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Determinants of CO_2 emissions in the European Union: The role of renewable and non-renewable energy

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ABSTRACT

A number of studies in the environment-energy-growth literature aim to pin down the determinants of carbon dioxide (CO_2) emissions as a result of large increases in CO_2 emissions over the last few decades. One criticism related to the existing literature is the selection of data. The majority of studies use aggregate energy consumption. The other criticism is the selection of panel estimation techniques. Almost all studies use panel methods that ignore cross-sectional dependence. To fulfill the mentioned gaps in the literature, this empirical study aims to investigate the impacts of renewable and non-renewable energy, real income and trade openness on CO_2 emissions in the Environmental Kuznets Curve (EKC) model for the European Union over the period 1980–2012 by employing panel estimation techniques robust to cross-sectional dependence. By using the dynamic ordinary least squares estimator, we show that renewable energy and trade mitigate carbon emissions while non-renewable energy increases CO_2 emissions, and the EKC hypothesis is supported. The Dumitrescu-Hurlin non-causality approach indicates that there is bidirectional causality between renewable energy and carbon emissions, and unidirectional causality running from real income to carbon emissions, from CO_2 emissions to non-renewable energy, and from trade openness to CO_2 emissions.

1. Introduction

Due to large increases in greenhouse gas emissions (GHGs) over the last few decades, environmental pollution has become one of the greatest global issues. A number of countries including member states of the European Union (EU) have thus signed the Kyoto protocol that brings along with binding obligations [102]. Over the first commitment period of the Kyoto protocol, the EU-15[1] as a whole aimed to mitigate GHGs by 8% compared to 1990 levels by 2012 even though each of member states declared different targets [104]. For instance, Luxemburg and Germany had a target of reducing GHGs by 28% and 21%, respectively, while Greece and Sweden had a target of increasing the level of emissions by 24% and 4%, respectively, compared to their 1990 levels. Even though several members did not meet their individual targets, the EU-15 as a whole had an average of 11.8% reduction in GHGs by the end of the first commitment period. The Kyoto protocol has been renewed by the Doha Amendment known as the second commitment period of 2013–2020. The EU has committed to decrease GHGs by an average of 20% below 1990 levels by 2020. Furthermore, the EU has projected to increase the share of renewables in energy mix up to 20% by 2020 [103]. According to the [105]; the EU has planned to reduce GHGs by 40% against to 1990 levels and increase the share of renewable energy up to 27% by 2030. As the EU's targets in the second commitment period and future projections by 2030 are much higher than those in the first period, the realization of commitments made becomes relatively harder but plays a central role to lessen environmental pollution. According to the [104]; one possible reason to drive down the level of emissions is to increase the share of renewable sources in energy mix. The proposed projection of increased renewable energy should be linked to the adverse effect of renewables on GHGs. Thus, the fundamental objective of the current study is to show whether or not increases in the share of renewable energy and decreases in the share of non-renewable energy are statistically and economically meaningful

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[1] The EU-15 countries that joined the European Union community before 2004 committed an overall 8% reduction in GHGs during the first commitment period.

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in explaining reductions in the level of emissions for the EU.

In order to analyze the influences of renewable energy and non-renewable energy on carbon dioxide (CO_2) emissions as a proxy for GHGs, this study builds on the well-known and commonly used Environmental Kuznets Curve (EKC) model which basically claims that increases in gross domestic product (GDP) contribute to carbon emissions until a certain level and then decrease the level of emissions. The level of CO_2 emissions are regressed on GDP, the square of GDP and energy consumption in the base EKC model [10,28,44]; on the other hand, recent empirical studies propose the modified EKC model by including trade openness into the base EKC model to show that trade openness may also explain changes in carbon emissions as well as to deal with omitted variables [37,49,56]. Increases in trade openness can impact carbon emissions through composition, scale and technique effects [43]. More precisely, scale effect basically means that increases in trade can lead to higher GDP, higher energy consumption and higher pollution. Composition effect implies that a country specializes in the production of some goods with respect to comparative advantage, and accordingly increases in trade may lead to higher or lower pollution depending on whether goods that the country keeps producing are in energy-intensive-polluted sectors or not. Last, technique effect refers to technology spillover through trade flows among countries, and thus adoption of environmentally-friendly technologies in producing goods may lead to environmental improvements. The net effect of trade openness on the environment can be positive or negative depending on which effect is dominated. The use of trade openness to explain changes in the level of emissions for the EU is rational because its trade openness increased from nearly 50% in 1980 to about 80% in 2014 [106]. By following recent studies and arguments, this study analyzes the relationship between CO_2 emissions, renewable and non-renewable energy, real income (GDP), the quadratic real income and trade openness in the EKC model for the EU.

This empirical study makes several contributions to the environment-energy-growth literature. As shown in Table 1 in the literature review section, the majority of existing literature use aggregate energy consumption in their models and thus fail to identify the effects of energy consumption by sources (i.e. renewable and non-renewable energy). The first objective of this study is, for the first time in the literature, to investigate the influences of real income, renewable energy consumption, non-renewable energy consumption and trade openness on CO_2 emissions in the modified EKC framework for the EU over the period 1980–2012. Although the study by Ref. [27] has so far attempted to analyze the effects of real income, renewable and non-renewable energy on the pollution in the base EKC model for the panel of EU over the period 1990–2008, it finds that both renewable energy and non-renewable energy increase CO_2 emissions. The sign of the coefficient on renewable energy is against the expectation. Possible reasons are the use of first-generation estimation techniques, short time-period (small-sample bias) and omitted-variable bias. Because almost all studies in the existing environment-energy-growth literature use conventional panel estimation techniques which fail to take into account cross-sectional dependence across countries in the panel, the second objective of this empirical study is to use second-generation panel methods robust to cross-sectional dependence. They are the cross-sectionally Augmented Dickey-Fuller (CADF) and the cross-sectionally Im-Pesaran-Shin (CIPS) unit root tests, the LM bootstrap cointegration test, the dynamic OLS (DOLS) estimator and the Dumitrescu-Hurlin non-causality test. Thus, the reported empirical results are robust and reliable due to the use of appropriate panel techniques. The next section gives a survey of the existing literature, the third section explores model and data, the fourth section indicates methodology and empirical results, and the last section represents conclusions and policy recommendations.

2. Literature review

A survey of the existing literature is given in Table 1. Studies given in part A investigate the relationship between CO_2 emissions as a proxy for pollution, GDP (or economic growth) and aggregate energy (electricity) consumption. As shown in the last column of Table 1, many studies build on the EKC framework while several works do not investigate the presence of the EKC hypothesis. Of those which examine the validity of the EKC hypothesis find conflicting results even for the same countries and regions. For instance [87] and [100] support the validity of the EKC hypothesis for Turkey; on the other hand [49] and [73] find no evidence for the EKC hypothesis for the same country. Furthermore, several recent studies in the first group use trade openness as additional variable but produce controversial outcomes. More precisely [21] finds that the coefficient on trade is statistically insignificant [54] and [70] show that trade contributes to the level of pollution [37,51] indicate that trade mitigates pollution. All studies in the first group; on the other hand, reach a consensus on that aggregate energy (electricity) consumption contribute to CO_2 emissions for analyzed countries and regions even though they report different directions of Granger causality among carbon emissions, energy consumption, real income and trade.

The second group of studies given in part B investigates the relationship between renewable energy, non-renewable energy and economic growth in a multivariate framework wherein most studies employ capital and labor as additional variables [36]. Because renewable energy and non-renewable energy may have different impact on economic growth (GDP), the second group decomposes the aggregate energy (electricity) consumption into energy consumption by sources and then analyzes the energy-growth nexus for several countries and regions. In fact [60] and [36] find unidirectional causality between renewable energy and economic growth while [3,91] and [48] reveal bidirectional causality between them.

Inspired, perhaps, by the second group, the third (and the last) group of studies given in the part C analyzes the link between CO_2 emissions, GDP and energy (electricity) consumption by sources (i.e. renewable and non-renewable energy). The number of studies in the last group is smaller as compared to that in the first group. On the other hand, only some portions of the third group examine the existence of the EKC hypothesis as is similar for the first group [5]. Except [13] and [27] the existing studies find that renewable energy mitigates CO_2 emissions. Of those, several recent studies employ trade openness as additional variable to deal with the issue of omitted-variable bias but produce conflicting results for the net effect of trade on carbon emissions. In other words [53] find that the net effect of trade openness is statistically insignificant while [6,96] and [56] exhibit that trade reduces the levels of emissions. On the other hand, studies in the third group show different type of causality directions among CO_2 emissions, real income, renewable and non-renewable energy, and trade.

The current empirical study falls into the third group and aims to analyze the influence of real GDP (the square of real GDP), renewable energy, non-renewable energy and trade on CO_2 emissions in the EKC framework for the panel of EU countries by accounting for heterogeneity and cross-sectional dependence in the panel. In addition, the study by Ref. [27] finds that renewable energy increases CO_2 emissions for the panel of EU by using the EKC model with first-generation estimation techniques. Overall, this study employs recently developed second generation econometric methods to report robust and reliable estimates.

Table 1
A survey of existing literature.

A) Studies focusing on total energy (electricity) consumption in environment-energy-growth literature

Study	Country	Year	Variables	Methods	Long-run and Causality Results	EKC Hypothesis
[86]	Turkey	1970–2002	CO_2, EC, GDP, POP	Regression Analysis	GDP, EC and POP contribute to CO_2;GDP$\rightarrow$ EC; POP $\rightarrow$ EC; EC$\rightarrow$ CO_2	Not investigated
[93]	USA	1960–2004	CO_2, EC, GDP, GDP^2	ADF, PP, OLS, VECM causality	EC contributes to CO_2; EC$\rightarrow$ CO_2; GDP $\nrightarrow$$CO_2$	No
[8]	France	1960–2000	CO_2, EC, GDP, GDP^2	ADF, PP, ERS, ARDL, VECM causality	GDP$\rightarrow$EC, GDP$\rightarrow$$CO_2$	Yes
[9]	Malaysia	1971–1999	CO_2, EC, GDP	ADF, PP, KPSS, VECM causality	$CO_2$$\rightarrow$GDP; GDP$\leftrightarrow$EC	Not investigated
[49]	Turkey	1960–2005	CO_2, EC, GDP, GDP^2, TR	ADF, ARDL, VECM causality	EC and TR contribute to CO_2; EC, GDP$\rightarrow$ CO_2; CO_2,EC$\rightarrow$GDP	No
[94]	Turkey	1960–2000	CO_2, EC, GDP	PP, ADF, KPSS, DFGLS, Granger causality	$CO_2$$\rightarrow$EC; GDP$\nrightarrow$ CO_2	Not investigated
[10]	Central America countries	1971–2004	CO_2, EC, GDP, GDP^2	IPS, Pedroni cointegration, FMOLS, VECM causality	EC contributes to CO_2; EC$\leftrightarrow$$CO_2$; GDP$\rightarrow$ CO_2; GDP$\rightarrow$ EC	Yes
[21]	Central and Eastern Europe	1980–2002	CO_2, EC, GDP, GDP^2,TR	OLS with FE and RE	EC contributes to CO_2, TR is insignificant	Yes
[73]	Turkey	1968–2005	CO_2, GDP, EC, EMP	ARDL, VECM causality	CO_2 and EMP decrease GDP, EC increases GDP; GDP$\nrightarrow$ CO_2; EC $\nrightarrow$$CO_2$	No
[74]	Albania, Bulgaria, Hungary, Romania	1980–2006	CO_2, EC, GDP	ARDL, VECM causality	Albania, Bulgaria, Romania: No causality; Hungary: EC$\rightarrow$GDP; GDP$\rightarrow$EC	Not investigated
[75]	BRIC countries	1992–2007	CO_2, EC, GDP, GDP^2,FD	LLC, IPS, ADF, PP, OLS, VECM causality	FD and EC contribute to CO_2;EC$\leftrightarrow$GDP; GDP$\leftrightarrow$$CO_2$	Yes
[54]	China	1953–2006	CO_2, EC, GDP, GDP^2,FD,TR	ADF, ARDL, VECM causality	EC and TR contribute to CO_2, FD mitigates CO_2	Yes
[76]	Russia	1990–2007	CO_2, EC, GDP, GDP^2	Ng-Perron, KPSS, Johansen cointegration, OLS, VECM	EC contributes to CO_2; EC$\leftrightarrow$GDP; GDP$\leftrightarrow$$CO_2$, EC$\leftrightarrow$$CO_2$	No
[70]	Pakistan	1972–2008	CO_2, EC, GDP, GDP^2,TR	ADF, PP, Johansen cointegration, VECM causality	EC and TR contribute to CO_2; EC$\leftrightarrow$$CO_2$; GDP$\rightarrow$$CO_2$	Yes
[51]	Panel of newly industrialized countries	1971–2007	CO_2, EC, GDP, URB, TR	LLC, IPS, Johansen cointegration, VECM causality	EC and GDP contribute to CO_2, TR mitigates CO_2; GDP$\rightarrow$ CO_2, EC$\rightarrow$ CO_2, TR$\rightarrow$$CO_2$, URB$\rightarrow$GDP	Not investigated
[38]	China	1995–2009	CO_2, EC, GDP, GDP^2,URB, TECH, IND	OLS with FE, GMM	IND, TECH, GDP$\rightarrow$ CO_2	No
[77]	South Korea	1991–2011	CO_2, EC, GDP	MS-RW, MS-AR, ARIMA, ARDL	GDP and CO_2 moving together.	Not investigated
[72]	MENA Countries	1990–2011	CO_2, EC, GDP, TR, URB	2SLS, 3SLS, panel GMM	EC, GDP and URB contribute to CO_2, TR is insignificant; GDP$\leftrightarrow$EC; EC$\rightarrow$ CO_2	Not investigated
[30]	ASEAN-5	1971–2008	CO_2, EC, GDP GDP^2	DFGLS, Johansen cointegration, VECM causality	Indonesia, Thailand: GDP$\leftrightarrow$CO2; Malaysia: GDP$\rightarrow$ CO_2; Indonesia, Thailand, Malaysia: EC$\leftrightarrow$$CO_2$	No
[88]	Malaysia	1971–2011	CO_2, EC, GDP, FD^2, FD,TR	Ng-Perron, ARDL, VECM causality	EC, GDP contribute to CO_2, TR and FD mitigate CO_2; GDP$\leftrightarrow$$CO_2$; EC$\leftrightarrow$$CO_2$, FD$\leftrightarrow$$CO_2$	Not investigated
[34]	BRICS	1990–2010	CO_2, ELC, GDP	Pesaran CD-test, Konya, DH and EK Granger causality	India: EC$\rightarrow$ CO_2; Russia: EC$\leftrightarrow$GDP, $CO_2$$\leftrightarrow$GDP; Brazil: $CO_2$$\rightarrow$GDP; South Africa: GDP$\rightarrow$EC, GDP$\rightarrow$ CO_2	Not investigated
[89]	Tunisia	1971–2010	CO_2, EC, GDP, GDP^2,TR	ZA, ARDL, VECM causality	EC, GDP and TR contribute to CO_2	Yes
[100]	Turkey	1960–2007	CO_2, EC, GDP, GDP^2	Gregory-Hansen cointegration, Johansen cointegration, OLS	EC, GDP contribute to CO_2	Yes
[45]	Tunisia	1971–2012	CO_2, EC, GDP, GDP^2 TR, FD, URB	DFGLS, ARDL, VECM causality	EC, TR, FD and URB contribute to CO_2;GDP, EC,FD, TR, URB$\rightarrow$ CO_2	No
[2]	G-7 Countries	1960–2010	CO_2, EC, GDP	ADF, Ng-Perron, ZA, Granger causality	Japan: GDP$\leftrightarrow$EC; GDP$\rightarrow$ CO_2; Italy: GDP$\rightarrow$EC; GDP$\rightarrow$$CO_2$; Canada: EC$\rightarrow$GDP; USA: EC$\leftrightarrow$$CO_2$; France: EC$\rightarrow$ CO_2	No for Japan and Italy
[7]	Saudi Arabia	1971–2010	CO_2, EC, P, GDP	ADF, PP, VECM causality	GDP$\rightarrow$ CO_2; P$\rightarrow$ CO_2; EC,P$\rightarrow$GDP	Not investigated
[59]	EU Countries	1992–2010	CO_2, EC, GDP, GDP^2, TR, URB	IPS, Breitung, Hadri, Pedroni cointegration, FMOLS, Granger causality	EC, TR and URB contribute to CO_2; GDP$\leftrightarrow$$CO_2$, EC$\leftrightarrow$$CO_2$, TR$\leftrightarrow$$CO_2$, GDP$\leftrightarrow$EC, URB$\rightarrow$ CO_2	Yes
[90]	99 countries	1975–2012	CO_2, EC, GDP, FD, FD^2	IPS, CADF, Pedroni cointegration, Johansen cointegration, FMOLS, DH causality	EC and GDP contribute to CO_2, higher FD mitigate CO_2; FD$\leftrightarrow$$CO_2$, EC$\leftrightarrow$$CO_2$, GDP$\rightarrow$ EC	Not investigated
[23]	Canada, Denmark, Iceland, Finland, Norway, Sweden, USA	1990–2011	CO_2, EC, GDP, GDP^2, GDP^3	DFGLS, ARDL	EC contributes to CO_2; GDP mitigate CO_2 in some countries	Yes for Iceland
[87]	Turkey	1974–2010	CO_2, EC, GDP, GDP^2, FD	ADF, PP, Ng-Perron, ARDL, Hatemi-J cointegration, VECM causality	EC and FD contribute to CO_2; EC, GDP $\rightarrow$ CO_2; FD$\leftrightarrow$$CO_2$	Yes
[4]	93 countries	1980–2008	CO_2, EC, GDP, GDP^2, TR, FD, URB	IPS, ADF, PP, OLS with FE, GMM	EC, TR and URB contribute to CO_2; FD mitigates CO_2;	Yes for upper income countries
[97]	Vietnam	1976–2009	CO_2, EC, GDP, GDP^2, FD	ADF, KPSS, Johansen cointegration, VECM causality	EC contribute to CO_2; FD mitigates CO_2; GDP$\leftrightarrow$$CO_2$, EC$\leftrightarrow$$CO_2$, FD$\leftrightarrow$$CO_2$, GDP$\rightarrow$EC, EC$\rightarrow$FD	Yes

(*continued on next page*)

Table 1 (*continued*)

A) Studies focusing on total energy (electricity) consumption in environment-energy-growth literature

Study	Country	Year	Variables	Methods	Long-run and Causality Results	EKC Hypothesis
[37]	USA	1960–2010	CO_2, EC, GDP, GDP^{2}, TR, URB, FD	ADF, ZA, ARDL, VECM causality	EC and URB contribute to CO_2, TR mitigates CO_2, FD is insignificant; $CO_2 \leftrightarrow$ GDP; EC $\leftrightarrow$ CO_2;URB $\leftrightarrow$ CO_2; GDP $\rightarrow$ URB; TR $\leftrightarrow$ GDP; $CO_2 \nrightarrow$ TR; GDP $\rightarrow$ EC	No

B) Studies focusing on energy (electricity) consumption by sources in energy-growth literature

Study	**Country**	**Year**	**Variables**	**Methods**	**Long-run and Causality Results**
[11]	OECD countries	1985–2005	GDP,REC,K,L	IPS, Pedroni cointegration, FMOLS, VECM causality	REC, K, L increase GDP; GDP $\leftrightarrow$ REC, GDP $\leftrightarrow$ K, GDP $\leftrightarrow$ L, K and L $\leftrightarrow$ REC
[12]	Eurasia	1992–2007	GDP, RELC, K, L	IPS, Pedroni cointegration, FMOLS, PECM causality	RELC, K, L increase GDP; GDP $\leftrightarrow$ RELC, GDP $\leftrightarrow$ K, GDP $\leftrightarrow$ L, K and L $\leftrightarrow$ RELC
[42]	China	1978–2008	GDP,REC,K, L, R&D	OLS	REC, K and R&D increase GDP
[14]	Panel of Emerging countries	1990–2007	GDP, RELC, NRELC, K, L	LLC, ADF, PP, Pedroni cointegration, FMOLS, VECM causality	NRELC, RELC, K, L increase GDP; GDP $\leftrightarrow$ RELC, GDP $\leftrightarrow$ NRELC, GDP $\leftrightarrow$ K, GDP $\leftrightarrow$ L
[15]	Central America	1980–2006	GDP, RELC, K, L	LLC, IPS, ADF, PP, Pedroni cointegration, FMOLS, VECM causality	RELC, K, L increase GDP; GDP $\leftrightarrow$ RELC
[16]	Panel of 80 countries	1990–2007	GDP, RELC, NRELC, K, L	LLC, ADF, PP, Pedroni cointegration, FMOLS, VECM causality	NRELC, RELC, K, L increase GDP; GDP $\leftrightarrow$ RELC, GDP $\leftrightarrow$ NRELC
[17]	Central American Countries	1990–2007	GDP, RELC, NRELC, K, L	LLC, ADF, PP, Larsson cointegration, VECM causality	NRELC, RELC, K, L increase GDP; GDP $\leftrightarrow$ RELC, GDP $\leftrightarrow$ NRELC
[3]	Latin American countries	1980–2010	GDP, RELC, NRELC,K,L, TR	LLC, IPS, Pedroni cointegration, DOLS, VECM Granger causality	NRELC, RELC, K, L, TR increase GDP; GDP $\leftrightarrow$ RELC, GDP $\leftrightarrow$ NRELC, NRELC $\leftrightarrow$ TR, RELC $\leftrightarrow$ TR
[60]	OECD countries	1980–2008	GDP, RELC	Breitung, IPS, Pedroni cointegration, DOLS, VECM causality	RELC increase GDP; GDP → RELC
[91]	Pakistan	1972:1–2011:4	GDP, REC, K, L	Ng-Perron, ARDL, Johansen cointegration, VECM causality	REC, K, L increase GDP; GDP $\leftrightarrow$ REC, GDP $\leftrightarrow$ K, GDP $\leftrightarrow$ L
[48]	OECD countries	1990–2010	GDP,REC,K, L, R&D	Pedroni cointegration, OLS with FE	REC, K, L, R&D increase GDP
[36]	Turkey	1990–2012	GDP, RELC, NRELC,K, L	ADF, ZA, ARDL, Gregory-Hansen cointegration, ARDL model, VECM causality	NRELC, K and L increase GDP; RELC → GDP, GDP $\leftrightarrow$ NRELC
[26]	Top 38 renewable energy consume countries	1991–2012	GDP, RELC, NRELC, K, L	CD test, CIPS, Pedroni cointegration, DOLS, FMOLS, DH causality	RELC, NRELC, K and L increase GDP; NRELC → GDP, RELC $\nrightarrow$ GDP

C) Studies focusing on energy (electricity) consumption by sources in environment-energy-growth literature

Study	**Country**	**Year**	**Variables**	**Methods**	**Long-run and Causality Results**	**EKC Hypothesis**
[31]	OECD countries	1996–2005	CO_2, GDP, CPI, REC	Threshold effect	GDP and REC contribute to CO_2 for lower threshold; REC mitigates CO_2 for upper threshold.	Not investigated
[85]	G7 countries	1980–2005	RELC, GDP, CO_2, Oil price	Breitung, IPS, LLC, ADF, PP, Pedroni cointegration, FMOLS, DOLS	GDP and CO_2 are major determinants of RELC	Not investigated
[53]	France	1960–2003	CO_2, GDP, GDP^2, nuclear, URB, TR	PP, ARDL, Granger causality	Nuclear mitigates CO_2, URB and TR is insignificant; GDP $\rightarrow$ CO_2; nuclear $\rightarrow$ CO_2	Yes
[13]	Panel of developed and developing countries	1984–2007	CO_2, GDP, Nuclear, RELC	LLC, IPS, ADF, PP, LLL cointegration, VECM causality	Nuclear mitigates CO_2, RELC and GDP contribute to CO_2; $CO_2 \leftrightarrow$ GDP, $CO_2 \leftrightarrow$ RELC, $CO_2 \leftrightarrow$ Nuclear, GDP $\leftrightarrow$ RELC	Not investigated
[68]	USA	1960–2007	CO_2, GDP, Nuclear, REC	Toda-Yamamoto causality	Nuclear $\rightarrow$ CO_2, $CO_2 \rightarrow$ REC, GDP $\rightarrow$ REC, $CO_2 \leftrightarrow$ GDP	Not investigated
[25]	EU countries	1990–2004	RELC, GDP, CO_2, Oil price	OLS with FE and RE, DFGLS	GDP and CO_2 increase RELC	Not investigated
[96]	Malaysia	1980–2009	CO_2, GDP, GDP^2, RELC, TR	ADF, PP, ARDL, VECM causality	TR and RELC mitigate CO_2; $CO_2 \leftrightarrow$ GDP, $CO_2 \leftrightarrow$ RELC, TR $\rightarrow$ CO_2, RELC $\leftrightarrow$ GDP,TR $\rightarrow$ GDP,TR $\rightarrow$ RELC	Yes
[27]	EU countries	1990–2008	CO_2, GDP, GDP^2,REC, NREC	OLS with FE	REC and NREC contribute to CO_2	No
[44]	MENA countries	1980–2009	CO_2, GDP, GDP^2,RELC, NRELC	Breitung, IPS, Pedroni cointegration, FMOLS, DOLS, VECM causality	RELC and NRELC contribute to CO_2; $CO_2 \leftrightarrow$ RELC, $CO_2 \leftrightarrow$ NRELC, GDP $\rightarrow$ CO_2, GDP $\rightarrow$ RELC, NRELC	Yes
[65]	EU countries	1996–2010	CO2, GDP, GDP^2, GDP^3, REC	OLS with FE and RE	REC mitigates CO_2	No
[92]	OECD countries	1980–2011	CO_2, GDP, GDP^2, REC, NREC, POP	ADF, PP, Breitung, Johansen cointegration, Westerlund cointegration, GMM, VECM causality	REC mitigates CO_2; NREC contributes to CO_2	Yes
[24]	USA, Japan, France, Korea, Spain, Canada	1970–2007	CO_2, GDP, nuclear	DFGLS, Johansen cointegration	Nuclear mitigates CO_2 in all countries, GDP mitigates CO_2 in USA, Canada and France	Not investigated

Table 1 (*continued*)

C) Studies focusing on energy (electricity) consumption by sources in environment-energy-growth literature

Study	Country	Year	Variables	Methods	Long-run and Causality Results	EKC Hypothesis
[18]	Central American countries	1980–2010	RELC, GDP, CO_2, Oil price	LLC, IPS, ADF, PP, non-linear panel cointegration, FMOLS, VECM causality	GDP, CO_2 and prices increase RELC; CO_2 ↔ RELC, GDP ↔ RELC, Prices → REC	Not investigated
[5]	Vietnam	1982–2011	CO_2, RELC, NRELC GDP, import, export, current account, L	ARDL	NRELC and import contribute to CO_2	No
[28]	Turkey	1961–2010	CO_2, GDP, GDP^2, RELC	ADF, KPSS, ARDL	RELC mitigates CO_2	Yes
[55]	North Africa	1971–2008	GDP, CO_2, combustible and waste (CRW)	Breitung, LLC, IPS, Pedroni cointegration, FMOLS, DOLS, Granger causality	CO_2 and CRW contribute to GDP; GDP → CRW, GDP → CO_2, CRW → CO_2	Not investigated
[6]	European countries	1990–2013	CO_2, GDP, TR, URB, FD, RELC by sources (wind, solar, hydro, nuclear, and CRW)	IPS, ADF, PP, Pedroni cointegration, FMOLS, VECM causality	Five sources of RELC and TR mitigate CO_2; FD, URB and GDP contributes to CO2	Not investigated
[19]	South America	1980–2010	CO_2, GDP, P, REC	ADF, PP, FMOLS, Granger causality	GDP ↔ REC; CO_2 ↔ GDP; CO_2 ↔ REC; REC → P	Not investigated
[56]	OECD countries	1980–2010	CO_2, GDP, GDP^2,RELC, NRELC, TR	Breitung, IPS, LLC, ADF, PP, Pedroni cointegration, FMOLS, DOLS, VECM causality	RELC and TR mitigate CO_2, NRELC contributes to CO_2; CO_2 ↔ RELC, CO_2 ↔ NRELC, CO_2 ↔ GDP, CO_2 ↔ TR, GDP ↔ RELC, GDP ↔ NRELC, GDP ↔ TR	Yes

Note: IPS (Im–Pesaran–Shin unit root test) [52], LLC (Levin–Lin–Chu unit root test) [63], PP (Phillips–Perron unit root test) [84], ADF (Augmented Dickey–Fuller unit root test) [35], DFGLS (Dickey–Fuller test in generalized least squares) [40], KPSS (Kwiatkowski–Phillips–Schmidt–Shin unit root test) [61], ZA (Zivot–Andrews unit root test) [101], Ng–Perron unit root test [71], Breitung unit root test [29] (FE (fixed effects), RE (random effects), GMM (generalized methods of moments), Johansen cointegration test [57], Pedroni cointegration test [78,80], Granger causality [46], VECM (vector error correction mechanism) causality [41], DH (Dumitrescu and Hurlin) causality [39], Toda-Yamamoto causality [98], FMOLS (fully modified ordinary least squares), ARDL (autoregressive distributed lag model) [81], DOLS (dynamic ordinary least squares), REC (renewable energy consumption), (RELC (renewable electricity consumption), NRELC (non-renewable electricity consumption), NREC (non-renewable energy consumption), TR (trade-trade openness), FD (financial development), URB (Urbanization), K (capital), L (labor), P(prices), POP (population), BRICS countries (Brazil, Russia, India, China, South Africa), ASEAN (Association of South East Nations), MENA (Middle East and North Africa), OECD (Organization for Economic Co-operation and Development), USA (United States of America), ↔ (bidirectional Granger causality), → (unidirectional Granger causality), ↛ (no Granger causality).

3. Model and data

The EKC model assumes that the pollution rises with income in early stages of economic growth, but after a turning point, increase in income leads to environmental improvement [47]. In other words, the EKC hypothesis presumes a quadratic relationship between economic growth and environmental pollution. In addition [95]; also indicates an assumption that the elasticity of CO_2 emissions with respect to real income is the same across countries although carbon emissions may vary across economies at any given level of real income. The studies by Refs. [27] and [44] investigate the environment-energy-growth nexus under the base EKC framework in which the level of CO_2 emissions is regressed on GDP, the square of GDP, renewable energy (REC) and non-renewable energy (NREC). For a panel study, it can be written:

$$(CO_2)_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 REC_{it} + \beta_4 NREC_{it} + e_{it} \tag{1}$$

In addition to energy by sources and real income [37,49] and [56] emphasize the importance of trade openness (TR) in determining CO_2 emissions. By inserting trade openness as an additional variable into the base framework, the modified EKC model that we use can be shown as in Equation (2):

$$\begin{aligned}(CO_2)_{it} = {} & \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 REC_{it} + \beta_4 NREC_{it} \\ & + \beta_5 TR_{it} + e_{it}\end{aligned} \tag{2}$$

where i and t stands for country and the time; e denotes normally distributed error term; $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ are the coefficient estimates on the relevant variables. CO_2 is carbon dioxide emissions in metric tons as a proxy for environmental pollution; GDP is the value of real gross domestic product in constant 2005 US$; REC is electricity production from renewable sources including hydro, geothermal, wind, solar, biomass and waste measured in kilowatt-hours; NREC electricity production from non-renewable sources including coal, oil and natural gas measured in kilowatt-hours; TR is trade openness measured as the ratio of total trade to GDP. The annual panel time-series data are from 1980 to 2012. The data on GDP and TR are taken from the World Bank's "World Development Indicators" (http://data.worldbank.org), and the data on CO_2 emissions, REC and NREC come from "U.S. Energy Information Administration" (www.eia.gov). This study converts the data into their natural logarithmic so as to obtain elasticity of CO_2 emissions with respect to the independent variables. It is worth-knowing that this study employs the longest available data given that the data for REC and NREC are not available before 1980 and after 2012. In case that the EKC hypothesis is valid, it is expected that $\beta_1 > 0$, and $\beta_2 < 0$. In addition, β_3 is expected to be negative whereas β_4 is expected to be positive following the recent state-of-the-art. The sign of β_5 is ambiguous because the net of effect of trade on carbon emissions is not certain. The EU-15 countries used in the current study is Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, the United Kingdom.

4. Methods and empirical results

This section explains panel estimation techniques that this study uses and represents the empirical results that we obtain using cross-sectional independence test, panel unit root tests, panel cointegration test, panel long-run estimator, and panel Granger causality test.

4.1. *Cross-sectional independence test and panel unit root tests*

In advance to analyzing stationarity properties of CO_2, GDP (GDP^2), renewable energy consumption (REC), non-renewable energy consumption (NREC) and trade openness (TR), this study first carries out the Pesaran's CD-test [82] to find out whether cross-sectional dependence exists within each panel time-series data. The correlation among a time-series data for EU members may take place due to either globally known events with heterogeneous effects on members or local spillover effects among members. Failure to take into account the issue of cross-sectional dependence may result in forecasting errors. Results from the Pesaran's CD-test for analyzed variables are reported in Table 2. Because the relevant p-values are smaller than 0.01, we have strong evidence to reject the null hypothesis of cross-sectional independence for CO_2 emissions, real income, the quadratic real income, renewable and non-renewable energy consumption and trade openness at 1% level of significance. In other words, the analyzed variables are cross-sectionally dependent.

In the presence of cross-sectional dependence across countries in the panel, first-generation conventional panel unit root tests (e.g. LLC, IPS and Hadri unit root tests) should not be used because they assume no dependency in the panel. This assumption may cause forecasting errors. Overall, the CADF and the CIPS panel unit root tests due to [83] are employed in this empirical study since they are robust to cross-sectional dependence. The application process of both tests is identical except the CIPS test use the cross-section average of the CADF test. Building on the Augmented Dickey-Fuller (ADF) approach, these panel unit root tests take:

$$\Delta x_{it} = \alpha_i + \beta_i x_{it-1} + \rho_i T + \sum\nolimits_{j=1}^{n} \theta_{ij} \Delta x_{it-j} + \varepsilon_{it} \tag{3}$$

where x_{it} stands for an analyzed variable, ε_{it} is error term, and Δ is the difference operator, and α and T are individual intercepts and time trends, respectively. The appropriate lag lengths (n) are selected based on the Schwarz Information Criterion. Both tests perform the null hypothesis that all individuals within a panel data are not stationary versus the alternative hypothesis that at least one individual is stationary:

$$H_0 : \beta_i = 0$$

$$H_a : \begin{cases} \beta_i < 0 & for\ i = 1, 2, \ldots, N_1 \\ \beta_i = 0 & for\ i = N_1 + 1, N_1 + 2 \ldots, N \end{cases}$$

Table 3 reports results from the Pesaran's CADF and CIPS panel unit root tests. Since we have enough evidence to reject the null hypothesis of unit root at 1% level of significance, we can claim that CO_2, GDP (GDP^2), REC, NREC and TR become stationary at their first differences. The panel time-series should be either stationary or cointegrated at their levels in order to assess statistically and economically meaningful coefficients on the independent variables. Because CO_2, GDP (GDP^2), REC, NREC and TR include unit root at their levels, this study apply a panel cointegration test to see whether or not the analyzed variables have a long-run relationship.

4.2. *Panel cointegration test*

The use of cointegration test helps reach the long-run information about non-stationary series. Thus, the problem raised from differentiation process of the series can be solved with this method.

Table 2
Results from Pesaran's cross-sectional independence test.

	CO_2	GDP (GDP^2)	REC	NREC	TR
CD-test	12.23**	53.53**	37.99**	18.33**	33.75**
P-value	0.00	0.00	0.00	0.00	0.00

Note: ** denotes significance at 1% level. The CD-test performs the null hypothesis of cross-sectional independence.

Table 3
Results from panel unit root tests.

	CADF		CIPS	
	Level	Δ	Level	Δ
CO_2	−2.47	−4.03**	−2.55	−5.36**
GDP (GDP^2)	−2.27	−2.85**	−2.12	−3.18**
REC	−2.16	−4.65**	−3.00**	−5.91**
NREC	−2.53	−4.02**	−2.57	−5.52**
TR	−2.18	−3.58**	−2.05	−4.63**

Note: ** denotes the statistical significance at 1% level. Δ is the first difference term. Critical values are not reported for the sake of brevity but can be provided upon request.

Because we find that the analyzed variables have cross-sectional dependence, this study employs the LM bootstrap cointegration test due to [99] strong to the presence of cross-sectional dependence. Using a bootstrap method through simulations, it reduces the distortions of the asymptotic tests. The validity of this test is also shown for small samples by Monte Carlo simulations. This test has recently been used in the literature [1,20,32]. An important advantage of the LM panel cointegration test is that the null hypothesis indicates cointegration for all cross-section units. Therefore, the existence of cointegration relationship for the panel is detected in case where the null hypothesis is not rejected. The LM test statistic is calculated as follows.

$$LM_N^+ = 1\Big/NT^2 \sum\nolimits_{i=1}^{N} \sum\nolimits_{t=0}^{T} \widehat{\omega}_t^{-2} S_{i,t}^2 \tag{4}$$

where T and N are time-period and sample size, respectively, $\widehat{\omega}_t$ and $S_{i,t}$ indicate the long-run variance and the partial sum process of the residuals, respectively.

Results from the LM bootstrap panel cointegration test are illustrated in Table 4. The null hypothesis of cointegration cannot be rejected because the reported p-values are far greater than a significance level. Overall, it is shown that there is a cointegration relationship between CO_2 and its determinants (GDP, GDP^2, REC, NREC and TR), indicating that the analyzed variables move together in the long-run. Therefore, it is concluded that there is a strong cointegration relationship between the dependent variable (CO_2 emissions) and independent variables (GDP, GDP^2, NREC, REC and TR) for the EU countries.

4.3. *Long-run estimates*

One of the most important outcomes of the presence of cointegration relationship between the variables is that the coefficients on the independent variables for the dependent variable become statistically and economically meaningful. Yet, the question “Which long-run estimator should be used” arises from the fact there are several estimators. The ordinary least squares (OLS) estimator is very popular and among commonly used ones in a variety of literature; however, the fully modified ordinary least squares (FMOLS) and the dynamic ordinary least squares (DOLS) estimators have been recently preferred to the OLS estimator [62]. The DOLS and FMOLS are also quite effective in eliminating the endogeneity issues in the regressors and serial correlations in the error terms and so the variables also have asymptotic properties [64]. On the other hand, the FMOLS estimator gets rid of the problems of endogeneity and autocorrelation by using non-parametric approach while the DOLS estimator eliminates the difficulties by using parametric approach, and lags and leads of the explanatory variables. Therefore, the DOLS estimator demonstrates more efficient and superior performance in small samples than both the OLS

Table 4
Results from the LM bootstrap panel cointegration test.

Test	Constant		Constant and Trend	
	Test Statistic	Bootstrap p-value	Test Statistic	Bootstrap p-value
LM bootstrap	5.103	1.00	13.140	0.989

Note: The bootstrap test statistic is calculated by using 1000 replications.

Table 5
Results from the panel DOLS.

Dependent Variable: CO_2			
Independent Variables	Coefficient	t-statistic	p-value
GDP	4.10**	10.82	0.00
GDP^2	−0.07**	−10.39	0.00
REC	−0.03**	−2.62	0.01
NREC	0.44**	18.49	0.00
TR	−0.06*	−2.29	0.02
R^2	0.99		
Coefficient Diagnostic (Null Hypothesis: $\beta_5 = 0$)			
Test statistic	Value	d.f.	p-value
F-statistic	5.26*	1, 374	0.02
t-statistic	−2.29*	374	0.02

Note: **, * denote the statistical significance at 1% level and 5% level, respectively. The coefficient diagnostic test shows that the inclusion of trade openness to the base EKC is statistically significant, and thus increases the goodness of fit of the model.

and the FMOLS estimators [58,69]. Furthermore [79]; notes that the DOLS generates unbiased coefficient estimates. More importantly [50]; mention that the DOLS technique is the best one in case of cross-sectional dependence. Moreover [60] and [3] are among those that prefer to use the DOLS in analyzing the energy-environment-growth nexus. In this study, because of the aforementioned advantages, we use the weighted DOLS technique allowing for heterogeneity in the long-run variances developed by Ref. [66].[2]

The results from the DOLS estimator are reported in Table 5. Because the natural logarithm values of the panel time-series data are used, the long run coefficient estimates of GDP, GDP^2, REC, NREC and TR are econometrically equal to the elasticities of CO_2 with respect to real income, the square of real income, renewable energy, non-renewable energy and trade openness, respectively. It is worth-mentioning that the reported coefficient estimates are all statistically significant referring to the p-values and t-statistics. Starting with the real income, an increase in real GDP has a significant impact on CO_2 emissions for the EU. More precisely, the (partial) marginal effect of GDP on CO_2 is calculated by $\beta_1 + 2^*\beta_2^*$GDP (4.10−2*0.07*GDP), and thus the (partial) marginal effect of real income on carbon emissions is clearly positive for low-income members; but, it decreases and eventually becomes negative as the EU countries shift to high-income groups. In other words, we can claim that EKC hypothesis is valid for the EU countries since the elasticities of CO_2 emissions with respect to real income and the quadratic real income are positive and negative, respectively. Overall, increases in GDP lead to environmental improvements after member states of the EU pass the threshold level. The validity of the EKC hypothesis is consistent with many studies including [28,44] and [56]. On the contrary, it is not consistent with [65] and [27] which previously investigate the EKC hypothesis for the EU. We believe that the discrepancy between these studies and the current study occurs due to the fact that both studies employ the OLS estimator with relatively shorter panel data.

The environmental impact of renewable energy is noted in Table 5. A 1% increase in REC provides a 0.03% reduction in CO_2 emissions. In other words, the use of renewable energy contributes to environmental improvements. As the state-of-the-art agrees with that renewable energy reduces the levels of carbon emissions; as countries use more renewable energy, they emit lower CO_2. The finding of this study is consistent with that of [6,65,92]. On the other hand, it is contrast to that of [27]. Possible reasons are the use of first-generation estimation techniques, short time-period (small-sample bias) and omitted-variable bias. In regards to non-renewable energy consumption, NREC leads to significant environmental degradation. The elasticity of CO_2 emissions with respect to non-renewable energy implies that a 1% increase in NREC increases the level of CO_2 emissions by 0.44%. Actually, there is a common consensus on the negative impact of fossil fuel based energy consumption on the environment in the literature (Table 1). As a summary of the effects of energy by sources, we find that increases in renewable sources in energy mix mitigate CO_2 emissions while increases in non-renewable sources in energy mix contribute to pollution for the EU. Thus, the EU's projects to increase the share of renewable energy up to 20% by 2020 and 27% by 2030 are economically and statistically rational to reduce the level of emissions by 20% and 40% below 1990 levels by 2020 and 2030, respectively. The EU should spend enough efforts to accomplish the given targets. One possible option to keep track of the projects should be to financially support scientific institutions, universities and researchers to work for generating energy from renewable sources at cheaper costs. In addition, regulatory policies should be proposed to increase the public awareness of renewable energy for clean environment.

As an environmental indicator variable, trade openness has recently offered a good insight for the contribution to environmental improvements for several countries and regions [37,56]. As it is in line with the above-mentioned studies, this study also finds that increases in trade openness mitigate carbon emissions for the EU. More precisely, with a strong level of significance, a 1% increase in trade openness leads to 0.06% decrease in CO_2 emissions in the long-run. As discussed in the introduction section, trade has three types of effects on the environment. The result of the current study indicates that the net environmental impact of increased trade openness reduces environmental deteriorations given that technique effect and composition effect dominate scale effect. It makes sense because developed countries in particular have made a good progress in inventing new technologies for over the last several decades and the panel of EU seem to take benefit from technology spillover through trade. More closely focusing on the composition effect we can reach interesting conclusions; for instance, it seems that energy intensive and dirty industries operated in the EU countries prefer to move to developing and undeveloped countries because they apply less environmental standards than the EU. The latter case mainly refers to the pollution-haven hypothesis which asserts that developed countries with public awareness of environmental pollution make dirty factories to relocate and operate in countries with lower environmental regulations and enforcements [33]. As a result, the

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[2] See Ref. [66] for more detailed statistical explains.

EU as a whole likely produces and exports non-energy intensive and environmentally-friendly goods, and imports dirty goods. Although it looks like the pollution shifts from one place to other places, and the level of overall pollution in the world stays unchanged, it is the fact that the EU takes advantages of freer trade and countries with low environmental standards.

4.4. Dumitrescu-Hurlin panel Granger causality test

The coefficients obtained from the DOLS estimator undoubtedly offer significant inferences. However, these results do not provide any information regarding the causal relationship between the analyzed variables. It is important for policy makers to know the directions of causality among the variables to regulate appropriate policies. Therefore, this study employs Granger causality test developed by Ref. [39] to demonstrate the causality relationship. This test has a very flexible use both in cases of T > N and T < N as well as for unbalanced and heterogeneous panels. Also, one of the major advantages of this test is that it can be used for panel data in the presence of cross-sectional dependence. Moreover, this test solves problems posed by homogeneity assumption in the standard Granger causality test. By using Monte–Carlo simulations [39]; show that the test statistics are relatively strong in cases of small data and cross-sectional dependence. This test considers the following linear heterogeneous model:

$$y_{i,t} = \alpha_i + \sum\nolimits_{i=1}^{K} \gamma_i^{(k)} y_{i,t-k} + \sum\nolimits_{i=1}^{K} \beta_i^{(k)} x_{i,t-k} + \varepsilon_{i,t} \tag{5}$$

where $K \in \mathbb{N}^+$ and $K \in \mathbb{N}^*$ *and* $\beta_i = (\beta_i^{(1)}, \ldots\ldots, \beta_i^{(K)})$ and α_i, $\gamma_i^{(k)}$, and $\beta_i^{(k)}$ indicate constant term, lag parameter and coefficient slope, respectively. The null hypothesis supports the existence of no homogenous Granger causality for all cross-section units whereas the alternative hypothesis assumes that there is at least one Granger causal relationship in the panel data. The null and alternative hypotheses are defined as:

$$H_0 : \beta_i = 0$$

$$H_1 : \begin{cases} \beta_i = 0 & \forall_i = 1, 2, \ldots \ \ldots \ \ldots N \\ \beta_i \neq 0 & \forall_i = N_1 + 1,\ N_1 + 2, \ldots \ \ldots, N \end{cases}$$

Results from the Dumitrescu–Hurlin Granger causality test are presented in Table 6. It indicates that there is bidirectional causality between renewable energy and carbon emissions. There is unidirectional causality running from real income to the level of emissions, from CO_2 emissions to non-renewable energy, from trade openness to pollution, from openness to renewable energy, from real income to non-renewable energy, from GDP to trade openness for the EU countries. The findings are in line with that of many studies including [56,70] and [87]. The finding of income-led trade hypothesis is also found by Ref. [22].

Empirical results obtained from the Dumitrescu–Hurlin Granger causality test are consistent with those from the DOLS estimator. More precisely, renewable energy, trade and real income can be used to forecast of future CO_2 emissions, even though there may not necessarily be a physical causality between them by the definition of Granger causality. Economists have been able to think of mechanisms by which the past may appear to influence the future as the past determines the future. In conjunction with the output of the DOLS, we also interpret the evidence of the Granger causality as suggestive piece of evidence that high rates of renewable energy and trade can have a negative effect on CO_2 emissions at least over the period for which we run the model. Moreover, increases in the level of carbon emissions has an influence on non-renewable energy, which is consistent with the argument we have made. Thus, the EU should continuously increase the amount of REC for the sake of environmental improvements. Considering there is unidirectional causality running from GDP to NREC, the reduction in the non-renewable energy does not harm the economy of the EU. Overall, the EU can reduce the amount of NREC without harming real income.

5. Conclusions and policy implications

Even though a lot of studies have analyzed the determinants of the environmental pollution, one criticism related to the existing literature is the selection of data. The majority of studies use aggregate energy consumption. The other criticism is the selection of panel estimation techniques. Almost all studies use panel methods that ignore cross-sectional dependence. Failure to take into account the issue of cross-sectional dependence may result in forecasting errors. The objective of this study is to examine the effects of real income, the square of real income, renewable and non-renewable energy, and trade on the levels of carbon emissions in the EKC model for the EU over the years 1980–2012 by using panel estimation techniques robust to cross-sectional dependence. The findings of this study can be summarized as follow. The presence of cross-sectional dependence in each time-series panel is detected by the Pesaran's CD test. The CADF and the CIPS unit root tests show that the analyzed variables become stationary at their first differences. The LM bootstrap cointegration test indicates that CO_2 emissions, renewable and non-renewable energy, GDP, GDP^2 and trade are cointegrated, and thus have a long-run relationship. The DOLS estimator reports that a 1% increase in renewable energy and trade mitigate carbon emissions by 0.03% and 0.06%, respectively, whereas a 1% increase in non-renewable energy contributes to environmental degradation by 0.44%. The existence of EKC is found for the EU as the elasticity of CO_2 emissions with respect to GDP and GDP^2 is positive and negative, respectively. The Dumitrescu–Hurlin Granger causality reveals the existence of bidirectional Granger causality between REC and CO_2 emissions, and unidirectional causality running from CO_2 emissions to NREC, from trade to emissions, from GDP to CO_2 emissions, and from GDP to NREC. Empirical results reported in this study are robust and reliable due to the use of appropriate estimation techniques.

In regards policy implications and recommendations, the EU should keep on increasing the share of renewable energy and decreasing the share of non-renewable energy for lower levels of CO_2 emissions. Since decreases in non-renewable energy do not detract the EU's real income, policies to reduce the amount of non-renewable energy consumption can be implemented without harming GDP. Given that countries can produce energy from non-renewable sources at a lower cost than renewable energy, the EU should support universities and researchers to make the production of energy from renewable sources relatively cheaper. Therefore, the implementation of increased renewable energy in energy mix can also be economically sustainable for each member states. Through the U.S. Energy Information Administration (EIA) that provides the detailed data on energy (electricity) production from sources, one may easily notice that some EU countries (e.g. Cyprus, Denmark and Hungary) produce zero or nearly zero energy from solar and wind while several members (e.g. Germany and Spain) produce a significant amount of energy from above-mentioned sources. These countries should be more incorporated in this matter. Policy makers should more focus on public awareness of renewable energy and clean environment. The EU should continue to specialize in the production of non-energy intensive and environmentally-friendly goods, and force firms in dirty industries by strict environmental regulations to move to countries with less environmental enforcements. In this way, the EU

Table 6
Dumitrescu–Hurlin panel causality tests.

Hypothesis	W-stat	Z-stat	Prob.	Result	Conclusion
GDP (GDP^2)→CO_2	3.01	4.48	0.00***	Yes	Unidirectional causality from GDP (GDP^2) to CO_2
CO_2→GDP(GDP^2)	0.98	−0.21	0.83	No	
REC→ CO_2	1.90	1.89	0.06*	Yes	Bidirectional causality between REC and CO_2
CO_2→REC	1.81	1.70	0.08*	Yes	
NREC→ CO_2	5.61	1.14	0.25	No	Unidirectional causality from CO_2 to NREC
CO_2→NREC	7.05	2.58	0.01***	Yes	
TR→ CO_2	1.41	−2.30	0.02**	Yes	
CO_2→TR	3.64	0.42	0.67	No	Unidirectional causality from TR to CO_2
REC→GDP(GDP^2)	1.16	0.21	0.83	No	No causality between GDP (GDP^2) and REC
GDP(GDP^2)→REC	1.21	0.31	0.75	No	
NREC→GDP(GDP^2)	5.62	1.14	0.25	No	Unidirectional causality from GDP (GDP^2) to NREC
GDP(GDP^2)→NREC	8.35	3.88	0.00***	Yes	
TR→GDP(GDP^2)	2.34	−1.17	0.24	No	Unidirectional causality from GDP (GDP^2) to TR
GDP(GDP^2)→TR	5.13	2.25	0.02**	Yes	
REC→TR	1.20	−1.53	0.12	No	
TR→REC	0.96	−1.90	0.06*	Yes	Unidirectional causality from TR to REC
NREC→TR	3.59	−0.87	0.38	No	
TR→NREC	4.07	−0.39	0.69	No	No causality between NREC and TR
NREC→REC	2.35	0.29	0.76	No	No causality between REC and NREC
REC→NREC	2.23	0.10	0.91	No	

Note: ***, **, * denote the statistical significance at 99% level, 95% level and 90% level, respectively.

should continue to benefit from increasing trade with the other countries. Increases in (intra-group) trade can also help members (through technology spillover) adopt and use new environmentally-friendly technologies.

References

[1] A. Afonso, C. Rault, Short- and long-run behavior of long-term sovereign bond yields, Appl. Econ. 47 (37) (2015) 3971–3993.

[2] A.N. Ajmi, S. Hammoudeh, D.K. Nguyen, J.R. Sato, On the relationships between CO_2 emissions, energy consumption and income: the importance of time variation, Energy Econ. 49 (2015) 629–638.

[3] U. Al-Mulali, H.G. Fereidouni, J.Y. Lee, Electricity consumption from renewable and non-renewable sources and economic growth: evidence from Latin American countries, Renew. Sustain. Energy Rev. 30 (2014) 290–298.

[4] U. Al-Mulali, C. Weng-Wai, L. Sheau-Ting, A.H. Mohammed, Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation, Ecol. Indic. 48 (2015a) 315–323.

[5] U. Al-Mulali, B. Saboori, I. Ozturk, Investigating the environmental Kuznets curve hypothesis in Vietnam, Energy Policy 76 (2015b) 123–131.

[6] U. Al-Mulali, I. Ozturk, H.H. Lean, The influence of economic growth, urbanization, trade openness, financial development, and renewable energy on pollution in Europe, Nat. Hazards 79 (1) (2015c) 621–644.

[7] A.S. Alshehry, M. Belloumi, Energy consumption, carbon dioxide emissions and economic growth: the case of Saudi Arabia, Renew. Sustain. Energy Rev. 41 (2015) 237–247.

[8] J.B. Ang, CO_2 emissions, energy consumption, and output in France, Energy Policy 35 (10) (2007) 4772–4778.

[9] J.B. Ang, Economic development, pollutant emissions and energy consumption in Malaysia, J. Policy Model. 30 (2) (2008) 271–278.

[10] N. Apergis, J.E. Payne, CO_2 emissions, energy usage, and output in Central America, Energy Policy 37 (8) (2009) 3282–3286.

[11] N. Apergis, J.E. Payne, Renewable energy consumption and economic growth: evidence from a panel of OECD countries, Energy Policy 38 (1) (2010a) 656–660.

[12] N. Apergis, J.E. Payne, Renewable energy consumption and growth in Eurasia, Energy Econ. 32 (6) (2010b) 1392–1397.

[13] N. Apergis, J.E. Payne, K. Menyah, Y. Wolde-Rufael, On the causal dynamics between emissions, nuclear energy, renewable energy, and economic growth, Ecol. Econ. 69 (11) (2010) 2255–2260.

[14] N. Apergis, J.E. Payne, Renewable and non-renewable electricity consumption–growth nexus: evidence from emerging market economies, Appl. Energy 88 (12) (2011a) 5226–5230.

[15] N. Apergis, J.E. Payne, The renewable energy consumption–growth nexus in Central America, Appl. Energy 88 (1) (2011b) 343–347.

[16] N. Apergis, J.E. Payne, Renewable and non-renewable energy consumption-growth nexus: evidence from a panel error correction model, Energy Econ. 34 (3) (2012a) 733–738.

[17] N. Apergis, J.E. Payne, The electricity consumption-growth nexus: renewable versus non-renewable electricity in Central America, Energy Sources Part B Econ. Plan. Policy 7 (4) (2012b) 423–431.

[18] N. Apergis, J.E. Payne, Renewable energy, output, CO_2 emissions, and fossil fuel prices in Central America: evidence from a nonlinear panel smooth transition vector error correction model, Energy Econ. 42 (2014) 226–232.

[19] N. Apergis, J.E. Payne, Renewable energy, output, carbon dioxide emissions, and oil prices: evidence from South America, Energy Sources Part B Econ. Plan. Policy 10 (3) (2015) 281–287.

[20] M.E. Arouri, A.B. Youssef, H. M'henni, C. Rault, Energy consumption, economic growth and CO_2 emissions in Middle East and North African countries, Energy Policy 45 (2012) 342–349.

[21] C. Atici, Carbon emissions in Central and Eastern Europe: environmental Kuznets curve and implications for sustainable development, Sustain. Dev. 17 (3) (2009) 155–160.

[22] T.O. Awokuse, Trade openness and economic growth: is growth export-led or import-led? Appl. Econ. 40 (2) (2008) 161–173.

[23] J. Baek, Environmental Kuznets curve for CO_2 emissions: the case of Arctic countries, Energy Econ. 50 (2015) 13–17.

[24] J. Baek, D. Pride, On the income–nuclear energy– CO_2 emissions nexus revisited, Energy Econ. 43 (2014) 6–10.

[25] A. Bengochea, O. Faet, Renewable energies and CO_2 emissions in the European Union, Energy Sources Part B Econ. Plan. Policy 7 (2) (2012) 121–130.

[26] M. Bhattacharya, S.R. Paramati, I. Ozturk, S. Bhattacharya, The effect of renewable energy consumption on economic growth: evidence from top 38 countries, Appl. Energy 162 (2016) 733–741.

[27] G. Boluk, M. Mert, Fossil & renewable energy consumption, GHGs (greenhouse gases) and economic growth: evidence from a panel of EU (European Union) countries, Energy 74 (2014) 439–446.

[28] G. Boluk, M. Mert, The renewable energy, growth and environmental Kuznets curve in Turkey: an ARDL approach, Renew. Sustain. Energy Rev. 52 (2015) 587–595.

[29] J. Breitung, The local power of some unit root tests for panel data, in: Advances in Econometrics, Nonstationary Panels, Panel Cointegration, and Dynamic Panels, vol. 15, JAI, 2000.

[30] V.G.R. Chandran, C.F. Tang, The impacts of transport energy consumption, foreign direct investment and income on CO_2 emissions in ASEAN-5 economies, Renew. Sustain. Energy Rev. 24 (2013) 445–453.

[31] C.L. Chiu, T.H. Chang, What proportion of renewable energy supplies is needed to initially mitigate CO_2 emissions in OECD member countries? Renew. Sustain. Energy Rev. 13 (6) (2009) 1669–1674.

[32] G. Chortareas, G. Magkonis, D. Moschos, T. Panagiotidis, Financial development and economic activity in advanced and developing open economies: evidence from panel cointegration, Rev. Dev. Econ. 19 (1) (2015) 163–177.

[33] M.A. Cole, Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages, Ecol. Econ. 48 (1) (2004) 71–81.

[34] W.N. Cowan, T. Chang, R. Inglesi-Lotz, R. Gupta, The nexus of electricity consumption, economic growth and CO_2 emissions in the BRICS countries, Energy Policy 66 (2014) 359–368.

[35] D.A. Dickey, W.A. Fuller, Distribution of the estimators for autoregressive time series with a unit root, J. Am. Stat. Assoc. 74 (366a) (1979) 427–431.

[36] E. Dogan, The relationship between economic growth and electricity consumption from renewable and non-renewable sources: a study of Turkey, Renew. Sustain. Energy Rev. 52 (2015) 534–546.

[37] E. Dogan, B. Turkekul, CO_2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA, Environ. Sci. Pollut. Res. (2015) 1–11.

[38] L. Du, C. Wei, S. Cai, Economic development and carbon dioxide emissions in China: provincial panel data analysis, China Econ. Rev. 23 (2) (2012)

371–384.

[39] E.I. Dumitrescu, C. Hurlin, Testing for Granger non-causality in heterogeneous panels, Econ. Model. 29 (4) (2012) 1450–1460.

[40] G. Elliott, T.J. Rothenberg, J.H. Stock, Efficient tests for an autoregressive unit root, Econ. J. Econ. Soc. (1996) 813–836.

[41] R.F. Engle, C.W. Granger, Co-integration and error correction: representation, estimation, and testing, Econ. J. Econ. Soc. (1987) 251–276.

[42] Y. Fang, Economic welfare impacts from renewable energy consumption: the China experience, Renew. Sustain. Energy Rev. 15 (9) (2011) 5120–5128.

[43] S. Farhani, A. Chaibi, C. Rault, CO_2 emissions, output, energy consumption, and trade in Tunisia, Econ. Model. 38 (2014) 426–434.

[44] S. Farhani, M. Shahbaz, What role of renewable and non-renewable electricity consumption and output is needed to initially mitigate CO_2 emissions in MENA region? Renew. Sustain. Energy Rev. 40 (2014) 80–90.

[45] S. Farhani, I. Ozturk, Causal relationship between CO_2 emissions, real GDP, energy consumption, financial development, trade openness, and urbanization in Tunisia, Environ. Sci. Pollut. Res. (2015) 1–14.

[46] C.W. Granger, Some recent development in a concept of causality, J. Econ. 39 (1) (1988) 199–211.

[47] G.M. Grossman, A.B. Krueger, Environmental Impacts of a North American Free Trade Agreement (No. W3914), National Bureau of Economic Research, 1991.

[48] R. Inglesi-Lotz, The impact of renewable energy consumption to economic growth: a panel data application, Energy Econ. (2015), http://dx.doi.org/10.1016/j.eneco.2015.01.003.

[49] F. Halicioglu, An econometric study of CO_2 emissions, energy consumption, income and foreign trade in Turkey, Energy Policy 37 (3) (2009) 1156–1164.

[50] M.J. Herrerias, R. Joyeux, E. Girardin, Short-and long-run causality between energy consumption and economic growth: evidence across regions in China, Appl. Energy 112 (2013) 1483–1492.

[51] M.S. Hossain, Panel estimation for CO_2 emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries, Energy Policy 39 (11) (2011) 6991–6999.

[52] K.S. Im, M.H. Pesaran, Y. Shin, Testing for unit roots in heterogeneous panels, J. Econ. 115 (1) (2003) 53–74.

[53] H. Iwata, K. Okada, S. Samreth, Empirical study on the environmental Kuznets curve for CO_2 in France: the role of nuclear energy, Energy Policy 38 (8) (2010) 4057–4063.

[54] A. Jalil, M. Feridun, The impact of growth, energy and financial development on the environment in China: a cointegration analysis, Energy Econ. 33 (2) (2011) 284–291.

[55] M.B. Jebli, S.B. Youssef, Economic growth, combustible renewables and waste consumption, and CO_2 emissions in North Africa, Environ. Sci. Pollut. Res. 22 (20) (2015) 16022–16030.

[56] M.B. Jebli, S.B. Youssef, I. Ozturk, Testing environmental Kuznets curve hypothesis: the role of renewable and non-renewable energy consumption and trade in OECD countries, Ecol. Indic. 60 (2016) 824–831.

[57] S. Johansen, Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models, Econ. J. Econ. Soc. (1991) 1551–1580.

[58] C. Kao, M. Chiang, On the estimation and inference of a cointegrated regression in panel data, Adv. Econ. 15 (1) (2000) 179–222.

[59] A. Kasman, Y.S. Duman, CO_2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis, Econ. Model. 44 (2015) 97–103.

[60] F. Kula, The long-run relationship between renewable electricity consumption and GDP: evidence from panel data, Energy Sources Part B Econ. Plan. Policy 9 (2) (2014) 156–160.

[61] D. Kwiatkowski, P.C. Phillips, P. Schmidt, Y. Shin, Testing the null hypothesis of stationarity against the alternative of a unit root: how sure are we that economic time series have a unit root? J. Econ. 54 (1) (1992) 159–178.

[62] G. Lee, Long run equilibrium relationship between inward FDI and productivity, J. Econ. Dev. 32 (2) (2007) 183.

[63] A. Levin, C.F. Lin, C.S.J. Chu, Unit root tests in panel data: asymptotic and finite-sample properties, J. Econ. 108 (1) (2002) 1–24.

[64] F. Li, S. Dong, X. Li, Q. Liang, W. Yang, Energy consumption-economic growth relationship and carbon dioxide emissions in China, Energy Policy 39 (2011) 568–574.

[65] A.J. Lopez-Menendez, R. Perez, B. Moreno, Environmental costs and renewable energy: re-visiting the environmental Kuznets curve, J. Environ. Manag. 145 (2014) 368–373.

[66] N.C. Mark, D. Sul, Cointegration vector estimation by panel DOLS and long-run money demand, Oxf. Bull. Econ. Stat. 65 (5) (2003) 655–680.

[68] K. Menyah, Y. Wolde-Rufael, CO_2 emissions, nuclear energy, renewable energy and economic growth in the US, Energy Policy 38 (6) (2010) 2911–2915.

[69] P.K. Narayan, R. Smyth, A panel co-integration analysis of the demand for oil in the Middle East, Energy Policy 35 (12) (2007) 6258–6265.

[70] M. Nasir, F.U. Rehman, Environmental Kuznets curve for carbon emissions in Pakistan: an empirical investigation, Energy Policy 39 (3) (2011) 1857–1864.

[71] S. Ng, P. Perron, Lag length selection and the construction of unit root tests with good size and power, Econometrica 69 (6) (2001) 1519–1554.

[72] A. Omri, CO_2 emissions, energy consumption and economic growth nexus in MENA countries: evidence from simultaneous equations models, Energy Econ. 40 (2013) 657–664.

[73] I. Ozturk, A. Acaravci, CO_2 emissions, energy consumption and economic growth in Turkey, Renew. Sustain. Energy Rev. 14 (9) (2010a) 3220–3225.

[74] I. Ozturk, A. Acaravci, The causal relationship between energy consumption and GDP in Albania, Bulgaria, Hungary and Romania: evidence from ARDL bound testing approach, Appl. Energy 87 (6) (2010b) 1938–1943.

[75] H.T. Pao, C.M. Tsai, Multivariate Granger causality between CO 2 emissions, energy consumption, FDI (foreign direct investment) and GDP (gross domestic product): evidence from a panel of BRIC (Brazil, Russian Federation, India, and China) countries, Energy 36 (1) (2011) 685–693.

[76] H.T. Pao, H.C. Yu, Y.H. Yang, Modeling the CO_2 emissions, energy use, and economic growth in Russia, Energy 36 (8) (2011) 5094–5100.

[77] J. Park, T. Hong, Analysis of South Korea's economic growth, carbon dioxide emission, and energy consumption using the Markov switching model, Renew. Sustain. Energy Rev. 18 (2013) 543–551.

[78] P. Pedroni, Critical values for cointegration tests in heterogeneous panels with multiple regressors, Oxf. Bull. Econ. Stat. 61 (s 1) (1999) 653–670.

[79] P. Pedroni, Purchasing power parity tests in cointegrated panels, Rev. Econ. Stat. 83 (2001) 727–731.

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

[81] M.H. Pesaran, Y. Shin, R.J. Smith, Bounds testing approaches to the analysis of level relationships, J. Appl. Econ. 16 (3) (2001) 289–326.

[82] M.H. Pesaran, General Diagnostic Tests for Cross Section Dependence in Panels, Working Papers in Economics No. 0435, University of Cambridge, Cambridge, 2004.

[83] M.H. Pesaran, A simple panel unit root test in the presence of cross-section dependence, J. Appl. Econ. 22 (2) (2007) 265–312.

[84] P.C. Phillips, P. Perron, Testing for a unit root in time series regression, Biometrika 75 (2) (1988) 335–346.

[85] P. Sadorsky, Renewable energy consumption, CO_2 emissions and oil prices in the G7 countries, Energy Econ. 31 (3) (2009) 456–462.

[86] N.P. Say, M. Yucel, Energy consumption and CO_2 emissions in Turkey: empirical analysis and future projection based on an economic growth, Energy Policy 34 (18) (2006) 3870–3876.

[87] F. Seker, H.M. Ertugrul, M. Cetin, The impact of foreign direct investment on environmental quality: a bounds testing and causality analysis for Turkey, Renew. Sustain. Energy Rev. 52 (2015) 347–356.

[88] M. Shahbaz, S.A. Solarin, H. Mahmood, M. Arouri, Does financial development reduce CO_2 emissions in Malaysian economy? A time series analysis, Econ. Model. 35 (2013) 145–152.

[89] M. Shahbaz, N. Khraief, G.S. Uddin, I. Ozturk, Environmental Kuznets curve in an open economy: a bounds testing and causality analysis for Tunisia, Renew. Sustain. Energy Rev. 34 (2014) 325–336.

[90] M. Shahbaz, S. Nasreen, F. Abbas, O. Anis, Does foreign direct investment impede environmental quality in high-, middle-, and low-income countries? Energy Econ. 51 (2015a) 275–287.

[91] M. Shahbaz, N. Loganathan, M. Zeshan, K. Zaman, Does renewable energy consumption add in economic growth? an application of auto-regressive distributed lag model in Pakistan, Renew. Sustain. Energy Rev. 44 (2015b) 576–585.

[92] S. Shafiei, R.A. Salim, Non-renewable and renewable energy consumption and CO_2 emissions in OECD countries: a comparative analysis, Energy Policy 66 (2014) 547–556.

[93] U. Soytas, R. Sari, B.T. Ewing, Energy consumption, income, and carbon emissions in the United States, Ecol. Econ. 62 (3) (2007) 482–489.

[94] U. Soytas, R. Sari, Energy consumption, economic growth, and carbon emissions: challenges faced by an EU candidate member, Ecol. Econ. 68 (6) (2009) 1667–1675.

[95] D.I. Stern, The rise and fall of the environmental Kuznets curve, World Dev. 32 (8) (2004) 1419–1439.

[96] J. Sulaiman, A. Azman, B. Saboori, The potential of renewable energy: using the environmental Kuznets curve model, Am. J. Environ. Sci. 9 (2) (2013) 103–112.

[97] C.F. Tang, B.W. Tan, The impact of energy consumption, income and foreign direct investment on carbon dioxide emissions in Vietnam, Energy 79 (2015) 447–454.

[98] H.Y. Toda, T. Yamamoto, Statistical inference in vector autoregressions with possibly integrated processes, J. Econ. 66 (1) (1995) 225–250.

[99] J. Westerlund, D.L. Edgerton, A panel bootstrap cointegration test, Econ. Lett. 97 (2007) 185–190.

[100] N.C. Yavuz, CO_2 emission, energy consumption, and economic growth for turkey: evidence from a cointegration test with a structural break, Energy Sources Part B Econ. Plan. Policy 9 (3) (2014) 229–235.

[101] E. Zivot, D.W.K. Andrews, Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis, J. Bus. Econ. Stat. 20 (1) (2002) 25–44.

Web References

[102] UN Treaty Collection, Kyoto Protocol to the United Nations Framework Convention on Climate Change, 2015. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-a&chapter=27&lang=en (accessed 18.11.15.).

[103] EEA, Trends and Projections in Europe 2013, 2013. http://www.eea.europa.eu/publications/trends-and-projections-2013 (accessed 18.11.15.).

[104] EEA, Progress towards 2008–2012 Kyoto Targets in Europe, 2014. http://www.eea.europa.eu/publications/progress-towards-2008-2012-kyoto (accessed 18.11.15.).
[105] European Council Report. http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf, 2014 (accessed 18.11.15.).
[106] World Development Indicators. http://data.worldbank.org/indicator/NE.TRD.GNFS.ZS, 2015 (accessed 18.11.15.).