demand. Its positive coefficient ($\beta_5 > 0$) denotes that an increase in electricity consumption (EC_{it}) also increases carbon emissions. This positive relationship between energy consumption and environmental pollution is explained by the share of non-renewable energy sources relevant to energy mixing, where an increase in electricity consumption due to an expanding business cycle implies an increase in carbon emissions [14]. By extension, when economies require higher levels of electricity consumption, this additional demand increases the share of fossil sources in the energy mix, leading to the generation of more carbon emissions [47, 82, 87]. Consequently, economies must promote the adoption of renewable energy sources to mitigate negative effects of non-renewable sources on carbon emissions.

In terms of corruption levels, the findings illustrate the presence of a quadratic relationship between corruption and carbon emissions, where coefficients $\hat{\beta}_6 < 0$ and $\hat{\beta}_7 > 0$ relevant to variable CPI_{it} represent U-shaped quadratic behavior.[8] According to the existing literature, corruption has different effects on environmental pollution. There is broad awareness of the negative effects of corruption on environment (e.g., the violation of environmental laws by firms, minimal levels of accountability and transparency, and the poor enforcement of environmental regulations by government officials). Certain studies support the notion that corruption has a negative impact on carbon emissions [3, 75, 78]. By contrast, others argue that corruption limits the rigidity of energy policies [33]. Several studies confirm that the impact of environmental and energy innovation measures are connected to institutional quality and the way public administrations implement specific policies [25, 69, 70]. Dasgupta and De Cian [25] confirmed that corruption processes can be considered as a channel of environmental degradation, while Welsch [121] concluded that corruption covers direct and indirect effects over environmental degradation. Whereas the *direct effect* connects corruption with the environment, via lower stringencies and regulation measures, the *indirect effect* connects corruption on per capita income levels and how this path impacts over environment.

Under these conditions, the findings derived from Eq. (3–5) show that corruption has a negative impact on economies with low CPI values, but that once these economies achieve a certain CPI value, the consequent reduction in corruption implies the generation of higher carbon emissions (Fig. 5).

Figure 5 shows an interaction diagram that introduces a variable that alters the magnitude and/or the direction of the relationship between the independent variable and the response variable GHGpc_{it} by amplifying or even inverting their causal effect. This behavior is linked to the rate of development of an economy. When economies report low corruption levels, they typically have strong law systems in place that limit negative environmental activities. Some studies show that corruption can enhance the decontamination process in certain cases, i.e., through existing laws and regulations and other political inflexibilities that promote efficiency, while in other cases, it is assumed that corruption causes energy policies to become more inflexible [50, 33]. On the other hand, when the degree of corruption is low, corruption reduces the rigidity of energy policies. Some empirical evidence reveals that in low-income countries, the degree of institutional quality contributes to reduce environmental degradation [19, 111]. By contrast, other studies find a negative relationship between the level of institutional quality and environment degradation [32, 77]. In line with

[8]The analysis also tested the cubic pattern, but the results for CPI_{it}^3 are statistically insignificant.

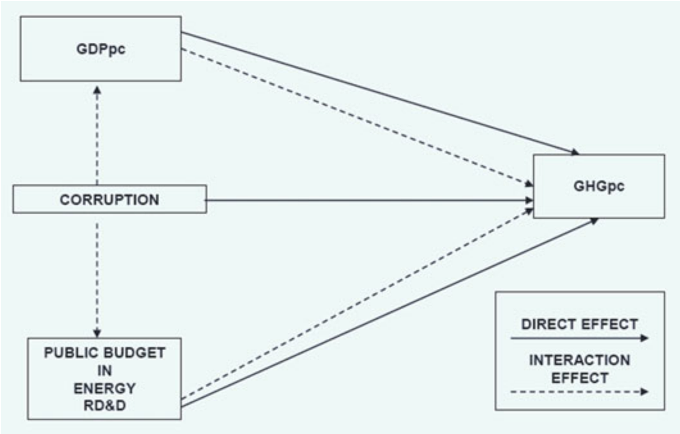

Fig. 5 Interaction graph of relationships incorporating a third variable. *Source* Own elaboration

these findings, Fig. 5 reflects the quadratic behavior of CPI; its turning point (CPI_{it} = 52.47) reflects the relationship between high and low levels of corruption. When CPI is lower than 52.47, increases in CPI levels will increase environmental degradation through energy restrictions and excessive regulation. Certain theories predict that in countries presenting low levels of corruption, the inflexibility of energy policies diminishes, especially in large sectors with high coordination costs. Moreover, when the degrees of corruption are high, corruptive coordination costs cause energy policies to become more stringent [33].[9] Therefore, reductions in emissions can be rendered compatible through higher CPIs by liberalizing environmental policies under less corrupt systems rather than expediting environmental measures. In other words, environmental liberalization would allow a faster reduction of carbon emissions in less corrupt administrations.

The positive sign of coefficient $\hat{\beta}_8 > 0$ which is associated with variable CPI * E_RDD_{it} (Eqs. 4 and 5) shows that a corrupt system implies a reduction of the positive impacts of energy innovation measures on emissions. By testing Eq. (5), an EKC's N-shaped scheme is confirmed. The main effect is found in the *indirect channel*, according to which corruption affects carbon emissions via public expenditures on energy RD&D activities and economic growth. Corruption reduces the net impacts of energy innovation measures on carbon emissions. In addition, the quadratic behavior of CPI implies that a reduction in corruption does not always support environmental correction. According to these results, an economy must liberalize, decrease or eliminate restrictions to accelerate environmental activities once

[9]Fredriksson et al. [33] test the predictions of a theoretical model by using panel data for 14 OECD countries; their empirical results show that corruption increases energy waste by reducing the stringency of energy regulations. In addition, capital owner lobbying is less successful in larger sectors, but corresponding effects are reduced in highly corrupt countries. On the other hand, worker lobbying is more successful in large sectors unless a country is heavily corrupted.

the economy has exceeded a certain level, below which corruption cannot be handled through deregulatory policies. In other words, economies must reach a certain level of maturity in terms of corruption levels before they can liberalize their energy sectors. Finally, the presence of CPI reduces income per capita, denoting the presence of an *indirect channel* between corruption and per capita carbon emissions via income.

This confirms our main hypothesis on the presence of *indirect effects*, noting that corruption increases carbon emissions levels through reductions in net effects of technological innovations. In addition, Eq. (5) applies interactive variable CPI * $GDPpc_{it}$ to study the role of the *indirect channel* that explores whether corruption (CPI_{it}) reduces economic growth ($GDPpc_{it}$) and thus carbon emissions ($GHGpc_{it}$). Coefficient $\hat{\beta}_9 < 0$ of Eq. (5) (Table 4) shows statistical significance for interaction term CPI * $GDPpc_{it}$; corruption has a negative effect on per capita income, implying that corruption reduces the impact of per capita income and in addition on per capita emissions. Zhang et al. [125] proved that the magnitude of direct effects decreases as per capita GDP increases. Thus, a lower corruption level may indirectly imply an increase in carbon emissions.

In other words, the findings endorse an *indirect channel* according to which corruption reduces the role of economic growth effects related to carbon emissions [23, 121]. By contrast, certain studies show that corruption can enhance economic growth [31, 50, 72] by showing a comprehensive relationship between corruption and economic growth [37, 113].

Furthermore, corruption crashes into carbon emissions through the reduced role of energy innovation effects. The impact of corruption derived from the EKC modeling approach has not been studied sufficiently in relation to the stringency of economic and environmental policies. Furthermore, this study confirms that the positive effects of energy innovation over environment are diminished by the existence of corruption.

In Eq. (2), the effect of corruption is isolated by omitting variables CPI, CPI^2, CPI * E_RDD, and CPI * GDPpc to determine how the EKC hypothesis performs and whether turning points adjust to the omission of the regulatory variable. In this specification, the comparison between Model 1 (Eq. 2) and Model 4 (Eq. 5) allows for the detection of the location for turning points of income (GDPpc) in both cases (i.e., where corruption is included as part of the modeling approach or not) (Fig. 6). This analysis is important, as it reflects how anti-corruption policies are relevant in coping with environmental problems.

Figure 6 shows the turning point of CPI levels distinguishes high corruption levels from low corruption levels and shows how the turning point (52.47) interacts with environmental pollution. When CPI_{it} is lower than 52.47 (i.e., high corruption levels), reductions in corruption reduce carbon emissions. Once the CPI_{it} takes values over 52.47, reductions in corruption levels (growing CPI values) increase the rigidity of energy regulation having as a consequence increases of carbon emissions.

Aiming to go further in this empirical analysis, a comparison of the turning points (see Table 5) of Eq. (2) (without the corruption variable) and Eq. (5) was also carried out. This comparison illustrates that when economic the corruption is present in an economy. Overall, the coefficients for both models (Eqs. 2 and 5) drop that corruption

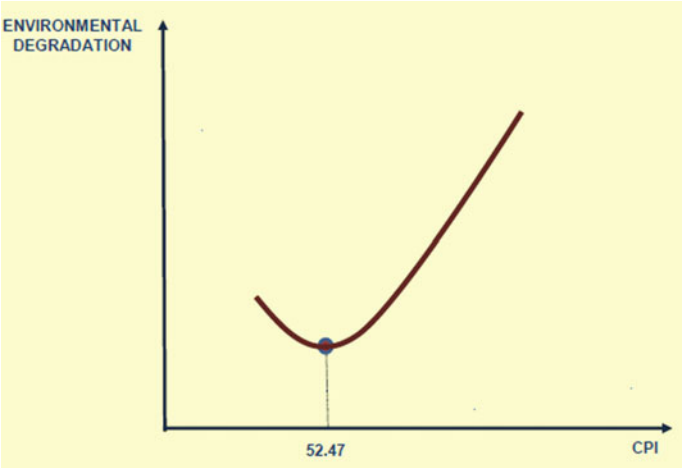

Fig. 6 CPI U-shaped behavior with turning points. *Source* Own elaboration

Table 5 Turning points and inflection point in proposed models (Eqs. 2–5)

	$X(1.^*)$, U$D	$X(2.^*)$, U$D	$I(1.^*)$, U$D
Model 1 (Eq. 2)	20,366.75	62,770.50	41,568.63
Model 2 (Eq. 3)	20,775.72	62,557.61	41,666.67
Model 3 (Eq. 4)	20,659.70	62,188.19	41,423.95
Model 4 (Eq. 5)	17,929.01	61,350.27	39,639.64

infers over the turning points in the connection between economic growth and on carbon emissions. Figure 7 presents a comparison between Eqs. (2) and (5) (main model).

Table 5 present the turning points[10] of proposed models, to analyze the isolation effect, when we omit the corruption process (Eq. 2) and the interaction effect (Eqs. 3 and 4). Figure 8 shows changes in turning points between Model 1 (Eq. 2) and Model 4 (Eq. 5) when we isolate the effect of variable CPI_{it} over per capita GHG emissions.

[10]For our estimation of turning points for the cubic model, we employed the following formulation [28]:

$$Xj = \frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}, \quad \forall j = 1,\ 2 \tag{23}$$

For the estimation of turning points, it is necessary to change coefficient β_1, as the breaking point at which the function reaches maximum and minimum values is dependent on CPI. When the CPI variable appears in moderate model GDPpc, this is expected to affect the coefficient of the first grade. Therefore, coefficient $\beta_1{}^* = (\beta_1 + \delta 3 * \text{CPI})$ where CPI takes its median value (70.4) is justified by the asymmetric distribution of that variable. In other words, breaking points of the model can be estimated from the $\beta_1{}^* = (0.00089 - 4.07\text{E}{-}6 * 70.4) = 0.000610472$ coefficient.

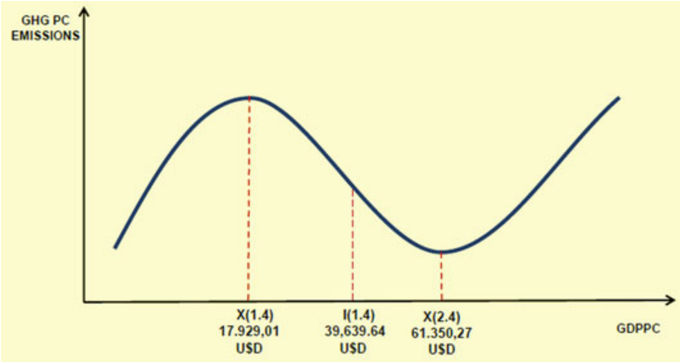

Fig. 7 EKC Model 4 (Eq. 5) estimated by FMOLS. *Notes* Coefficients $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$ denote a cubic polynomial in a N-shaped EKC. Coefficients β_1, β_2, and β_3 also allow for the calculation of turning points in the cubic EKC model. ($X(1)$) represents the first turning point, and ($X(2)$) is the second one

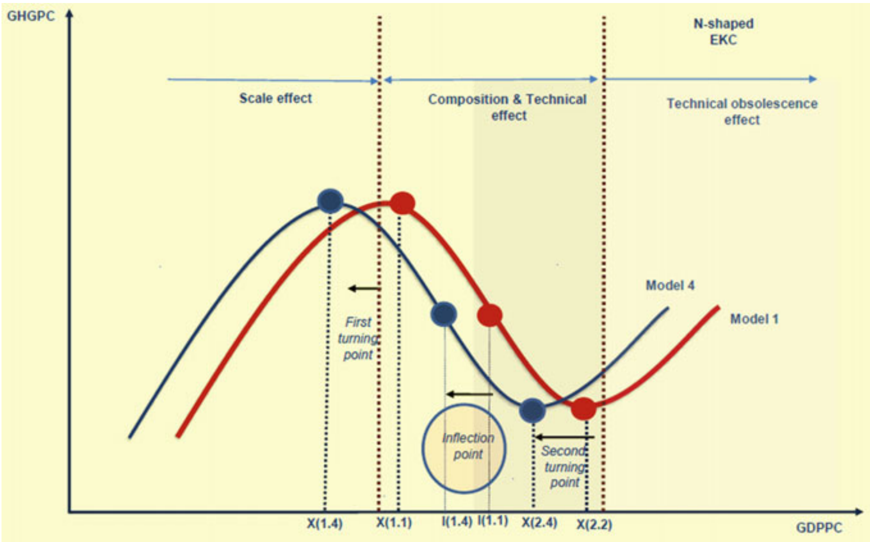

Fig. 8 Comparison between Model 1 (Eq. 2) and Model 4 (Eq. 5). *Source* Own elaboration

At this point, more attention should be paid to turning points of both models ($X(1.1) = 20{,}366.77$ U$D and $X(1.2) = 62{,}770.50$ U$D for Eq. 2) and ($X(1.4) = 17{,}929.01$ U$D and $X(2.4) = 61{,}350.27$ U$D for Eq. 5). The empirical results underline relevant adjustments in turning point, when we isolate the effects of CPI. The estimation of the turning points reveals that $X(1.4) < X(1.1.)$. This result is related to the U-shaped behavior of CPI and the interaction with the economic growth. When CPI reduces the economic growth, indirectly [121] this connection slows

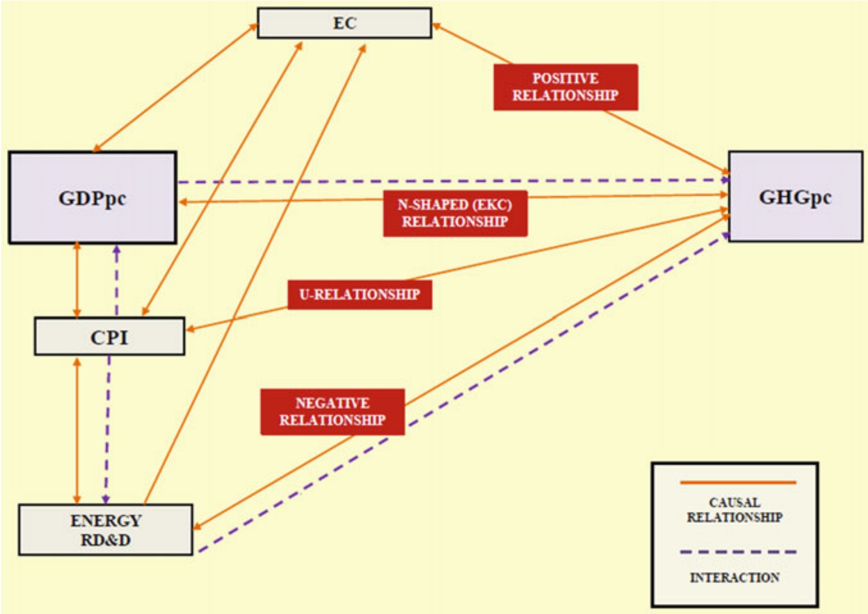

Fig. 9 Conceptual and Dumitrescu–Hurlin panel causality scheme of relationships between variables in Model 4. *Source* Own elaboration

down environmental degradation. Indirectly, in early stages of economic development, reduced levels of governance can contribute to control carbon emissions; by contrast developed systems can show an indirect connection between governance and environmental quality [32, 77]. On the other hand, the second turning point, confirming than in long term and in advanced societies the existence of corruption reduces the positive effect of energy innovation process ($X(2.1) > X(2.4)$), is speeding the arrival of technical obsolescence. The inflection points are going to determine the income level where scale effect starts to overcome composition and technical effect [16]. This result shows that in the long run, corruption has a net negative effect on environmental quality. By contrast, in the short run, it is cheaper to reduce emissions when corruption is not present [2, 72]. Finally, Table 6 depicts the results of Dumitrescu–Hurlin panel causality tests.

The Dumitrescu–Hurlin [30] panel causality test (Table 6) reveals the existence of bidirectional causality between selected variables, with the exception of a unidirectional causality running from energy RD&D to energy use (Fig. 9). This reveals the feedback hypothesis between energy use and economic growth.

Table 6 Pairwise Dumitrescu–Hurlin panel causality tests

Null hypothesis:	*Causality*	*W-stat.*	*Zbar-stat.*	*P value*
GHG does not homogeneously cause GDP	GHG ↔ GDP	2.50908*	3.38124*	(0.0007)
GDP does not homogeneously cause GHG		5.05687*	9.68668*	(0.0000)
EC does not homogeneously cause GDP	EC ↔ GDP	1.86227**	1.78047**	(0.0750)
GDP does not homogeneously cause EC		3.30398*	5.34850*	(9.E−08)
E_RDD does not homogeneously cause GDP	E_RDD ↔ GDP	1.60903	0.97917	(0.3275)
GDP does not homogeneously cause E_RDD		3.81792*	6.02950*	(2.E−09)
CPI does not homogeneously cause GDP	CPI ↔ GDP	1.10395	−0.09629	(0.9233)
GDP does not homogeneously cause CPI		3.41378*	5.62026*	(2.E−08)
EC does not homogeneously cause GHG	EC ↔ GHG	5.15275*	9.92398*	(0.0000)
GHG does not homogeneously cause EC		4.71982*	8.85252*	(0.0000)
E_RDD does not homogeneously cause GHGPC	E_RDD ↔ GHG	2.60450*	3.25519*	(0.0011)
GHGPC does not homogeneously cause E_RDD		3.46328*	5.21866*	(2.E−07)
CPI does not homogeneously cause GHGPC	CPI ↔ GHG	1.97506**	2.05960**	(0.0394)
GHG does not homogeneously cause CPI		2.00895**	2.14346**	(0.0321)
E_RDD does not homogeneously cause EC	E_RDD → EC	2.31151*	2.58531*	(0.0097)

(continued)

Table 6 (continued)

Null hypothesis:	*Causality*	*W-stat.*	*Zbar-stat.*	*P value*
EC does not homogeneously cause E_RDD		1.44487	0.60384	(0.5459)
CPI does not homogeneously cause EC	CPI ↔EC	2.46778*	3.27901*	(0.0010)
EC does not homogeneously cause CPI		3.78933*	6.54968*	(6.E−11)
CPI does not homogeneously cause E_RDD	CPI ↔E_RDD	2.57725*	3.19288*	(0.0014)
E_RDD does not homogeneously cause CPI		4.83036*	8.34430*	(0.0000)

6 Conclusion and Policy Implications

This study shows the link between energy innovation and decontamination, contributing to a reduction in carbon emissions. The manifestation of corruption reduces net effects of innovation measures on environmental correction. Given that energy innovation processes adjust environmental pollution, improvements in energy innovations allow society to decrease emissions levels with lower GDPpc values through EKC patterns [12, 111]. This study demonstrates that reductions in corruption are necessary to elevate the effects of energy measures on carbon emissions.

Our results confirm the presence of an N-shaped connection between economic growth and per capita GHG emissions for select OECD countries under the presence of additional control variables such as public expenditures on energy RD&D, electricity consumption, and corruption. Accordingly, the results show a significant impact of corruption on RD&D and carbon emissions as well.

The N-shaped EKC pattern found implies that carbon emissions initially increase with income, reach a certain turning point, and then begin to decline with further climbs of income. Moreover, the results confirm the relevance of energy RD&D policy activities that help countries decrease emissions levels, even when they reach high-income levels [111]. Energy RD&D measures contribute positively to environmental quality on the path to sustainable economic growth.

This study also examines the influence of corruption on environmental quality by studying its influence on turning points within the EKC framework. Corruption has a significant impact on carbon emissions when taken implicitly, explicitly, or even as an interaction term as shown by the models estimated. As far as corruption is concerned, it exhibits a U-shaped (quadratic scheme), while it has significant impacts on carbon emissions. In this sense, both direct and indirect impacts of corruption on pollution were tested. The empirical findings show that corruption works through direct channels in these OECD countries, while it is positively correlated with the critical threshold level of income, beyond which carbon emissions decline. Hence, higher corruption levels seem to cause delays in long-run governmental concerns and controls for environmental quality, resulting in postponed formulations and implementations of rigid environmental policies. In contrast, indirect impacts were found for two different variables. The first is identified between corruption and per capita emissions through the role corruption plays in energy innovation activities and through the ways it limits positive effects of innovations on per capita emissions. Although it was found to be statistically insignificant, the second indirect effect was analyzed through the impacts of corruption on per capita income. The negative interaction found between CPI and $GDPpc_{it}$ confirms that corruption reduces the direct effects of per capita income on carbon emissions via the EKC model.

The inclusion of other variables such as energy innovation and electricity consumption also rendered a significantly negative impact on carbon emissions across all estimates. By contrast, as economic growth increases, it extensively exploits energy resources in various ways, potentially in the form of high levels of industrial production, transportation, and domestic use, which contribute significantly to the generation of carbon emissions. Thus, electricity consumption positive affects the inflexibility of environmental quality policies, while corruption has a negative influence on environmental quality. This study also highlights a need for the development of more graduated policies aimed at the reducing fossil energy sources in the energy mix. Our empirical findings indicate that advances in energy processes are needed to reduce the share of such fossil energy sources and to improve environmental quality. In other words, environmental policies should focus on measures able to promote energy innovations and anti-corruption policies along with incentives for the innovation and embracing better pollution cut technologies. Therefore, there is a strong need for countries to develop specific anti-corruption policies to improve energy RD&D efforts and to promote the development of energy replacements that reduce environmental pollution levels. Finally, future studies should pay more attention to energy regulation measures, energy prices markets, and other behaviors of corruption in relation to per capita growth.

Appendix

Sources and constructions of variables

- $GHGpc_{it}$: This denotes emissions measured in millions of tons of CO_2 per capita for country "*i*" and for year "*t*" [81].
- $GDPpc_{it}$: This denotes income per capita measured in millions of US dollars at current prices and PPPs for country "*i*" and for year "*t*" [81].
- CPI_{it}—Corruption Perception Index: This denotes corruption levels based on a variable that covers 177 countries and scores them on a scale of 0 (highly corrupt) to 100 (very clean). The Transparency Index (CPIN) developed by Transparency

International [112] is a good proxy for corruption for the legislative process and for the enforcement of environmental policies [112].

- EC_{it}: This denotes electricity consumption measured in Gw/h for country "*i*" and for year "*t*" [51].
- E_RDD_{it}: This denotes public expenditures on energy research development and demonstration (RD&D) measured in millions of US dollars at current prices and PPPs for country "*i*" and for year "*t*" [81].
- CPI_{it} * E_RDD_{it}: This variable captures interactions between CPI_{it} and E_RDD_{it} over GHG_{it} (Eq. 2).
- CPI_{it} * GDP_{it}: This denotes interaction terms of CPI_{it} and GDP_{it} over GHG_{it} (Eq. 4).
- $LABOUR_{it}$: Labor productivity is a key driver of economic growth and of changes in living standards. Labor productivity growth implies a higher level of output for every hour worked. Labor productivity is also a key driver of international competitiveness, e.g., as measured by unit labor costs (ULC) [81].
- $INFLAT_{it}$ is the inflation index for consumer prices (annual %) for country *i* and for year *t* [123].

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Energy Efficiency in Europe; Stochastic-Convergent and Non-Convergent Countries

Angeliki Menegaki and Aviral K. Tiwari

Abstract Energy efficiency emerges as one of the most important pillars for consumer-centered clean energy transition in Europe. Based on commitments of the European Commission announced in December 2016, Europe prioritizes effort sharing among countries and each country is responsible for finding ways of implementation. This chapter examines the integration properties of primary and final energy efficiency convergence as well as energy productivity convergence (as a proxy for energy efficiency) in 35 European countries over the period 1995–2014. Besides the conventional unit root tests, we apply some of the most recently developed Lagrange multiplier (LM) tests that account for structural breaks, autocorrelation, and cross-sectional dependence which is typically expected to permeate economic unions. Results show there is convergence in energy efficiency despite the economic crisis and the different accession dates of the countries in the European Union as well as the shocks injected into the system by the issuance of the various energy directives so far. Most breaks take place within the period of 1995–2003. The strongest evidence for convergence applies for Finland and Romania (which also happens to belong to the same convergence club for primary energy), while the weakest applies for Ukraine and the UK (which also belongs to the same convergent club for primary energy).

Keywords Club convergence · Energy efficiency · Europe · Nonlinearities · Structural breaks

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1 Introduction

Energy efficiency is defined as "using less energy to provide the same service" [1] or output, in general. Although sometimes confounded with each other, the concept of energy efficiency is different from the concept of energy conservation, because the latter refers to refraining from the consumption of energy in order to save energy. According to the International Energy Agency [2], energy efficiency is highly important in enhancing the sustainability of energy systems (since it secures the existing energy supplies) and promotes strategic objectives for economic competitiveness and sustainability, social development, job creation, cost savings to consumers, and the necessary means to reduce greenhouse gases. Therefore, it is also a prerequisite for reverting climate change. The degree of decoupling of energy consumption from economic growth can be regarded as a proxy for energy efficiency.

Up to date, Europe has achieved its 2020 targets for final energy consumption, but not for the primary energy consumption which appeared to reach only a rough 17% [3]. European Union countries aimed at achieving 20% energy efficiency in their 2020 strategy, which is also implemented by 20% penetration of renewable energies and 20% reduction of greenhouse gases. While the latter two goals have been expressed in binding targets, energy efficiency was the only non-binding target. The non-bindness together with the economic recession afflicting Europe which may delay infrastructure and technology investments, but at the same time, it reduces energy demand and makes the study of this magnitude, if not compelling, then at least interesting.

The "Clean Energy for All Europeans" package issued in November 30, 2016, for the unilateral reform of the European Union's electricity market also suggests a revision for the Energy Efficiency Directive. This new package requires the decarbonization of the electricity market and a new energy efficiency target of 30% by 2030. The latter impacts on all economic sectors and is supposed to cause and be caused by a revival of technologies. Additional emphasis is placed on the energy performance of buildings through their renovation and the electrification of road transport. Namely, these two sectors are expected to lead the way toward efficiency [4]; European countries are supposed to take their own measures to implement their national efficiency plans. In this framework, it is useful to know which countries reach convergence in their energy efficiency and whether Europe converges as a whole or in various subgroups (clubs). For this reason, we employ not only panel data analysis for the pooled data, but also time series analysis for single countries and club convergence analysis. Last but not least, our paper recurs to the usage of some of the recently developed LM tests that investigate stationarity (no unit roots), while hosting endogenously determined structural breaks, autocorrelation, and cross-sectional dependence, which are appropriate for a research context such as ours, because Europe involves an economic union of countries permeated by homogeneous energy and other economic and social directives.

This chapter uses primary energy efficiency and final energy efficiency in order to investigate the convergence or non-convergence of this non-binding attribute, dictated from the European Commission to all member states. We believe it will provide policy-makers with useful information about where Europe stands on this matter and whether targets need to be revised in order to be realistic. Besides primary energy efficiency, we deem necessary to study final energy efficiency which takes into account the conversion of raw energy into electricity. We expect efficiency to be more eloquently imprinted in final energy savings since this is manifested in the consumption of electricity in buildings, transport, industry, and services.

This chapter contributes to the literature in the following ways:

First, it examines the behavior of energy efficiency convergence in Europe which has not been studied in the energy economics literature. It does this both at the union level and for each particular country as well as groups of countries. Second, it identifies the structural shocks that perturbate the energy efficiency path which European economies are asked (through European Directives) to embark on. Third, it peruses some of the most up-to-date time series and panel unit root tests, which take into account autocorrelation, cross-sectional dependence, and the structural breaks. We fill the gap in the literature, because we study the convergence of a concept that has not been studied before, we do that for Europe which is a region of high interest because of the common energy and environmental policies it follows and implement all this with up-to-dated econometric techniques.

The rest of the paper is organized as follows: Sect. 2 consists of the overview of energy efficiency in Europe, Sect. 3 deals with the literature review of all the studies that have dealt with the investigation of the unit roots in the convergence of energy-related variables, Sect. 4 deals with the data and methodology, Sect. 5 includes the empirical analysis and results, Sect. 6 is the discussion, and Sect. 7 concludes the paper.

2 Energy Efficiency in Europe

Worldwide, is the European Union the most energy efficient region, but also the largest energy importer [5]. The energy prices paid by Europeans are also too high and compromise the competitiveness of European products in global markets. Following its social, environmental, and economic needs, the EU has issued a number of directives that guide toward energy efficiency. The most recent is Directive 2012/27/EU, which amends or reverts the valid directives up to the point of the issuance of 2012 Directive, namely 2009/125/EC (for eco-design and labeling), 2010/30/EU (for the energy performance of buildings), 2006/32/EC (the energy services directive), and 2004/8/EC (on the promotion of cogeneration of heat and power) [4]. According to the most recent relevant directive, European member states must achieve a 20% energy efficiency increase by 2020. This percentage has escalated to a more ambitious percentage, namely 30% by 2030. Notwithstanding that Europe is confronted with additional environmental targets which are binding, such as 20% penetration of renewable energies and 20% reduction of greenhouse gases by the same benchmark year 2020, energy saving is not binding and appears as a policy ambition with no concrete foundations and legal stipulations among European countries. Hence, it has not materialized fast enough, and therefore, European economies must take costly measures to catch up [6].

Energy use in Europe during the period of 2008–2012 has returned to the levels of 1990, while energy use during the wider time period between 1990 and 2012 has remained stable, although economic growth was being achieved in that time [7]. The fulfillment of the 2020 target appears to be on a good level, but only 2/3 of the experienced energy efficiency is genuine with the remaining 1/3 to be due to the economic crisis afflicting Europe since 2007 and the subsequent decreased demand of energy. Europe-wide, Germany holds the first position in the energy efficiency progress, while significant progress has also been made by Greece, Bulgaria, Slovakia, Hungary, and Denmark. It is noted, however, that countries which rely on imports of the Russian gas such as Latvia, Lithuania, and others have worsened their position in energy efficiency.

The economic recession afflicting Europe since 2007 has set back energy efficiency development in Europe. The countries that have been hit most severely by the

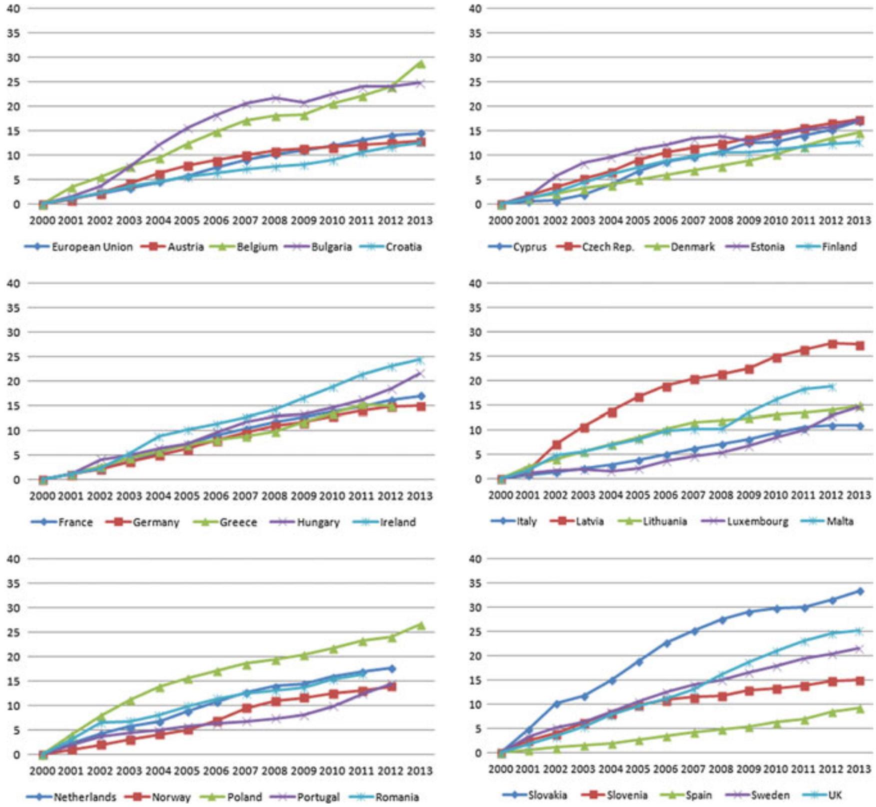

Fig. 1 Annual overall efficiency growth rates of European countries since 2000

economic crisis are the PIGS (Portugal, Italy, Spain, Greece), but some European countries such as Poland, Slovakia, Romania, Estonia, and Czech Republic have seen a growth in their industrial production, because of the cheaper production costs they enjoy. Overall, from 2000 to 2013, energy efficiency has been 1.2% per year, and this has been reduced to 1% after the beginning of the economic crisis [8]. Energy efficiency has achieved more progress in households (1.7% yearly gain) and cars (about 1.2% yearly gain). There are differences in the energy efficiency across European countries though. Energy efficiency annual rates range from 0.6 to 3.3% based on the individual progress each country has made and other inherent characteristics such as the prevalent lifestyle, culture, demographic characteristics, and modal shift in transport. Primary energy intensity in Europe has followed a decreasing path since 2000 because of the improvement in power generation efficiency mainly due to the penetration of renewable energies.

A visual inspection of the subgraphs in Fig. 1 gives a clear picture of the energy efficiency progress having been implemented from 2000 to 2013. The figure does not provide information on the absolute energy efficiency, but only on its annual growth rates. Thus, for example, we observe in the third subgraph that Greece and Germany follow an almost identical energy efficiency growth path, but it is also known that Germany has the leading position in energy efficiency in the whole Europe. Countries that reveal some of the lowest paths in all subgraphs are Croatia, Italy, and Spain.

3 Literature Review

The literature of energy efficiency convergence has started more than twenty years ago with the work by Nilsson [9] and Goldemberg [10]. These studies found evidence that countries tended to converge to a common pattern of energy use. Afterward, a number of studies have proliferated both in energy economics and in the broader field of environmental and resource economics with the study of carbon emissions convergence.

As revealed by the title of this paper and the methods employed herein, this piece of research deals only with the most up-to-date methods of convergence investigation, namely the stochastic convergence approach. That been said, the paper does not deal with the distribution approaches such as beta convergence (catch up the process from high to low convergence), gamma convergence (intra-generation mobility), or sigma convergence (spread of distribution).

Another strand of energy convergence studies which we will not handle in this paper is the papers which study convergence by means of decomposition analysis. Theil decomposition analysis, Divisia decomposition analysis, Laspeyres or Fisher index decomposition analysis are the most frequently reported. Decomposition methods separate among various effects such as within and between group decomposition, contribution of energy transformation indexes, contribution of energy to GDP formation, and an account of within-group inequalities.

Since energy consumption per capita is by itself a measure or proxy for energy efficiency, the interest on whether energy consumption per capita is stationary is motivated by the need to know about the effects shocks have on it. If a unit root is present, a permanent effect is due after the shock. There are numerous papers that examine the stationarity or non-stationarity of energy consumption and other variables typically perused in the energy–growth nexus. Actually, the investigation of stationarity of energy consumption is the first step in every energy–growth nexus study. Hence, practically, stationarity studies would be at least as many in number, as the number of energy–growth studies.

However, the current literature review will not include pure energy–growth nexus studies per se. It includes only studies whose main and exclusive focus is to investigate stochastic efficiency (through stationarity investigation) and does not include studies that fall within the energy–growth nexus field whose focus is mainly on the causality analysis. A succinct literature review for this type of studies up to 2012 is provided by Smyth [11].

To make our search yardstick in the current literature review more concrete, we have employed Scopus bibliographic database (www.scopus.com) with keywords: "energy" plus "structural breaks" or "nonlinearity," "unit root," and "fractional integration" in their titles, keywords, and abstracts and have identified 27 studies on the investigation of the convergence of energy variables which appear to be mostly energy consumption per capita, total energy consumption (in aggregate or disaggregate form). None of the studies is concerned with the study of the convergence of energy efficiency as such. The collected studies are shown in Tables 1 and 2. We provide separately studies with aggregate magnitudes (Table 1) and studies with disaggregate magnitudes.

Studies either focus on whole economies or group of economies or even sectors of a particular economy such as is done in Ozturk and Aslan [17] or Aslan and Kum [19]. Typically, studies employ tests that have not been used before in a particular country or set of countries, and thus, they corroborate their results and prove their robustness to make sound policy recommendations. They also demonstrate the difference of results when breaks are inserted [17] and linear tests versus nonlinear unit root tests are employed [19].

Table 1 Energy consumption convergence studies

Study [1]	Period [2]	Variable [3]	Test [4]	Countries [5]	Result [6]	Agg/disagg [7]
Narayan and Smyth [12]	1979–2000	Energy consumption per capita	ADF	182 countries	Univariate test with break(s): rejects H_0 of unit root for 56 countries, namely 31% of the sample Panel data unit root test: stationarity (yes)	1
Ozcan [13]	1980–2009	Energy consumption per capita	LM (LS and IPS)	17 Middle East countries	Univariate tests (with one or two breaks): no stationarity LM tests: stationarity (yes)	1
Hsu and Lee [14]	1971–2003	Energy use	Panel SURADF (hosts cross-sectional effects and identifies which countries contain a unit root)	84 countries	Conventional unit root tests reveal stationarity even if only one series in the panel is strongly stationary	1
Chen and Lee [15]	1971–2002	Energy consumption per capita	CBL panel unit root	104 countries (7 regional panels)	Non-stationarity (even with proper consideration of cross-sectional correlations)	1
Mishra et al. [16]	1980–2005	Energy consumption per capita	CBL panel unit root	13 Pacific island countries	60% of individual countries: stationarity Whole sample: stationarity	1

(continued)

Table 1 (continued)

Study [1]	Period [2]	Variable [3]	Test [4]	Countries [5]	Result [6]	Agg/disagg [7]
Ozturk and Aslan [17]	1970–2006	Energy consumption per capita	LM (IPS)	Turkey (7 sectors)	LM univariate test without break $\underset{\text{then}}{\Rightarrow}$ non-stationarity except for the residential sector	1
Narayan et al. [18]	1973–2007	Energy consumption (sectoral)	LM (LS)	Australia (6 states in 9 industries)	Stationarity except for South Australia	1
Aslan and Kum [19]	1970–2006	Energy consumption	LM (LS)	Turkey (7 sectors)	Linear unit root is rejected in 4/7 sectors (transport, non-energy use, final energy consumption, cycle, and energy) LM test reveals stationarity with two structural breaks	1
Hasanov and Telatar [20]	1980–2006	Primary energy consumption per capita	ADF, LM (KSS, S)	178 countries	Simultaneous use of structural breaks and nonlinear unit root tests contribute to the higher probability of evidencing stationarity	1
Kum [21]	1971–2007	Energy consumption per capita	LM	15 East Asia and Pacific countries	No break $\underset{\text{then}}{\Rightarrow}$ non-stationarity One break $\underset{\text{then}}{\Rightarrow}$ stationarity	1

(continued)

Table 1 (continued)

Study [1]	Period [2]	Variable [3]	Test [4]	Countries [5]	Result [6]	Agg/disagg [7]
Yilanci and Tunali [22]	1960–2011	Energy consumption per capita	LM (FLM)	109 countries	FLM Stationarity for 24 countries after acknowledging the unknown nature of breaks. For the remaining countries, the standard LM test is used	1
Zhu and Guo [23]	1993–2013	Nuclear energy consumption per capita	CBL panel unit root, longitudinal clustering	27 countries	If no breaks $\underset{\text{then}}{\Rightarrow}$ non-stationarity (low, upper-middle, developing countries) If breaks $\underset{\text{then}}{\Rightarrow}$ stationarity (total, lower-middle, high, developed countries)	0
Lean and Smyth [24]	1978–2010	Final energy demand (10 fuel types in 4 sectors)	LM (SP, LS)	Malaysia	Stationarity for 50–70% of energy types in 25–50% of sectors (no break, one break and two breaks)	0
Kula et al. [25]	1960–2005	Electricity consumption per capita	LM (LS)	23 high-income countries	Stationarity for 21/23 countries	0
Kula [26]	1923–2008	Electricity consumption per capita	LM (LS)	Turkey	Stationarity	0

(continued)

Table 1 (continued)

Study [1]	Period [2]	Variable [3]	Test [4]	Countries [5]	Result [6]	Agg/disagg [7]
Lean and Smyth [27]	1973 m1–2008 m7	Petroleum consumption (24 types in 5 sectors)	LM tests (FI)	USA (5 sectors)	Univariate unit roots: non-stationarity for less than 50% of sectors and products for 9/24 series Multivariate unit roots: non-stationarity for the commercial and industrial sectors, stationarity for the residential sector. Evidence for fractional integration (FI)	0
Apergis et al. [28]	1982–2007	Coal consumption	LM (IPS, CBL, DBC, W)	USA (50 states)	Stationarity with structural breaks	0
Apergis et al. [29]	1980–2007	Total natural gas consumption in billions of cubic feet (per state)	Panel unit roots (various)	USA (50 states)	Panel unit roots: non-stationarity Panel unit roots with endogenously determined structural breaks: stationarity	0
Apergis and Payne [30]	1960–2007	Petroleum consumption	LM (LS, NP)	USA (50 states)	Stationarity; endogenously determined structural breaks	0

(continued)

Table 1 (continued)

Study [1]	Period [2]	Variable [3]	Test [4]	Countries [5]	Result [6]	Agg/disagg [7]
Aslan [31]	1960–2008	Natural gas consumption	LM (KSS)	USA (50 states)	60% of states follow nonlinear behavior For 27/50 states: non-stationarity For 23/50 states: stationarity	0
Barros et al. [32]	1981 m1–2010 m10	Renewable energy consumption	FI	USA	Non-stationarity	0
Barros et al. [33]	1973 m1–2011 m10	Nuclear energy consumption	FI	USA	Non-stationarity	0
Gil-Alana et al. [34]	1973 m1–2009 m5	Electricity consumption	FI	USA	Non-stationarity	0
Apergis and Tsoumas [35]	1989 m1–2009 m12	Fossil, coal and electricity consumption	FI	USA (different sectors)	Stationarity	0
Apergis and Tsoumas [36]	1989 m1–2009 m12	Solar, geothermal and biomass energy consumption	FI	USA (different sectors)	Stationarity	0
Narayan et al. [37]	1971–2003	Crude oil production	LM	60 countries	No breaks $\underset{\text{then}}{\Rightarrow}$ non-stationarity Breaks $\underset{\text{then}}{\Rightarrow}$ stationarity	0

(continued)

Table 1 (continued)

Study [1]	Period [2]	Variable [3]	Test [4]	Countries [5]	Result [6]	Agg/disagg [7]
Borozan and Borozan [38]	2001–2013	Electricity consumption per capita	LM	Croatia	Non-stationarity	0
Wang et al. [39]	1965–2011 (nuclear) 1990–2011 (RES)	Non-fossil energy consumption	LM (LS, IPS) FLM	Japan	Non-stationarity (nuclear) Stationarity (RES)	0
Wesley Burnett and Madariaga [40]	1970–2013	Energy intensity	Dynamic panel data (GMM model)	50 US states plus Columbia district	Strong decoupling hypothesis is rejected Weak decoupling hypothesis is not rejected Evidence of convergence	1
Herrerias et al. [41]	1995–2011	Electricity, coal consumption	Club convergence modeling	Chinese regions	Different convergence between rural and urban areas	0
Mishra and Smyth [42]	1973–2014	Energy consumption per capita	LM and RALS-LM	Australia (sector level)	Convergence is confirmed for 6 out of 7 sectors	1

Note Column [4], ADF: augmented Dickey–Fuller, LS: Lee and Strazicich [43] one break: SP: Schmidt and Phillips [44] no break, IPS: Im, Pesaran et al. [45], SURADF: panel seemingly unrelated regressions [46], CBL: Carrion-i-Silvestre et al. [47], KSS: Kapetanios et al. [48], and Sollis [49], F.I: fractional integration [50], DBC: del Barrio-Castro [51], W: Westerlund [52], NP: Narayan and Popp [53], FLM: Fourier-type Lagrange multiplier [54], and S: Sollis [49] with simultaneous structural change and nonlinearity
1: aggregate, 0: disaggregate

Table 2 Club convergence results

	Club belonging countries		Coefficient	*t*-stat
Energy productivity				
First club	Bulgaria, Estonia, Sweden, Iceland	Constant log *t*	−3.263 0.974	−5.140 3.897
Second club	Belgium, Czech Republic, Greece, France, Croatia, Latvia, Lithuania, LXB, Hungary, NRL, Austria, Poland, Portugal, Romania, Slovenia, UK	Constant log *t*	−1.087 0.013	−7.580 0.225
Third club	Germany, Spain, Italy, Cyprus, Malta, Slovakia	Constant log *t*	−0.729 0.143	−1.322 0.656
Final energy efficiency				
First club	Belgium, Bulgaria, Czech Republic, Denmark, Germany, Iceland, Greece, Spain, France, Croatia, Italy, LXB, Hungary, NRL, Portugal, Romania, Sweden	Constant log *t*	4.498 0.356	0.131 0.029
Second club	Estonia, Cyprus, Latvia, Austria, Poland, Slovenia, Slovakia, Finland, Norway, FYROM	Constant log *t*	8.150 −0.715	0.235 −0.058
Primary energy efficiency				
First club	Greece, Italy, Lithuania, Hungary, UK, Moldova, Ukraine	Constant log *t*	11.602 −1.783	0.333 −0.143
Second club	Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Spain, France, Croatia, Cyprus, Latvia, LXB, Malta, NRL, Austria, Poland, Portugal. Romania, Slovenia, Slovakia, Finland, Sweden, Iceland, Norway, FYROM, Albania, Serbia	Constant log t	12.001 −2.843	0.352 −0.234

4 Data and Methodology

In the present section, we provide information about the perused data (Sect. 4.1) and the logic behind the conventional unit root tests as well as the logic behind the newly developed unit root tests (Sect. 4.2) which we apply both as panel unit root tests and as time series unit roots for individual countries.

4.1 Data

We have employed Eurostat yearly data from 1995 to 2014 on 35 European countries. The perused variables are the final energy efficiency index, the primary energy efficiency index (code: nrg_ind_334a), and the energy productivity (code: t2020-rd310). The latter variable was available only for 29 countries. Final energy is the difference between primary energy and the consumption in energy transformation and losses. Next, we provide the definitions of the energy efficiency variables as provided by Eurostat. Please note that the MTOE stands for million ton of oil equivalent.

$$\text{Final energy efficiency index} = \frac{\text{Final consumption in Mtoes}}{\frac{\text{GDP at constant prices in national currency (base year 2005)}}{\text{Coefficient to convert constant prices in national currency in euros of 2005}}}$$

$$\text{Primary energy efficiency index} = \frac{\text{Primary consumption in Mtoes}}{\frac{\text{GDP at constant prices in national currency (base year 2005)}}{\text{Coefficient to convert constant prices in national currency in euros of 2005}}}$$

Energy productivity is expressed as the ratio of GDP/gross inland energy consumption for a calendar year in € per kg of oil equivalent. The sample of countries includes: Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, UK, Iceland, Norway, FYROM, Albania, Serbia, Moldova, and Ukraine. The Convergence is expressed as $\ln\left(\frac{\text{energy efficiency in year } t}{\text{average of energy efficiency in all countries in a year } t}\right)$, namely the natural logarithm of the ratio of energy efficiency for each country i relative to the average of the European countries in the sample.

4.2 Methodology

Empirically, the convergence hypothesis is tested with unit roots on different types of energy consumption. Evidence of unit root supports the non-convergence hypothesis, while the rejection of the unit root constitutes evidence of the convergence hypothesis. Panel unit root tests jointly test the existence of convergence, while unit root testing identifies the countries that reveal convergence. Studying convergence with panel and time series analysis is a more recent and modern trend compared to the nonparametric methods such as for example β-convergence or γ-convergence [55].

We have perused an extensive gamut of second generation panel unit root tests and some newly proposed Lagrange multiplier (LM) tests with and without structural breaks, and almost all of them have rejected the unit root hypothesis for the energy efficiency convergence, toward supporting the convergence state of energy efficiency.

Allowing for breaks gives more power to tests of unit roots. More specifically, we have employed the unit root tests which are briefly explained in Sect. 4.2.1 and two LM tests whose methodology is explained in Sect. 4.2.2.

4.2.1 Second-Generation Unit Root Tests

We start the analysis with the application of some second generation widely used unit root tests. This type of tests takes into account cross-sectional dependence. They are based on the augmented Dickey–Fuller (ADF) [56] and they test the joint null hypothesis of a unit root against the alternative of at least one stationary series in the panel. More specifically, the perused second-generation unit root tests are Moon Perron [57], Pesaran [58], Chang Instrumental Variable test [59] and the Kapetanios, Shin, and Shell abbreviated as KSS [48] based on Ucar and Omay [60] nonlinear panel unit root test.

Among the conventional second-generation unit root tests are placed the Moon Perron [57], the Pesaran CIPS [58], and the Chang IV test [59]. Next, we briefly present the statistics on which these tests rely.

First, Moon and Perron [57] use a factor structure to model cross-sectional dependence, assuming that the error terms are generated by common factors and idiosyncratic shocks. Thus, the MP tests consider the factors as nuisance parameters and suggest pooling de-factored data to construct a unit root test. The two modified t-statistics with standard normal distribution under the null hypothesis are shown in Eqs. (1) and (2):

$$t_a = \frac{T\sqrt{N}\left(\rho^{+}_{\text{pool}} - 1\right)}{\sqrt{2\gamma_e^4 / w_e^4}} \underset{T,N\to\infty}{\overset{d}{\to}} N(0, 1) \tag{1}$$

$$t_b = T\sqrt{N}\left(\rho^{+}_{\text{pool}} - 1\right)\sqrt{\frac{1}{NT^2}\text{trace}\left(Z_{-1}Q_{\wedge}Z'_{-1}\right)\frac{w_e^2}{\gamma_e^4}} \underset{T,N\to\infty}{\overset{d}{\to}} N(0, 1) \tag{2}$$

where w_e^2 denotes the cross-sectional average of the long-run variances of residuals e, and γ_e^4 is the cross-sectional average of w_e^4. Moon and Perron [57] propose feasible statistics t_a^* and t_b^* based on an estimator of the projection matrix and estimators of long-run variances, w_{ei}^2.

Pesaran [58] advances a modified IPS statistics based on the average of the individual CADF, which is denoted as a cross-sectional augmented IPS (CIPS) shown in Eq. (3):

$$\text{CIPS} = \frac{1}{N}\sum_{i=1}^{N} t_i(N, T) \tag{3}$$

where $t_i(N, T)$ is the t-statistic of the OLS estimate for the equation $y_{it} = \alpha_i + y_{it}^0$ [57].

Last, the statistic of the Chang nonlinear instrumental variable (IV) unit root test is presented. It is based on the IV that is nonlinear transformations of the lagged levels; it yields asymptotically normal unit root tests for panels with dependence and heterogeneity. The data generating process is described as shown in Eq. (4):

$$y_t = ay_{t-1} + \sum_{k=1}^{\rho} \alpha_k \Delta y_{t-k} + \varepsilon_t \tag{4}$$

The IV estimation of the last equation has instruments of the following type $\left(F(y_{t-1}), \Delta y_{t-1}, \ldots, \Delta y_{t-\rho}\right)$. The transformation F is called instrument generating function. To test the unit root hypothesis, namely that $\alpha = 1$, a t-ratio statistic is constructed as $\tau = \widehat{\frac{\alpha - 1}{s(\hat{a})}}$, with $s\left(\hat{a}\right)$ being the standard error of $\hat{a}$.

Based on Hansen [61] who wanted to study cross correlation with more powerful unit root tests, Pesaran [58] proposed a test that augments the ADF regression with the cross-sectional average of the lagged levels and the first differences of the individual time series. This is termed as CADF for the time series version. The CADF is described as shown in Eq. (5):

$$\Delta y_{i,t} = a_\iota + \beta_i y_{i,t-1} + \gamma_i \overline{y_{t-1}} + \delta_i \Delta \overline{y_\iota} + \varepsilon_{i,t} \tag{5}$$

where α_i, β_i, γ_i, and δ_i are slope coefficients estimated from the ADF for country i, $\overline{y_{t-1}}$ is the mean of the lagged levels, $\Delta \bar{y}_i$ is the mean of first differences, and $\varepsilon_{i,t}$ is the error term. The test has been further developed by Constantini and Lupi [62].

4.2.2 Newly Developed LM Tests

It is quite some time now that research has moved away from the traditional augmented Dickey–Fuller-type time series and panel unit root tests [56], because these tests albeit very insightful cannot provide the more sophisticated information lent by the observation of a structural change. Not accounting for structural breaks treats the series as uniform and disregards the particular information that exists for a part of it. Therefore, these unit root tests are biased toward accepting the null hypothesis of a unit root. While the traditional methods allow breaking the series into subseries at the points the researcher suspects there is a structural change, there is always a lot of trial and error manipulation in that treatment.

A new trend in unit root analysis has been inaugurated by Zivot and Andrews [63] or Perron [64] and others who suggested the endogenous determination of break points in time series. The reverse side of the coin suggested that even this treatment of endogenous determination may generate some side effects too and overstate stationarity with breaks. Therefore, the family of the LM tests appears as less vulnerable to this defect, and the breaks do not affect the decision for a unit root situation. Examples of such tests are Im et al. [65] with one and two breaks, Westerlund [52], and Carrion-i-Silvestre et al. [47] with multiple breaks. The latter is a generalization of Hadri unit root test [66]. The test by Westerlund [52] permits breaks in the levels, while tests by Carrion-i-Silvestre et al. and Im et al. allow breaks (originally) in the mean and trend.

In this paper, besides the commonly used unit root tests, explained in the previous section and the results shown in the following section, we also apply the Hadri and Rao [67] and the Im et al. [65] tests. The former, hereafter HR test is a recently developed test that examines time series properties within a panel data framework. Its superiority lies in that it examines stationarity within the context of the presence of structural breaks, and at the same time, it can account for the presence of cross-sectional dependence through a bootstrap procedure [68]. The cross-sectional dependence is a matter that needs to be taken into consideration for country group entities such as the European Union, where countries are permeated by common directives and goals. The HR test is based on an LM procedure that tests the null hypothesis that all individual series are stationary versus the alternative of at least one unit root. It is calculated by constructing the simple average of the individual univariate KPSS stationary tests, also shown next.

The Hadri and Rao [67] test is an extension of Hadri [66] test. The HR statistic considers the six models (Models 1–6) as represented by Eqs. (6)–(11), respectively [67]:

$$\text{Model 1}: y_{it} = a_i + r_{it} + \varepsilon_{it} \quad \text{intercept only} \tag{6}$$

$$\text{Model 2}: y_{it} = a_i + r_{it} + \beta_i t + \varepsilon_{it} \quad \text{intercept and trend} \tag{7}$$

$$\text{Model 3}: y_{it} = a_i + r_{it} + \delta_i D_{it} + \varepsilon_{it} \quad \text{intercept and break} \tag{8}$$

$$\text{Model 4}: y_{it} = a_i + r_{it} + \delta_i D_{it} + \beta_i t + \varepsilon_{it} \quad \text{intercept, trend and break in intercept} \tag{9}$$

$$\text{Model 5}: y_{it} = a_i + r_{it} + \beta_i t + \gamma_i DT_{it} + \varepsilon_{it} \quad \text{intercept, trend and break in slope} \tag{10}$$

$$\text{Model 6}: y_{it} = a_i + r_{it} + \delta_i D_{it} + \beta_i t + \gamma_i DT_{it} + \varepsilon_{it} \quad \text{intercept, trend, break in slope and intercept} \tag{11}$$

$$\text{With } r_{it} = r_{it-1} +_{u_{it}} \quad \text{being a random walk} \tag{12}$$

The initial values of Eq. (12) are $r_{i0} = 0$ for very i.

Also, note that y_{it}, are the series we are testing where $i = 1, \ldots, N$ are cross section units and $t = 1, \ldots, T$ are the time periods. The following are unknown parameters: $\alpha_i', \beta_i', \gamma_i', \delta_i'$. Two of the models, namely Model 3 and Model 6, are already proposed by Carrion-i-Silvestre et al. [47]. The four models derive their moments of statistics in closed from through the characteristic functions. The null hypothesis is specified as shown in Eq. (13)

$$H_0 : \sigma_{u,1}^2 = \sigma_{u,2}^2 = \cdots = \sigma_{u,N}^2 = 0 \tag{13}$$

while the alternative is specified as shown in Eq. (14)

$$H_1 : \sigma_{u,1}^2 > 0 \quad \text{for } i = 1, 2, \ldots, N_1,\ \sigma_{u,1}^2 = 0,\ i = N_1 + 1, \ldots, N \tag{14}$$

which can host both homogeneity and heterogeneity.

The proposed LM test statistic is shown in Eq. (15)

$$\text{LM}(\lambda) = N^{-1} \sum_{i=1}^{N} \left(\hat{\omega}_i^{-2} T^{-2} \sum_{i=1}^{T} \widehat{S}_{i,t}^2 \right) \tag{15}$$

$\widehat{S}_{i,t}^2 = \sum_{j=1}^{t} \hat{\varepsilon}_{i,t}$ is the partial sum of OLS estimated residuals $\hat{\varepsilon}_{i,t}$, λ_i indicates the location of the breaks over T, and $\hat{\omega}_i^2$ is the consistent long-run variance of $\hat{\varepsilon}_{i,t}$ for each i [69].

To make our analysis more robust, we have additionally perused the Im et al. [65] test in the framework of Lee and Strazicich [43]—LS test hereafter, minimum Lagrange multiplier (LM) unit root test that endogenously determined structural breaks and does not reject the null hypothesis of a unit root through spurious rejections. Therefore, it does not suffer from similar distortions as does the unit root test of Zivot and Andrews [63]. The test assumes the data following the relationship shown in Eq. (16) as:

$$y_t = \delta' \text{Z}_t + \text{X}_t, \quad \text{where } X_t = \beta X_{t-1} + \varepsilon_t \text{ and } \delta' = (\delta_1, \delta_2, \delta_3) \tag{16}$$

The following four cases apply for Eq. (16) [43]:

(i) If $Z_t = [1, t]'$, the model collapses to the Schmidt and Phillips model [44].
(ii) If $Z_t = [1, t, D_t]'$, with $D_t = 1$ for $t \geq T_\text{B} + 1$ and zero otherwise, the model is known as Model A that hosts a one-time change in the intercept. T_B represents the time period of structural change.
(iii) If $Z_t = [1, t, D_t]'$, with $\text{DT}_t = t$ for $t \geq T_\text{B} + 1$ and zero otherwise, the model is known as Model B. This is a model version of little practical use, since most time series can be described by Model A and Model C.
(iv) If $Z_t = [1, t, D_t, DT_t]'$, with $\text{DT}_t = t - T_\text{B}$ for $t \geq T_\text{B} + 1$ and zero otherwise, the test is known as Model C that hosts a shift in intercept and change in trend slope.

The corresponding LM statistic is derived from the relationship and is shown in Eq. (17):

$$\Delta y_t = \delta' \Delta Z_t + \varphi \widetilde{S_{t-1}} + u_t \quad \text{with } \widetilde{S}_t = y_t - \widetilde{\psi}_x - Z_t \tilde{\delta} \tag{17}$$

where $t = 2, \ldots, T$, $\widetilde{\psi}_x$ is the restricted MLE of ψ_x. For more details, the interested reader should further refer to Im et al. [65] and Lee and Strazicich [43]. The pertaining model is decided based upon the minimization of the residual sum of squares from each regression under the null hypothesis and is selected based on the Schwarz information criterion.

5 Empirical Analysis and Results

In the following two subsections, we provide separately the results for panel data unit roots (Sect. 5.1) and time series unit roots of individual countries (Sect. 5.2). Detailed result tables can be found in the SM of this paper. We also provide a separate section (Sect. 5.3) for club convergence results which we present for strengthening the robustness of the results.

5.1 Panel Unit Root Tests

For final energy efficiency convergence, one test did not reject the unit root hypothesis, namely the Pesaran test. For primary energy efficiency convergence, only the Choi test failed to confirm the stationarity hypothesis and thus cannot support convergence. The rest of the tests (Moon Perron, CIPS, and Chang IV) confirmed stationarity in energy efficiency convergence. For energy productivity convergence, the Pesaran test also failed to produce evidence of a unit root. More detailed results on all the estimated versions of the above tests are provided in Table 1 in the SM. Also, details of the various versions of the tests are provided under the table in the form of brief notes.

As far as the LM panel unit root tests with structural breaks are concerned, for the final energy efficiency convergence, the panel Lee and Strazicich min LM t test with one break and two breaks was also significant with break points in the years 1998 and 2000 and 2008, respectively. The HR statistic was not significant at panel level. For primary energy efficiency convergence, the panel Lee and Strazicich min LM t test with one break and two breaks was significant with break points in the years 1998 and 1997 and 2008, respectively. The HR statistic was not significant at panel level. For energy productivity convergence, the panel Lee and Strazicich min LM t test with one break and two breaks was also significant with break points in the years 1996 (one break) and 1996 and 2003 (two break points), respectively. The HR statistic was not significant at a panel level. The Kapetanios, Shin, and Shell test, abbreviated as KSS [48], was significant. To save space, we do not provide detailed results of each test. However, detailed results of all the above tests are available upon request.

5.2 Time Series Unit Root Results for Individual Countries

This section provides results for individual countries both from the conventional unit root tests and the corresponding LM newly developed ones. Tables 1–3 in Chap. "Investigating the Trans-boundary of Air Pollution Between the Brics and Its Neighboring Countries: An Empirical Analysis" show results from the covariate-augmented Dickey–Fuller (ADF) test and the IV-ADF. Also, results for Kapetanios et al. (KSS) unit root tests are presented. Results have also been estimated for individual countries with Choi test, Demetrescu and Hassler [71], and Constantini and Lupi [62], and they are available upon request. Furthermore, Tables 1–3 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation" show results from Hadri and Rao [67] panel stationarity tests with one structural break. Tables 1–3 in Chap. "Rediscovering the EKC Hypothesis on the High and Low Globalized OECD Countries" show results from Lee and Strazicich min LM t-stat for one and two breaks.

5.3 Club Convergence

By club convergence is meant a steady-state equilibrium that takes place by groups of countries. This is a regression t test of the null hypothesis of convergence

$$H_0 : \delta_i = \delta, \quad \alpha \geq 0$$
$$H_A : \delta_i \neq \delta \quad \text{for all } i, a < 0$$

Phillips and Sul [70] run the following regression and compute a conventional robust t-statistic, t_b for coefficient b

$$\log\left(\frac{H_1}{H_t}\right) - 2\log L(t) = a + b\log t + u_t \tag{18}$$

with $t = [rT], [rT] + 1, \ldots -T$ with $r > 0$, $b = 2a$, $u_t = -\epsilon_t$, $\alpha = -2\log L(1) + u_1$.

Under convergence, the ratio $\log\left(\frac{H_1}{H_t}\right)$ diverges to ∞, either as 2 log $L(t)$ when $a = 0$ or as 2 a log t, when $a > 0$. The results from convergent clubs analysis are shown in Table 2. Based on those results, there are is not any significant club convergence in energy efficiency across Europe. The analysis identifies only one club in energy productivity, where both coefficients are significant at 5% in Eq. (18). This club consists of Bulgaria, Estonia, Sweden, and Iceland.

6 Discussion

The evidence for unit roots in the final energy efficiency index, primary energy efficiency index, and energy productivity is supported by all the tests we have used, but it appears that energy efficiency appears as stationary in more countries under the second generation unit root tests and the LM-type tests. There is a culmination of the occurrence of significance in unit root tests under the KSS and LM tests. While the evidence for stationarity across tests is not largely different between final energy efficiency and primary energy efficiency, the stationarity in energy productivity has the lowest number of conventional significant tests except for the LM tests, which constitutes further evidence for the superiority of those tests. Noteworthy is the fact that based on the KSS test for stationarity in the final energy efficiency, all countries were significant. Almost the same applies to the LM test (depicted as LM2 test in Fig. 2) with two breaks where 32 out of 35 countries were significant.

Referring to the countries that appear significant: Based on the HR results (Table 1 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation"—in the SM), only the following countries reveal convergence in final energy: Bulgaria, Czech Republic, Denmark, Germany, Portugal, Romania, Slovenia, Albania, Moldova, and Ukraine. When it comes to primary energy, only three of the above countries reveal the evidence of convergence (Table 2 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation"). These are Czech Republic, Portugal, and Slovenia. However, when energy productivity is used as a proxy for energy efficiency (Table 3 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation" in SM), two of the countries in our sample appear as convergent. These are Belgium

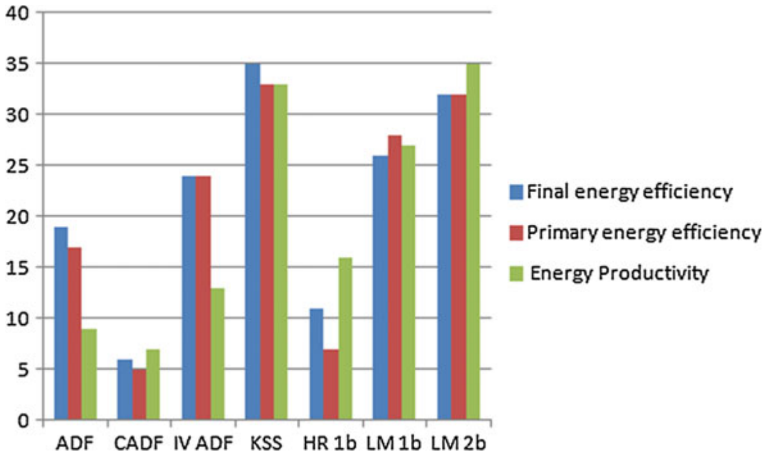

Fig. 2 Occurrence of significance across the employed unit root tests in energy efficiency convergence across European countries. *Note* 1b stands for one break, 2b stands for two breaks

and Denmark. Overall, Czech Republic, Portugal, Slovenia, Belgium, and Denmark are the only countries where energy efficiency convergence is corroborated, at least twice, namely in two out of the three considered energy variables.

Results are different from the LM tests with one or two breaks. For final energy, in the two breaks test, almost all countries reveal convergence except for Belgium, Denmark, and the Netherlands (Table 1 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation") in the S.M. In the primary energy counterpart tests, again all countries appear as convergent except for Croatia, Netherlands, and the UK (Table 2 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation"). In the energy productivity case (Table 3 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation"), all countries appear as convergent.

Returning to the LM test with one break, under the framework for final energy, all countries appear as convergent except for the following: Belgium, Denmark, Germany, France, Croatia, Cyprus, Hungary, Sweden, and UK (Table 1 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation"). In the primary energy framework, all countries are convergent except for Germany, Greece, France, the Netherlands, Poland, Sweden, and the UK (Table 2 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation"). In the energy productivity convergence framework, Estonia and Spain are not convergent (Table 3 in Chap. "Testing the Environmental Kuznets Curve Hypothesis: The Role of Deforestation").

Furthermore, based on the results from all tests, it appears that for some countries, convergence is more robust (namely, it is confirmed in all six tests or in five out of the six tests): Thus, final energy convergence is robust in Romania (all tests), Portugal, Slovenia, and Serbia (in five out of six tests). Apart from Portugal, the rest of these countries are newcomers in the European Union, and hence, they are presented with huge margins for energy efficiency. Within the framework of primary energy, seven countries appear convergent in five out of six tests. These are Denmark, Luxembourg, Hungary, Portugal, Romania, Slovenia, and Finland. None of these countries appears as convergent in all six tests. Last, with respect to energy productivity, that is more robust for Finland (in all six tests) and for Denmark, Germany, Croatia, Lithuania, Hungary, the Netherlands and Slovenia in five out of six tests.

We observe no obvious relationship patterns between convergence and the accession status of the country to the European Union. Namely, non-convergent countries appear to belong to all accession cycles of the European Union, even for the founding member countries. Since the LM test with two breaks reveals most countries to be convergent, this gives us reason to support further the necessity to use tests that accommodate more than one structural break. Given the evidence from the LM two-break test, most European countries have a break after 2007 when the economic crisis began in Europe. Also, some of the breaks might be due to the various energy directives issued in Europe, but each country appears to have its own distinct effects patterns, which cannot be disentangled from the rest of the economic, social, and historic conditions prevalent in each country, and additional research would be demanded on this aspect.

Regarding the historical significance of the breaks for the different countries, we believe they should be examined for each country separately as a point for further research. Figure 3 enables a visual inspection of the number of countries with significant breaks from both the HR and LM tests. The highest number of breaks appears to exist in the years 1997, 1999, and 2002. Also, the largest concentration of breaks appears to exist between the years 1995 and 2003. European Union enlargements have taken place in the years 1973 (three countries), 1981 (one country), 1986 (two countries), 1995 (three countries), 2004 (ten countries), 2007 (two countries), and 2013 (one country) with 1952 being the foundation year.

Based on Fig. 4 next, Finland and Romania gather the occurrence of the largest number of significant tests (namely six tests), for energy productivity and final energy, respectively. Next, five countries appear significant with five out of six tests under the final energy convergence framework. These are Luxembourg, Portugal, Slovenia, Finland, and Serbia. Six countries appear significant under the primary energy framework (Denmark, Luxembourg, Hungary, Portugal, Romania, and Slovenia). Last, seven countries appear significant under the energy productivity framework. These are Denmark, Germany, Croatia, Lithuania, Hungary, Netherlands, and Slovenia. Conversely, the occurrence of the lowest number of significant tests (only two out of six) applies for Belgium, Denmark, Croatia and Poland (for final energy) and Greece and Croatia for primary energy.

Understandably, the more significance tests accumulated for one country, the more robust the convergence of that country. For the sake of brevity, we will not describe Fig. 4 in further detail. Thus, one can see that the vast majority of countries have at least three tests as significant, and all of the countries have at least two significant tests.

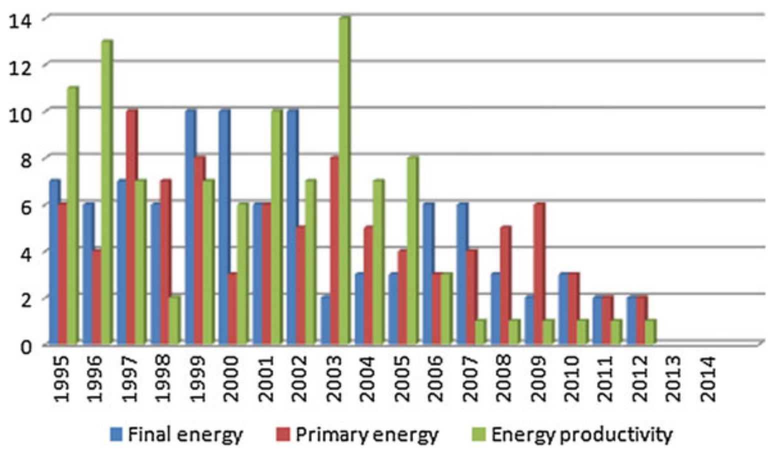

Fig. 3 Number of European countries showing significant breaks in energy efficiency convergence across the investigated time span

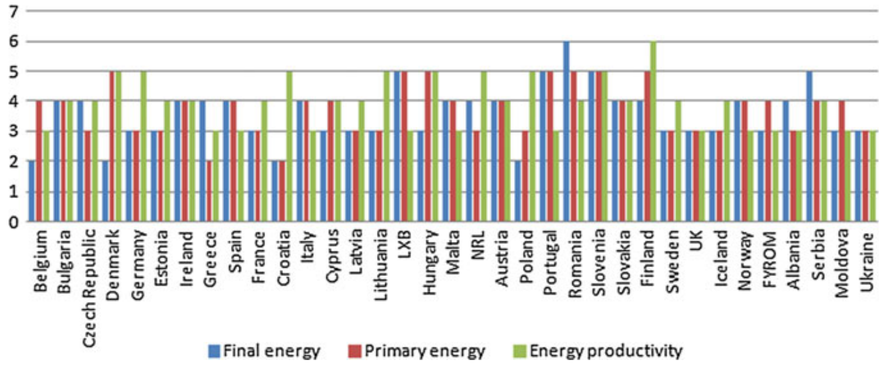

Fig. 4 Significance occurrence of energy efficiency convergence tests across European countries in the investigated period

7 Conclusion

The investigation of the unit root hypothesis in energy variables is a new ascending field in energy economics. However, different tests may give contradicting results, and thus, it is useful to compare and validate results not only with various tests but with linear and nonlinear ones too. However, this paper examines energy efficiency which is a variable that has rarely been examined in the energy economics field and has received little attention so far. Convergence in this variable is another concept that is of high importance for European countries due to the demands of relevant energy directives. European countries are members of a country coalition which poses some energy and environmental goals that all member states should respect and comply with. Thus, countries for which energy efficiency is not stationary that entails that shocks have a lasting effect on their efficiency, and therefore, additional measures need to be recommended for them in order to address their energy and environmental goals in the long run. On the other hand, if stationarity (no unit roots) is confirmed, shocks have only temporary effects, and thus, energy efficiency perturbations will redress the balance.

Besides the conventional unit root tests, we have applied some of the most recently developed Lagrange multiplier (LM) tests that account for structural breaks, autocorrelation, and cross-sectional dependence which is typically expected to permeate economic unions. Results show there is convergence in energy efficiency despite the economic crisis and the different accession dates of the countries in the European Union as well as the shocks injected into the system by the issuance of the various energy directives so far. Most breaks take place within the period 1995–2003. The strongest evidence for convergence applies for Finland and Romania (with all six tests significant at least for one of the considered variables, namely final energy, primary energy, and energy productivity). On the other hand, some of the weakest convergence applies for Ukraine and the UK (with only three significant tests out of six tests, applying for all three considered variables).

The Lee and Strazicich test reveals that more countries are stationary which constitutes some evidence that the identification of structural breaks enables higher incidence of stationarity in the corresponding tests. Since European countries have entered the European Union at different stages and dates, each one of them has followed a different path of energy convergence, but with a common goal. Also, the economic crisis afflicting Europe nowadays has caused a different response and adaptation from each country with respect to energy consumption and efficiency technologies. The fact that some high-income countries appear as non-convergent may be due the fact that these countries have reached a saturation point as regards their energy efficiency and additional levels of that might require a major restructuring of those economies. On the other hand, additional future research is necessary that will accommodate more structural breaks that might lead to the evidence of a higher incidence of stationarity (no unit roots).

Moreover, a grouping of significant structural breaks has shown that most countries have breaks that fall within the period of 1995–2003 which is a time span that is characterized by the accession of more country members to the European Union.

Undoubtedly, there are valuable synergies that can be exploited among the three environmental goals in Europe: energy saving, renewable energies, and decarbonization. Removing barriers to serve the promotion of one goal will inevitably, by some point, contribute to the implementation of the others. The energy efficiency plans are centered on some basic pillars such as the cogeneration of heat and power, the adoption of energy efficient technologies in transport and electric appliances, as well as cooling and heating methods.

To boost energy efficiency in Europe, a complete set of regulatory, financial, and informational instruments must take place. The first will display the technological baseline according to which energy efficiency can materialize. For example, the production of energy smart electric appliances falls within this strand of measures. The second type of measures is financial, and they provide the motives to capital owners to invest in energy efficiency infrastructure. The third type of measures requires actions that will fill the gap in information and knowledge of consumer and entrepreneurs.

The rejection of the unit root hypothesis (evidence for stationarity) in all tests is strong evidence that any deviation from equilibrium will only have a short-run effect and governments need not take additional corrective measures.

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European Commission's Energy and Climate Policy Framework

Michael L. Polemis and Panagiotis Fotis

Abstract In 2007, the European Commission (EC) provided its targets of energy and climate policy framework ("20–20–20" targets), with which the EC aimed to achieve a 20% reduction in EU greenhouse gas emissions from 1990 levels, an increase in the share of EU energy consumption produced from renewable resources (RES) to 20% and a 20% improvement in the EU's energy efficiency. In 2014, the EC introduced the new key achievements of its energy and climate policy framework (EU Energy Roadmap 2050, [16], 15 final). On 30 November 2016, the European Commission proposed an update to the Energy Efficiency Directive including a new 30% energy efficiency target for 2030. The aim of this chapter is to analyse the effect of renewable energy use and economic growth on pollution within EU. We attempt to explore the relationship between pollution, economic growth and renewable energy consumption and analyses the effect of environmental efficient indicators on local and global pollutants.

Keywords Sustainable development · Environmental policy · Renewable energy sources · Dynamic panel data analysis · Energy efficiency directive

JEL classification C21 · C23 · L16

1 Introduction

In 2007, all EU member states adopted a new law intended to reduce at least 20% greenhouse gas emissions and to achieve 20% share of renewable energies in EU energy consumption by 2020 (see also [47, p. 109]). Particularly, "*The European*

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Council agreed that the best way to reach such ambitious goals was for every Member State to know what was expected, and for the goals to be legally binding. This meant that the levers of government could be fully mobilised; and the private sector would have the long-term confidence required to justify the investment needed to transform Europe into a low-carbon, high energy efficiency economy" [15, 30 final, p. 3]. Within this framework, the EU aimed to achieve the "20–20–20" targets, including a 20% reduction in the level of greenhouse gas emissions compared to 1990 levels.

Recently, the EU energy roadmap 2050 has been adopted as a basis for implementing energy efficiency measures and reducing emissions. Particularly, in 2014, European Commission (EC) presented the key achievements of its energy and climate policy framework. According to it, "*greenhouse gas emissions in 2012 decreased by 18% relative to emissions in 1990 and are expected to reduce further to levels 24 and 32% lower than in 1990 by 2020 and 2030 respectively on the basis of current policies, … the share of renewable energy has increased to 13% in 2012 as a proportion of final energy consumed and is expected to rise further to 21% in 2020 and 24% in 2030, … the EU had installed about 44% of the world's renewable electricity (excluding hydro) at the end of 2012, … the energy intensity of the EU economy has reduced by 24% between 1995 and 2011 whilst the improvement by industry was about 30%, … the carbon intensity of the EU economy fell by 28% between 1995 and 2010"* [16, 15 final, p. 2]. On 30 November 2016, the EC proposed an update to the Energy Efficiency Directive including a new 30% energy efficiency target for 2030.

The scope of this chapter is to present the relationship between pollution, economic growth and renewable energy consumption. It also explores the effect of environmental efficient indicators on environmental pollutants and draws valuable policy implications towards European Commission's Energy and Climate Policy Framework. The results obtained by the analysis clarify if the recent adopted 30% energy efficiency target for the year of 2030 by EC is satisfied or policy implications should be strengthened towards more installed renewable energy and more efficient energy use among the EU countries.

2 The Energy Efficiency Directive

The European electricity sector has undergone fundamental changes in response to the three pillars set by the European Union (EU), namely (a) environmental sustainability, (b) security of supply and (c) competitiveness. These three policy objectives have been underpinned by specific energy policy goals which have to be achieved until 2030. These goals include inter alia the reduction of Greenhouse Gas Emissions by 40% compared to 1990 levels, the increase of renewable energy supply by at least 27% of total demand and the increase of energy efficiency by 27% compared with the business-as-usual scenario.

Some resulting trends are already more and more apparent, as the European fuel mix used to generate electricity has undergone significant changes over the past decades and several EU countries report a steady increase in the penetration of Renewable Energy Sources (see, e.g. Dagoumas and Polemis [18]; Polemis [55]). The quantity of renewable energy produced within the EU-28 increased overall by 73.1% between 2004 and 2014, equivalent to an average increase of 5.6% per year [24]. Among RES, there was a particularly rapid expansion in the output of solar energy, accounting for a 6.1% share of the EU-28's renewable energy produced in 2014 [24]. Future energy scenarios show the increasing role that solar energy will play in the overall primary energy mix over the next decades. For instance, under the IRENA's Remap scenario for Europe the solar capacity additions will reach 270 GW of solar power by 2030 [35].

According to the 2012 Energy Efficiency Directive[1] "*all EU countries are required to use energy more efficiently at all stages of the energy chain, from production to final consumption*".[2] Table 1 presents the target of energy consumption (primary and final) for each individual member state in 2020:

On 30 November 2016, the Commission, among others, proposed a new 30% energy efficiency target for 2030.[3] The basic measures to achieve the updated target are the following[4]:

- Energy distributors or retail energy sales companies have to achieve 1.5% energy savings per year through the implementation of energy efficiency measures.
- EU countries can opt to achieve the same level of savings through other means, such as improving the efficiency of heating systems, installing double glazed windows or insulating roofs.
- The public sector in EU countries should purchase energy efficient buildings, products and services.
- Every year, governments in EU countries must carry out energy efficient renovations on at least 3% (by floor area) of the buildings they own and occupy.
- Energy consumers should be empowered to better manage consumption. This includes easy and free access to data on consumption through individual metering.
- National incentives for SMEs to undergo energy audits.
- Large companies will make audits of their energy consumption to help them identify ways to reduce it.
- Monitoring efficiency levels in new energy generation capacities.

[1]See https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN.

[2]See https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive.

[3]See "The new Energy efficiency measure," available at https://ec.europa.eu/energy/sites/ener/files/documents/technical_memo_energyefficiency.pdf.

[4]Ibim. See also https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition.

Table 1 Energy efficiency directive: absolute level of energy consumption in 2020

EU Member State	Absolute level of energy consumption in 2020 (Mtoe)	
	Primary energy consumption	Final energy consumption
Austria	31.5	25.1
Belgium	43.7	32.5
Bulgaria	16.9	8.6
Croatia	11.15	7.0
Cyprus	2.2	1.8
Czech Republic	39.6	25.3
Denmark	17.4	14.4
Estonia	6.5	2.8
Finland	35.9	26.7
France	219.9	131.4
Germany	276.6	194.3
Greece	24.7	18.4
Hungary	24.1	14.4
Ireland	13.9	11.7
Italy	158.0	124.0
Latvia	5.4	4.5
Lithuania	6.5	4.3
Luxembourg	4.5	4.2
Malta	0.7	0.5
Netherlands	60.7	52.2
Poland	96.4	71.6
Portugal	22.5	17.4
Romania	43.0	30.3
Slovakia	16.4	9.0
Slovenia	7.3	5.1
Spain	119.8	80.1
Sweden	43.4	30.3
United Kingdom	177.6	129.2
Sum of indicative targets EU28	1526	1077
EU28 target 2020	1483	1086

Source https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive and https://ec.europa.eu/energy/sites/ener/files/documents/article_3_eed_indicative_national_energy_efficiency_targets_2020_january_2017.pdf

3 Literature Review

Fotis and Polemis [30] cast light on the relationship between sustainable development environmental policy and renewable energy use. They utilize a dynamic GMM approach over a panel of 34 EU countries spanning the period 2005–2013. Their findings suggest a positive monotonic relationship between development and pollution. Energy saving positively affects environmental degradation, while energy intensity increases air pollution. Their findings imply that even though the Europe "20–20–20" climate and energy package strategy seems to be achieved, the recently adopted Energy Roadmap 2050 must be updated on regular basis in order to be effectively implemented and monitored by government officials and firms' stakeholders. The authors argue that EU countries must increase the use of new technology and renewable energy capacity in order to align environmental policies towards more efficient energy use and sustainable development among the EU periphery. Morse [48] explores the relationship among environmental performance, as represented by the Environmental Performance Index (EPI 2016),[5] development (GDP/capita) and income inequality (Gini coefficient) over the period 1995–2014. In general, the empirical results suggest that environmental performance increases with increasing development and declining Gini coefficients (less inequality).[6]

Fotis and Pekka [27] empirically examine the effect of renewable energy use and economic growth on pollution within EUROZONE from 2005 to 2013 by utilizing Dynamic Panel Generalized Method of Moments techniques. The empirical results pose that economic growth positively affects environmental pollutants. The use of RES negatively affects the level of environmental degradation. Halkos and Polemis [33], argue that local (NO_X per capita emissions) and global (CO_2 per capita emissions) pollutants redefine the EKC hypothesis when financial development indicators are taken into consideration. They argue that in the case of global pollution an N-shape relationship is evident both in static and dynamic framework with a very slow adjustment.

Apergis [5] uses panel and time series-based methods of cointegration for a dataset of EU13 countries from 1960 to 2013. The empirical results are mixed under both methodologies. However, when quantile cointegration is used, the results support the validity of EKC hypothesis in the majority of sample countries. Rodriguez et al. [57] analyse a balanced panel data of EU13 countries, Japan and US over the period 1979–2004. They find a positive, but decreasing relationship between CO_2 emissions and development (GDP per capita) and a relative decoupling between the two variables. Mazur et al. [47] also use fixed and random effects panel models in

[5]Mukherjee and Chakraborty [49] use Environmental Performance Index (EPI2008) to explore the relationships among environmental quality, human and economic development and political and governance regimes through a cross-country framework of 146 countries in 2008.

[6]For a survey of the literature on an empirical and theoretical perspective, see also Bernard et al. [11]. For relevant studies, see also Dögl and Behnam [22], Lopez-Menendez et al. [43], Lee et al. [41], Galeotti et al. [32], Coondoo and Dinda [17], Richmond and Kaufmann [56], Markandya et al. [44], Kukla-Gryz [39], Markandya et al. [44], Alvarez et al. [4], Dinda [20] and Stern (2004). Panayotou [51] has also given a critical overview of the research done from 1992 to 2000.

order to explore the EKC hypothesis for a panel data on EU28 countries during the period 1992–2010. The empirical results do not support the validity of the EKC hypothesis within the EU28 countries. However, they find evidence in favour of an inverted U-shaped relationship for the EU18 countries. Ajmi et al. [2] utilize annual data from 1960 to 2010 on per capita energy consumption, economic development (real GDP per capita) and CO_2 emissions for the G7 countries excluding Germany arguing the absence of the EKC hypothesis since cubic N-shaped (United Kingdom) and inverted N-shaped (Italy and Japan) relationships are evident between CO_2 emissions and real GDP per capita.

Lopez-Menendez et al. [43] explore the EU27 countries over the period 1996–2010. They use fixed and random effects panel models with additional explanatory variables related to the high renewable energy intensity (the proportion of electricity generated from renewable sources) in order to investigate the relationship between CO_2 emissions and development (per capita GPD). The empirical results show evidences of inverted N-shaped curve for the EU27 countries. However, the consideration of specific country effects in the empirical model lead to the conclusion that only 4 countries (Cyprus, Greece, Slovenia and Spain) exhibit an inverted U-shaped relationship, while 11 countries correspond to increasing patterns, 9 countries show a decreasing path and the remaining 3 countries lead to U-shaped curves. Chang et al. [14] show that increased carbon emissions resulting from economic development cannot be outweighed by technological improves in environmental protection at different levels of economic development. The authors also state that industrial structure of economies under scrutiny plays a crucial role in lowering the degree of carbon emissions. Since this is associated with international activity and energy use, policy makers should evaluate all of them together in order to reduce environmental pollution.

Danaeifar [19] uses spatial panel data model for 30 EU countries over the period of 1992–2008. The results confirm the existence of an inverse U-shaped relationship between development, global CO_2 emissions and local aerosols pollutants. Baycan [10] examines the EKC relationship in EU25 countries over the period from 1995 to 2005. The empirical results show a statistically significant U-shaped EKC relationship between each of the air pollutants employed and per capita income development for EU15 and EU25 member countries. Jaunky [37] uses the Blundell–Bond system generalized methods of moments (GMM) to test the EKC hypothesis for 36 high-developed (income) countries for the period 1980–2005. The author supports the existence of the EKC hypothesis for Malta, Oman, Portugal and the United Kingdom. Iwata et al. [36] explore a panel data analysis of 28 countries (17 EU countries) over the period 1960–2003 and show that CO_2 emissions increase monotonically in all countries under scrutiny, the effects of nuclear energy on CO_2 emissions are significantly negative and CO_2 emissions decrease and increase with income in OECD and non-OECD countries, respectively. Donfouet et al. [21] use data from EU countries over the period of 1961–2009 and present evidences regarding spatial EKC hypothesis. The authors find evidence of an inverted U-shaped relationship between CO_2 emissions and development (per capita income) after controlling for spatial interdependence. Marrero [45] uses data on EU24 countries over the period from

1990 to 2006 and concludes that the EKC hypothesis does not hold for the EU24 countries. Acaravci and Ozturk [1] examine EU19 countries over the period from 1965 to 2005 and state that the validity of EKC hypothesis holds only for Denmark and Italy.

Table 1 presents the main research regarding the effect of energy efficient indicators and Growth on environmental pollutants at the country level within EU.

4 Descriptive Statistics

Table 2 presents the average values of environmental pollutants, real (per capita) GDP growth rate and control variables for the EU34 and EU28 member states. SO_2, NO_X and NMVOC present sulphur oxides, nitrogen oxides and non-methane volatile organic compounds correspondingly, while GGE presents of greenhouse gas emissions (CO_2 equivalent). The calculation of the real (per capita) GDP growth rate in terms of volumes is intended to allow comparisons of the dynamics of economic development both over time and between economies of different sizes. The GDP at current prices are valued in the prices of the previous year. Therefore, the computed volume changes are imposed on the level of a reference year, and they are not inflated by price movements (chain-linked series). MI denotes energy intensity, that is, the ratio between the gross inland consumption (the sum of primary production, recovered products, total imports, variations of stocks, total exports and bunkers) of energy and GDP.

The variable *RENEWS* may be considered as an estimate of the indicator described in Directive 2009/28/EC (OJ L 140).[7] The variable *RENEWG* (the ratio between the electricity produced from renewable energy sources and the gross national electricity consumption plus electricity imports, minus exports) measures the contribution of electricity produced from renewable energy sources to the national electricity consumption. The variable *ES* is implemented by Directive 2012/27/EU on energy efficiency (OJ L 315).[8] Under the Directive, all EU member states are required to use energy more efficiently at all stages of the energy chain from its production to its final consumption. Tables 3 and 4 present the average values of environmental pollutants, real (per capita) GDP growth rate and control variables for each EU28 member state and EU19 (EUROZONE) member states correspondingly.

Table 5 presents the average values of environmental pollutants, real (per capita) GDP growth rate and control variables for OECD member states.

Tables 2, 3, 4 and 5 reveal that the mean value of real per capita GDP growth rate for EU34 countries under the period 2005–2013 is 1.41, while the corresponding values

[7] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

[8] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.

Table 2 The effect of energy efficient indicators and Growth on environmental pollutants: main empirical at the country level within EU

Papers	Period	Pollutants	Number of countries	Methodology	Results
Yang et al. [66]	1998–2013	GHG[a]	Russia	–	Existence of inverted U shape
Wang et al. [65]	2000–2013	CO_2	China	Semi-parametric panel fixed effect	Mixed results per industrial sector
Sephton and Mann [60]	1830–2003 1850–2002	SO_2 and CO_2	UK	Threshold cointegration techniques	Existence of EKC
Zhang and Zhao [68]	1995–2010	CO_2	China	Fixed effect, FGLS, PCSE, etc. techniques	Mixed results per region
Shahbaz et al. [61]	1970–2010	CO_2	Turkey	VECM Granger causality approach	Existence of inverted U shape
Sephton and Mann [58, 59]	1857–2007	CO_2	Spain	Threshold cointegration techniques	Existence of inverted U shape
Fosten et al. [25]	1830–2003 1850–2002	SO_2 and CO_2	UK	Threshold cointegration techniques	Existence of inverted U shape
Esteve and Tamarit [23]	1857–2007	CO_2	Spain	Two-regime threshold cointegration model	Existence of inverted U shape
Wang et al [64]	1997–2010	CO_2	Beijing City, China	Partial least square regression	Non-existence of inverted U shape
Akbostanci et al. [3]	1992–2001 1968–2003	CO_2	Turkey	VAR model GLS model	Non-existence of inverted U shape Positive monotonic/N shaped
Soytas and Sari [62]	1960–2000	CO_2	Turkey	VAR model	Non-existence of EKC

(continued)

Table 2 (continued)

Papers	Period	Pollutants	Number of countries	Methodology	Results
Brannlund and Ghalwash [13]	1984, 1988, 1996	SO_2, CO_2 NO_x	Sweden	Seemingly unrelated regressions (SURE)	Positive (concave) relationship
Kunnas and Myllyntaus [40]	1800–2003	SO_2, CO_2 NO_x	Finland	OLS	Existence of EKC for SO_2 and NO_x
Johansson and Kriström [38]	1900–2002	SO_2	Sweden	OLS—AR(2) process	Non-existence of inverted U shape
Lise [42]	1980–2003	CO_2	Turkey	OLS	Non-existence of inverted U shape linear (positive) relationship
Friedl and Getzner [31]	1960–1999	CO_2	Austria	OLS with structural break	Non-existence of inverted U shape (N shaped)

Source Fotis and Polemis [30]
[a]Greenhouse gas emissions

for EU28 and the EUROZONE member states are 1.38 and 1.23, respectively. Poland, Romania, Bulgaria, Czech Republic and Sweden exhibit high levels of Growth rates, and this fact merely[9] explains the difference of Growth rates between EU28 and the EUROZONE member states. Countries with the highest values of average real GDP growth rate (Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Malta, Poland, Romania and Slovakia) present both high and low levels of environmental pollutants. For instance, Bulgaria, Poland, Romania and Czech Republic exhibit high levels of pollution, but Estonia, Latvia, Lithuania and Slovakia exhibit low levels of pollution. This may also imply a shift of structural changes in the economies of Estonia, Latvia, Lithuania and Slovakia towards environmental friendly energy use practices and technological developments at both demand and supply sides of energy, such as end-use appliances.

Also, countries with the highest levels of energy saving (ES) such as Germany, Spain, Italy, France, UK, Turkey and Poland, show the highest levels of pollution among the EU34 member states. This evidence may be due to the fact that all these

[9]However, the mean values of real per capita GDP growth rates of Croatia and Hungary for the period under scrutiny are 0.41 and 0.63, respectively.

Table 3 Average values of environmental pollutants, real (per capita) GDP growth rate and control variables for EU34 and EU28 member states: 2005–2013

	Environmental pollutants				Control variables				GDP growth rate
	SO_2	NO_X	NMVOC	GGE	ES	RENEWS	RENEWG	MI	*I*
EU34									
Mean	4.87	5.24	5.14	4.81	1.15	1.03	1.16	2.36	1.41
Standard deviation	0.73	0.57	0.61	0.63	0.66	0.45	0.47	0.41	3.90
Min	3.10	3.56	3.41	3.47	−0.41	−0.72	−1	1.92	−14.67
Max	6.41	6.21	6.13	5.99	2.34	1.82	2.02	7.87	10.88
Variance	0.53	0.32	0.38	0.40	0.44	0.20	0.28	0.17	15.21
Skewness	0.50	−0.23	−0.60	−0.04	−0.25	−1.17	−1.30	8.37	−0.81
Kurtosis	2.43	2.68	3.38	2.14	2.50	5.80	1.67	11.13	5.19
EU28									
Mean	4.84	5.22	5.11	4.80	1.24	1.01	1.13	2.31	1.37
Standard deviation	0.69	0.57	0.62	0.64	0.62	0.43	0.44	0.23	3.99
Min	3.10	3.56	3.41	3.47	−0.41	0.72	−1	1.92	−14.67
Max	6.12	6.21	6.13	5.99	2.34	1.71	1.83	2.93	10.88
Variance	0.47	0.33	0.38	0.38	0.39	0.18	0.25	0.05	15.88
Skewness	−0.14	−0.18	−0.57	−0.57	−0.32	−1.35	−1.40	0.53	−0.80
Kurtosis	2.39	2.67	3.35	3.35	2.92	6.25	2.01	2.53	5.05

Source Fotis and Polemis [30]

Notes SO_2: sulphur oxides, NO_X: nitrogen oxides, NMVOC: non-methane volatile organic compounds, GGE: greenhouse gas emissions (CO_2 equivalent), MI: energy intensity, RENEWG: the ratio between the electricity produced from renewable energy sources and the gross national electricity consumption (% of gross electricity consumption), RENEWS: share of renewable energy in gross final energy consumption (%), ES: energy saving from primary energy consumption, I: real GDP growth rate

Table 4 Mean values of environmental pollutants, real GDP growth rate and control variables: for each EU28 member state: 2005–2013

	Environmental pollutants				Control variables				GDP growth rate
	SO_2	NO_X	NMVOC	GGE	ES	RENEWS (%)	RENEWG (%)	MI	*I* (%)
EU 28	189,489	349,238	282,610	157,230	40.24	16.52	22.73	232.42	1.38
Belgium	86,286	257,881	151,084	127,349	36.13	4.86	6.64	181.12	1.13
Bulgaria	534,513	157,257	102,675	52,414	9.52	12.69	12.21	717.86	2.55
Czech Rep.	174,175	233,732	176,453	134,982	25.02	8.74	7.38	378.79	2.12
Denmark	19,490	161,744	129,925	66,112	15.09	20.81	30.91	92.18	0.31
Germany	440,559	1,393,112	1,212,636	936,434	214.87	9.82	17.37	139.36	1.23
Estonia	65,748	39,156	26,675	14,329	2.92	21.57	7.09	490.42	2.64
Ireland	42,359	103,357	96,257	69,276	12.06	5.09	13.66	88.10	1.02
Greece	386,839	348,754	194,714	120,389	19.70	9.78	12.30	154.13	−2.12
Spain	673,427	1,112,679	705,394	355,167	90.40	11.97	27.10	142.20	0.56
France	330,818	1,159,437	881,986	467,390	153.02	11.49	15.10	149.51	0.91
Croatia	42,859	70,817	71,375	20,776	7.10	24.41	36.77	231.21	0.41
Italy	265,797	1,027,049	1,101,167	492,123	128.84	12.00	20.86	122.86	−0.47
Cyprus	23,528	20,179	10,405	8693	1.86	5.33	1.92	178.60	0.94
Latvia	6186	39,561	56,144	10,340	4.08	32.64	42.57	333.77	2.69
Lithuania	24,319	55,604	75,443	13,191	4.82	19.27	7.08	342.84	2.52
Luxembourg	1923	43,299	12,443	11,712	4.29	2.64	3.91	139.97	2.18
Hungary	34,236	143,662	129,545	63,775	16.38	7.42	5.62	286.22	0.63
Malta	9139	7804	3075	3121	0.46	1.18	0.36	172.08	2.33
Netherlands	45,292	313,578	163,941	211,285	52.92	3.82	8.36	150.89	1.05

(continued)

Table 4 (continued)

	Environmental pollutants				Control variables				GDP growth rate
	SO_2	NO_X	NMVOC	GGE	ES	RENEWS (%)	RENEWG (%)	MI	*I* (%)
Austria	20,288	190,265	122,169	78,389	27.46	28.90	65.40	129.38	1.40
Poland	1,042,823	841,407	631,323	361,238	62.80	8.76	6.18	332.08	3.84
Portugal	90,346	199,481	189,295	65,162	17.84	23.24	38.26	159.17	−0.38
Romania	431,437	273,608	365,980	114,090	23.44	20.86	30.73	411.49	2.63
Slovenia	15,647	49,754	40,387	12,307	4.94	18.48	30.70	232.74	1.10
Slovakia	70,252	92,539	122,120	40,253	11.06	8.64	17.96	384.18	3.91
Finland	65,948	174,014	112,777	41,804	25.42	31.94	27.88	215.10	0.81
Sweden	31,253	159,590	206,538	21,945	32.72	46.70	56.17	154.13	1.63
UK	500,382	1,280,183	946,262	616,985	142.92	3.21	7.37	111.39	1.05

Source Fotis [28, 29]
Note Table 3

Table 5 Average values of environmental pollutants, real (per capita) GDP growth rate and control variables for EUROZONE member states: 2005–2013

	Environmental pollutants				Control variables				GDP growth rate
	SO_2	NO_X	NMVOC	GGE	ES	RENEWS	RENEWG	MI	*I*
Mean	4.70	5.14	5.00	4.73	1.17	0.97	1.11	2.27	1.23
Standard deviation	0.67	0.63	0.68	0.69	0.70	0.46	0.56	0.19	4.24
Min	3.10	3.56	3.41	3.47	−0.41	−0.72	−1	1.92	−14.67
Max	6.11	6.20	6.13	5.99	2.34	1.57	1.83	2.74	10.88
Variance	0.46	0.40	0.47	0.48	0.49	0.21	0.36	0.04	18.01
Skewness	−0.17	−0.05	−0.33	0.08	−0.18	−1.47	−1.34	0.76	−0.80
Kurtosis	2.50	2.27	2.72	1.94	2.40	6.18	2.59	2.89	5.12

Source Fotis and Pekka [27]
Notes Table 3

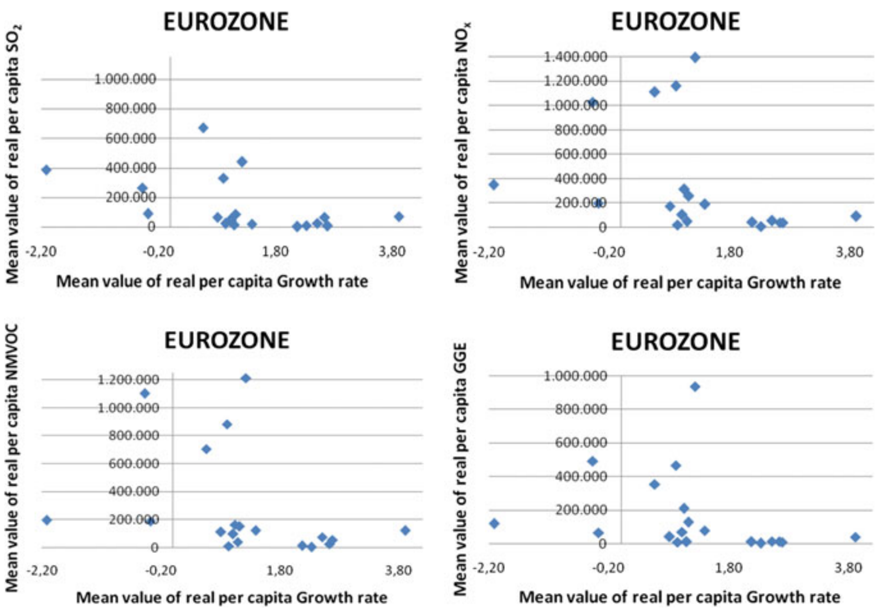

Fig. 1 The relationship between the environmental pollutants and the real gross domestic product growth rate for the EUROZONE countries: 2005–2013 (*Notes* The horizontal axis depicts the real GDP growth rate at 2005 constant prices and the vertical axis depicts the average (2005–2013) environmental pollutant per capita at 2005 constant prices. The explanation of the variables is given in Table 2). *Source* Fotis [28]

countries exhibit low levels of renewable energy use as a percentage share of gross final energy consumption and low levels of the contribution of renewable energy sources in gross final energy consumption (lower levels of RENEWS and RENEWG than the corresponding mean values). Spain is the only country from the group of countries with the highest levels of energy saving (ES) that exhibit higher percentage value of RENEWG than the corresponding mean value of the EU34 countries.

Lastly, there exist three countries (Greece, Portugal and Italy) which exhibit negative real GDP growth rates. Greece shows an almost double level of environmental pollutants with respect to the average level of EU34 countries and Italy exhibits the same level of environmental pollutants with the corresponding average level. On the contrary, Portugal exhibits low level of environmental pollutants with respect to the corresponding average value, but its economic growth is much higher than the level of economic growth of Italy and Greece.

Figure 1 presents relationship between the Environmental pollutants and the Real Gross Domestic Product Growth Rate for the EUROZONE (EU19) member states.

Figure 1 shows mixed evidences concerning the relationship between environmental pollutants and real GDP growth rate. Visual inspection of Fig. 1 supports a monotonic relationship between the variables under scrutiny. The majority of the sample countries exhibit high and low levels of positive real GDP growth rate with low or at least modest levels of environmental pollutants. However, there exist some countries which exhibit a positive monotonic relationship between environmental pollutants with respect to real GDP growth rate. The group of these countries consists of countries associated with low levels of economic growth such as Germany, Netherlands, France and Spain.

5 Data and Empirical Methodology

5.1 Data

In this section, we ullustrate the pure effects of "20–20–20" targets and development on environmental pollution. The econometric estimations are based on three pooled panel data sets[10] for EU34 member states (EU28, 5 candidates and Norway) ($T = 9, N = 34$), EU28 member states ($T = 9, N = 28$) and EUROZONE member states ($T = 9, N = 19$) covering period 2005–2013. The reason for using panel data sets to investigate possible cointegrating vectors instead of time series analysis is that residual-based cointegration tests are known to have low power and are subject to normalization problems. Since economic time series are typically short, it is desirable to exploit panel data in order to draw sharper inferences [28, 29]. Besides, cross-sectional data suffer from assuming that the same characteristics (i.e. structure of the markets, degree of regulation, etc.) apply to all national economies, while there are difficulties in obtaining reliable time series data of sufficient length.

5.2 Empirical Methodology

We estimate reduced-form models between per capita pollutant emissions, per capita real GDP growth rate and the non-linear values (i.e. quadratic and cubic terms) of per capita real GDP growth rate [38–26, 48, 56, 63], and per capita indicators of energy efficiency. Equation 1 depicts the basic cubic function in its semi-logarithmic form:

$$\log E_{i,t} = \alpha_i + \beta \log E_{i,t-1} + \beta_1 I_{i,t} + \beta_2 I_{i,t}^2 + \beta_3 I_{i.t}^3 + \beta_4 \log X_{i,t} + \varepsilon_{i,t} \qquad (1)$$

[10]The samples are from the Eurostat database.

Following standard notation t stands for the period and i stands for the countries under scrutiny. $\log E_{i,t}$[11] denotes the vector of the environmental pollutants at period t (the dependent variables of the empirical models) and $\log E_{i,t-1}$ denotes the vector of the environmental pollutants at period $t-1$. $I_{i,t}$ denotes Growth rate (development) and $\log X_{i,t}$[12] denotes the vector of control variables that influence environmental degradation. As usual $\varepsilon_{i,t}$ is the error term. All the variables are measured in MWh at 2005 constant prices for all the member states and are deflated by the annual average rate of change of Harmonised Index of Consumer Prices (HICP).

6 Method of Estimations and Empirical Results

6.1 Method of Estimations

The estimator of dynamic error components models, which uses differences rather than levels for instruments, has a singularity point and very large variances over a significant range of parameter values [30]. Therefore, in order to allow for the dynamic aspects in the empirical models, we use dynamic panel data techniques such as Dynamic Panel GMM (DPGMM) estimators attributed to Arellano and Bond [7][13] and Arellano and Bover [8]/Blundell and Bond [12].[14]

The DPGMM estimator by Arellano and Bond [7] is also known as a two-step difference GMM (DIF-GMM) where the lagged levels of the regressors are instruments for the equations in first differences. The DPGMM estimator by Arellano and Bover [8]/Blundell and Bond [12] is also known as the System GMM estimator (SYS-GMM), since it combines regression in first differences with the original equation, included by further instrumental variables (see also [52]. The SYS-GMM estimator uses lagged first differences of the variables as instruments in the level equations.

[11] $\log E_{i,t} = \begin{bmatrix} \log SO_{2,t} \\ \log NO_{X,t} \\ \log NMVOC_t \\ \log GGE_t \end{bmatrix}$, where $\log SO_2$ is the natural logarithm of sulphur oxides emissions, $\log NO_X$ is the natural logarithm of nitrogen oxides emissions, log NMVOC is the natural logarithm of non-methane volatile organic compounds emissions and log GGE is the natural logarithm of total greenhouse gas emissions (CO_2 equivalent).

[12] $\log X_{i,t} = \begin{bmatrix} \log MI \\ \log RENEWS \\ \log RENEWG \\ \log ES \end{bmatrix}$, where log MI denotes the natural logarithm of energy intensity, log RENEWS denotes the natural logarithm of the share of renewable energy in gross final energy consumption, log RENEWG denotes the natural logarithm of electricity generated from renewable sources (% of gross electricity consumption) and log ES denotes the natural logarithm of the indicator of energy saving for monitoring progress towards "20–20–20" targets.

[13] See, *inter alia*, Polemis and Fotis [54, p. 428].

[14] See also Holtz-Eakin et al. [34].

Both estimators (DIF-GMM and SYS-GMM) are designed to deal with small T and large N panels, that is, few time periods and many individual units (cross sections). Recall that in this paper, we deal with short T dynamic panel data sets ($T = 9$ and $N = 34$ or 28 or 19).

Following Fotis et al. [26] and Fotis and Polemis [30][15] α_i and $\varepsilon_{i,t}$ are independently distributed across i, $\varepsilon_{i,t}$ has zero mean and it is independent over t and i. Also, it is assumed that $E\left(E_{i,1}, \varepsilon_{i,t}\right) = 0$ for $i = 1 \ldots N$ and $t = 2 \ldots T$. The last assumption concerning the initial conditions of environmental indicators in conjunction with the assumptions regarding α_i and $\varepsilon_{i,t}$ suffice for a consistent estimation of Eq. 1 using DPGMM estimators for $T \geq 3$.

6.2 Empirical Results

6.2.1 Estimates for EU34 Member States

Table 6 presents the DIF-GMM parameter estimates of Eq. 1 regarding the EU34 member states.[16] The results reveal that the growth coefficient is statistical significant and positive, except from the growth coefficient in the empirical model with NMVOC dependent variable. However, the quadratic and cubic growth coefficients are not always statistically significant. For instance, the cubic growth coefficients are statistically insignificant and in the cases where the quadratic growth coefficients are statistical significant either they exhibit a positive effect of growth rate on environmental pollutant (see, i.e. the empirical model with SO_2 dependent variable) or a negligible effect between the two variables (see, i.e. the empirical model with SO_2 dependent variable where the estimated coefficient is almost zero). These results depict a positive relationship between environmental pollutants and GDP growth rate and minimal or zero evidence for the Environmental Kuznets Curve (EKC) hypothesis in the EU34 countries for the period 2005–2013.

In terms of the other control variables included in Eq. 1, it is evident that energy intensity (*MI*) positively affects all the environmental pollutants. The empirical results reveal that within EU34 member states energy intensity mostly affects positively the level of SO_2 emissions. Similarly the effect of energy saving on environmental pollutants is positive. This effect reveals an inefficient way of energy use within EU. Different technological or regulatory aspects within EU member states may be critical factors affecting the way they use energy saving towards monitoring EU's energy policy. However, emissions from all the environmental pollutants are eliminated by the increase of the share of renewable energy in gross final energy

[15] See also, among others, Marrero [45].

[16] The estimation of β in Eq. 1 (E_{t-1}) is always highly statistical significant and smaller than 1 for all the dependent variables employed within the EU34 countries. For instance, the estimated value 0.77 reveals the importance of the inclusion of the lagged dependent variable in the right hand side of Eq. 1.

Table 6 Mean values of environmental pollutants, real GDP growth rate and control variables: 2005–2013

	Environmental pollutants				Control variables				GDP growth rate
	SO_2	NO_X	NMVOC	GGE	ES	RENEWS (%)	RENEWG (%)	MI	*I* (%)
OECD member country									
Norway[a]	19,248	178,408	157,508	28,651	18.81	62.84	101.61	118.68	1.29
5 candidates of EU									
Montenegro	–	–	–	–	0.80	–	–	531.54	–
FYROM[b]	–	–	–	–	1.78	–	–	520.02	–
Albania	–	–	–	–	1.86	–	–	–	–
Serbia	–	–	–	–	9.17	–	–	715.24	2.39
Turkey[a]	2,456,311	997,556	946,517	351,566	74.18	–	–	228.50	–

Notes Table 3
[a]OECD member countries
[b]Former Yugoslav Republic of Macedonia
Source Fotis [28]

consumption increases. This result reveals that the more the renewable energy we use, the less the pollution. The same could be said for the effect of electricity generated from renewable sources of gross electricity consumption (RENEWG) on environmental pollutants, at least in most of the models employed which the parameter estimate of RENEWG is statistical significant.

6.2.2 Estimates for EU28 Member States

Table 7 presents the DIF-GMM parameter estimates of Eq. 1. The said estimates, as the estimates for EU34 member states, are almost all highly statistically significant, and robust given that Eq. 1 represents structural and not spurious long-run relation. GMM parameter estimates are shown for the one-step GMM estimator case with standard errors that are asymptotically robust to heteroskedasticity and have been found to be more reliable for finite sample inference than the GMM standard errors.[17]

Within the EU28 countries, the empirical results reveal a positive effect of economic growth on environmental pollutants. Even thought there is a positive relationship between the two variables, the effect of real per capita GDP growth rate on all the environmental pollutants employed is quite close to zero. However, the non-statistically significant parameter estimates of quadratic and cubic coefficients of income indicate that the EKC hypothesis does not exist in the EU28 countries for the period 2005–2013.[18]

The empirical results also reveal that, mainly, energy intensity positively affects SO_2 emissions. The effect of energy saving on environmental pollutants is positive, while emissions from all the environmental pollutants are eliminated by the increase in the share of renewable energy in gross final energy consumption increases. Therefore, the empirical results that emerge from the EU28 member states regarding control variables coincide with the ones drawn from the EU34 member states.

6.2.3 Estimates for EU19 (EUROZONE) Member States

Similarly with Fotis and Pekka [27], we present the DIF-GMM and SYS-GMM parameter estimates of Eq. 1 regarding the EUROZONE (EU19 member states). The parameter estimates of Growth rate (I, I^2 and I^3) are almost all highly statistically significant, and the whole estimates are robust given that Eq. 1 represents structural and not spurious long-run relation. Standard errors of GMM parameter estimates are asymptotically robust to heteroskedasticity and have been found to be more reliable for finite sample inference than GMM standard errors.

[17] The estimation of β in Eq. 1 (E_{t-1}) is always highly statistical significant and smaller than 1 for all the dependent variables employed within the EU28 countries. This result reveals the importance of the inclusion of the lagged dependent variable in the right hand side of Eq. 1.

[18] A similar result regarding carbon dioxide emissions (CO_2) has been reported in the literature by Martínez-Zarzoso et al. [46].

Table 7 Estimates for EU34 member states [a]

	EU34			
Ind. var.	Dep. var.[b]			
	SO_2	NO_X	NMVOC	GGE
c^c	62.15*** (35.49)	0.91* (16.16)	−70.39* (23.31)	−75.38 (24.21)
E_{t-1}^d	0.44* (0.11)	0.71* (0.09)	0.77* (0.08)	0.53* (0.08)
I	0.74* (0.24)	0.30*** (0.15)	0.13 (0.12)	0.51* (0.15)
I^2	0.05** (0.25)	−0.01 (0.02)	−0.00 (0.02)	−0.03** (0.02)
I^3	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.02)
ES^d	0.39* (0.11)	0.79* (0.11)	0.57* (0.13)	0.75* (0.09)
$RENEWS^d$	−0.12* (0.01)	−0.03* (0.01)	0.00 (0.01)	−0.03** (0.01)
$RENEWG^d$	−0.18* (0.09)	0.81 (0.04)	0.02 (0.04)	0.09** (0.04)
MI^d	0.08(0.07)	0.10*** (0.05)	0.01 (0.07)	0.12*** (0.07)
Wald chi^2	*407.90* (0.00)*	*923.59* (0.00)*	*695. 91* (0.00)*	*258.45* (0.00)*
No of instruments	*33*	*33*	*33*	*33*
Max lags	*5*	*5*	*5*	*5*

Source Fotis and Polemis [30]
The numbers in parentheses of the parameter estimations refer to the Robust Standard Errors (heteroskedasticity consistent asymptotic standard errors)
The italic numbers in parentheses of the Wald chi^2 estimations refer to the *p*-values of the individually significance tests
Significant at *1%, **5% and ***10%, respectively
[a]One-step results
[b]Dependent variables (in logs)
[c]c denotes the constant term [d]in logs

The empirical results from Table 8 reveal that within the EUROZONE, as within EU34 and EU28 member states, there exists a positive relationship between real per capita GDP growth rate and pollution. The statistically insignificant parameter estimates of quadratic and cubic coefficients of growth rate (I) indicate that the EKC hypothesis does not exist in the EUROZONE during the sample period.[19] Energy intensity (*MI*) positively affects all the environmental pollutants. The empirical results reveal that in EUROZONE energy intensity mostly affects GGE (CO_2 equivalent) emissions. For instance, an increase in energy intensity by 1% causes almost 0.1% increase in GGE (CO_2 equivalent) emissions (SYS-GMM), while under DIF-GMM the corresponding response of SO_2 emissions is almost the same. Energy saving has also positive effect on environmental pollutants, revealing a negative

[19]Following the estimations for EU34 and EU28 member states, the estimation of coefficient β in Eq. 1 (E_{t-1}) is always highly statistical significant and smaller than 1 for all the dependent variables employed within the EUROZONE. We also estimate the dependent variable with two lags in the right hand side of Eq. 1 (E_{t-2}) since it is found to be (highly) statistical significant in all the empirical models employed.

Table 8 Estimates for EU28 member states [a]

	EU28			
Independent variables (in logs)[b]	dependent variables (in logs)			
	SO_2	NO_X	NMVOC	GGE
c^c	−0.13 (0.88)	1.54* (0.39)	1.40* (0.52)	0.81 (0.63)
E_{t-1}	0.52* (0.10)	0.48* (0.09)	0.59* (0.09)	0.32* (0.08)
$\boldsymbol{I}$	0.01* (0.00)	0.01** (0.00)	0.00*** (0.00)	0.02** (0.00)
I^2	0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)
I^3	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)
ES	0.62** (0.25)	0.63* (0.10)	0.36* (0.10)	0.72* (0.22)
RENEWS	−0.23** (0.10)	−0.15** (0.06)	−0.04 (0.04)	0.04 (0.04)
RENEWG	−0.00 (0.00)	0.00 (0.00)	−0.00 (0.00)	0.00 (0.00)
MI	0.85** (0.40)	0.22*** (0.13)	0.13** (0.06)	0.63* (0.20)
Wald chi²	*368.19* (0,00)*	*1495.52* (0,00)*	*513.90* (0,00)*	*411.82* (0,00)*
No of instruments	*33*	*178*	*91*	*120*
Max lags	*5*	*5*	*5*	*5*

Source Fotis [28]
The numbers in parentheses of the parameter estimations refer to the Robust Standard Errors (heteroskedasticity consistent asymptotic standard errors)
The italic numbers in parentheses of the Wald chi^2 estimations refer to the *p*-values of the individually significance tests
Significant at *1% **5% and ***10%, respectively
[a]One-step results
[B]Except from real (per capita) GDP growth rate coefficients
[c]c denotes the constant term

effect on pollution. However, in the empirical models which the parameter estimate of RENEWG is statistical significant (see the models with SO_2 and GGE-dependent variables under DIF-GMM and SO_2 and NO_X-dependent variables under SYS-GMM) emissions from almost all the environmental pollutants are eliminated by the increase in the share of renewable energy in gross final energy consumption (RENEWS) and by the effect of electricity generated from renewable sources of gross electricity consumption (RENEWG) on environmental pollutants (Table 9).

Table 9 Estimation results from the EUROZONE (EU19) member states [a]

	DIF-GMM				SYS-GMM			
Ind. var.[b]	Dep. var.[c]				Dep. var.[c]			
	SO_2	NO_X	NMVOC	GGE	SO_2	NO_X	NMVOC	GGE
c^d	1.37 (1.03)	3.32** (1.69)	0.67 (0.82)	−1.23*** (0.74)	−0.43 (0.56)	0.95 (0.81)	0.21*** (0.13)	−0.28 (0.26)
E_{t-1}	0.49* (0.09)	−0.02 (0.19)	0.71* (0.14)	0.38* (0.11)	0.92* (0.06)	0.31** (0.14)	0.90* (0.02)	0.65* (0.08)
E_{t-2}	–	0.19*** (0.10)	–	0.23** (0.11)	–	0.43* (0.06)	–	0.34* (0.08)
I	0.01* (0.00)	0.01*** (0.00)	0.01*** (0.00)	0.01* (0.00)	0.01* (0.00)	0.00 (0.00)	0.01* (0.00)	0.01* (0.00)
I^2	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)
I^3	−0.01* (0.00)	−0.00 (0.00)	−0.00 (0.00)	0.00 (0.00)	−0.01 (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)
ES	0.25 (0.23)	0.20 (0.54)	0.24 (0.21)	0.54** (0.26)	0.06** (0.03)	0.23 (0.18)	0.10* (0.03)	−0.00 (0.06)
RENEWS	−0.09* (0.03)	0.01 (0.07)	0.01 (0.03)	−0.06** (0.03)	−0.03*** (0.02)	−0.04** (0.02)	0.01 (0.00)	−0.03 (0.03)
RENEWG	−0.01* (0.00)	−0.00 (0.00)	−0.00 (0.00)	−0.02* (0.00)	−0.00 (0.00)	−0.00 (0.00)	0.00*** (0.00)	−0.01* (0.00)
MI	0.41 (0.49)	0.36 (0.37)	0.21 (0.15)	1.04* (0.23)	0.04 (0.07)	0.09** (0.04)	0.06 (0.04)	0.13*** (0.07)
Wald chi²	*646.11* (0.00)*	*273.05* (0,00)*	*106,028* (0,00)*	*400.63* (0,00)*	*30310.46* (0.00)*	*8295.17* (0,00)*	*8487.07* (0,00)*	*5854.82* (0,00)*
No of instruments	*86*	*79*	*36*	*32*	*117*	*107*	*117*	*60*
Max lags	3	*3*	*1*	*1*	*3*	*3*	*3*	*1*

Source Fotis and Pekka [27]
The numbers in parentheses of the parameter estimations refer to the Robust Standard Errors (heteroskedasticity consistent asymptotic standard errors)
The italic numbers in parentheses of the Wald chi^2 estimations refer to the p-values of the individually significance tests
Significant at *1% **5% and ***10%, respectively
[a]One-step results
[b]Independent variables (in logs)
[c]Dependent variables (in logs)
[d] c denotes the constant term

7 Discussion and Policy Implications

The estimated parameters of the empirical models employed in this paper suggest the absence of the EKC hypothesis. The non-linear parameters of Growth rate (Development) are found to be not statistically significant, and the obtained results suggest the existence of a monotonic pattern between environmental pollutants and real (per capita) GDP growth rate.[20] The estimated coefficients of both energy efficiency indicators (RENEWS and RENEWG) are negatively correlated with the level of economic growth. In particular, the share of electricity produced from renewable energy sources to the national electricity consumption (RENEWG) contributes to the elimination of emissions, but a more pronounced effect is revealed when we investigate the share of renewable energy in gross final energy consumption (RENEWS). Therefore, Europe's energy policy within EU should be strengthened towards more installed renewable energy capacity.

The empirical results also suggest that EU energy policy should focus on the promotion of a more efficient energy use at all stages (i.e. from the production to final consumption). On the one hand, countries with the highest levels of energy saving indicator exhibit the highest levels of emissions among the EU28 member states. This happens since all these countries are characterised by low levels of RENEWG and RENEWS than the corresponding mean value of EU28 countries. On the other hand, most of the countries with low levels of energy saving exhibit high levels of RENEWS as well as high levels of RENEWG. Therefore, a convergence of environmental policies towards more efficient energy use among the EU countries should be done in the merit of Europe's energy policy the next years.

The empirical results also reveal that energy intensity positively affects SO_2 emissions. Therefore, we argue that policy makers' energy strategy should be based on eliminating SO_2 emissions by using more efficient technology at all stages of the energy chain. However, the statistical analysis in Sect. 3 showed that countries with the highest values of average real GDP growth rate exhibit high ratio of energy intensity and high levels of pollution. This may also imply a shift of structural changes in the economies towards environmental friendly energy use practices and technological developments at both demand and supply sides of energy, such as end-use appliances. The positive relationship between energy consumption and SO_2 emissions seems to be more important than the relationship between energy consumption and other pollutants. Even though energy intensity was reduced by 24% between 1995–2011 within the EU28 member states, it seems that this endeavour must be reinforced in the future. As in the case of the renewable energy intensity indicators, the recent update by the EC of a new 30% energy efficiency target for 2030 will certainly improve more the elimination of emissions. However, energy intensity flows must be kept up more closely in nowadays. Therefore, a further research on this topic should try to answer the question whether all member states use energy more efficiently, at all stages of the energy chain from its production to its final consump-

[20] See also Fotis and Polemis [30], Fotis and Pekka [27], Mazur et al. [47], Baycan [10], Iwata et al. [36], Marrero [45], Martínez-Zarzoso et al. [46], Azomahou et al. [9].

tion, or European Commission has to reconsider its strategy for monitoring more efficiently progress towards European energy efficiency targets.

Regarding the empirical results for the EUROZONE, it is highlighted that the use of RES affects negatively the level of environmental pollutants. However, energy saving and energy intensity contribute more to air pollution. Electricity produced from RES seems to decrease the level of electricity consumption and thus the level of emissions, but a more pronounced effect is revealed by the contribution of the share of renewable energy in gross final energy consumption. Renewable energy should continue to be at the core of Europe's energy policy and the implementation of the recent update by the European Commission regarding the 30% energy efficiency target for 2030 must be the paradigm for the future.

All in all, the role of firms' stakeholders on the reduction in pollution is of great importance [30]. The adverse effect of energy saving indicator on pollution reveals that firms should use more advanced techniques and promote the use of RES in order to improve environmental quality. Moreover, we argue that firms' stakeholders should follow a more environmental friendly strategy. This, will help them to improve their products and services to the final consumers.

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Does Technological Progress Provide a Win–Win Situation in Energy Consumption? The Case of Ghana

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Abstract This chapter examines whether in the long-run technological progress provides a win–win situation as a demand-side management strategy in the country's energy sector. The data used is annual and methodology is time series. Generally, the results show that technological progress provides a win–win situation by (1) directly reducing energy consumption, (2) minimizing the high energy price incidence on consumers, and (3) reducing the energy-inducing effect of demographic patterns. As a policy recommendation, the government should invest directly in technological innovation and provide the economic and political milieu to boost private investment in technological innovation.

Keywords Technological progress · Energy consumption · Ghana

1 Introduction

In the face of the growing energy challenges and climate change problems, energy efficiency and demand-side management programmes have taken a central role in public policy discourse. First, it provides the least-cost solution to mitigating greenhouse gas emissions and energy insecurity issues [13, 35]. Further, it provides additional resources to the government (who do not have to invest in additional generation capacity) to fund other developmental projects in the economy [22]. Growth potentials and employment generation opportunities have also been associated with energy efficiency improvements [16]. As a consequent, investment commitments in energy

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efficiency have surged globally. In 2015, investment in energy efficiency reached USD 212 billion which represents an increase of 6%. Further, in 2016, energy efficiency investment surged by 9% [21]. The investment in energy efficiency saw a further 3% increase in 2017 to reach USD 236 billion [21].

A good understanding of the drivers of energy demand is a *sine qua non* to designing effective and efficient demand-side management policies. In the empirical literature, based on the neoclassical theory of demand, the roles of price, income, demography and technology have been examined. For a normal good, the theory of demand hypothesizes an inverse relationship between demand and the price of the commodity, all things being equal. The channels are based on the substitution and income effects. The substitution effect causes the end-users to switch from expensive energy sources to cheaper sources, while the income effect reduces the real income of the end-user towards the energy product. In the empirical energy literature, several studies have found evidence of a negative price elasticity of energy demand [1, 28, 41, 43, 45]. The negative price effect suggests that, from the perspective of energy efficiency and conservation, raising the price of energy will promote efficiency and conservation and hence lower energy consumption. Therefore, a government policy to raise the taxes on energy prices may be recommended. However, such a policy, though has positive implications for improving efficiency and conservation, can have undesirable consequences on welfare (especially in poor communities) and production and hence economic growth. In other words, the price mechanism tool for promoting energy efficiency and conservation may not produce a win–win situation for the economy.

On income, the hypothesized relationship is positive for a normal good, all things being equal. An increase in income places consumers in a better position to buy more electrical gadgets or purchase automobiles; this shows the scale effect of income. However, higher income can also spur investment in advanced technology and therefore promote the technical aspects of producing energy services. Thus, empirically, the effect of income may depend on the weights of the scale and technical effects. Largely, the findings have found a positive income elasticity of demand [4–4, 12, 14, 20, 30, 43]. While the positive effect of income is an indication that the goal of economic growth is consistent with the Sustainable Energy for All (SE4All) goal, it suggests the absence of scale economies in the provision of energy services. Thus, given that energy supply does not grow proportionally, policies to stimulate economic growth that do not enhance the technical aspects of production could put pressure on the energy system and threaten energy security and the SE4All goal.

The effect of demography, which has largely focused on urbanization, has rather remained a complex issue in the empirical literature due to the different schools of thought about the role of urbanization. The modernization theory of urbanization as espoused by Kessides [27] postulates a positive effect of urbanization on energy consumption. According to this school of thought, the concentration of people at one place puts pressure on resources. Studies such as Liddle [29], Hameed and Khan [19], Adom et al. [4], Ekpo et al. [14] and Jones [23, 24] confirmed the modernization view of urbanization. In contrast, the compact theory by Elliot et al. [15] postulates an inverse relationship between energy consumption and urbanization. According to this theory, the concentration of people, production, and consumption at one place provides the benefits of economies of scale which improves the efficiency of input use. Moreover, urbanization changes the energy-use structure towards more clean sources such as electricity and gas. Poumanyvong et al. [37] found that in low-, middle- and high-income economies urbanization reduces energy consumption. The studies by Sadorsky [40] for developing economies and Keho [26] for selected African countries rather found a mix of positive and negative effects of urbanization on energy consumption. Especially on the positive effects of demography on energy, policy recommendations of population control measures, though, may help reduce the energy requirement, poor farming communities that resort to household labour will suffer in the end. Thus, such a policy does not provide a win–win situation.

The above suggests that, in terms of improving energy consumption efficiency and management, there is the need to search for a policy tool that will ensure a win–win situation. In this respect, technological progress has that potential. First, technological progress leads to efficiency improvement in energy consumption but, overall, may depend on the extent of rebound effect that such technological progress induces. In the energy demand literature, studies have confirmed the energy consumption reduction effect of technology albeit with less evidence at the country level. Popp [36] analysed the effect of new technologies on energy consumption for 13 energy-intensive industries and found that technology generally reduces energy consumption. Berndt et al. [11] also confirmed that technological change enhances fuels and electricity energy savings in American manufacturing firms. However, earlier study by Jorgenson and Fraumeni [25] reported that technology increases energy consumption. Mountain et al. [32] reported of a negative effect of technological change on oil consumption; a positive effect of technological change on natural gas and mixed results for electricity consumption depending on the type of industry in Ontario. At the country level, Azomahou et al. [9] reported of the energy-reducing effect of technology for OECD countries. Second, the energy efficiency-induced effects of technological progress can reduce the sensitivity of consumers to price shocks, and this could lower the price incidence on end-users of energy. Third, the benefits of scale economies associated with technological progress can also totally or partially eliminate the energy-inducing effect of demographic changes. Finally, though the scale economies of technological progress can affect consumer behaviour by making their demand more income responsive, the improvement in the technical production of energy services should neutralize any consequential effect that might arise. Thus, in sum, technological progress can provide a win–win situation in promoting energy conservation and efficiency. However, these indirect effects of technological progress have not been examined in the empirical literature. The aim of this study is to examine technological progress as a win–win tool for promoting energy conservation and efficiency, using the case of Ghana.

The main innovation in this study is to provide a quantitative understanding into technological progress as a win–win demand-side management strategy. We hypothesize that (1) technological progress reduces energy usage; (2) it reduces the energy-inducing effect of demography, using demographic dependency ratio as the proxy [31]—this has important implications on the finances of households and investment decisions in energy-efficient technologies, and (3) technological progress reduces the energy price incidence on consumers. Further, one of the fundamental econometric concerns that researchers have to deal with in estimating energy demand is the issue of identification. In a highly regulated market, energy price may be identified by energy supply. On the other hand, in a non-regulated market, the identification of price may depend on the patterns in both demand and supply. Thus, irrespective of how one may envisage the problem, endogeneity caused by either simultaneity bias, measurement error, or reverse causality is a problem the researcher is confronted with. In the literature, instrument-based techniques like the two-stage and three-stage least squares and generalized methods of moments, and other cointegrating regressions that deal with serial correlation and endogeneity issues have been used. This study follows the cointegration-based approach. The choice of this estimator is based on its ability to deal with both serial correlation and endogeneity issues; its applicability to both stationary and nonstationary series; and its better performance in finite samples as has been reported in Monte Carlo studies [1]. In addition, this article uses a data transformation approach recommended in Adom et al. [5]. The study uses trend/potential energy consumption (devoid of short-term cyclical variations). The use of actual energy consumption poses two important problems: reverse causality problem and the problem of not capturing the true long-run effects of the demand drivers. The use of potential energy consumption helps capture the true long-run effects and also deal with the problem of reverse causality. We show, in this study, that this approach provides much more reliable long-run estimates and produces relatively lower standard errors of the parameters.

Ghana like other emerging economies in Africa faces energy challenges due to the growing demand and poor supply of energy [6, 1]. There is the option of expanding generation capacities/energy supply, but this is a very capital-intensive venture that not many countries in the developing world (which does not exclude Ghana) may have the financial muscle to undertake such investments. For this reason, the option of demand-side management becomes very crucial in developing economies like Ghana. In this regard, the roles of pricing and technological progress and the need to check demographic patterns remain topical in this quest. The benefits of energy demand management can cut across borders to the countries that import electricity from Ghana, such as Togo, Burkina Faso, Benin and Cote d'lvoire (sometimes). Therefore, issues of demand-side management or energy efficiency improvements are important not only from the perspective of Ghana. As acknowledged by Adom [1], efficiency improvements in Ghana are likely to have positive cross-border effects in improving energy supply to these economies.

The rest of the study is organized as follows. Section 2 presents the method and data. Section 3 discusses the main findings of the study. Section 4 highlights the key points in the study and their implications for policy design.

2 Method and Data

2.1 Empirical Model

Based on the neoclassical demand theory, this paper specifies the empirical demand model as a function of price (PE), income (Y) and other factors (X); this is depicted in Eq. 1, where u denotes the stochastic term, which captures other unobserved factors that drive energy consumption and A denotes knowledge accumulation. Equation 2 is a logarithmic transformation of 1, where $\ln A = c$.

$$E^D = Af(\text{PE}, Y, X)e^u \tag{1}$$

$$\ln E_t^D = c + \ln f(\text{PE}, Y, X) + u_t \tag{2}$$

Further, a Cobb-Douglas functional form expressed in Eq. 3 is assumed, where the arguments are nonzero. Equation 4 is the result for inserting 3 into 2.

$$f(\text{PE}, Y, X) = \text{PE}^{\beta} Y^{\delta} X^{\phi} \tag{3}$$

$$\ln E_t^D = c + \beta \ln \text{PE} + \delta \ln Y + \phi \ln X + u \tag{4}$$

The vector X includes variables like demographic dependency, trade openness, and the underlying energy demand trend. Demographic dependency (DD) captures the effect of demography on energy consumption. Higher demographic dependency means higher demand on an existing energy-using equipment or appliance. In terms of road transport energy, for instance, this implies more people on the road hence increases in the travelling times and traffic congestion on the road. For other energy-using services, such as cooking, washing, refrigeration, and ironing, the scale of use will increase and cause energy consumption to increase, all else equal. A higher dependency ratio also implies that household savings will be negatively affected since children or old people add more to consumption than production. As a result, households finance these extra consumption through savings, and this decreases households' investment in energy-efficient appliances. Thus, higher demographic dependency is likely to obstruct the replacement of obsolete equipment. Consequently, energy use will increase. However, for other energy-use services, such as lighting, air conditioners, music and television, higher demographic dependency will cause economies of scale and hence lower energy consumption per unit. Moreover, we expect higher dependency ratio (young) to increase the demand for goods and hence production. But, in the case of Ghana, where mostly every product is imported, such a scale effect induced by demographic dependency seems less probable. From the above, it is not straight forward to deduce the exact effect of demographic dependency on energy consumption; it becomes an empirical issue.

Trade openness (TOP) has scale, structural, and technical effects. In the former case, trade openness could spur economic growth and then raise the energy demand requirements in the country. Also, where there exists weak environmental policies in the home country, trade openness could make the home country a dumping place for inefficient appliances and equipment and thereby increase the influx of higher energy-intensive or energy-inefficient firms. These could raise the energy demand requirement and the associated carbon dioxide emissions; what is referred to in the literature as the *Pollution-haven hypothesis*. On the structural effect, trade openness could change the demand patterns and cause the emergence of import-substituting goods. This shift in the production structure is less energy-intensive and therefore should lower energy consumption. On the technical effect, trade openness could facilitate direct technological diffusion and indirect technological diffusion. Openness exposes the local firms to international competition, and in order to remain competitive, local firms might invest in energy-efficient machinery and plants to remain cost competitive. There could also be learning and imitation opportunities associated with trade openness which could help lower the energy requirements in the country. The effect of trade openness is thus indeterminate a priori. Ghani [18] noted that trade liberalization interacts with human capital to reduce average growth of energy consumption for developing countries. Sadorsky [39], Raza et al. [38], and Tsiotras and Estache [44] rather found that both imports and exports increase energy consumption. Najarzadeh et al. [33] in their study found a positive effect of export but a negative effect of import on energy consumption for OPEC member countries. Keho [26] also found a negative effect of imports on energy intensity for Cameroon, Ivory Coast, and Togo.

Finally, the underlying energy demand trend (UEDT) captures other important unmeasured exogenous factors that could affect energy consumption. This, for example, captures things like technical progress, knowledge of carbon dioxide emissions and climate change [17]. To capture this effect, we include the trend term and its square. Specifically, we use this term to capture technological progress [2, 17]. There are learning effects associated with technological progress. Therefore, the trend term is hypothesized to have a concave effect on energy consumption. If we consider the above controls, the empirical model takes the form in Eq. 5.

$$\ln E_t^D = c + \beta \ln \mathrm{PE}_t + \delta \ln Y_t + \emptyset_1 \mathrm{DD}_t + \emptyset_2 \mathrm{TOP}_t + \theta_1 \mathrm{Trend}_t + \theta_2 \mathrm{Trend}^2 + u_t \tag{5}$$

2.2 Empirical and Econometric Strategy

As the empirical strategy, this study first estimates Eq. 5 excluding the technical progress term and then include it later. The rationale is to examine how the presence of technological progress in the model redefines the energy consumption—price, energy consumption—demography, and energy consumption—income relationships. Changes in these coefficients due to the inclusion of the technical progress term would imply that technological advancement affects behavioural responses. By promoting energy efficiency, technological progress creates economies of scale both in production and consumption. Therefore, for example, technological progress should reduce the price incidence on consumers by making them less immune to price shocks but make consumption more responsive to income changes. Moreover, we expect the advancement in technology, via economies of scale, to also have a compensatory effect on demographic dependency (if found to have a positive effect) and hence energy consumption. Thus, our empirical strategy provides a way to investigate both the direct and the possible indirect effects of technical progress.

To estimate the above model, first, Eq. 5 should mimic a strict exogenous regressor case. Second, the error-term should not have a long memory of its past. These requirements make the use of the ordinary least squares (OLS) an inappropriate estimator since it will produce consistent but inefficient estimates if those requirements are violated. This study estimates Eq. 5 using the approach by Stock and Watson [42], which is called the Dynamic OLS (DOLS). The DOLS modifies the cointegrating equation to exhibit strict exogeneous regressor case by introducing the lead and lag of the first difference of the independent variables as additional regressors. This procedure helps deal with both serial correlation and endogeneity issues. The technique has other desirable attributes. It is applicable to both stationary and nonstationary series. Further, it performs better in finite samples as has been shown in Monte Carlo studies [1]. Equation 6 is the DOLS form of Eq. 5. We conduct several diagnostic tests on the results.

$$
\begin{aligned}
\ln E_t^D = {} & c + \beta \ln \mathrm{PE}_t + \delta \ln Y_t + \emptyset_1 \mathrm{DD}_t + \emptyset_2 \mathrm{TOP}_t + \theta_1 \mathrm{Trend}_t + \theta_2 \mathrm{Trend}^2 \\
& + \sum_{t=-k}^{K} \beta_i \Delta \ln \mathrm{PE}_{t-k} + \sum_{t=-k}^{K} \delta_i \Delta \ln Y_{t-k} + \sum_{t=-k}^{K} \emptyset_{1i} \Delta \mathrm{DD}_{t-k} \\
& + \sum_{t=-k}^{K} \emptyset_{2i} \Delta \mathrm{TOP}_{t-k} + \sum_{t=-k}^{K} \theta_{1i} \Delta \mathrm{Trend}_{t-k} \\
& + \sum_{t=-k}^{K} \theta_{2i} \Delta \mathrm{Trend}_{t-k}^2 + u_t
\end{aligned}
\tag{6}
$$

Since the actual energy consumption data is not devoid of the short-term cyclicality, it is (1) vulnerable to the reverse causality problem and (2) unable to capture the true long-run effects of the identified regressors. Presently, the general literature on energy consumption uses actual energy consumption, which makes them defective in terms of the two problems identified above. As a way to go round this problem, we derive potential energy consumption using the Hodrick–Prescott filter, which is devoid of the short-term cyclicality. The Hodrick–Prescott approach filters the cyclical component of the raw data in order to derive a smoothed-curve representation of the original time series that is more sensitive to the long-term and less sensitive to the short-term. The use of the non-cyclical component has two advantages. First, it helps address potential reverse causality problem and helps capture the true long-run effects of the model parameters. In order to show that such an approach improves model efficiency, we compare the results of both actual and potential energy consumption.

2.3 Data and Variable Description

This article uses annual time series data that span from 1970 to 2016. As a measure of energy consumption, we use two indicators: total energy consumption and total electricity consumption. Total energy consumption is in kilotons, while total electricity is in gigawatts. Data on these variables were obtained from the World Bank development indicator (WDI) database. Also, we use two indicators of demographic dependency: total demographic dependency as a per cent of working-age population and youth dependency as a per cent of working-age population. Data on these variables also come from WDI. We use real energy price index, which we construct using the principal component analysis (PCA). Basically, we use information on Brent crude oil price and average end-user tariff of electricity to construct this index. The use of the prices of only crude oil and electricity means that our measure of real energy price index is not very representative since it ignores the prices of other energy types. However, we were limited by the sample period we considered. Moreover, studies have also shown the close connection between crude oil price and the price of natural gas [1].Thi. Even though our index may not be very encompassing, in the case of Ghana, it includes the most important energy price information that changes in them receive a lot of public reaction. Data on Brent crude oil price are from BP statistical review of world energy, and data on electricity price are from Volta River Authority, Energy Commission (Ghana), and Electricity Company of Ghana. Income is measured using the real gross domestic product per capita, while trade openness is measured using the total trade (sum of total exports and imports) as a per cent of gross domestic product. Data on these variables were also sourced from WDI.

3 Discussion of Results

3.1 Preliminary Test of the Data

Table 1 shows the test of unit root based on the Phillip-Perron test. Generally, the test reveals evidence of stationarity of the series at first difference. Further, the study applied the unit root test with structural break allowing the break to decay slowly (innovation outlier) and immediately (additive outlier). The results presented in Table 2 shows that except for electricity consumption, the rest of the variables do

Table 1 Phillip-Perron unit root

	Constant	Constant and trend
ln EU	−1.833	−2.313
d ln EU	−6.107***	−6.031***
ln EC	−2.696	−2.673
d ln EC	−7.384***	−7.690***
ln EP	−2.096	−2.055
ln EP	−6.766***	−6.750***
ADR	−0.750	−4.748***
*d*ADR	−4.161***	–
ADR_YOUNG	−0.672	−4.182***
*d*ADR_YOUNG	−3.908***	–
TOP	−0.867	−2.281
*d*TOP	−6.048***	−5.958***
ln *Y*	0.717	−1.040
d ln *Y*	−4.333***	−5.878***

***, ** and * denote 1%, 5% and 10% statistical significance levels, respectively

not exhibit unit root with structural break at first difference. Next, the paper applied the Bounds cointegrating test to test for level relationship, using the Narayan [34] finite-sample critical values. Table 3 reveals evidence of level relationship since the calculated *f*-statistics both for aggregate energy consumption and electricity consumption exceeds the upper critical *F*-value at 10 and 5% significance levels. The evidence of cointegration implies that indeed price, openness, income, demographic dependence and technological progress can indeed be treated as the 'long-run forcing' variables explaining energy consumption and electricity consumption in Ghana. We can therefore proceed to estimate the long-run effects of these variables.

3.2 Long-Run Estimates—Actual Energy Consumption

3.2.1 Baseline Model

Table 4 shows the long-run estimates of the demand drivers. The columns with '*R*' attached to the model number denote when we use an alternative measure of demographic dependency. We explain this in the course of discussing the results. Models *M*1 and *M*3 present the baseline estimates of energy consumption and electricity consumption, where we exclude the effects of technological progress. The rationale (as mentioned earlier) is to see if the introduction of technological progress redefines the demographic dependency-energy consumption, price–energy consumption, and

Table 2 Break point unit root test

	Break type			
	Innovation outlier test		Additive outlier test	
	Con	Con and trend	Con	Con and trend
ln EU	−4.168	−4.611*	– 3.407	−3.439
d ln EU	−7.327***	–	−7.405***	−7.539***
ln EC	−4.549***	−4.865**	−6.320***	−5.117**
d ln EC	–	–	–	–
ln EP	−2.994	−3.867	−3.004	−3.872
ln EP	−7.907***	−7.785***	−8.075***	−7.939***
ADR	−3.742	−4.142	−1.894	−5.717***
*d*ADR	−8.245***	−8.480***	−4.269*	–
ADR_YOUNG	−4.765***	−3.406	−2.116	−5.395***
*d*ADR_YOUNG	–	−7.697***	−4.351*	–
TOP	−3.845	−4.060	−3.036	−3.070
*d*TOP	−6.760***	−7.630***	−7.051***	−7.264***
ln Y	−1.935	−5.118**	−2.110	−2.678
d ln Y	−6.666***	–	−5.939***	−7.264***

***, **, and * denote 1%, 5% and 10% statistical significance levels, respectively

Table 3 Bounds test of level relationship

	Narayan finite-sample critical values					
	1%		5%		10%	
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
	3.892	5.173	2.85	3.905	2.402	3.345
$F\|EU_{BASELINE} = 3.984$						
$F\|EC_{BASELINE} = 4.529$						
$F\|EU = 3.726$						
$F\|EC = 4.061$						

income–energy consumption relationships. The price of energy has a significant negative effect on total energy and electricity consumption. The elasticities suggest an increase in energy and electricity consumption by 1.71% and 6.34% following a 10% rise in the price of energy, all things being equal. This confirms the findings of Ulusoy and Demiralay [45], Adom [1]. A higher energy price induces behavioural changes among end-users, such as increasing the investments in energy-efficient appliances and machinery, deliberate management of energy consumption levels, and the shutdown of energy-using appliances. The negative price elasticity is an indication that the government can raise taxes on energy as a tool to stimulate energy conservation and efficiency in the country.

Table 4 Long-run estimates: DOLS

	Total energy consumption				Total electricity consumption			
	*M*1	*M*2	*M*1*R*	*M*2*R*	*M*3	*M*4	*M*3*R*	*M*4*R*
ln EP	−0.171[a] (0.0494)	−0.056[b] (0.0254)	−0.168[a] (0.0428)	−0.051[c] (0.0253)	−0.634[a] (0.1057)	−0.421[a] (0.1124)	−0.619[a] (0.0960)	−0.448[a] (0.1264)
ln *Y*	1.841[a] (0.3001)	2.247[a] (0.3140)	2.172[a] (0.3335)	2.270[a] (0.3865)	5.701[a] (0.6833)	7.125[a] (1.0034)	6.655[a] (0.7454)	7.012[a] (1.1343)
ADR	0.043[a] (0.0073)	0.026 (0.0162)	–	–	0.048[b] (0.0195)	–	–	–
DR_YG	–	–	0.046[a] (0.0073)	0.025[c] (0.0147)	–	–	0.067[a] (0.0140)	0.077 (0.0977)
TOP	−0.001 (0.0015)	−0.001 (0.0009)	−0.001 (0.0014)	−0.002[c] (0.0009)	−0.014[a] (0.0036)	−0.013[c] (0.0022)	−0.015[a] (0.0028)	−0.013[a] (0.0025)
TREND	–	0.073[a] (0.0150)	–	0.077[a] (0.0171)	–	0.118[a] (0.0346)	–	0.116[b] (0.0466)
$TREND^2$	–	−0.002[a] (0.0004)	–	−0.002[a] (0.0005)	–	−0.003[b] (0.0013)	–	−0.002 (0.0014)
CON	−10.746[a] (2.3128)	−12.331[a] (2.1139)	−13.126[a] (2.6949)	−12.267[a] (2.2002)	−37.631[a] (5.4513)	−45.255[c] (5.2802)	−45.633[a] (5.7410)	−49.548[a] (5.3456)
$A.R^2$	0.822	0.861	0.817	0.849	0.842	0.888	0.837	0.861
SER	0.050	0.043	0.050	0.045	0.117	0.098	0.0119	0.109
SSR	0.042	0.046	0.043	0.050	0.232	0.145	0.239	0.179
LEAD	2	0	2	0	2	2	2	2
LAG	2	2	2	2	2	2	2	2

[a,b,c]Denotes 1, 5 and 10% significance levels. DOLS estimated using HAC standard errors. Covariance matrix estimated using the Bartlett Kernel, Newey-West. Automatic leads and lags selection based on the Akaike information criterion. Maximum is set to 2. Given the sample, the maximum allowed was 3. The estimation experimented with 3, 2 and 1 and 2 provided the most consistent results with relatively lower standard errors

Income has a significant positive effect on total energy and electricity consumption. The elasticity is elastic which suggests that a percentage increase in income will cause a more than a percentage rise in energy and electricity consumption. All things being equal, an increase in income per capita by 10% will cause total energy and electricity consumption to increase by 1.84% and 5.7%, respectively. Several studies both in the case of Ghana [2, 1, 26, 7] and in the general literature [26, 45] have confirmed the positive effects of income. While the positive income effects indicate that the goal of economic growth is consistent with the SE4All goal, it further suggests the absence of scale economies in the provision of energy services in Ghana.

Dependency ratio has a significant positive effect on energy and electricity consumption in the long-run. The estimates show that by increasing demographic dependency by 10%, total energy and electricity will increase by 36.48% and 40.73%,

Table 5 Simple correlation matrix

Correlation *t*-statistic Probability	Demographic dependency	Youth demographic dependency
Demographic dependency	1.000000	
	–	
	–	
Youth demographic dependency	0.999891	1.000000
	453.9231	–
	0.0000	–

respectively.[1] Higher dependency ratio exerts scale effect on energy use, as well as delays households' investment in energy-efficient technologies; this is because the dependants compete with these technologies for households' savings. The evidence provided by this study contradicts the work of Longo and York [31] which recorded a negative effect of dependency ratio on energy and electricity consumption for nations in the world.

Finally, in the baseline model, trade openness exerts a negative effect, but the effect is only significant in the case of electricity consumption. The coefficient suggests that increasing trade openness by 10% will reduce electricity demand by 11.88%.[2] This suggests that openness policy or globalization will foster electricity-use conservation/efficiency in the country. In the case of Ghana, strict efficiency standards and labelling have been implemented for refrigerators and air conditioners that consume a significant amount of electricity. This prevents the importation of any sub-standard products into the Ghanaian market. Moreover, a similar policy has been implemented for compact fluorescent lamp (CFL) in addition to a policy that removes import duties on importers of CFL into the country. These tight domestic policies along with the openness policy have facilitated the negative effect of trade openness on electricity consumption.

In $M1R$ and $M3R$, we use youth demographic dependency ratio instead. The correlation matrix reveals a significant positive high correlation of approximately 100% (see Table 5). This shows that, in Ghana, youth dependency ratio dominates the dependency problem in the country. The results remain robust. Price exerts a significant negative effect in both cases, while the negative effect of trade openness is significant only for electricity consumption. Both income and demographic dependency (youth) show significant positives effect on energy and electricity consumption.

[1]Calculated as the product of the coefficient and the mean of demographic dependency ratio (see [8, 40]).

[2]Calculated as the product of the coefficient and the mean of trade openness.

3.2.2 The Effect of Technological Progress

Models $M2$ and $M4$ show the results when we control for technological progress. As shown in these columns of Table 4, technological progress has a concave effect on energy and electricity consumption. This suggests that advancement in technology will directly cause energy and electricity consumption to fall. The main conduit is through the energy efficiency-induced effects. Interestingly, after controlling for technological progress, the size of the price elasticity and the coefficient of demographic dependency all experienced a significant decline, but the income elasticity increases, which are indications of behavioural changes in the energy market caused by technological progress. This suggests different things. The reduction in the price elasticity implies that technological progress helps reduce the sensitivity of consumers to price changes. In other words, it reduces the energy price incidence on consumers. This certainly makes sense since the energy bill for the consumer is the product of the price of energy and quantity of energy consumed (determined by technology type). With technological advancement, consumers are able to enjoy economies of scale in consumption, which reduces the quantity part of the energy bill significantly. Therefore, changes in the price that pushes the bill up are positively compensated downwards by the efficiency improvement in resource-use embedded in the technology.

Assume two types of consumers: one that uses an energy-saving bulb and another that does not use an energy-saving bulb. In the former case, the consumer needs not necessary to adjust his consumption downward following a price shock due to the possible economies of scale that the energy-saving bulb provides. Thus, for such consumers, technological progress makes them immune to price shocks or changes. On the contrary, in the latter case, the consumer may have to adjust his consumption behaviour by practising energy conservation (i.e. putting lights off during day or when sleeping) in order to be able to withstand a price shock that raises the energy bill. Similarly, for two similar firms (in product type) that operates different plants—-efficient and inefficient—technological progress provides economies of scale to the firm that operates the efficient plant but the reverse, which is diseconomies of scale, is experienced by the firm that operates the obsolete (inefficient) technology. Therefore, the efficient firm is more likely to withstand shocks in price making it less sensitive to price changes than the inefficient firm. This provides a revenue window for the government who can capitalise on the economies of scale enjoyed by raising reasonable tax revenues from energy usage.

Also, the economies of scale associated with technological progress helps minimize the positive effect of demographic dependency. In fact, in models $M2$ and $M4$, the positive significant effect of demographic dependency seems to disappear, but we are cautious to define this as representing the total erosion of the demographic dependency effect by technological progress. On the other hand, we see that such economies of scale make consumption of energy more responsive (positively) to changes in income. This could be a potential source of the rebound effect. Should this be seen as a worrying situation? Certainly not! So long as households and firms continue to enjoy economies of scale in the provision of energy services, potential rebound effects should not create any worrying situation for the energy security in the country. Other results in $M2$ and $M4$ show that the effect of trade openness still remains significantly negative only in the case of electricity consumption.

Models $M2R$ and $M4R$ show the alternative result when we use youth demographic dependency rate. In both columns, it is evident that technological progress has a concave effect on energy and electricity consumption emphasizing the earlier point that an advancement in technology causes lower energy and electricity consumption. Similar to the earlier result, there is a significant drop in the size of the price and demographic dependency coefficients but a rise in the income coefficient. This again confirms the earlier results that technological progress through economies of scale reduces the price incidence on consumers and the energy-inducing effects of demographic dependency while raising the sensitivity of demand to income. But, in this case, we see that, although the size of the demographic dependency coefficient diminishes, technological progress seem not to erode completely the positive demand requirements imposed by demographic dependency, at least for total energy consumption. This makes some sense. Higher demographic dependency means larger family size. For cooking fuel (which is mostly wood fuel/biomass and Liquefied Petroleum Gas [LPG] in Ghana), this means higher demand since more food has to be cooked. For transport energy demand, this implies more people on the road, heavy traffic and more travelling hours.

On the side of electricity, larger family size is less likely to change the consumption levels of most appliances. For example, there would be no need to get additional television, air condition, refrigerators, bulbs, and iron (but the usage will increase since there will be ironing of more clothes). In other jurisdictions, there would be more heating and cooling, but this is not a frequent practice due to the tropical nature of Ghana, albeit few homes have installed water heaters. One could also argue that from the production side, larger family size raises the demand for industrial products such as clothes and food. While this may be true in other jurisdictions, it is less probable in the case of Ghana, where the use of imported second-hand clothes dominates (due to its economical nature) and food is mostly in their raw form obtained from an agricultural sector that is less mechanized. Thus, for total energy consumption, it is less probable that technological progress would help erode totally the positive demands imposed on energy by demographic dependency, but it looks more optimistic in the case of electricity consumption. Further results in these columns reveal that trade openness seems to exert significant negative effect on aggregate energy consumption and electricity consumption which suggests that globalization is consistent with the energy efficiency and conservation goals.

In Table 4, we used actual consumption which includes short-term cyclicality. As mentioned earlier in this paper, this could pose two problems: (1) over-representation of the true long-run effects and (2) reverse causality from energy consumption to any of the right-hand side variables. For example, in the second case, technological progress as discussed provides economies of scale to consumers and this helps improve their cost outlays. The revenue boost could raise consumption levels of energy, and given supply, such demand pressures could push prices of energy upwards. We discuss these issues in the next section where we estimate potential total energy and electricity consumption.

3.3 Long-Run Estimates—Potential Energy Consumption

3.3.1 Baseline Model

Table 6 contains the results when we use potential energy consumption as the dependent variable. Likewise in Table 4, $M1$ and $M3$ show the baseline result, where we do not control for the effects of technological progress. The first obvious thing contained in these columns is that except for the coefficient for openness, the coefficients for price, income and demographic dependency are relatively lower when compared with that obtained in Table 4. This buttresses the earlier point made that the use of actual consumption might exaggerate the true long-run effects. Also, the standard errors of the parameters are in general lower in this table, suggesting an improvement in model efficiency. In these columns, the results remain consistent. The price of energy exerts a significant negative effect on energy and electricity consumption, but a higher income and demographic dependency cause consumption levels of energy both total and electricity to increase. Further results show the negative effect of openness on energy consumption, but the effect in both cases remains statistically insignificant. In $M1R$ and $M3R$, we estimate the same model using youth dependency rate instead of total dependency rate. Here also, we witness a significant drop in the size of all the coefficients, except that for openness, when compared with similar models in Table 4. The negative effect of the price of energy and the positive effects of income and demographic dependency remain robust in these columns. Similarly, the effect of openness remains insignificantly negative. Thus, on the whole, at least from the baseline result, we can make a claim of a robust result.

3.3.2 The Effect of Technological Progress

Finally, the study controls for the effects of technological progress. Here too, we witness a fall in the size of the coefficients when compared to the similar model in Table 4, which lends support to the claim that using the actual consumption levels exaggerate the long-run effects of the demand drivers. In columns $M2$ and $M4$, technological progress has a concave effect on energy and electricity consumption. Comparing these models to their respective baseline models, it is evident that the introduction of technological progress has redefined the effects of price, income and demographic dependency on energy and electricity consumption. In both models, consumers become less responsive to price while consumption levels become more responsive to income changes; this is mainly explained by the economies of scale that is associated with technological progress. In the case of demography dependency, the introduction of technological progress seems to wipe out the positive demand

Table 6 Long-run estimates: DOLS

	Total energy consumption				Total electricity consumption			
	*M*1	*M*2	*M*1*R*	*M*2*R*	*M*3	*M*4	*M*3*R*	*M*4*R*
ln EP	−0.112[a] (0.0415)	−0.056[a] (0.0093)	−0.116[b] (0.0406)	−0.050[a] (0.0080)	−0.215[b] (0.0753)	−0.044[b] (0.0205)	−0.231[a] (0.0760)	−0.048[b] (0.0189)
ln *Y*	0.800[a] (0.2212)	0.999[a] (0.0825)	1.016[a] (0.2770)	1.014[a] (0.0855)	1.998[a] (0.3558)	3.159[a] (0.1286)	2.468[a] (0.4778)	3.231[a] (0.1239)
ADR	0.021[a] (0.0069)	0.050 (0.0069)	–	–	0.034[b] (0.0154)	0.007 (0.0168)	–	–
DR_YG	–	–	0.023[a] (0.0052)	0.044[a] (0.0061)	–	–	0.039[a] (0.0116)	0.004 (0.0123)
TOP	−0.001 (0.0014)	−4.52E−05 (0.0001)	−0.001 (0.0013)	−0.0003[b] (0.0001)	−0.001 (0.0027)	−4.81E−05 (0.0004)	−0.002 (0.0024)	−0.0003 (0.0004)
TREND	–	0.057[a] (0.0030)	–	0.058[a] (0.0032)	–	0.091[a] (0.0082)	–	0.089[a] (0.0073)
$TREND^2$	–	−0.001[a] (0.0001)	–	−0.009[a] (0.0001)	–	−0.003[a] (0.0002)	–	−0.003[a] (0.0001)
CON	−1.546 (1.6485)	−5.976[a] (0.2975)	−3.144 (2.0213)	−5.281[a] (0.2627)	−11.117[a] (2.9662)	−16.920[a] (1.1532)	−14.610[a] (3.6038)	−17.091[a] (0.9516)
$A.R^2$	0.867	0.993	0.883	0.994	0.753	0.987	0.804	0.986
SER	0.031	0.007	0.030	0.007	0.057	0.013	0.051	0.013
SSR	0.017	0.0007	0.015	0.001	0.056	0.0026	0.045	0.027
LEAD	2	2	2	2	2	2	2	2
LAG	2	2	2	2	2	2	2	2

[a,b,c]Denotes 1, 5 and 10% significance levels. DOLS estimated using HAC standard errors. Covariance matrix estimated using the Bartlett Kernel, Newey-West. Automatic leads and lags selection based on the Akaike information criterion. Maximum is set to 2. Given the sample, the maximum allowed was 3. The estimation experimented with 3, 2 and 1 but 2 provided the most consistent results with relatively lower standard errors

requirements imposed on energy by higher demographic dependency. As before, we are cautious to interpret this to mean the total/complete eradication of the positive effects of demographic dependency on energy consumption by technological progress. Other results indicate a negative but insignificant effect of openness on consumption levels.

*M*2*R* and *M*4*R* are the alternative models for *M*2 and *M*4, when we use youth dependency rate. In both cases, technological progress has a concave effect on energy and electricity consumption. However, the introduction of the technological progress term seems to alter consumer behaviour in the energy market. Compared to the baseline models *M*1*R* and *M*3*R*, consumers become less responsive to price changes but consumption becomes more responsive to income changes in the case of electricity consumption. As explained earlier, this behavioural change could be driven by the economies of scale that is associated with technological progress/development. In the case of demographic dependency, technological progress seems to help completely erode the significant positive demand requirements imposed on electricity consumption by higher demographic dependency. Other results show significant negative effect of openness on total energy consumption and not electricity consumption. These results confirm that, generally, the results obtained are somewhat robust from a statistical point of view.

The above results have revealed that technological progress provides three advantages, at least based on the results obtained in this paper.

1. It reduces energy consumption.
2. It reduces the energy price incidence on end-users of energy.
3. It reduces the energy-induced effects of higher demographic dependence.

By directly reducing energy consumption, technological innovation provides an investment buffer in the energy sector. Thus, there would be no need for the government to invest in additional generation capacity to match the growing demand in energy in the country. The investment amount saved from additional generation capacity could be invested in other depriving sectors of the economy to create a much more inclusive growth in the country. Since technological innovation improves both the technical aspects of production and consumption, the consequences of demographic patterns on energy-use patterns are minimized due to the benefits of economies of scale both in production and consumption. Consequently, for households that depend on children as a labour force, technological innovation improves the consumption productivity of energy without necessary having to reduce the number of users in a household. Further, the economies of scale in consumption helps minimize the high price incidence on consumers as consumption productivity of energy improves. Thus, compared to other demand-side management strategies, such as increasing energy price and reducing population growth, technological innovation or progress provides a win–win situation by enhancing energy security and reducing the price incidence on consumers without negatively affecting production and employment.

3.4 Diagnostics[3]

Lastly, we subjected the model to some diagnostics. Table 7 shows the coefficient variance decomposition, which is used to test for multicollinearity. Following the recommendation of Belsely et al. [10], there is multicollinearity problem if for the associated eigenvalues for the lowest condition number, two or more variables each have eigenvalues of more than 0.5. In our case, this is not so. Therefore, we conclude based on Belsely et al. recommendation that there is no multicollinearity problem in both cases. Next, we tested for normality using the Jarque–Berra test; this is shown in the bottom part of Table 8 . It is evident that we fail to reject the null hypothesis of normally distributed errors. The *Q*-statistics both for the autocorrelation function and partial autocorrelation function are not significant at all lag levels. Therefore, we reject the claim of serially correlated errors in our model. Finally, Fig. 1 shows the plot of the actual and fitted model, as well as the plot of the residuals. It is evident that the actual data and fitted model for both total energy consumption and electricity consumption are like two peas in a pod. Thus, they are very indistinguishable, which

[3]These diagnostics are only performed for the general model which is the final model.

Table 7 Coefficient variance decomposition

Model: energy consumption							
Eigenvalues	27.91449	0.990219	0.005206	0.000219	9.38E−07	7.19E−08	1.32E−09
Condition	4.73E−11	1.33E−09	2.54E−07	6.02E−06	0.001408	0.018355	1.000000
Variance decomposition proportions							
Associated eigenvalue							
Variable	1	2	3	4	5	6	7
ln EP	0.320713	0.282256	0.396456	0.000575	7.79E−08	2.14E−10	9.78E−14
ln Y	0.025886	0.974096	1.86E−05	1.17E−08	1.71E−10	3.42E−10	8.77E−14
DR	0.460984	0.538894	3.18E−05	7.79E−05	5.02E−06	7.33E−06	1.41E−09
TOP	0.110808	0.017167	0.531639	0.158780	0.180929	0.000676	6.61E−07
CON	0.999964	3.64E−05	1.55E−08	3.39E−10	1.14E−13	2.66E−13	6.34E−17
TREND	0.677963	4.04E−05	0.146367	0.175629	1.25E−06	2.59E−07	7.05E−10
$TREND^2$	0.085353	0.787084	0.092213	0.033674	0.000412	0.000501	0.000763
Model: electricity consumption							
Eigenvalues	24.95926	0.778337	0.008499	0.000434	1.64E−06	2.97E−07	1.45E−09
Condition	5.80E−11	1.86E−09	1.70E−07	3.34E−06	0.000884	0.004883	1.000000
Variance decomposition proportions							
Associated eigenvalue							
Variable	1	2	3	4	5	6	7
ln EP	0.107070	0.151655	0.739450	0.001826	1.49E−07	8.24E−11	1.85E−13
ln Y	0.051831	0.948148	2.08E−05	5.89E−08	3.60E−12	1.81E−09	3.59E−14
DR	0.252052	0.747518	0.000162	0.000212	5.98E−08	5.61E−05	6.11E−10
TOP	0.000223	0.054389	0.447381	0.250888	0.247115	3.35E−06	4.90E−07
CON	0.999950	5.03E−05	2.03E−08	5.18E−10	1.04E−14	1.27E−12	2.17E−17
TREND	0.329106	0.013097	0.323102	0.334691	4.00E−06	6.28E−07	5.63E−10
$TREND^2$	0.000329	0.682685	0.232646	0.080006	0.002749	0.000520	0.001065

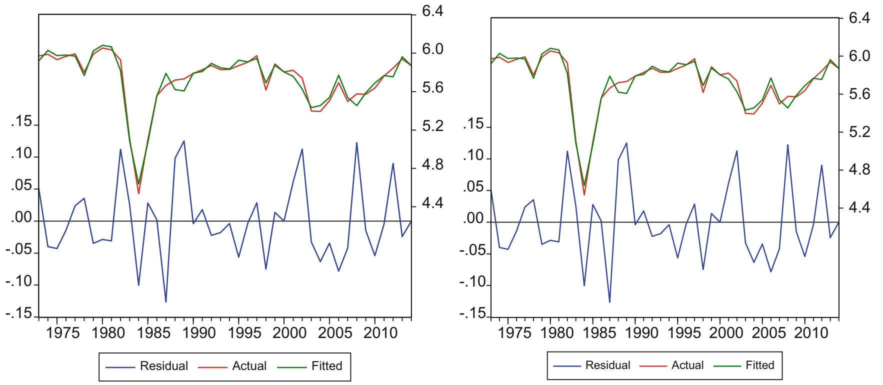
Table 8 Autocorrelation/serial correlation test and normality test

Lags	Energy consumption model				Electricity consumption model			
	AC	PAC	*Q*-stat	Prob	AC	PAC	*Q*-stat	Prob
1	−0.021	−0.021	0.0207	0.886	−0.021	−0.021	0.0207	0.886
2	0.164	0.163	1.2579	0.533	0.164	0.163	1.2579	0.533
3	−0.157	−0.155	2.4255	0.489	−0.157	−0.155	2.4255	0.489
4	0.033	0.004	2.4775	0.649	0.033	0.004	2.4775	0.649
5	0.018	0.072	2.4945	0.777	0.018	0.072	2.4945	0.777
6	0.022	−0.010	2.5189	0.866	0.022	−0.010	2.5189	0.866
7	−0.043	−0.055	2.6174	0.918	−0.043	−0.055	2.6174	0.918
8	−0.224	−0.224	5.3351	0.721	−0.224	−0.224	5.3351	0.721
9	−0.200	−0.204	7.5680	0.578	−0.200	−0.204	7.5680	0.578
10	−0.078	−0.034	7.9191	0.637	−0.078	−0.034	7.9191	0.637
11	−0.155	−0.190	9.3581	0.589	−0.155	−0.190	9.3581	0.589
12	−0.259	−0.377	13.486	0.335	−0.259	−0.377	13.486	0.335
13	0.045	0.049	13.614	0.402	0.045	0.049	13.614	0.402
14	0.054	0.128	13.806	0.464	0.054	0.128	13.806	0.464
15	0.072	−0.076	14.161	0.513	0.072	−0.076	14.161	0.513
16	−0.083	−0.212	14.646	0.551	−0.083	−0.212	14.646	0.551
17	0.048	−0.022	14.814	0.609	0.048	−0.022	14.814	0.609
18	0.022	0.017	14.850	0.672	0.022	0.017	14.850	0.672
19	0.205	0.034	18.222	0.508	0.205	0.034	18.222	0.508
20	0.170	−0.082	20.639	0.419	0.170	−0.082	20.639	0.419
Normality test	1.4642 [0.4809]				1.4642 [0.4809]			

suggests that these models are best-fit models. The plot of the residuals in the lower part of Fig. 1 shows that the degree of variability is uniform over time taking away any doubt of heteroscedastic errors. Also, the errors seem not to be persistent, which confirms the earlier claim of no serial correlation in errors. Lastly, there is no problem of significant outlier in the dataset as depicted by the plot of the residuals. What these diagnostic statistics suggest to us is that, at least from the statistical point of view, we can attach some importance to the results obtained in this paper.

4 Closing Remarks

This chapter examined the long-run effects of technological progress on energy and electricity consumption in Ghana, using time series data from 1970 to 2016 and the Stock-Watson dynamic OLS estimator. The results reveal that, in the long-run, technological progress leads to a reduction in energy and electric-



Model: Electricity consumption Model: Energy consumption

Fig. 1 Plot of actual, fitted and residuals

ity consumption. Moreover, technological progress seems to cause behavioural changes in the energy market. First, it reduces the energy price incidence on end-users by making them less sensitive to price shocks due to the benefits of economies. Second, technological progress mediates the positive demand requirements imposed on energy by higher demographic dependency. While, in the case of electricity, technological advancement seems to erode completely the positive demand requirements imposed by demographic dependency on electricity consumption, the compensation seems to be partial in the case of total energy consumption. Lastly, technological progress makes energy demand become more responsive to changes in income, which could be explained to be a channel of possible rebound effects. However, as explained in the text, this should not raise a cause of concern for the security of the energy system so long as the technical aspects of providing energy services are enhanced.

These results have several implications. From the perspective of the government, technological advancement leads to significant energy savings, which is very good to ensuring energy security, mitigating carbon dioxide emissions, and reducing additional investment commitment in additional plant capacity. Thus, investment saved could be used to improve other deprived sectors in the economy. Further, it minimizes the high energy price incidence on consumers and makes energy consumption less responsive to demographic patterns. By reducing the price incidence on consumers, technological innovation also provides an extra revenue window for consumers that could be used in other vital spending areas such as education, health, housing and food. Also, for households that especially rely on household labour, technological innovation reduces the tendency to reduce family size in order to keep up with energy expenditures. Therefore, compared to other demand-side management strategies, such as raising energy price and reducing population growth, technological innovation provides a win–win demand-side management strategy in the economy by promoting energy security and reducing the price incidence on consumers without affecting production and employment negatively.

Based on the above, the government of Ghana should directly invest in technological innovation and create both the economic and political environment for technological innovation investments. Specifically, we suggest the following.

1. The government should provide tax rebates or completely remove taxes on energy-saving technologies. Currently, there is a policy in place that removes taxes on all importers of CFLs bulbs. This is a good policy and should be extended to include other energy-saving technologies.
2. The government should implement an efficiency labelling standards for energy-saving technologies. At the moment, there is a government appliance labelling standards policy for refrigerators and air conditioners that prevent the importation of refrigerators and air conditioners that fail the required efficiency standards. This policy should also be broadened to include other appliance types in the economy.
3. The government should implement sound macroeconomic policies that will lower the cost of capital in the country. Presently, the cost of capital is very high and this hinders investment in new technologies. The government can alternatively implement an interest rate ceiling for energy-saving technologies in the country.

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Asian Energy and Environmental Challenges in Era of Globalization: The Case of LNG

Sofiane Oudjida

Abstract In a context marked by tensions on energy markets (oil and gas in particular) and the constant rise of environmental concerns, several Asian countries are exploring the most promising ways to reconcile economic growth, energy consumption and respect for the environment in a globalized world. Liquefied natural gas (LNG) has emerged as the most appropriate energy to meet environmental criteria due to its multiple advantages: cleanliness, energy efficiency, cost competitiveness and flexibility. As a partner in renewable energies, it is the energy of the future that will play a decisive role in the energy transition. LNG growth is due to technological innovations in the shipping industry. The purpose of this chapter is to discuss the issue of environmental and energy challenges in the era of globalization in the Asian region. Hence, this chapter consists of four main sections. The first section highlights the recent trends in the LNG industry which have led to the emergence of new techniques, new processes and new markets. Recent developments in LNG markets have also been discussed in this section with a special focus on the "Big 5" Asian buyers. The second and most important section describes the key commercial aspects of LNG, namely LNG pricing, LNG contracts and contract renegotiation, particularly in the new context of US LNG exports. The third section focuses on the issue of globalization of LNG markets and contributes to current affairs debate on the creation of an LNG trading hub in Asia. The fourth and last section is devoted to the environmental aspects of LNG use and to discuss the intentions of the main importing countries for an energy mix in favour of LNG and other less polluting (renewable) energy. Due to data constraints, we favour the descriptive approach—this approach is nowadays neglected—which constitutes a solid basis for further research.

Keywords Energy · Environment · LNG · Globalization · Shale gas · Asia

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1 Introduction

In a context marked by tensions on energy markets (oil and gas in particular) and the constant rise of environmental concerns, it seems that several countries are exploring the most promising ways to reconcile economic growth, energy consumption and respect for the environment in a globalized world.

A source of energy that is widespread, reliable and adapted to replace other fossil fuels, liquefied natural gas (LNG[1]) remains one of the fastest growing sources of energy in the world in the coming years. LNG is undeniably a key driver of global gas expansion. It provides multiple benefits: cleanliness (commercially attractive and environmentally friendly fossil fuel), energy efficiency (very high efficiency in power plants) and transport flexibility (diversification of import sources and routes, improved security of supply). LNG is the answer to tomorrow's new energy world as we move towards clean energy sources.

The LNG industry is relatively young compared to oil and gas. Indeed, in 2014, the modern global LNG industry celebrated its 50th anniversary[2] coinciding with the delivery of the first shipment of LNG to the UK market from the CAMEL[3] plant in Arzew (Algeria). For Asia-Pacific,[4] the history of LNG began in 1969 with the signing of long-term contracts with the Japanese company, Tokyo Gas Company and Tokyo Electric Power Company, first started importing LNG from Alaska. Japanese utility companies have led the development of an LNG market around the world METI [69].

Today's LNG industry has a very different aspect from that of the years 90. The rapid progress of technology applied to this industry has contributed enormously to the lower costs and to the improvement of the profitability of the projects. In this chapter, we will focus on the "Big 5" Asian buyers: Japan, Korea, Taiwan, China and India.

2 Recent Trends in the LNG Industry

The emergence of new technologies, including regasification on board (of LNG carriers) and floating production, has led to the emergence of new markets, new techniques and processes, among which there is a need to identify:

[1]Natural gas is produced from associated gas of oil fields or independent gas fields, comprised mainly of methane. Because it is in gaseous form at normal temperature/pressure, transported by pipeline in the gaseous form, or by tanker as LNG after becoming a liquid form by being cooled to −162 °C, either method of which is adopted.

[2]The modern LNG industry began in September 1964 with the delivery by of the first shipment of 27,000 m^3 of Algerian methane on board the "Methane Princess" vessel bound for Convey Island regasification terminal in Great Britain. Methane Princess arrived at his destination on 12 October 1964, after a journey of 1600 miles (2600 km).

[3]Compagnie Algérienne de Méthane Liquide.

[4]Throughout this chapter, we use the International Energy Agency's (IEA) definition of the Asia and Oceania region.

(i) **Massive emergence of unconventional gases**: Unconventional[5] gases (coal gas, shale gas, tight gas, etc.) are perceived as a "Game changer" on the energy scene. The extraction of "Shale Gas" in the United States in 2009 rapidly transformed the international gas trade. This "Shale Gas Revolution" could offer consumer countries a diversification of their gas supplies. This will inevitably lead to strong competition on the supply side, with conventional domestic production and external supplies via gas pipelines or LNG carriers.

(ii) **FLNG Development**: Floating Liquefied Natural Gas (FLNG) promises to revolutionize the LNG industry. By using floating terminals, it makes it possible to produce LNG offshore at a much lower cost than LNG produced onshore.

(iii) **Expanding LNG Use in downstream**: The expanded use of LNG as a "clean" alternative fuel for trucks and ships is expected to meet increasingly stringent environmental requirements (SECA[6] and ECA[7] regulations). Regarding existing and possible future Emission Control Areas, see Appendix 4.

(iv) **LNG train size growth**: The trend towards increasing size (as well as the number of trains) has appeared in recent years to save costs. Several large capacity LNG trains 7.8 mtpa are in various stages of construction or commissioning (the size was between 2 and 4 mtpa in the years 1996–99).[8]

(v) **The race for gigantism in shipping**: LNG shipping is expected to play an increasingly important role in the coming years in the context of this LNG dynamic, making it possible, through the flexibility it provides, to adjust supply to demand in a market that has become more global. Since 2009, date of entry into service of the first Q-Max—type carrier, called Mozah—the LNG is delivered by the largest LNG carriers ever built in the world, carrying up to 266,000 m^3. This type of LNG carrier is presented as a major development in the transportation of LNG because it transports 80% more load than older LNG carriers, and this, consuming 40% less energy per unit load.

(vi) **Small-Scale LNG**: Small-Scale LNG (or ss-LNG) is another emerging technology to enable broader and less capital intense access to gas. The value proposition of ss-LNG is largely to enable access to gas in large quantities where typical transmission or distribution infrastructure is not available. In case of small-scale LNG market, the IGU[9] defines small-scale liquefaction and regasification facilities as plants with a capacity of less than 1 mtpa (from

[5]Estimates of Unconventional gases remain speculative. Thus, it should be recalled that the figures of "recoverable resources" made public by the US Energy Information Administration (EIA) are for some countries (provisional figures in $T.m^3$), as follows: China 36.1; USA 24.4; Argentina 21.9; Mexico 19.3; South Africa 13.7; Brazil 6.4; Poland 5.3; France 5.1; total world 197 $T.m^3$.

[6]SECA: Sulphur Emission Control Area.

[7]ECA: Emission Control Area.

[8]The first LNG mega-trains in the world were inaugurated in Qatar, and they still have no equivalent today.

[9]See, for example, the International Gas Union (IGU), [49] World LNG Report.

0.05 to 1 mtpa) and ss-LNG carriers[10] are defined as vessels with a LNG storage capacity of less than 30,000 m^3 (see Appendix 3).

There are three main uses of ss-LNG: bunkering fuel for boats, fuel for trucks and finally autonomous power generation in areas not connected to natural gas networks. The small-scale market, or also the LNG retail market, is still quite immature. This market is characterized by the sale of LNG in very small quantities, typically in the range of 100–1000 m^3. There is no doubt that importing countries will increasingly have to use this technology to supply LNG to the many regions, especially to supply islands and remote areas.

On the Asian continent, the exciting potential of ss-LNG plants is dictated by several factors, among others, to support remote areas and scattered islands with the cleanest fossil fuel available and also for electricity. This is particularly the case in South-East Asian countries such as Indonesia, Philippines and Myanmar. Other countries are considering the use of ss-LNG projects, such as India and China.

According to some sources,[11] the size of the market is predicted to grow in 2030 from 80 to approximately 100 mtpa.

2.1 The Global LNG Market

The LNG trade has become unquestionably global. With a greater share of gas reserves located in a few geographically remote areas such as Russia, the Middle East, Australia[12] and, more recently, the United States, intercontinental trade is becoming increasingly profitable.

2.1.1 Recent Developments in LNG Markets

The main changes in this market can be identified as follows:

(i) **Increased contractual flexibility**: the market is developing from a market based entirely on long-term contracts to a more flexible market based on short-term contracts of different durations (<4 years).

(ii) **Increase in spot and short-term[13] LNG trade**: the structure of LNG trade is changing rapidly. Traditionally, LNG is delivered under long-term agree-

[10] According to a new, the existing fleet of small LNG vessels consists of 27 LNG carriers and 17 LNG/LPG carriers plus some LNG bunkering units.

[11] On this subject, see in particular: PwC [81], Verians [96].

[12] Australia was ranked as the fourth largest exporter of LNG in the world in 2010, after Qatar, Indonesia and Malaysia, according to the US Energy Information Administration (EIA). Australia is now the world's second-largest LNG exporter. It will become the world's largest LNG exporter by 2020.

[13] According to the GIIGNL definition, the duration of a short-term contract is less than or equal to 4 years.

ments between buyers and sellers and has only been marginally negotiated on the basis of spot contracts. But since the 1990s, the negotiation of LNG spot cargoes has grown steadily, with faster growth over the past five years. Before 2004–2005, the share of spot marketing accounted for about 10% of the total LNG traded. Data from the International Group of Liquefied Natural Gas Importers (GIIGNL) reveals that spot and short-term trading of LNG have grown from 18.9% in 2010 to 27% in 2017.

(iii) **LNG re-exports**[14] **activity**: one of the new developments is the LNG re-export activity. The re-export of LNG is perceived as an authorized mode of arbitration in 2008. This activity is beginning to grow in importance: five shipments were re-exported in 2008. They all concern LNG cargoes received from Qatar[15] and which, not having found of buyer at good price in Northern Europe. These huge detours of Qatari cargoes tell a lot about the difficulties that the LNG sellers. As of 2010, LNG re-exports have increased and diversified considerably. Another recent example, Cove Point export terminal in Maryland, 2nd US LNG export terminal, sent its first shipment offshore in March 2018. Price swings prompted Royal Dutch Shell on Thursday to divert the first shipment from the new Cove Point export plant in the United States away from Asia to Britain.[16]

(iv) **Panama Canal**: Since the Panama Canal was widened in June 2016, some 372 LNG carriers have used it, of which 337 had booked in advance for the scheduled day. Other ships carrying LNG arrived without having booked a slot, but most of them still managed to pass through the canal on the very same day. Five vessels had to wait, but only for three or four days at most.[17]

2.1.2 Global LNG Market in 2017

LNG consumption has increased by a factor of 2.8 or almost tripled,[18] from 103.3 million ton per year (140.5 Bcm) at the turn of the century to 289.8 million ton (394.1 Bcm) in 2017, according to GIIGNL Annual report 2018. From a structured market in 2000, with 12 exporting countries and 11 importers, the LNG market is now completely open with increasing flows and a number of importing and exporting countries that "exploded": 19 exporting countries and 40 importing countries in the world (Qataris volumes dominate this trade) (Table 1).

[14]The re-export must also cover the costs of handling the LNG in the port where the re-export will take place.

[15]Qatar is currently the leader with low gas production costs ranging from 0 to $2 per MMBtu. This is also the case in some regions of Russia. Similarly, in 2011, this country alone accounted for one-third of LNG traded on the spot and short-term market, followed by Nigeria (12%) and Trinidad & Tobago (11%). Moreover, it accounted for 31% of all international LNG trade, with 75.4 Mt.

[16]See https://gcaptain.com/first-lng-cargo-from-new-us-export-terminal-changes-course-for-britain/.

[17]Petrostrategies, p. 4, 17 September 2018.

[18]In comparison with 2010, imports recorded their highest annual growth rate (+9.9%).

Table 1 Exporters versus LNG Importers, a relational history of more than half a century

	1964	1974	1984	1994	2004	2014	2017
Number of exporting countries	1[a]	4	7	8	12	19	19
Number of importing countries	1[b]	5	6	9	14	29	40
Total	2	9	13	17	26	48	59

[a]Algeria, 1st largest LNG exporter in the world
[b]UK, 1st LNG-importing country
Source GIIGNL, various reports

Table 2 Global LNG market in 2017

	2014	2015	2016	2017
(1) *Demand*				
# of import countries	30	33	39	40
Regasification Capacity (Mt/year)	751	777	830	850
(2) *Supply*				
# of exporters countries	19	19	19	19
Liquefaction capacity (Mt/year)	298	308	340	365
(3) *Ratio Liquefaction Cap./Regasification Cap.* (%)	40	39	41	43

Source Petrostrategies [77]

For the first time in a long period, capacity utilization by regasification terminals throughout the world increased in 2017, although it had hither to been declining. It rose by 2% points, to 79.5%. Another significant indicator: the ratio between global liquefaction and regasification capacities increased to 43% in 2017, although it had been steadily decreasing over the last few years (see Petrostrategies [77]) (Table 2).

Qatar is planning to launch a fourth liquefaction train to increase North Field's capacity to 110 million ton per year (mtpa). The output from the field will rise from 77 mtpa now. Although the commissioning of a certain amount of liquefaction capacity was delayed in 2017, the market was mainly kept balanced by demand, which increased considerably, especially in China. In total, LNG imports jumped 9.9% to 289.8 million tons (MT), the highest level since 2010. While global liquefaction capacity increased by 25 MT in 2017 LNG imports grew by 36 MT (Table 3).

In 2017, five of the world's largest ten exporters of LNG are located in the Asia region while all five of last year's leading LNG importers are Asian nations (see Table 4).

Three countries (Japan, China and South Korea) made up approximately 54% of global LNG imports in 2017. The share of Asia-Pacific is and will remain high despite emerging countries start to import LNG.

The Asia-Pacific region continued to be a core driver in global demand, with China alone adding 12.7 MT of imports in 2017—the largest ever annual growth by a

Table 3 Trends in the utilization rate of global gas-liquefaction capacity (in millions of tons)

	2012	2013	2014	2015	2016	2017
Nominal capacity[a]	282	286	298	308	340	365
LNG imports[b]	236	237	239	245	264	290
Utilization rate (%)	83.8	82.8	80.3	79.6	77.5	79.5

[a]At year end
[b]During the year
Source of basic data: GIIGNL annual reports
Source Petrostrategies [77]

Table 4 LNG exports and imports in 2017

Global share of LNG exports in 2017					
27%	20%	9%	7%	6%	31%
Qatar	Australia	Malaysia	Nigeria	Indonesia	Rest of the World
Global share of LNG imports in 2017					
28%	13%	13%	6%	6%	34%
Japan	South Korea	China	India	Taiwan	Rest of the World
• 66% Asia-Pacific share					

Source Author calculation based on GIIGNL [34]

single country.[19] This growth can be attributed to the strong enforcement of coal-to-gas switching policies through China, as policymakers aim to improve urban air quality across the country. Other countries driving global LNG growth include South Korea, Pakistan and Turkey, which together added a combined total of 11.9 MT in imports.

At the end of 2017, the total regasification capacity reached 850 mtpa and the aggregate nominal liquefaction capacity reached 365 mtpa (Table 2).

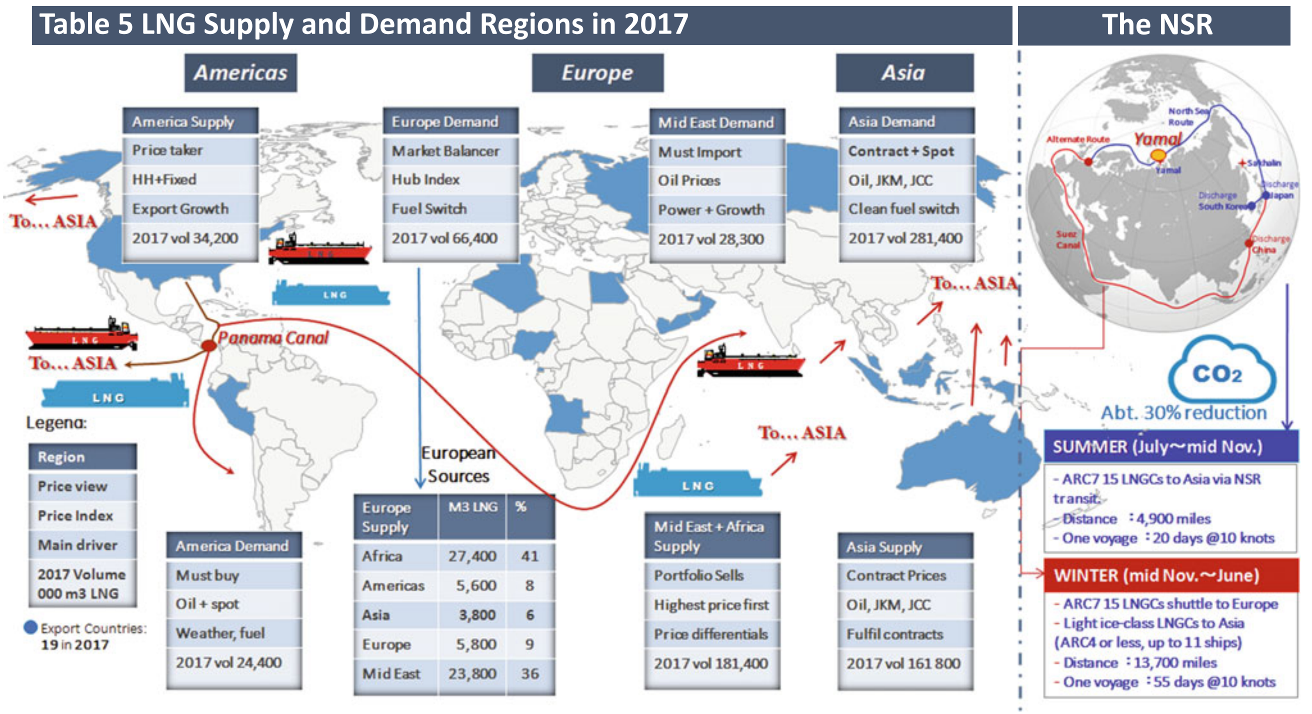
2.2 Asia-Pacific Market

The majority—66%—of the world's LNG is consumed in the Asia-Pacific region (see Table 4). Asian countries consumed 290 MT of LNG in 2017, with 27% of global LNG volumes supplied from Qatar.[20] The five largest LNG importers in this region are Japan, Korea, China, Taiwan and India.

[19]Unless otherwise noted, all figures in this section are taken from the latest report "IGU 2018 World LNG Report" available on website: www.igu.org/news/2018-world-lng-report.

[20]GIIGNL [33], The LNG industry, GIIGNL annual report 2018.

Table 5 LNG supply and demand regions in 2017 and the NSR



Source Author based on data from Williamson [98]

Source Author based on data from Mitsui O.S.K. Lines [71]

2.2.1 Mature Asian Markets: Japan, South Korea and Taiwan

In the Asia-Pacific region, LNG trades started in 1969 when Japan introduced LNG, first time, from Alaska with a fixed pricing. In 1973–74, prices were linked to crude oil and the first Indonesian[21] contract into Japan was at 90% oil parity. Since then, Japan has dominated the LNG market throughout the 1970s and 1980s. The second largest market entrant is South Korea, which started LNG imports in 1986 followed 4 years later by Taiwan.[22] These three countries have dominated the global LNG market for a long time. The future of LNG in the mature markets is dependent, particularly, on nuclear power development in Japan and Korea. Many Japanese nuclear plants, closed post-Fukushima-Daiichi, are still in the process of being reopened. To the extent that these plants are able to reopen, LNG import requirements will fall significantly from post-2011 levels [76].

South Korea and Taiwan have also been growth markets. In these two countries, LNG helped to offset the shutdown of some nuclear power plants. In the last months of the year, India has also increased its purchases of LNG due to a shortage of coal.

2.2.2 Emerging Markets: China and India

Two of the today's growing economies in the world, India and China,[23] are relatively new comers in the LNG market, with India and China having started imports in 2004 and 2006, respectively.

In contrast, "emerging Asia" will become the engine driving the growth in demand for LNG. The share of combined LNG demand from these countries globally will rise from today's 23–42% in 2030. Improving macroeconomics, stricter implementation of environmental policies and ongoing gas market reforms will continue to push up China's gas consumption and LNG imports. India's LNG demand is expected to be largely driven by industrial sectors where fuel-switching opportunities exist for LNG as a feedstock. In South and Southeast Asia, LNG demand will be primarily driven by power demand growth and a reduction in local gas production (Kuang, [56]).

In 2017, China absorbed about 40% of the additional LNG supply to meet its strong domestic demand growth. LNG was favoured over gas pipeline imports which were less competitive. China overtook South Korea to become the world's second largest LNG-importing country in 2017 (see Fig. 1).

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[21] Indonesia began exporting LNG in 1977 and, in 1984, had overtaken Algeria to become the world's leading supplier of this product.

[22] Called also "Chinese Taipei." For an explanation of this term, see for example:

—What is "Chinese Taipei"? The Economist, Apr 9th 2018 also available on www.economist.com.

—Why is Taiwan Called Chinese Taipei?, available on www.scienceabc.com/social-science/why-is-taiwan-called-chinese-taipei.html.

[23] To understand China's energy strategy, in particular its international strategy through its three state companies, NOCs (Sinopec, PetroChina and CNOOC), we refer the reader to Suisheng [94] article.

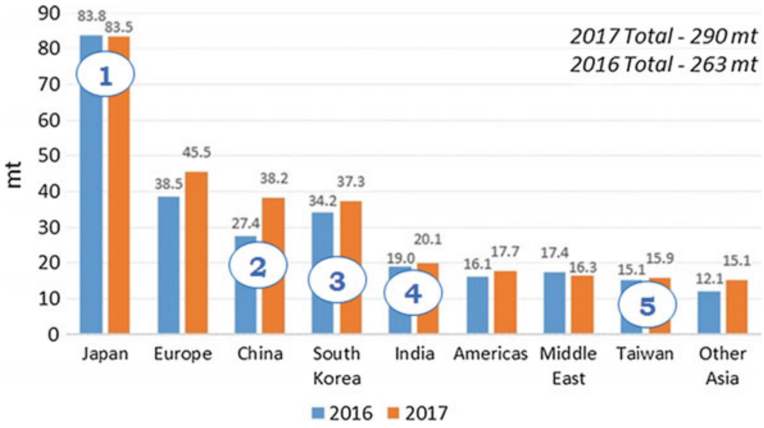


Fig. 1 LNG imports by Country/Region in 2016/2017. *Source* Gas Strategies [30]

The development mentioned above has led to the reorientation of LNG trading from the Atlantic Basin to the Asia-Pacific Basin. Qatar has significantly increased its exports to China and Pakistan, while deliveries to the United Kingdom have fallen for the second year in a row.

3 Trade—Pricing of LNG and Contracts

The Asia-Pacific region, historically the largest LNG market, is one of the most dynamic regions in the world and is experiencing high economic and energy growth. The post-Fukushima-Daiichi era has reoriented LNG flows to Asia.

Indeed, Asia—in Japan, China, South Korea and India, among others—has become a privileged destination for exporters: Demand is important, and high prices are mainly due to indexation of crude oil prices, which is highly volatile. Most of Asia LNG imports are traded predominantly under long-term contracts (LTCs) between suppliers and buyers. However, the LNG market has changed significantly, and the share of spot and short-term trades is growing and fast.

In the light of the mutations observed in recent years, the commercialization of LNG in Asia should have a lot of change in the coming years with the emergence of new gas giants, the competition between exporters worldwide (Qatar, Australia, …), the significant expansion of global liquefaction capacity (mainly Australia and USA), the development of new markets, the expansion of the LNG "*importers' club,*" the opening of new trade routes for LNG (expansion of the Panama Canal,[24] Northern Sea Road[25]) (Table 5).

3.1 The LNG Pricing

After analysing market fundamentals (supply and demand), we now turn to the key market variable, namely the price of LNG and its determination, particularly in the Asia-Pacific region. As already mentioned, most LNG trades are dominated by oil-indexed long-term contracts (LTCs). However, the share of spot and short-term trades is growing and fast. Spot trades grew from 10% of total LNG trade in 2003 to 27% in 2017, and volumes continue to climb (regarding commercial flows of LNG, see Fig. 2). There is no gas trading hub in Asia. However, three countries—Singapore, Japan and China—are increasingly expressing intentions of having own LNG trading hubs.[26] For a long time, international trade in natural gas[27] (LNG also) was considered as a regional market. Indeed, the market is divided into three[28] main consumption areas instead of one global[29] market: North America, Europe and Asia-Pacific (Fig. 3). The latter—Asia-pacific market—will be discussed further in the following section.

(i) **North American Region**: In North America—the United States, Canada and Mexico—have strong pipeline connections, and exports to these countries are typically considered as part of an integrated supply mix. With large supplies of natural gas and an extensive pipeline system, the North American/Atlantic Basin region has historically been able to supply almost all of its natural gas requirements from indigenous sources.

(ii) **European Region**: The world's first LNG market was actually established in Europe in 1964 when LNG deliveries from Algeria were sent to the United Kingdom. Deliveries to France, Spain and Italy followed shortly after and other European countries, such as Turkey, Greece and Portugal, began importing LNG in the 1990s and early 2000s. The discovery of natural gas in the North Sea allowed the United Kingdom to cease LNG imports until relatively

[24]This itinerary shortens the voyage for US LNG to Asia by 22 days and saves approximately 30% in cost per roundtrip.

[25]Crossing the Northern Sea Route in the Arctic allows for a 30% reduction in CO_2.

[26]See more details below.

[27]Globally, World gas trade is around 70% by pipeline and 30% as LNG. In 2017, LNG's share in total trade has increased to 32% (versus 30% in 2015).

[28]Another classification exists. It breaks down the market into two distinct LNG trade regions: Atlantic Basin versus Pacific Basin.

[29]In all three markets, there are significant price differences between the North American market (US Henry Hub) and the Asian market (Japan LNG), and an intermediate price for the European market (UK NBP). Much of the difference is due to the freight differential, due to the remoteness of the European and Asian markets from major sources of LNG supply. The gap has narrowed in recent years and is now only a few dollars.

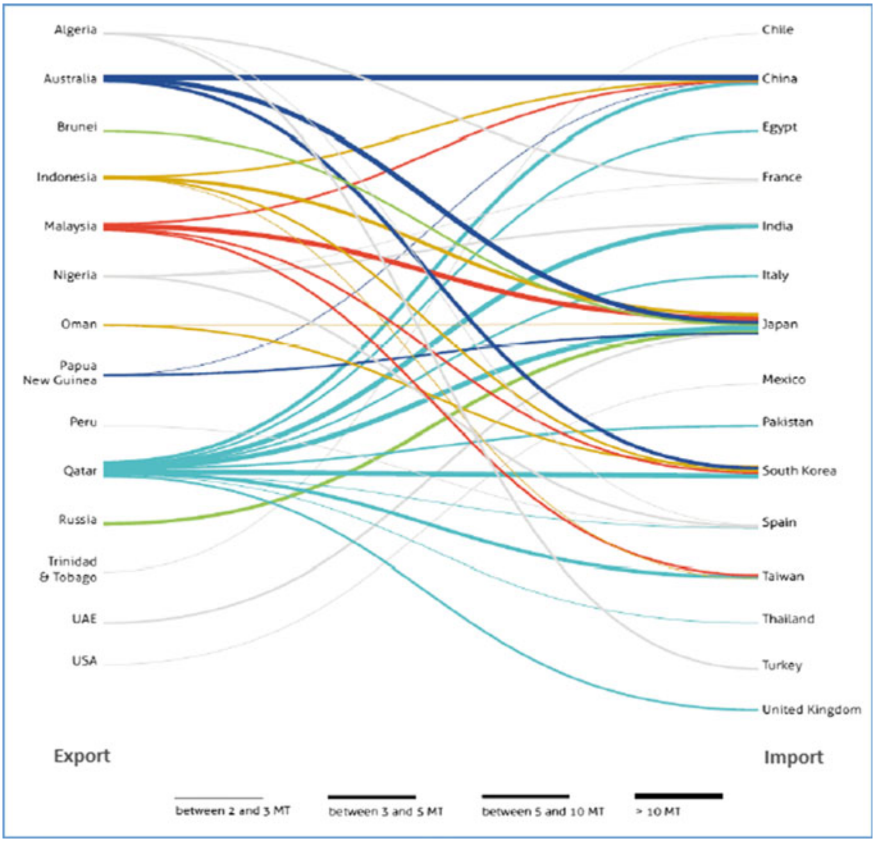
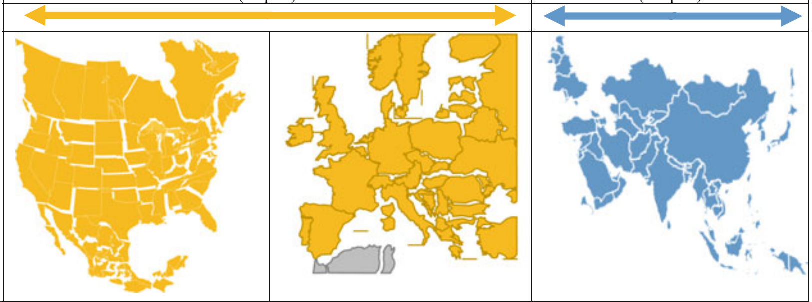


Fig. 2 Commercial flows of LNG. *Source* GIIGNL [34]

recently when declines of North Sea reserves necessitated the resumption of LNG imports into the UK.

(iii) **Asia-Pacific Region**: LNG is essential for countries that cannot use pipelines supply but have a maritime facade, so they can get supplies from LNG carriers. This is the case of Japan for imports (1st importer) and Qatar for exports (1st exporter) has historically been the largest market for LNG. Japan is the world's largest LNG importer, followed by South Korea and Taiwan. These three countries have few indigenous resources and rely almost exclusively on LNG for their natural gas supply. China and India have recently emerged as LNG importers and could become significant buyers of LNG over time (Sakmar [87]).

	1. North America	2. Europe	3. Asia Pacific
	Gas-on-gas market (Liquid)		Oil-linked market (Illiquid)
Three regional markets			
Hub*	**Hub pricing (Spot market)** ☑	**Hub & oil-linked pricing (Hybrid market)** ☑	**Oil-linked pricing (Oil-linked LNG market)** ☒
Comments	▪ Liberal gas markets ▪ Gas-to-gas competition – NYMEX (Henry-Hub linkage)	▪ Continental Europe – Oil or oil products linkage ▪ Gas-to-gas competition mostly in North West Europe, ICE (NBP), TTF/Zee index	▪ Linkage to oil (for LNG) ▪ Japan LNG import S&P Global Platts (JKM) ▪ JCC
Price setting formula	Henry Hub price + c (c constant)	Price of crude oil & petroleum products * a + b (b constant)	Crude oil price * a + b (b constant)
Prices 2017**	\$2.8/MMBTU	\$5.8/MMBTU	\$7.3/MMBTU
➔	To satisfy their needs in a sustainable way and to address major supply uncertainties, many buyers of LNG still want prices using oil-based pricing.		

*There is no competitive trading hub in Asia. Regarding the debate on the future gas hub in Asia, see Table 10
**Average (up on 2017 \$0.5 to \$1/MMBTU vs. 2016).The latest LNG prices, November 2018, are listed in the Appendix 2.
Source: Author from various sources.

Fig. 3 LNG Priced at "Market." *There is no competitive trading hub in Asia. Regarding the debate on the future gas hub in Asia, see Table 10. **Average (up on 2017 \$0.5–\$1/MMBTU vs. 2016). The latest LNG prices, November 2018, are listed in the Appendix 2. *Source* Author from various sources

3.2 The Different Asian Markets for LNG

The Asia-Pacific gas/LNG market is the fastest growing in the world, but it is a complex and fragmented market. Due to geographical, political, geopolitical and economic problems, Asia is not a "geographically" defined market. Unlike the European and North American markets, this region is not well interconnected by pipelines except for some connecting networks, notably between China and Russia. This is one of the reasons why LNG trading is dominated by this region (Asia). The region has three distinct markets with their own specific dynamics:

- The **first market** is that of developed and mature economy countries, including Japan, Korea and Taiwan (known by its acronym JKT). This market is isolated and lacks natural gas resources. Its main supply is still through LNG.
- The **second market** is made up of the two emerging BRIC countries: China and India. Both countries have strong potential for growth in natural gas demand, and their supplies include domestic production and imports via pipelines or through LNG.
- The **third market** is the Southeast Asian region, which consists of several major LNG producers (such as Indonesia, Malaysia and Brunei).

To date, Japan (1st) and China (2nd) dominate the Asian market. Japan has traditionally been the largest consumer of natural gas in Asia. Asia will be the core growth region in the coming decade.

3.3 LNG Contracts

Although it is widely held that the LNG market has long been dominated by LTCs, there are three types of contracts that are conventionally distinguished:

– Spot and short-term contracts (less than 2 years)
– Medium-term contracts (between 2 and 5 years)
– Long-term contracts (longer than 5 years).

Traditionally, LNG import contracts are based on LTCs[30] (>20 years), in which the importer assumes the volume risk, with the commitment to pay the unused volumes as well, that the producer endorses the price risk. This type of contract is perceived as a risk-sharing instrument between producer (also known as seller) and consumer (also known as customer) and a means of promoting the necessary investments in the gas chain. LTCs have the following advantages:

(i) The gas remains competitive for the importer;
(ii) The outlets for the producer are always assured;
(iii) The financing of gas infrastructure (pipelines, LNG terminals) is guaranteed, with a low risk.

Contracts of the same type are concluded according to two main types: DES[31] or FOB[32] delivery conditions. In a FOB clause, the buyer is free to divert the cargo to

[30]Consumer contracts normally cover a period of 20–30 years with volume and price commitments. This is the most common form of pricing for direct sales to consumers in developing countries.

[31]Delivered ex-ship or Ex-ship contract: in an LNG ex-ship contract, ownership of the LNG transfers to the buyer as the LNG is unloaded at the receiving terminal; payment is due at that time. The two terms are used mainly in LNG shipping contracts. See the Glossary of LNG Terms, published by Petroleum Economist and PwC, 2006.

[32]Free on board: in an LNG FOB contract, the buyer lifts the LNG from the liquefaction plant and is responsible for transporting the LNG to the receiving terminal. The buyer is responsible for the

any other unloading port of its choosing after loading. A crucial difference between the two types of contracts[33] concerns the question of ownership of the gas. Since 1 January 2011, the effective date of the Incoterms[34] 2010, a new term called DAP (Delivered At Place) is expected to replace the DES.

3.3.1 Long-Term Contracts

Historically, the global LNG market has been dominated by LTCs under which producers sell large quantities of LNG to large customers who are either electric operators or gas operators. These LTCs (15–25 years) were governed by the “Take-or-Pay” principle (commonly known by the acronym ToP) which required the buyer to pay the LNG price even if it could not be used in full, with little flexibility or opportunity to resell such a surplus.

LNG producers-sellers were particularly keen on this type of contract because it guaranteed the revenues necessary to justify the heavy or capital investment (several billion dollars) throughout the LNG chain (from E&P to the construction of a gas-liquefaction unit). Countries with heavy dependence on LNG (mainly Asian countries) had a preference for SPAs covering a long period of time to secure supplies. The LNG was delivered in LNG carriers designated by the seller and the contracts contained clauses, including the “destination” clause, which prevented buyers from reselling it to a third party. In the conventional LNG trade, most contracts are on a fixed- and long-term basis and traditionally Asian LNG prices have been linked to Japan’s crude oil import prices.[35] Conventional LNG contracts also usually contain a destination clause that often restricts any reselling or rerouting of the LNG cargoes.[36]

In the 1990s, with the entry into this market of new suppliers (Middle East) and buyers (United States, Europe, Taiwan, India and China), the situation changed with the emergence of flexible volumes and contract terms. This flexibility has been the cause of the development of the short-term market or spot market.

Nowadays, with more LNG supply coming online, contracts are increasingly being renegotiated to shorter terms. Due to production gains, the availability of uncommitted short-term supply has increased, and pricing structures are transforming to accommodate greater sourcing options. Thus, buyers are benefiting from more competition in the market and achieving lower costs for LNG (Black and Veatch [6]).

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shipping, either owning the LNG ships or chartering them from a ship-owner. In a FOB contract, the seller requires assurance that the shipping protocols provide a safe and reliable off take for the LNG to prevent disruption to the Sales and Purchase Agreement (SPA).

[33] See Appendix 1.

[34] Incoterms is a registered trademark of the International Chamber of Commerce (ICC).

[35] A few years ago, at the tenth ministerial session of the member countries of the Gas-Exporting Countries Forum (GECF), held in April 2010 in Oran, the countries of this forum agreed to index gas prices to oil prices on the spot market (short term).

[36] IEA, Gas Resiliency Assessment of Japan, 2016.

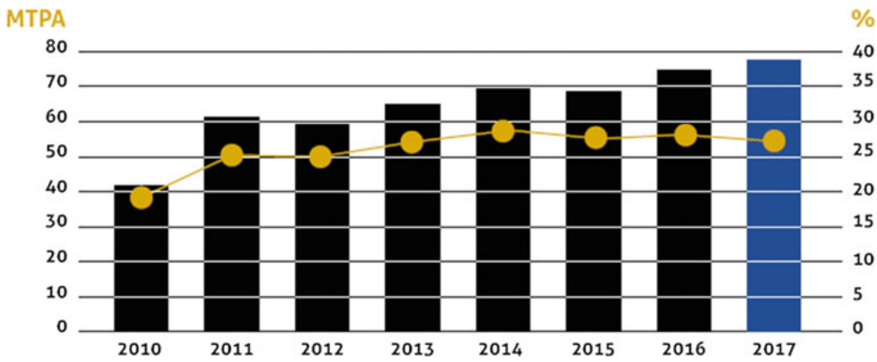

Fig. 4 Spot and short-term versus total LNG trade. *Source* GIIGNL [33]

3.3.2 The Emergence of Short-Term and Spot Contracts

Spot and short-term[37] LNG trading around the world have increased significantly beyond the 27% threshold (compared to 5% in 2000). In fact, they reached 77.6 MT imported on a spot or short-term basis in 2017, or 27% of total trade. On the supply side, the rise of spot and short-term volumes was essentially underpinned by the development of US exports, which accounted for 10.4% of LNG volumes delivered under contracts of 4 years or less in 2017 [28] (Fig. 4).

This trend is expected to continue towards short-term/flexible volumes especially since the advent of shale gas (in the USA) which has caused a fundamental shift in LNG markets.

3.3.3 Renegotiation of Contracts

Asia-Pacific countries are struggling to negotiate the price of LNG[38] because of the lack of gas or alternative energy resources. However, the massive arrival of US LNG on the market creates the conditions for a globalization of natural gas and the end of a "regionalization" of trade. But can this phenomenon become reality in the coming years?

In view of several changes, recent years have seen a significant reduction in the duration of the contract where contracts of yesteryear are rare.

[37] According to the GIIGNL definition, the short term is less than or equal to 4 years.

[38] In Asia, long-term LNG contracts have begun a wave of price renegotiation and reviews. Examples include the renegotiations between: India versus Qatar, India versus Australia, India versus Russia, China versus Qatar, China versus Australia and South Korea versus Qatar.

Table 6 Contract evolution by volume, before 2014, 2015–17

	Signed			
	Before 2014	In 2015	In 2016	In 2017
Short term (up to one year) (%)	8	16	2	24
Flexible destination clause (%)	39	41	42	22
Average contract duration (year)	16	10	9	4
Average contract volume (Bcm/year)	1.7	1.0	1.2	1.0

Note Short-term excludes single spot transactions
Source IEA [46]

New types of contractual formulas[39] are evolving in many cases, with shorter timeframes and greater spot indexation. Thus, the duration of LTCs is now between 5 and 10 years (compared to historically periods of more than 20 years), ensuring that sufficient quantities of gas are delivered over the long term to meet customer needs.

The greater reliance on short-term and spot market trades has brought about lower extension of expiring LTCs. Developments like these give cause to speculation that in the future, long-term LNG trading contracts may become obsolete. With regard to LNG contracts, buyers continue to sign shorter contracts. The average time of the contract in 2017 was less than 7 years (see Table 6).

Today we have two competing contracting models (see Table 7). The traditional model still used for integrated LNG projects from reservoir through end user, with prices indexed to oil prices, coexisting with the new tolling model seen in the wave of US liquefaction projects. This should provide arbitrage opportunities for global LNG traders, while LNG project developers will see enhanced spot liquidity as they optimize not only the rights they retained to process uncontracted volumes from the new projects but also those volumes from contracts which are soon to expire [70].

According to Pedersen [76], nearly 80% of US LNG export volumes for projects currently under construction have been contracted on pricing terms directly linked to the Henry Hub price, or under a hybrid pricing mechanism with links to Henry Hub.

As an example, we might mention the sales arrangement between Cheniere Marketing and Électricité de France (EDF) for the delivery of LNG cargoes on an ex-ship basis (DES). The sales price for the LNG cargoes was linked to the Dutch Title Transfer index (TTF), a natural gas pricing index in continental Europe.

[39]More recently, for Driftwood LNG project, Tellurian offers potential LNG customers several formulas: two classical formulas (buy LNG from the liquefaction plant or lease processing capacity for your own gas) and an innovative formula which involves joining as an investor, with a share in the project's entire value chain, including access to gas production, gas transmission and liquefaction (see Petrostrategies [77]).

Table 7 Traditional and new LNG contracting models

	International	North America
Natural gas supply	Integrated with field production	Purchased at market prices
Liquefaction cost	Passed through by seller to buyer	Long-term tolling fee charged to buyer
Transportation	Dedicated tanker fleet	Buyer's responsibility
Marketing/pricing	Point-to-point long-term S-curve	Cost recovery
Price risk	Passed to end user	Buyer's responsibility

Source Ross and Varghese [86]

3.3.4 Wholesale Price Structure in 2017

The natural gas market in Asia is going through a transformation. Both the institutional environment and price mechanisms are changing radically. The Asia-Pacific region, characterized by a traditional market structure with long-term contract and oil indexation, has consistently had the highest price levels among all regional markets. As a result, new potential price setting mechanisms are now being actively discussed in the region.

The structure of the national natural gas markets in Asia limits competition. In several countries, Governments still participate directly or indirectly in market control, in the determination of energy prices, including the natural gas/LNG price. In the absence of pipelines in most Asian countries, given its geographical location, and with the objective of securing long-term supplies, natural gas is mainly imported on the basis of LTCs and the evolution of the price of gas depends on that of crude oil (or petroleum products). According to the table below, it is still apparent that the oil price indexing mechanism (OPE) still dominates the Asian market (Table 8).

The shale gas boom in the United States has created downward pressure on gas prices in other markets. Companies in natural gas-importing countries in Asia or Europe may renegotiate with major gas-exporting countries to change contract terms, particularly price clauses.

3.3.5 The Shale Revolution and LNG Exports from the USA

In the United States, natural gas production from shale gas fields began in the 1980s, but the combined use of hydraulic fracturing and horizontal drilling increased considerably during the first decade of the 2000s. The high natural gas prices at that time were an additional incentive to start production. The shale gas issue has profoundly

Table 8 Worldwide natural gas imports by price formation mechanism (Bcm)

Price formation mechanism				
Region	OPE	GOG	BIM	Total
North America	0	135.1	0	135.1
Europe	151	295.3	0	446.3
Asia	108.6	19.5	0	128.1
Asia-Pacific	189.1	36.4	0	225.5
Latin America	20.4	9	0	29.4
FSU	6.1	10.0	29.9	46.0
Africa	6.0	8.4	4.3	18.9
Middle East	11.8	6.9	17.3	36.0
Total	492.9	520.6	51.5	1065.2

Note OPE oil price escalation, *GOG* gas on gas, *BIM* bilateral monopoly
Source IGU [48], Wholesale Gas Price Survey 2018 Edition, A Global Review of Price Formation Mechanisms, June 2018

changed the North American gas market and is beginning to change the global energy landscape for two main reasons:

(i) the abundance of resources;
(ii) the sharp increase in production.

The major consequence of this change is that shale gas has seen its price fall on the local market, where it has been abundant. American producers then turned to exports in order to find more attractive prices.[40] Exports of US shale gas began in February 2016. A first LNG shipment is part of Sabine Pass first liquefaction unit in Louisiana, to reach Brazil. This event marks a new era in global LNG trade as the USA is set to become a net exporter of domestically sourced shale gas. Indeed, in March 2018, the Cove Point terminal in Maryland became the second largest LNG export terminal. Other liquefaction units are under construction in the United States. Latin America being the dominant destination (47%) and Europe received only a small proportion of these new exports (12% at the end of January 2017).

But it is important to keep in mind that LNG exports from the United States have their price (and coverage) based on the prices of European gas hubs (mainly the NBP in the United Kingdom). A total of 65 mtpa of new LNG capacity from the US is expected by 2021, most of which between 2018 and 2019. This represents more than half of the new global capacities that will enter production in the next 5 years. As the volume of US exports increases, large volumes are likely to arrive in Europe, or move shipments from Europe to other destinations, such as Asia.

US LNG exports have continued to travel the world, reaching 28 countries per government data. About 60% of our exports have been sold on a spot basis, an added flexibility that the long rigid LNG market craves.

[40] It should be noted that most of the LNG projects being considered in the United States are located along the Gulf of Mexico. The only exception is Jordan Cove, a project located on the West Coast. It would therefore compete with Canadian projects in the region for proximity to Asian markets.

Table 9 Global US LNG destinations[a] (2016–2018)

Regions	Latin America and Caribbean	East Asia and Pacific	South Asia	Europe and Central Asia	Middle East and North Africa
Share %	34.2	41	5.9	9.8	9.2

[a]Cumulative starting from February 2016 through September 2018
Source US Department of Energy, LNG Monthly (September 2018)

Today, the USA became a large net exporter of natural gas for the first time since 1958, as increasing shipments of LNG to world markets and natural gas pipeline deliveries to Mexico exceeded imports from Canada and other countries. The table below shows the export development of US LNG exports between February 2016 through September 2018 (Table 9).

Between 2014 and 2018, North American natural gas bounced back from its low of sub \$2–\$3 per MMBtu, while LNG in Japan went from \$16.50 to as low as \$5.50 per MMBtu and is now[41] at \$10.7 per MMBtu. The abundance of cheap LNG has transformed the natural gas industry from being a continental or regional market to being a globalized market.

4 Globalization

The LNG market is becoming increasingly global and is beginning to link regional markets in Asia, Europe and North America with many supply options. Suppliers and consumers all benefit from the development of the sector, which has multiple sales and purchasing options, ranging from traditional LTCs to local and shorter-term agreements to meet the evolving needs of customers and suppliers. There is no doubt that growing demand for LNG is driving gas globalization. With a larger share of gas reserves located in some geographically remote regions such as Russia (18.1%), the Middle East—Qatar (12.9%) and Iran (17.2%)—Australia (1.9%), and the United States (4.5%), intercontinental trade is becoming more and more profitable. Although much has been written about the topic, the debate on the globalization of the gas and LNG market is still relevant today.

Indeed, the topic of the globalization of gas markets has been addressed by several economists and experts; we refer the reader to the following authors (list is only indicative): Yergin [100], HalmØ [41], Sakmar [87] and Yafimava [99].

This section reviews the latest trends in the global LNG market in the Asia-Pacific region and contributes to recent debates on the creation of an LNG trading hub in Asia and the globalization of the LNG market.

[41]In October 2018, the average price of spot-LNG imported into Japan was contracted is \$10.7 per MMBtu.

4.1 Definition of Globalization

It can be defined as the abrupt interconnection of previously disjointed markets, whether they are local (in the geographical sense) or they are disjoint in terms of products. The globalization process can therefore affect the technical boundaries of markets as much as their geographical boundaries. As a result, traditionally regional markets have been interconnected.

Ayoub [5] defines globalization as "*…it can therefore be said that globalization requires, as the introduction of a "market economy," characterized by (a) legal recognition and the defense of private property, (b) freedom to undertake and contract, and (c) the existence of a free competition. These are, clearly, the main features that define the capitalist system itself.*"[42]

In 2009, Yergin wrote the following about globalization[43]: "*Globalization is also driving the emergence of a second global energy business—LNG (liquefied natural gas). LNG has been an international business since the 1960s. What is developing now is a much larger, more global, more flexible, more traded gas business.*"

The LNG industry is entering a transition phase and is experiencing major changes to adapt to this new environment.[44] Buyers are looking for greater flexibility in sourcing and are looking to remove destination clauses, still very present in the Pacific Basin, to take advantage of arbitrage opportunities and to be able to resell surplus LNG. The natural gas markets in different regions are gradually becoming more integrated. This globalization process of LNG markets seems obvious and is due to several reasons (see Sect. 4.2).

4.2 Reasons of Globalization

These markets in different regions are gradually becoming more integrated. This process of globalization is due to several reasons, among others:

(i) Transportation costs (particularly LNG) have fallen significantly over the past two decades (with the exception of recent years), and represent a much lower share of the wholesale price of gas than 15–20 years ago[45];
(ii) The share of spot LNG trade has increased, which means that short-term price differences between regions can be more easily be exploited for gas re-export[46];
(iii) The arrival of large quantities of US LNG (shale gas) in which should encourage arbitrage trading and price convergence;

[42] Our own translation of the original French text.
[43] See Shahbaz et al. [88] regarding definition of globalization.
[44] See Yergin [100].
[45] Brito and Hartley [9].
[46] For more details, see Sect. 2.1.1.

(iv) The emergence of new routes (Northern Sea Route—to Asia, enlarged Panama Canal);
(v) The emergence of new operators (Portfolio Marketers and LNG Commodities traders);
(vi) The development of new markets (and also small-scale LNG market);
(vii) The expansion of the LNG "*importers' club,*" etc.

4.3 Towards Establishing an LNG Hub in Asia?

In contrast to Europe and the USA, natural gas hubs do not exist in Asia. However, hubs in Asia are in the stage of initial formation. The idea of an LNG hub in Tokyo strongly appears in the debate in 2011, after the Fukushima-Daiichi accident. At that time, the price of oil on international markets was trading at over $100 (Brent average oil price was $ 111.27 per barrel). Japan needed more imported LNG (a very expensive country because of indexation) to replace nuclear power following the shutdown of several sites. So the country was going through very difficult times with the combined effect of a terrible earthquake and the shutdown of nuclear facilities.

According to METI [69], Japan expressed the willingness to establish a highly fluid LNG market and become an LNG trading and price formation hub sometime in the first half of the 2020s under "Three Fundamental Principles": (i) private first, (ii) globalism and (iii) action-oriented."

Asia, more specifically, East Asia is creating its own regional gas pricing system through the establishment of gas trading hubs. For this purpose, three countries compete to become an LNG trading hubs and create a price point, it can be Singapore, China (Shanghai) or Japan (Tokyo). The table below gives a comparison between three cities (Table 10).

For the emergence of a hub of any kind, a series of determining factors must be met, such as:

– Physical interconnection with other markets;
– Storage availability well connected to the hub.

4.4 Gas Price Convergence Within Regions: True or False?

In the general view of gas market analysts, gas prices in North America, Europe and Asia diverged before the fall in oil prices in 2014, more precisely throughout the period 2005–2014. These explanations are not unanimously accepted: a few informed observers have found this a little odd. Among the observers, Floris Merison at the Energy Delta Institute (EDI) conducted a recent study[47] that showed that

[47]For more details on these results, visit energy post's website at http://www.energypost.eu/globalisation-gas-market-going-longer-think/.

Table 10 Comparison between the three likely hubs in Asia

	Singapore Hub	Shanghai Hub	Tokyo Hub
Advantages	• First mover–current location of 24 companies operating in the Asian LNG space • Sufficiently neutral politically that others may accept it as an index	• The location where domestic and international (LNG and pipeline) gas supplies come together in Asia's biggest (and most rapidly expanding) gas market • Result of a price reform with a compelling market logic (the only one in Asia?)	• Demand for LNG as physical trade • Liberalization of wholesale market
Disadvantages	• A market of 6 mt—although with plans to expand significantly—may not be large enough to set prices for Asia • Location may be too far from the major Asian LNG markets to provide a compelling price reference; but close enough to SE Asian countries	• Lack of transparency of supply and demand i.e. not genuinely "market-driven" • Overly dominated by three Chinese state-owned companies (and hence the Chinese government)	• Third party access (TPA) to infrastructure • Arbitrage between pipeline gas and LNG
Comments	• Unlikely to develop enough size and liquidity to be a reference for the big Asian markets, but could for emerging South East Asian gas/LNG markets	• Shanghai is currently a "city gate benchmark" rather than a hub price, but nevertheless it could evolve into the dominant price reference for Asia • China has no stake in the traditional LNG status quo	• Improve Internal Pipeline Connectivity • Unbundle Pipeline Ownership • Establish TPA/UIOLI[a]/secondary capacity market for regasification capacity • Create Virtual Hub

[a]Use it or lose it (UIOLI) rules
Sources Yafimava [99], KPMG [55], Hashimoto [42], World Gas Intelligence (2017)

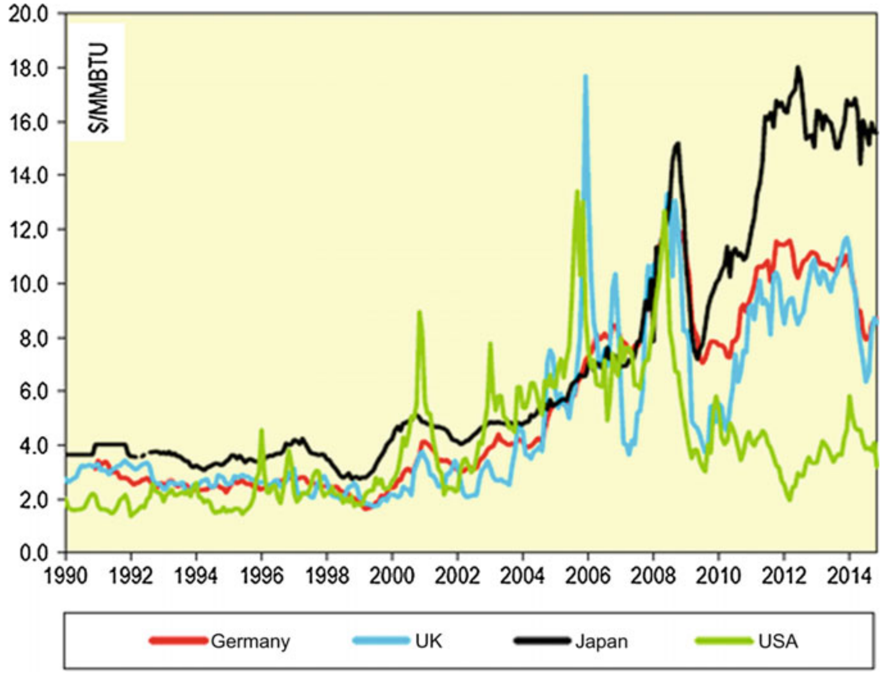

Fig. 5 Example of the regular view of global gas price divergence. *Source* Adapted from Merison [67]

the conventional view of price divergence is wrong. As a result, global gas prices converged—as might be expected from market trends (Fig. 5).

Further analyses were carried out up to 2018. These include Gas Strategies[48] which focus on LNG prices in Asia (see Fig. 6).

It seems that the consequences of the Fukushima-Daiichi accident and the growth in demand kept the Asian market under pressure with spot prices move around the long-term average depending on the seasonality. Since summer 2014, long-term prices have fallen in line with oil price. Spot prices have fallen quicker and further than long-term prices. As a result, shale gas and US LNG exports have stimulated re-convergence.

From the figure above, it can be seen that the different market prices are approaching, but is this a convergence?

Finally, a final study that we can quote on this subject comes from Enerdata. Enerdata [26] estimates "*that gas prices will rise through 2040 with a convergence of Asian and European market prices whereas North American market will keep its own price dynamics. More ambitious climate policies such as limiting the long-term*

[48]For more details, see the following link http://www.gasstrategies.com/blogs/drawn-out-ball-game-asian-spot-lng-prices-stay-below-long-term-contract-prices.

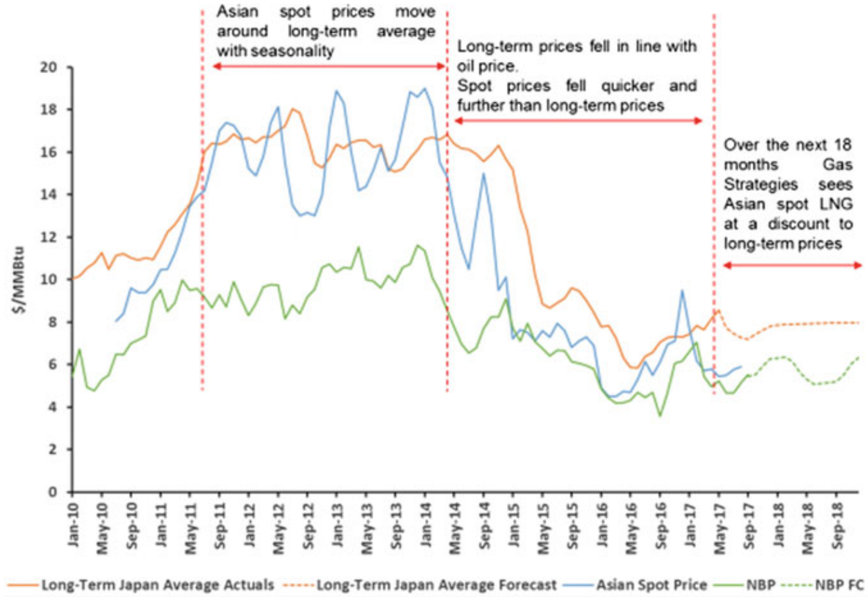

Fig. 6 Asian spot LNG prices to stay below long-term contract prices. *Source* Adapted from Gas Strategies, Reuters Eikon, ICE. Available at http://www.gasstrategies.com/blogs/drawn-out-ball-game-asian-spot-lng-prices-stay-below-long-term-contract-prices

increase of global temperature to 2 degrees would result in decreasing gas prices from around 2030.”

For our part, the massive arrival of US LNG on the market in the near future and other exports from USA, Australia, Canada, East Africa and Russia should lead to a convergence of price levels on all three markets and create the conditions for globalization of the LNG market. Therefore, they will contribute to increased diversification, flexibility and stability.

4.5 The Gas Market Is Globalizing

Several experts agree on a new trend in gas marketing: from a regional business to a global business.

– In the geographical sense, the gas market is globalized, thanks to the multiplication of liquefaction and liquefaction terminals and also maritime transport by LNG carriers. Today, there are LNG cargo loading and unloading terminals on all five continents, unlike previous decades. Similarly, the size of the shipping market has grown significantly. More than 520 LNG carriers were in service in 2017, and there are currently some 560 that operate in the oceans and seas.

1970	1990	2010
♦ 5 importing countries ♦ 3 continents	♦ 8 importing countries ♦ 3 continents	♦ 22 importing countries ♦ 4 continents
♦ LTCs	♦ LTCs ♦ Spot	♦ LTCs ♦ Spot/Short-term
♦ Hub: 0	♦ Hub in USA (1988)	♦ Hub in USA (1988) ♦ Hubs in Europe : UK NBP (1996); Belgium Zeebrugge (2000) ; Dutch TTF (2003) ; Italian PSV (2003) ; French PGEs (2004); Austrian CEGH (2005); EGT German (2006).
8 LNG Carriers	72 LNG Carriers	359 LNG Carriers

Fig. 7 Globalizing LNG Market? *Source* Own elaboration based on http://www.gasinfocus.com

– In the commercial sense, throughout the five decades, long-term contracts always dominate commercial transactions between buyer and seller. It was not until the 2000s that spot markets and short-term markets began to stand out and take on a little importance. Similarly, only two out of three markets are considered “liquid.” The Asian market is still not as such (see Fig. 7).

Structural changes are underway. Among which we can mention:

– The diversification of gas supply sources and an acceleration of liquefaction capacities where the race for first place will be between the USA, Australia and Qatar;
– The Fragmentation of downstream markets, both geographically and in terms of use;
– The gradual shift from oil indexes to regional gas and LNG market indices;
– The development of flexibilities including the elimination of destination clauses, cargos swaps, reduction in contract duration and tenders, increase in short-term transactions and other spot arbitrations.

With these changes, globalization will undoubtedly have positive aspects on the Asian market. The essential point that results from the current debate on the globalization of LNG trade is that compared to crude oil; in the past, the oil market was produced, exported and controlled by a limited number of countries, while over time, the oil market has become global where the product has moved from a regional market to a global market. Today, it is the same story with LNG where several factors tend to make the LNG market a global market over time.

This situation would allow price convergence and market globalization, which would also allow Asian countries to secure competitively priced LNG supplies—a cleaner and more environmentally friendly source of energy than others—in the long term, both reliable and stable, in order to reduce their dependence on coal and nuclear energy (in Japan nuclear energy may be making a significant comeback[49]).

5 Environmental Aspects of LNG

In a context of strong climate constraints but also economic development challenges for Asian countries, the question of using natural gas as a transitional energy is increasingly being raised. Natural gas is a fossil fuel and therefore emits greenhouse gases. But compared to other fossil fuels, it emits very low levels of pollutants per unit of energy produced during combustion compared to coal in particular. Natural gas emits much less sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2) and particulate matter. Natural gas therefore makes it possible to reduce CO_2 emissions quite significantly, in particular by replacing the two competing fossil fuels: coal (in the electricity sector) and oil (in the transport sector).

In the Asia and Pacific region, energy demand is projected to almost double by 2030. The Asian Development Bank (ADB[50]) has estimated the region will need to invest $14.7 Trillion in power infrastructure between 2016 and 2030 to meet demand. Throughout the region, countries have common objectives for decarbonizing and diversifying the energy mix to meet global commitments on climate change, reducing impact, in particular air pollution, and improving Energy security.

The first section allowed us to learn about the LNG market, market fundamentals and recent trends, this section is devoted to the environmental aspect of LNG use in the Asian region. There are many reasons why natural gas or LNG should be encouraged and promoted by deliberate government policy, but in this section, we limit ourselves here to its environmental benefits. Also, this section will allow us to answer the other question in our chapter.

5.1 Natural Gas, Energy of the Twenty-First Century?

Natural gas, in the form of liquefied natural gas, is destined to become more and more important to energy future in Asia-pacific.

Energy experts are coming together to predict a favourable future for natural gas in the twenty-first century. This optimistic view has been demonstrated and proven by numerous studies and reports. Thus, the countries of the Asian region have adopted an approach based on encouraging the use of gas (or LNG) as a "clean" product in

[49]According to the new 5th Strategic Energy Plan adopted by Cabinet decision on July 2018, the aim is for nuclear energy to account for 20–22% of energy output by 2030. There are five plants with a total of nine reactors that have met the new standards. For further discussion refer to the website of the Ministry of Economy, Trade and Industry http://www.meti.go.jp.

[50]See ADB [2].

Table 11 The age of natural gas in the world

Century	Eighteenth century	Nineteenth century	Twentieth century	Twenty-first century	Twenty-second century
Energy source	• Wood	• Coal	• Oil	• Natural gas	• Hydrogen, • Nuclear fusion, • Renewable
Chemical make-up	HC10	HC2	CH2	CH4	H U
# of C Atoms to each H	1H = 10 C	1H = 1–2 C	1H = 1/2 C	1H = 1/4 C	N.A.
	• The trend towards de-carbonization is at the heart of energy evolution				

Source Author from various sources

order to meet the challenges of the twenty-first century, in particular the fight against global warming and environmental protection, particularly since COP21 in Paris at the end of 2015.

In 2011, the International Energy Agency even predicted that the world would quickly enter a "*golden age of gas.*" Although we are far from this reality for the moment, the fact remains that, according to IEA forecasts, the share of natural gas in the global energy mix is expected to increase from 21% in 2008 to more than 25% in 2035. Arguments in the same direction, Maria van der Hoeven, former Executive Director of the International Energy Agency (IEA), said: "*Gas is the "lucky fuel." It may not be ideal, and it might not be the first choice of policymakers, society or the media. That first choice is often renewable energy, domestic coal or nuclear, depending on the political context. Indeed, gas is rarely the cheapest, cleanest, or most secure energy source* - *but its key advantage is that it is a good combination of compromises*.[51]"

In 2012, the IEA published its recommendations for the development of shale gas to make it "socially acceptable." This collection of "*golden rules*[52]" on the extraction of unconventional gases such as shale gas proposes more regulation, transparency, investment, environmental protection and best practices.

For the last thirty years, less oil has been discovered than is consumed, while the situation is completely the opposite for gas. In the case of natural gas, there is currently a situation of "abundance" and that its deposits will be exhausted less quickly. This should continue, even if demand growth is strong (around 2% per year) (Table 11).

[51] World Gas Conference, Kuala Lumpur, June 5, 2012.

[52] The report is entitled "Golden Rules for a Golden Age of Gas."

Indeed, Hydrogen,[53] the only non-carbonaceous fuel, is found in abundance on Earth, in the form of water or hydrocarbons, mainly in Argentina, Australia, Chile, Morocco, Oman, Saudi Arabia, or South Africa. The many advantages of this gas make it a very efficient energy vector by 2050 and beyond.

5.2 Natural Gas/LNG as a Bridge Fuel?

On the Asian continent, coal and natural gas often compete for the production of energy (in general) and electricity (in particular). Because it is very inexpensive and available in large quantities, Asia consumes a larger proportion of the world's coal (74.5%). Its share in world consumption increased from 2197.6 mtoe in 2007 to 2780 mtoe in 2017.

Also fossil fuels such as oil and gas and relatively easy to find, particularly compared to some alternative energy sources. Most fossil fuels are close to the surface of the earth (Ramos, [82]). There are, in fact, many pros of using fossil fuels. But of course, there are also quite a few cons that should also be discussed. From an environmental point of view, natural gas—LNG—has a good image with the public: its combustion emits few particles and pollutants, and less CO_2 than the other two fossil fuels (coal and oil) (Table 12).

With two-thirds of the world's proven reserves of conventional natural gas, the lifetime at the current rate of natural gas[54] consumption is 60 years. Thus, because it is an attractive energy option, known by its 3A's—abundance, availability and affordability—natural gas is more environmentally friendly than coal and, therefore, it is likely to be favoured by governments seeking to reduce carbon emissions.

By weighing the advantages and disadvantages of various options, LNG offers a safer and more environmentally friendly alternative and therefore its acceptability is justified; because nowadays, in any project, social acceptability has become a necessity. Thus, moving from the 3A's to the 4A's,[55] LNG could ensure a smooth transition to cleaner energy over the next few decades.

[53] There has been a growing interest in hydrogen for several years. Indeed, hydrogen, the only non-carbon fuel, is found in abundance on Earth, in the form of water or hydrocarbons, mainly in Argentina, Australia, Chile, Morocco, Oman, Saudi Arabia or South Africa. The multiple advantages of this gas make it a very efficient energy vector by 2050 and beyond. For more information on this topic, see—for example—ACIL Allen Consulting [1], Commonwealth of Australia [11], McKinsey [65] and METI [68].

[54] At year end 2017, the *R*/*P* ratio for the natural gas was 52.6% compared to 61.9 in 2001.

[55] So the 4A's are abundance, availability, affordability and acceptability.

Table 12 Gas: The Pros and Cons arguments

Pros
1. Most experts agree on the global impact of natural gas with regard to its CO_2 emissions: • CO_2 emissions from gas (per unit of energy produced) are lower than coal (40%) and oil (20%)
2. Natural gas is a flexible source of energy which may help meeting variable needs: • Adapted to seasonal demand • Alternative source of energy during the deployment of renewables (e.g. wind)
3. Lifetime of methane in atmosphere is shorter than carbon dioxide: • Methane = 12.4 years • CO_2 = more than 150 years
Cons
1. While natural gas emits less CO_2 than other fossil fuels. It is a source of CO_2 emissions when burned
2. The main debated topic about GHG emissions from natural gas is the issue of methane emissions
3. Global Warming Potential for methane is estimated to be 28 by IPCC over a 100-year time horizon: • Methane = 12.4 years • CO_2 = more than 150 years [1 ton of CH_4 = 28 ton of CO_2]
4. In 2015, about 13% of total methane emissions were considered to come from oil and gas operations (55% from natural gas operations)
5. In 2016, WMO noted atmospheric methane had reached a record high at 1853 parts per billion, about 257% of its pre-industrial level

Source Adapted from Laurent [58]

5.3 LNG and Its Comparative Environmental Advantages

LNG is the answer to the new world of energy as we move towards clean energy sources. Environmental concerns have dominated the energy news in the last decade and have increased since COP21 in Paris, on December 2015.

Compared with other fossil fuels, LNG is considered the cleanest and most environmentally friendly fuel. This is most notable in the use of LNG as a marine fuel rather than heavy fuel oil or marine diesel. LNG typically produces lower emissions of carbon dioxide (CO_2) and virtually no nitrogen oxides (NO_x), particulate matter (PM) or sulphur oxides (SO_x). A comparison of the emission factors for marine fuels is shown in the Table 13.

5.4 The Role of LNG in the Energy Mix

First of all, it would be appropriate to define the term “energy mix.” This term refers to the combination of the various primary energy sources used to meet energy needs

Table 13 Emission factors for marine fuels (g/g of fuel)

Emission	HFO[1]	MDO[2]	LNG
SO_x^a	0.049	0.003	Trace
CO_2	3.114	3.206	2.750
CH_4	Trace	Trace	0.051
NO_x	0.093	0.087	0.008
PM	0.007	0.001	Trace

[a] 2012 figure based on average HFO sulphur content of 2.51 %
[1] HFO: Heavy Fuel Oil
[2] MDO: Marine Diesel Oil
Source Le Fevre [59]

in a given geographic region. It includes fossil fuels (oil, natural gas and coal), nuclear energy, non-renewable waste and the many sources of renewable energy.

These primary energy sources are used, for example, for generating power, providing fuel for transportation and heating and cooling residential and industrial buildings.[56] In others words, the term energy mix refers to how final energy consumption breaks down by primary energy source. Each energy choice (as part of the "mix") implies an environmental, economic or social impact. In the "energy mix," natural gas—and LNG—is the fossil energy whose combustion has the lowest impact on the environment because 4 hydrogen atoms are associated with one carbon atom (CH_4).

According to GECF[57] Global Gas Outlook GECF [32], the share of natural gas in the global energy mix will increase from 22% in 2016 to 26% in 2040. Coal will see a 7% decrease (from 27 to 20%), to be gradually replaced by natural gas, renewables (17%) and nuclear (6%). Concurrently, the share of oil in the global energy mix will decrease by 3–29% in 2040.

A recent DBS Asian Insights[58] report indicates the energy mix in Asia was composed of 33% crude oil, 28% coal, 24% natural gas and 15% renewable energy and others. The same report forecasts a clear shift towards renewables in the global energy mix, from 15% in 2016 to 22% in 2030, as government policies are geared towards cleaner energy.

Asian countries will focus on and invest in LNG and renewable energy, mainly by investing in wind and solar projects, and will fight to reduce its greenhouse gas emissions by 26% compared to current levels and reduce the level of fine dust by 62% by 2030. It is for this purpose that several Asian countries have adopted energy mix strategies, which we will see Table 14.

[56] For the definition of this term, see for example www.planete-energies.com/en/medias/close/about-energy-mix.

[57] GECF (Gas-Exporting Countries Forum) countries possess two-thirds of proven conventional gas reserves and have the ability to provide a secure gas supply. The development and integration of gas networks can improve access to energy, stimulate development and improve welfare. Doha, the capital city of Qatar, hosts the permanent headquarters of the Secretariat of the GECF.

[58] DBS Bank, Asian Insights SparX report, 2030 Energy Mix, 5 July 2018.

Table 14 Some dominant elements of LNG dependency, energy mix and energy strategy of the 5 major Asia countries

Market	Rank	Countries	Dependency on imported LNG (2017)			Importing LNG 1st time		NG/LNG in energy Mix		Climate change targets 2030 (%)	National energy policy (NEP)
			% worldwide	Main suppliers	#	Supply source	Start-up date	2016/17 (%)	2030 (%)		
Mature market (JKT)	#1 	Japan	29	Australia, Malaysia, Qatar, Russia, Indonesia	5	Alaska	1969	39	27	26	Based on the Strategic Energy Plan (Japan's 2030 NEP), Japan tackles the policy targets related to Safety, Energy security, Economic efficiency and Environment simultaneously (3E + S)
	#3 	Korea	13	Qatar, Australia, Indonesia, Oman, Malaysia	5	Indonesia	1986	15	18.8	37	South Korea indicates action plans for de-nuclear and de-coal policies. The new Energy strategy (Green Energy Transition)aims to triple the share of renewables in the country's power mix by 2030. South Korea also plans to continue to diversify its LNG supply

(continued)

Table 14 (continued)

Market	Rank	Countries	Dependency on imported LNG (2017)			Importing LNG 1st time		NG/LNG in energy Mix		Climate change targets 2030 (%)	National energy policy (NEP)
			% worldwide	Main suppliers	#	Supply source	Start-up date	2016/17 (%)	2030 (%)		
	#5 	Taiwan	6	Qatar, Malaysia, Indone-sia, Papua New Guinea, Russia	5	Indonesia	1990	32	50	50	The new NEP vision focuses on near-term to 2025 and is based on 4 pillars: 1. Achieving the goal of a nuclear-free 2. Actively developing green energy and increasing the share of renewables in total electricity generation to 20% by 2025 3. Accelerating the construction of Taiwan's 3rd LNG receiving terminal, and expanding the use of natural gas 4. Completing revision of the Electricity Act to facilitate energy transformation
Emergent markets	#4 	India	7	Qatar, Nigeria, Australia	3	Qatar	2004	7	8	33–35	The NEP focuses on four key areas: 1. Electricity at affordable prices; 2. Improved security and independence; 3. Greater sustainability; 4. Economic growth. The policy focuses on two time horizons: near-term to 2022, and medium-term to 2040

(continued)

Table 14 (continued)

Market	Rank	Countries	Dependency on imported LNG (2017)			Importing LNG 1st time		NG/LNG in energy Mix		Climate change targets 2030 (%)	National energy policy (NEP)
			% worldwide	Main suppliers	#	Supply source	Start-up date	2016/17 (%)	2030 (%)		
	#2 	China	13	Australia, Qatar, Malaysia, Indonesia and the USA	3	Australia	2006	6	15	60–65	China's NEP directives are encouraging coal-to-gas switching to combat air pollution and are set to continue driving up the share of natural gas in the country's energy mix and domestic consumption of the fuel

Source Author from various sources, particularly: DBS Bank [13], GIIGNL [33]

- **In Japan**: In its strategy "Structure of the 5th Strategic Energy Plan," the METI[59] has adopted three chapters. In the 3rd Chapter (Efforts for Energy Transitions and Decarbonization towards 2050), section 3 states the following: (i) Renewable energy: Aim to develop and utilize renewable energy as the major power source, economically independent and decarbonized; Development of high-performance low-price storage batteries; (ii) Nuclear power: Practical option for decarbonization; Pursuit of safe reactors and development of back end technologies for restoring social trust; (iii). Fossil fuel: Major power source during the transitional period until the achievement of decarbonization; Shift to gas; Fadeout of inefficient coal use; CCS and shift to hydrogen.
- **In South Korea**: South Korea's shift from coal and nuclear towards renewables and LNG for power generation could help soak up growing supplies of the super-cooled fuel in the coming years. President Moon Jae-in,[60] has put environmental protection at the heart of energy policy making in response to mounting anxieties about air pollution and nuclear safety. However, this change in the energy mix[61] does not necessarily mean the end of the South Korean nuclear industry.
- **In Taiwan**: In pursuit of the Tsai administration's goal to completely phase-out nuclear power, the Tsai government is aiming to rebalance the country's energy mix to gas (50%), coal (30%), renewables (20%), while eliminating nuclear and oil as fuel sources for electricity production by 2025.
- **In China**: In recent years, China has begun to diversify its energy mix and turn to renewable energy. The biggest shift will be seen in China, moving away from coal and betting on different energy sources. China's 13th Five-Year plan (2016–2020) sets targets for increasing the use of natural gas, including almost doubling the share of natural gas in China's energy mix in five years, up to 10% primary energy by 2020 and 15% by 2030.
- **In India**: India is the 14th largest gas consumer (54 Bcm) and the 4th largest LNG importer (26 Bcm) in 2017. LNG imports have consistently increased over the years, from 29% in 2007/2008 to 45% between 2015/16 and recently to 51%. To combat one of the worst air pollution in the world, the Indian government is keen to encourage the use of natural gas to promote a gas-based economy. To achieve this goal, it has set a target of increasing the share of natural gas in India's primary energy mix to 15% by 2022, compared to about 6.5% in 2015, as this energy mix has increased significantly in 2018.

[59]More detailed information is available on the METI website.

[60]Moon Jae-in was elected by a landslide on 9 May 2017 to replace ousted President Park Geun-hye.

[61]Regarding the reform of South Korea's energy industry, see the OIES paper, NG 132, "South Korea's Energy Policy Change and the Implications for its LNG Imports," Keun Wook Paik, June 2018.

In short, it is impossible for the objectives[62] set at COP21 to be achieved without rapid action to phasing-out fossil fuels, in particular coal, which is too consumed in this region of Asia, for the reasons explained in Sect. 5.2, but also oil and gas.

5.5 *Environmental Risks and Popular Concerns Related to Shale Gas*[63]

Hydraulic fracturing (also known as "hydro-fracking" or just simply "fracking") is the process of creating long vertical wells below the earth's surface and then horizontal wells that break open the shale and allow the natural gas to be released and captured. Fracking uses millions of gallons of water to create these wells. A proprietary mix of chemicals in the water is used to create the fissures in the shale.[64]

Environmental risks and other popular concerns related to the extraction of "shale gas" mainly concern 4 aspects: water supply, earthquakes, damage to local roads due to increased truck traffic and air quality impact.

The shale gas revolution in the United States, aiming to exploit the large reserves of unconventional gas (coalbed methane or CBM, shale methane, etc.), has changed the global energy landscape, particularly the natural gas and LNG market:

(i) On the one hand, the higher volumes of gas produced in the USA have lowered the prices of the US domestic market;
(ii) On the other hand, the possibility to transport it, thanks to LNG in more profitable markets, have allowed the market to assume a global connotation dropping the geographical logic of the market, existing so far.

In a nutshell, this last section provided an opportunity to review some of the environmental aspects of LNG and to discuss the intentions of the main LNG-importing countries in Asia for an energy mix in favour of LNG and other less polluting (renewable) energy. Indeed, the benefits of LNG have been demonstrated and proven by numerous studies and reports. Thus, the countries of the Asian region have adopted

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[62] In order to address the challenges of climate change, the signatory countries to COP21 agreed on 3 main objectives:

(i) Maintaining temperatures below 2 °C (by 2100) above pre-industrial levels and taking all possible measures to prevent temperatures from rising by more than 1.5 °C;

(ii) Resilience and adaptation to climate change, in particular through "low carbon" development and;

(iii) Adoption of financing methods to achieve this "low carbon" development.

[63] This subject has generated long and often contradictory debates between the Pros and Cons in the USA and outside this country that initiated this process. For this reason, we cannot deal with this subject in detail in this chapter. However, we refer the interested reader to the question of the exploitation of non-conventional gases (shale gas in particular) to consult the following reports, studies and publications (non-exhaustive list): Deijns [14], Le [60], UNCTAD [95].

[64] See, for example, Sax J. Is Fracking Good or Bad? August 13, 2014 [Online]. http://blog.petrieflom.law.harvard.edu/2014/08/13/is-fracking-good-or-bad/(page consulted 26 September 2018).

an approach based on encouraging the use of gas (or LNG) as a "clean" product in order to best meet the challenges of the twenty-first century, in particular the fight against global warming and environmental protection, since the commitments made at COP21 in Paris.

6 Concluding Remarks

This chapter has reached a number of conclusions about the future of LNG in Asia as an environmentally friendly energy source in the era of the globalization of gas markets.

In recent years, the LNG industry has grown rapidly and is moving towards globalization, thanks to new technologies and the significant growth in global demand that no other energy source has experienced, and this, in a context of uncertainties that continue to upside on the energy outlook of the planet before the rise of environmental issues. This rapid transformation of the LNG industry is due to a combination of technological, commercial and environmental factors.

– ***With regard to the technological aspects***:

Rapid advances in industry technology have contributed enormously to lower costs and improved project profitability, notably through the construction of more flexible and scalable LNG infrastructures. The technological progress made throughout the LNG chain over the years can be summarized as follows:

- *Exploration and Production*: application of innovative technologies for unconventional gases; offshore technologies.
- *Liquefaction*: small-scale LNG and Infrastructures; floating Storage Regasification Unit (FSRU); LNG train size growth; gas extraction units with liquefaction unit (F-LNG).
- *Shipping/Transportation*: construction of gas carrier ships (LNG, CNG); development of LNG Bunkering at port level; ice-breaking LNG Carrier.

In a nutshell, the development of LNG Technology makes natural gas available worldwide and will facilitate its access and use in Asian countries without a domestic natural gas supply or access to a pipeline network.

– ***With regard to the commercial aspects***:

While technology has evolved, the LNG trade has also evolved rapidly from a limited initial trade between a few number of suppliers and buyers (niche market) to a significant number of importers and exporters on all five continents (regional markets).

The global energy market is now characterized by the domination of fossil fuels, which account for three quarters of primary energy consumption, and also by a relatively low level of oil (and gas) prices since 2014 and the emergence of shale gas, which are new market realities facing consumer-importing countries on the one hand, and producer-exporting countries on the other, which must adapt or redefine their strategies:

- On the one hand, consumers/importers find themselves in an advantageous position to diversify their sources of supply and (re) negotiate contracts in a more flexible than existing ones.
- On the other hand, producers/exporters must adapt their strategies to face competition from new entrants to this market, especially for the coming years. The dilemma is to defend either a pricing strategy or a volume strategy.

The "traditional" exporters are more than ever confronted with competition from new comers, specifically Australia and the United States and its shale gas. It is thanks to unconventional gases that the USA has changed the game; they have moved from a net importer to a net exporter and the gas flows originally intended for that country have been redirected to the European and Asian markets. The latter—the Asian market—remains the most attractive and the most applicant due to higher prices than other regional markets.

Another factor contributing to the attractiveness of the Asian market is the creation of new commercial shipping routes with the enlargement of the Panama Canal (advantage for US LNG exports) and the Northern Sea Route (advantage for Russian LNG exports). Its new routes will allow exporters to reduce transportation costs and gain in price competitiveness.

In addition, the arrival on the international scene of new exporting countries—other than Australia and the USA—will contribute to the alignment of prices and the globalization of the LNG market. Tomorrow's LNG map will be different from the one we have today, with a pattern of global gas trade and the emergence of other countries importing and exporting conventional and/or unconventional gas.

Finally, LNG will become a commodity, just like oil, and the "nationality" of the molecule marketed on the "liquid" market will be of little importance, whether it comes from North America, from Australia, Qatar, Russia or elsewhere … The essential thing is to satisfy the growing demand of the populations by accessing a clean and non-polluting energy, instead of coal/ oil, in order to respect the commitments made in Paris in the matter of preservation of the environment.

- ***With regard to the environmental aspects***:

For environmental concerns, LNG is gaining importance as an environmentally friendly source of energy, able to fuel economic growth in many parts of the world, particularly in the Asia-Pacific region. Indeed, LNG offers several advantages including reduced pollutant emissions, improved energy efficiency and a low risk to the environment in the event of a spill at sea. Moreover, LNG is a key pillar of a gradually decarbonizing energy and electricity system.

Switching from coal to LNG remains a strategic choice for some countries seeking to fill the energy supply gap, in order to replace coal (available and cheap), and in some cases nuclear energy, in the energy mix. Other uses of LNG such as marine fuel, road fuel and bunkering will surely have a favourable environmental impact.

It should be noted that the debate on unconventional hydrocarbons, in particular the controversial method of extracting shale gas, has not been addressed—in detail—in this chapter nor its potential environmental impact.

Finally, scenarios of keeping oil prices low—prices below $ 50 a barrel—are not totally out of the question. Past experiences have shown the slowdown of investments in renewable energies (wind, solar, etc.) in favour of fossil fuels.

Last but not least, LNG could be used as a "transition bridge" while waiting for the arrival of other more "clean," more respectful and acceptable energy sources such as hydrogen and renewable energy. In short, LNG helps—not hinders—renewables and will be an essential part of the energy transition.

Box 1. Asia LNG Pricing Evolution

On the Asian continent, except for the LNG price of some Indonesian exports linked to the Indonesian oil production price index, other LNGs are mostly linked to the Japanese integrated crude oil price (JCC).

Indeed, Asian long-term contracts (LTCs) generally price LNG in formula indexed to the crude oil prices is as follows:

$$\mathbf{P}\text{LNG} = \mathbf{P}\text{Base} + \boldsymbol{\beta} * \text{PCrude} + [\textbf{Shipment Charges}] \Rightarrow \text{ a linear function}$$

$$Y(x) = Ax + B$$

where

- PLNG is the price of LNG in US$/MMBtu;
- PBase is the base price (constant);
- β is the constant and is known as "the slope" and typically expressed as a percentage;
- PCrude is the crude oil price index in $/bbl (in the case of Japan, this would be the Japan Crude Cocktail—JCC).
- Most popular coefficient 14.85%.

However, the constant and the slope vary in time and are negotiated by the buyer and seller.

Table 15 Asia LNG pricing evolution

Period	Formula	Explanation
Between 2 chocks (1970s–1980s)	$P_{\text{LNG}} = 17.2 * P_{\text{Crude}}$	• This period saw the first price adjustments. Because before the first oil shock (1973), prices were Administered (fixed)
After 1st counter-chock (Oil collapse)	$P_{\text{LNG}} = A * P_{\text{Crude}} + B$	• Oil parity pricing formula—JCC indexed prices
After 1990	$P_{\text{LNG}} = A * P_{\text{Crude}} + B +$ *S*-curve	• S-curve with floors and ceilings
2016: gas indexation (start of US exports)	$P_{\text{LNG}} = P_{\text{HH}} * 115\% +$ Liquefaction Fee + Shipping Cost	• New type of gas pricing formula (Cost plus pricing system) • Export from Sabine Pass LNG (Louisiana, USA)

Source Own interpretation from various sources

Table 16 LNG pricing at old and new paradigm

Terms		Old paradigm	New paradigm
Duration		Average 20 years	Average 10 years
Formula and indexation		Oil linked	Mixed: oil, gas, hub
Flexibility		Limited	By off take, direction, usage
Volumes		Large (2–3 mtpa)	Small–medium (0.5–1.5 mtpa)
Price level		Europe and Asia arbitrage	No arbitrage
Market size[a]	# Importing countries	14	40 [2017]
	Quantity	140 mtpa	~290 mtpa [2017]
	LTCs trade	>90%	~74%

Sources Gyetvay and Nazarov [39] and own interpretation[a]

Box 2. LNG Shipping Industry

Maritime transport is an environmentally friendly mode of transport in terms of ton carried. It accounts only for a very minor share of sea and ocean pollution and less than 3% of air pollution [51]. The safety instructions on a modern LNG Carrier are infinitely stricter than those that must be observed in a commercial airliner.

Countries with a coastline and ports equipped for LNG Carriers and a liquefaction site use the supply of natural gas in its liquefied form (liquefied natural gas or LNG). LNG Shipping is one of the vectors of the globalization of the gas market.

According to Drewry's latest LNG Report, today, about 566 LNG carriers sail the world's seas and oceans transporting LNG from production areas to consumption areas. There are two main groups of LNG carriers:

1. Spherical (Moss) containment system (22%);
2. Membrane containment system (75%);
3. Others (3%).

Table 17 LNG fleet in 2017/2018

	2017	2018
Fleet (end-period)		
No. of vessels*	520	566
Capacity ('000 cbm)	75,142	83,494
Growth (% capacity)	0.5	1.1
Order book (end-period)		
No. of vessels	123	124
Capacity ('000 cbm)	19,741	18,833
% of fleet (% capacity)	26.3	22.6

Source Drewry Maritime Research [17] (Data)
* LNG fleet now includes FSRUs and small vessels in the range of 0–50,000 cbm

Table 18 LNG carrier

Spherical (Moss) type

Membrane type

Source DNV Maritime illustrations

Table 19 LNG carrier classes

#	Type	Dimensions (m)	Ship size (m^3)
1	Small	LOA ≤ 250; B ≤ 40	≤90,000
2	Small conventional	LOA 270–298; B 41–49	120,000–150,000
3	Large conventional	LOA 285–295; B ≤ 43–46; DL ≤ 12	150,000–180,000
4	Q-Flex	LOA ≈ 315; B ≈ 50; DL ≤ 12	200,000–220,000
5	Q-Max (maximum size)	LOA ≈ 345; B ≈ 53–55; DL ≤ 12	More than 260,000
Particular classification (By Sea)			
	Med-max (Mediterranean max. size)	LOA ≈ 220; B ≈ 35	~75,000
	Atlantic max (Atlantic max. size)	LOA ≤ 300; B ≤ 48.90–51.9	165,000–177,000

Notes (i) *LOA* length overall, *B* beam (or breadth), *DL* laden draft, *Max* maximum
(ii) New "conventional" vessel size established in 155–175,000 m^3
Sources Own elaboration based on MAN [63] and Shipyards website

The rise of natural gas as an acceptable clean energy source has encouraged the construction of increasingly large LNG Carriers (Double Hull). Indeed, there are currently 5 main classes (size classification) of LNG Carriers (see Table 19).

Box 3. The Energy CO_2 Emissions and INDC Targets of Selected Asian Countries

According to the World Health Organization (WHO) website, Indian cities such as New Delhi, Varanasi and Patna were among the most polluted, based on the amount of suspended particles less than 2.5 μg found in each cubic meter of air.

Also in Asia, Chinese cities such as Xingtai and Shijiazhuang and the industrial City of Jubail in Saudi Arabia, the world's largest petrochemical industrial complex, are also considered highly polluted. According to the same source, two main conclusions can be drawn:

- 9 out of 10 people in the world breathe air containing high levels of pollutants.
- Around 7 million people deaths every year from exposure to fine particles in polluted air (see Fig. 8).

Table 20 shows the energy CO_2 emissions (oil, gas and coal combustion) of the top 5 LNG consuming countries in the Asian region in 2007 and 2017. The last column shows the country's share of the global total emissions. Thus, emissions from the group of "Big 5" Asian buyers accounted for 41% of global CO_2 emissions in 2017. While the Asia-pacific region accounts for almost half (48.8%) of global emissions.

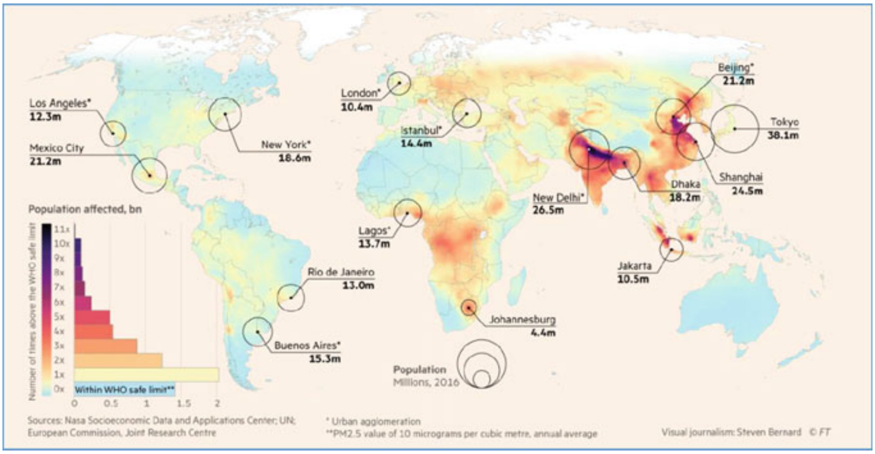


Fig. 8 Air pollution: a global problem. *Sources* WHO www.who.int and FT www.ft.com (or www.ft.com/steve-bernard)

Table 20 Carbon dioxide emissions (Mt CO_2)

Rank 2017	Country	2007	2017	Share 2017 (%)
1	China	7214.8	9232.6	27.6
3	India	1365.5	2344.2	7.0
5	Japan	1266.0	1176.6	3.5
9	South Korea	545.4	679.7	2.0
22	Taiwan	276.3	284.5	0.9
	Total 5 countries	4260.0	13,717.6	41.0
	Total Asia-Pacific	12,623.2	16,330.4	48.8
	World	30,078.7	33,444.0	

Source BP Statistical Review of World Energy 2018

The other major advance of the agreement is the establishment of a new version of the review and transparency mechanisms for national climate contributions, known as the INDCs. It also acts as an upward revision process every 5 years (after 2020) for all Parties. Almost all Parties have submitted their Intended Nationally Determined Contributions (INDCs) to the United Nations.

Table 21 lists the targets of the top five Asian LNG buyers under their INDCs. When the Paris Agreement comes into effect in 2020, these targets would become legally binding which means that Asia must look for ways to limit their fossil fuel consumption. The implication here is that Asia must embrace a more sustainable energy future Lo [61].

Described as historic, the COP21 or the Paris Climate Conference led to a new international climate agreement, applicable to all countries, aiming to keep global warming below 2 °C; in accordance with the recommendations of the Intergovern-

Table 21 INDC targets of selected Asian countries

Country	Targets
China	Stabilization of emissions around 2030
India	India Emission intensity in 2030 will be 33–35% below 2005
Japan	Emissions in 2030 will be by 26% below 2013
South Korea	Emissions in 2030 will be 37% below BAU
Taiwan[a]	Greenhouse gas emission reduction by 50% from the business-as-usual level by 2030

[a]IDB, Ministry of Economic Affairs, Taiwan
Source Lo [61] Asian Energy Challenges in the Asian Century, Journal of Asian Energy Studies (2017), Vol. 1, No. 1, 1–6

Table 22 The conversion factors for the different units

Natural gas and LNG	To convert					
	Billion cubic metres NG	Billion cubic feet NG	Million tonne oil equivalent	Million tonne LNG	Trillion British thermal units	Million barrels oil equivalent
From	*Multiply by*					
1 billion m^3 NG	1.000	35.315	0.860	0.735	34.121	5.883
1 billion ft^3 NG	0.028	1.000	0.024	0.021	0.966	0.167
1 million tonnes oil equivalent	1.163	41.071	1.000	0.855	39.683	6.842
1 million tonnes LNG	1.360	48.028	1.169	1.000	46.405	8.001
1 trillion British thermal units	0.029	1.035	0.025	0.022	1.000	0.172
1 million barrels oil equivalent	0.170	6.003	0.146	0.125	5.800	1.000

Source BP—Statistical review of world energy [7]

mental Panel on Climate Change (IPCC).[65] COP21 concluded an agreement committing 195 States to reduce their greenhouse gas emissions. The Paris Agreement has since entered into force on 4 November 2016 (Table 22).

[65]See website www.diplomatie.gouv.fr.

Appendices

Appendix 1

Characteristics of Asia-Pacific LNG price indexes

Index	Japan/METI	JKM	RIM Japan	ANAE	EAX	SLInG
Publisher	METI	Platts	RIM Intelligence	Argus Media	ICS	SGX and EMC
Start of stats	Mar. 2014	Feb. 2009	Feb. 2016	2012	Jan. 2014	Sept. 2014

(continued)

(continued)

Index	Japan/METI	JKM	RIM Japan	ANAE	EAX	SLInG
Ship (Cargo) size	Any	2.9–3.7 Bcf	2.9 Bcf tankers & partial cargoes	2.9–3.3 Bcf and partial cargoes normal-ized	0.6–5.6 Bcf & partial volumes	2.9–3.7 Bcf
Index coverage area	LNG delivered to Japan	Spot physical cargoes delivered into Japan and South Korea	Japan, South Korea, Taiwan and China	Japan, South Korea, Taiwan, China	Physical cargoes to Japan, South Korea, Taiwan & China	Vessels on the water with potential to deliver to Singapore
Assessment type	Census sent from METI to market players	Daily phone or electronic survey of market players	Trading info from OTC market; Price assessment from JOE LNG market deals & bids/offers	Daily phone or electronic survey of market partici-pants	Daily phone or electronic survey of bids, offer (first-hand or observed)	Survey of select market partici-pants
Assessment frequency	Monthly price sa segments	Daily, with market close prices	Assessed & published daily	Assessed & published daily	Assessed & published daily	Half-monthly assess-ments, published twice weekly
Sale or delivery	DES contracted and arrival	DES	DES	DES	DES	FOB
Assessment forward range	Any forward period for LNG delivery (contract-based); within-month (arrival-baaed)	Prompt delivery; 3rd & 4th or 4th & 5th half-month forward	Half-monthly assess-ments for the 3rd–5th half-months forward	Prompt delivery; 2nd–5th half-months forward	3rd–6th half-months out	3rd–6th half-months out

(continued)

(continued)

Index	Japan/METI	JKM	RIM Japan	ANAE	EAX	SLInG
Index calculated	Contract-based (for deals made in-month) and arrival based (for cargoes arriving that month)	Prompt or deferred spot prices averaged for assessed half-months	Monthly average price for half-months calculated daily	Physical and forward swap are assessed daily for forward half-months	Daily front and second month ahead prices for all countries averaged	Half-monthly prices are averaged for the first full month
Types of trades included	Spot LNG to be delivered	Spot LNG to be delivered	Deals done and bids/offers on LNG cargoes	Spot LNG to be delivered in 6–12 weeks	Global prompt & mid-term charter LNG	Spot LNG able to be shipped to Singapore
Number of contributors	−15	Not specified in Methodology	Not specified in Methodology	Not specified in Methodology	Varies daily; no minimum data threshold	50
Contributor requirements	Companies/consumers of spot LNG	Any market participant; buy/sell prices must pass the “repeatability” test	None; market prices assessed from OTIC market trading information	All credible mark market sources, market participants and brokers/trading platforms	Active or past LNG industry participants, not only the physical market	Active in the physical LNG market
Data cleaning	N/A	Data aligned with standard assessment specifications	Higher bids & lower offers are prioritized as closer to market values	Market condition adjustments if assessment hierarchy would skew results	Data verified with trading counterparty technical-purpose cargoes excluded	Top 15% and bottom 15% removed as outliers

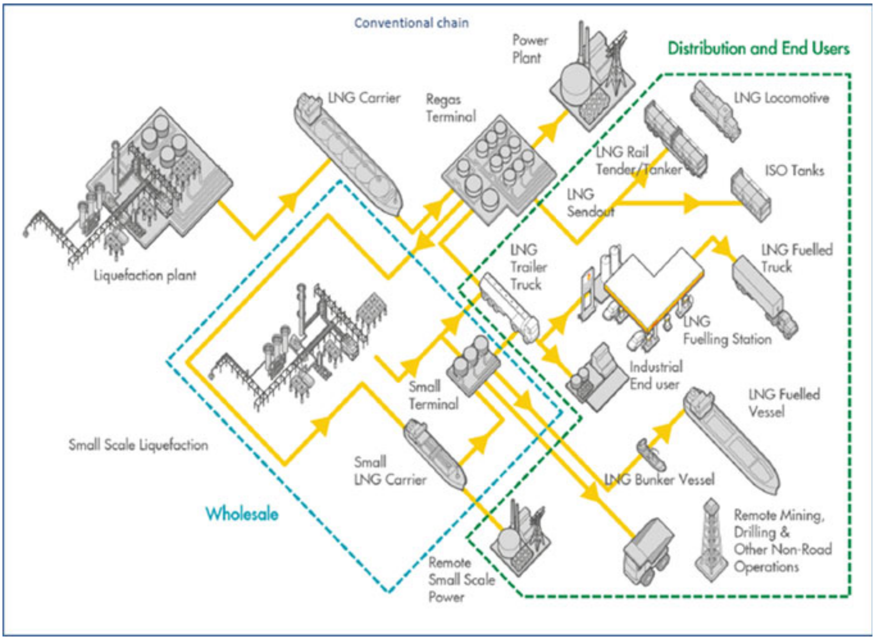
Source US EIA [23]. Perspectives on the Development of LNG Market Hubs in the Asia Pacific Region, March 2017, page 45

Appendix 2

Note Last Updated December 2018. *Source* Waterborne Energy, Inc. Data in $US/MMBtu

Appendix 3

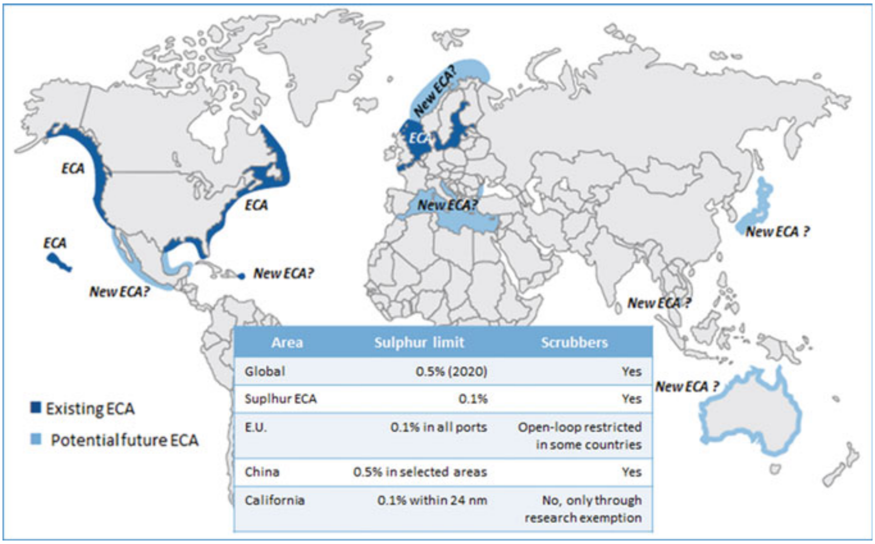
Small-scale LNG Value network, wholesale and retail.



Source Shell (edited version)

Appendix 4

Existing and potential future emission control areas and Sulphur Regulations.



Source Adapted from DNV-GL [15] and Langfeldt [57]

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Correction to: How Total Factor Productivity Drives Long-Run Energy Consumption in Saudi Arabia

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