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RESEARCH ARTICLE

The influence of renewable and non-renewable energy consumption and real income on CO_2 emissions in the USA: evidence from structural break tests

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Abstract The objective of this study is to explore the influence of the real income (GDP), renewable energy consumption and non-renewable energy consumption on carbon dioxide (CO_2) emissions for the United States of America (USA) in the environmental Kuznets curve (EKC) model for the period 1980–2014. The Zivot-Andrews unit root test with a structural break and the Clemente-Montanes-Reyes unit root test with a structural break report that the analyzed variables become stationary at first-differences. The Gregory-Hansen cointegration test with a structural break and the bounds testing for cointegration in the presence of a structural break show CO_2 emissions, the real income, the quadratic real income, renewable and non-renewable energy consumption are cointegrated. The long-run estimates obtained from the ARDL model indicate that increases in renewable energy consumption mitigate environmental degradation whereas increases in non-renewable energy consumption contribute to CO_2 emissions. In addition, the EKC hypothesis is not valid for the USA. Since we use time-series econometric approaches that account for structural break in the data, findings of this study are robust, reliable and accurate. The US government is advised to put more weights on renewable sources in energy mix, to support and encourage the use and adoption of renewable energy and clean technologies, and to increase the public awareness of renewable energy for lower levels of emissions.

Keywords CO_2 emissions · Renewable energy · Non-renewable energy · Real GDP · EKC model · Structural break

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Introduction

The amount of carbon dioxide (CO_2) emissions has tremendously increased for over the past years. In detail, the world CO_2 emissions increased from 19.35 million kilotons in 1980 to 35.84 million kilotons in 2013, indicating that it increased by about 84% along this period (WDI 2017).[1] The United States of America (USA) as being the second largest emitter produced more than 14% of the global CO_2 emissions, which was even more than that the European Union as a whole produced in the same year. In addition, the USA was the largest economy with the real GDP of $16,597 billion in 2015 and accounted for about 22% of the world GDP (WDI 2017). Moreover, the USA was the second largest consumer of primary energy with nearly 97 quadrillion Btu in 2013 and consumed nearly 18% of the world total (EIA 2017)[2]. Soytas et al. (2007), Baek (2015), Dogan and Turkekul (2016) show that increases in aggregate energy consumption contribute to carbon emissions in the USA just as many studies including Ang (2007, 2008), Apergis and Payne (2009), Zhang and Cheng (2009), Jalil and Feridun (2011), Pao et al. (2011), Tiwari et al. (2013), Shahbaz et al. (2013), Farhani et al. (2014), Yavuz

[1] Available at data.worldbank.org (accessed on 01/03/2017).
[2] Available at http://www.eia.gov/tools/faqs/faq.cfm?id=87&t=1 (accessed on 01/03/2017).

(2014), Farhani and Ozturk (2015), Kasman and Duman (2015), Shahbaz et al. (2015), Seker et al. (2015), Kais and Ben Mbarek (2015), Tang and Tan (2015), Dogan and Seker (2016a), and Zhang and Gao (2016) reach the same conclusion for various countries and regions.

Even though the USA plays an important role in the world energy market and world affairs, and is responsible for a considerable portion of the world production and emissions, it has nor undertaken a commitment to reduce greenhouse gas emissions at a global framework, and neither joined the Kyoto protocol. In this line, the other interesting fact is that a large part of the USA energy needs has been met by fossil fuels (coal, oil, petroleum, and natural gas) such that nearly 91 and 83% of total energy consumption came from fossil fuels in 1980 and 2013, respectively (WDI 2017). As being in the same class as the USA, the share of fossil fuels in the EU's total energy consumption dropped from 92 to 72% over the same period. Interestingly, the EU carbon emissions reduced by about 20% from 1980 to 2013. The positive relationship between the levels of emissions and the use of non-renewable energy is the first notable subject. The other remarkable point is that the EU as a whole; as opposed to the USA, has joined the Kyoto protocol with a commitment of decreasing the levels of emissions, and accordingly projected to increase the share of renewable sources in energy mix[3]. The negative effect of renewable energy consumption on carbon emissions for the EU is statically found by Lopez-Menendez et al. (2014) and Dogan and Seker (2016b). Nevertheless, we believe that the US government should be willing to do its bit for the environment. For a purpose of guidance to the US government, we aim to investigate the effects of renewable energy consumption and non-renewable energy consumption on the levels of CO_2 emissions for the USA. Table 1 shows the studies that we count in the environment-growth-renewable energy nexus. Chiu and Chang (2009), Sulaiman et al. (2013), Shafiei and Salim (2014), Baek and Pride (2014), Boluk and Mert (2015), Jebli and Youssef (2015), Al-Mulali et al. (2015a), Jebli et al. (2016), Bilgili et al. (2016), Al-Mulali and Ozturk (2016), Dogan and Seker (2016b, c), and Bento and Moutinho (2016) show that renewable energy is environmentally friendly as it mitigates carbon emissions; on the contrary, non-renewable energy is environmentally unfriendly as it contributes to the level of emissions. Likewise, the US government will be advised to put more weights on renewable sources in energy mix, support and encourage the use and adoption of renewable energy and clean technologies, and increase the public awareness of renewable energy for lower pollution even though it refuses to affiliate with the commitments under the Kyoto protocol if this study finds a negative relationship between renewable energy consumption and carbon emissions, and a positive one between non-renewable energy consumption and CO_2 emissions for the USA. The investigation of the impact of energy consumption by sources is thus essential for policy implications. Table 1 also shows that majority of the existing studies in the environment-growth-renewable energy nexus are based on panel data and thus produce identical coefficient parameters across countries within the panel. Therefore, single-country studies are of interest for researchers and policy makers so as to obtain more accurate and consistent results for individual countries.

Because the USA is an important country for researchers and policy makers to investigate, there are several well-known studies in the literature; however, their contributions are limited. The first group of studies focusing on the USA uses aggregate energy consumption and thus fails to reveal the relationship between renewable and non-renewable energy consumption and the environment (Dogan and Turkekul 2016; Baek 2015; Soytas et al. 2007). The second group ignores the importance of energy consumption to explain the environmental Kuznets curve (EKC) for the USA (Koirala and Mysami 2015). The third group does not consider non-renewable energy consumption and the EKC hypothesis in the model (Jaforullah and King 2015). The last group investigates the causal relationship between renewable energy, economic growth, and CO_2 emissions but does not analyze the long-run coefficient estimates; thus, fails to determine whether or not the effect of renewable energy consumption on pollution is statistically significant and negative (Menyah and Wolde-Rufael 2010; Payne 2012). More importantly, a major criticism to the existing studies in the literature, we notice, is the selection of methodology. Because countries most likely experience unexpected shocks (structural change) in energy markets, environment, and macroeconomic variables, the use of econometric methods without structural break can cause estimation errors (Dogan 2016; Vaona 2012).

To fulfill the abovementioned gaps in the literature, this study for the first time analyzes the effects on CO_2 emissions of real GDP, renewable energy consumption, and non-renewable energy consumption for the USA in the EKC model by using estimation techniques with structural break. This study employs the Zivot-Andrews unit root test with structural break, the Clemente-Montanes-Reyes unit root test with structural break, the Gregory-Hansen cointegration test with structural break, the bounds testing for cointegration in the presence of structural break, and the autoregressive distributed lag (ARDL) model for long-run estimates.

The next section presents model and data; methods, empirical findings, and policy recommendations are discussed in the third section; the last section brings together the overall results and policy implications.

Model and data

Following the recent works by Boluk and Mert (2014), and Farhani and Shahbaz (2014), we use the EKC model as in

[3] Available at http://www.eea.europa.eu/publications/trends-and-projections-in-europe-2015 (accessed on 01/03/2017).

Table 1 A survey of literature on the environment-GDP-renewable energy nexus

Study	Case	Period	Variables	Methodology	Conclusions
Chiu and Chang (2009)	Panel of OECD countries	1996–2005	CO_2, GDP, CPI, REC	Threshold effect	GDP and REC increases CO_2 for lower threshold; REC decreases CO_2 for upper threshold.
Sadorsky (2009)	Panel of G7 countries	1980–2005	REC, GDP, CO_2, P (prices)	Breitung, IPS, LLC, ADF, PP, Pedroni cointegration, FMOLS, DOLS	GDP and CO_2 are major determinants of REC
Iwata et al. (2010)	France	1960–2003	CO_2, GDP, GDP^2, nuclear, URB, TR	PP, ARDL model	Nuclear decreases CO_2. EKC is valid.
Apergis et al. (2010)	Panel of developed and developing countries	1984–2007	CO_2, GDP, nuclear, REC	LLC, IPS, ADF, PP, LLL cointegration	Nuclear decreases CO_2, REC and GDP increases CO_2
Bengochea and Faet (2012)	Panel of EU countries	1990–2004	REC, GDP, CO_2, P	OLS with FE and RE, FGLS	GDP and CO_2 increase REC
Sulaiman et al. (2013)	Malaysia	1980–2009	CO_2, GDP, GDP^2, REC, TR	ADF, PP, ARDL model	TR and REC decrease CO_2. EKC is valid.
Boluk and Mert (2014)	Panel of EU countries	1990–2008	CO_2, GDP, GDP^2, REC, NREC	OLS with FE	REC and NREC contribute to CO_2. EKC is not valid.
Farhani and Shahbaz (2014)	Panel of MENA countries	1980–2009	CO_2, GDP, GDP^2, REC, NREC	Breitung, IPS, Pedroni cointegration, FMOLS, DOLS	REC and NREC increase CO_2. EKC is valid.
Lopez-Menendez et al. (2014)	Panel of EU countries	1996–2010	CO2, GDP, GDP^2, GDP^3, REC	OLS with FE and RE	REC decreases CO_2. EKC is not valid.
Shafiei and Salim (2014)	Panel of OECD countries	1980–2011	CO_2, GDP, GDP^2, REC, NREC, POP	ADF, PP, Breitung, Johansen cointegration, Westerlund cointegration, GMM, AMG	REC decreases CO_2; NREC increases CO_2. EKC is valid.
Baek and Pride (2014)	USA, Japan, France, Korea, Spain, Canada	1970–2007	CO_2, GDP, nuclear	DFGLS, Johansen cointegration	Nuclear decreases CO_2 in all countries, GDP decreases CO_2 in USA, Canada and France
Apergis and Payne (2014)	Panel of Central American countries	1980–2010	CO_2, REC, GDP, P	LLC, IPS, ADF, PP, non-linear panel cointegration, FMOLS	GDP, CO_2 and P increase REC
Jebli and Youssef (2015)	Panel of North Africa	1971–2008	GDP, CO_2, combustible and waste (CRW)	Breitung, LLC, IPS, Pedroni cointegration, FMOLS, DOLS	CO_2 and CRW increase GDP
Al-mulali et al. (2015a)	Panel of European countries	1990–2013	CO_2, GDP, TR, URB, FD, REC by sources (wind, solar, hydro, nuclear, and CRW)	IPS, ADF, PP, Pedroni cointegration, FMOLS	Five sources of REC decrease CO_2; GDP increases CO_2
Al-Mulali et al. (2015b)	Vietnam	1982–2011	CO_2, REC, NREC, GDP, IM, EXP, CA, L	ARDL model	NREC and IMP increase CO_2; REC is insignificant. EKC is not valid.

Table 1 (continued)

Study	Case	Period	Variables	Methodology	Conclusions
Boluk and Mert (2015)	Turkey	1961–2010	CO_2, GDP, GDP^2, REC	ADF, KPSS, ARDL model	REC decreases CO_2. EKC is valid.
Apergis and Payne (2015)	Panel of South America	1980–2010	CO_2, GDP, REC, P	ADF, PP, FMOLS	GDP, CO_2 and P increase REC
Dogan and Seker (2016b)	Panel of EU	1980–2012	CO_2, GDP, GDP^2,REC, NREC, TR	CADF, CIPS, LM bootstrap cointegration, DOLS, Dumitrescu-Hurlin causality	REC decreases CO_2, NREC increases CO_2. EKC is valid.
Al-Mulali and Ozturk (2016)	Panel of 27 advanced countries	1990–2012	CO_2, GDP, GDP^2,REC, NREC, TR, URB	ADF, IPS, Kao and Johansen-Fisher cointegration, FMOLS	REC decreases CO_2, NREC increases CO_2. EKC is valid.
Jebli et al. (2016)	Panel of OECD countries	1980–2010	CO_2, GDP, GDP^2,REC, NREC, TR	Breitung, IPS, LLC, ADF, PP, Pedroni cointegration, FMOLS, DOLS	REC decreases CO_2, NREC increases CO_2. EKC is valid.
Bilgili et al. (2016)	Panel of OECD countries	1977–2010	CO_2, GDP, GDP^2,REC	LLC, IPS, ADF, Pedroni cointegration, FMOLS, DOLS	REC decreases CO_2. EKC is valid.
Dogan and Seker (2016c)	Panel of top renewable energy countries	1985–2011	CO_2, GDP, GDP^2,REC, NREC, TR, FD	CADF, CIPS, LM bootstrap cointegration, DOLS, FMOLS	REC decreases CO_2, NREC increases CO_2. EKC is valid.
Bento and Moutinho (2016)	Italy	1960–2011	CO_2, GDP, REC, NREC, TR	Zivot-Andrews test, Gregory-Hansen cointegration, ARDL model	REC and GDP decrease CO_2, NREC increases CO_2

IPS Im-Pesaran-Shin test, LLC Levin-Lin-Chu test, *PP* Phillips-Perron test, *ADF* augmented Dickey-Fuller test, *KPSS* Kwiatkowski–Phillips–Schmidt–Shin test, *FE* fixed effects, *RE* random effects, *REC* renewable energy, *NREC* non-renewable energy, *FMOLS* fully modified ordinary least squares, *DOLS* dynamic ordinary least squares, *CPI* consumer price index, *TR* trade, *FD* financial development, *URB* urbanization

Eq. 1 wherein CO_2 emissions are regressed on GDP, the square of GDP, renewable energy consumption (REC) and non-renewable energy consumption (NREC):

$$CO_2 = \left(GDP, GDP^2, REC, NREC\right) \quad (1)$$

One can alternatively express the EKC model in an econometric framework by inserting a constant term (β_0) and an error term (ε_t) as in Eq. 2:

$$(CO_2)_t = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t{}^2 + \beta_3 REC_t + \beta_4 NREC_t + \varepsilon_t \quad (2)$$

where CO_2 is the carbon dioxide emissions in kilotons; GDP is the real gross domestic product in constant 2005 US$; REC is renewable energy consumption including biomass, wind, solar, geothermal, hydroelectric power in British thermal unit (BTU); NREC is non-renewable energy consumption including coal, natural gas, and petroleum in BTU. The data are obtained from the "World Development Indicators" (http://data.worldbank.org) and the "US Energy Information Administration" (www.eia.gov). The annual data cover the period 1980–2014. Since the time-series data are converted into their natural logarithm, β_k (k = 1, 2, 3, 4) can be interpreted as the elasticities of CO_2 emissions with respect to GDP, GDP^2, REC and NREC. In case of the validity of the EKC hypothesis the signs of β_1 and β_2 are positive and negative, respectively. The expected signs of β_3 and β_4 are negative and positive suggesting that renewable energy comes from environmentally friendly clean sources while non-renewable energy are environmentally unfriendly sources.

Methods and empirical findings

This section explores the stationarity properties of the analyzed time-series variables, cointegration relationship among them, and the long-run estimates of GDP, GDP^2, and renewable and non-renewable energy consumption on carbon emissions. In addition, we consider possible structural break in time-series econometric approaches.

Unit root tests

A fundamental purpose of using a unit root test is to control whether or not each time-series data contain unit root. Although the empirical findings are statistically and economically not meaningful a researcher will presumably estimate a spurious regression—a fairly high R^2 (goodness of fit of the model) and significant coefficients—unless either the variables under consideration are stationary at levels or are cointegrated in case they are non-stationary at levels. In order to avoid such econometrical problems, we apply both the Zivot-Andrews unit root test with endogenously determined structural break (ZA) (Zivot and Andrews 2002) and the Clemente-Montanes-Reyes unit root test with endogenously determined structural break (CMR) (Clemente et al. 1998) on CO_2 emissions, GDP (GDP^2), and renewable and non-renewable energy consumption. These tests are preferred to those (e.g., the Augmented Dickey-Fuller and the Phillips-Perron unit root tests) because the latter ones do not account for structural break in identifying integration properties of time-series data.

The results from the ZA test and CMR test are reported in Table 2. Based on their reports, we cannot reject the null hypothesis that CO_2 emissions, GDP (GDP^2), renewable and non-renewable energy consumption are stationary at levels; on the other hand, we have enough evidence to conclude that they become stationary at first-differences at 5% level significance. The years are the endogenously determined break dates. These should refer to a variety of situations, i.e., banking crisis, global financial crisis, real estate bubble, and upsurge in oil price, which remarkably affected US economy. As discussed earlier, we need to check whether or not the analyzed variables are cointegrated since we conclude that they are all, I(1), integrated of order one.

Table 2 Unit root tests with structural break

	Zivot-Andrews unit root test				Clemente-Montanes-Reyes unit root test			
	Level		1st difference		Level		1st difference	
	t-statistic	BD	*t*-statistic	BD	*t*-statistic	BD	*t*-statistic	BD
CO_2	−5.19**	2004	–	–	−2.90	1985	−4.87**	2006
GDP(GDP^2)	−4.32	2004	−6.46**	2008	−2.11	1990	−4.99**	2006
REC	−4.64	2001	−6.32**	2002	−2.91	2007	−7.47**	2000
NREC	−4.93	2002	−5.72**	2008	−2.71	1985	−6.28**	2006

The appropriate lag lengths are selected based on the Akaike Information Criteria

**Stands for the statistical significance at 5% level. BD is break date

Cointegration tests

In order to check the existence of cointegration relationship between carbon emissions, GDP, the square of GDP, and renewable and non-renewable energy consumption, this study first uses the Gregory-Hansen cointegration test with endogenously determined structural break based on the regime-trend shifts by Gregory and Hansen (1996) as indicated in Eq. 3:

$$Y_t = \beta_o + \beta_1 \varphi_t + \delta_1 T + \delta_2 \varphi_t T + \sum_{i=1}^{4} \alpha_{1i} X_{it} + \sum_{i=1}^{4} \alpha_{2i} \varphi_t X_{it} + \varepsilon_t \quad (3)$$

where Y_t is the dependent variable, X_{it} are the independent variables, ε_t is assumed to be I(0) error term, and φ_t is the dummy variable to consider a structural break in the constant, slope and trend.

$$\varphi_t = \begin{cases} 1\ldots\text{if } t > [n\tau] \\ 1\ldots\text{if } t > [n\tau] \end{cases}, 0 < \tau < 1 \text{ and } t = 1, 2, 3\ldots.\text{n}.$$

The results from the Gregory-Hansen cointegration test with a single structural change is posted in Table 3. We have enough evidence to reject the null hypothesis of no cointegration in favor of the alternative hypothesis of cointegration at 5% level of significance because the estimated statistics are greater than the 5% critical value. The years 1988–1989 are the endogenously determined break dates that may reflect to banking crisis that took place late 1980s, and a huge decrease in oil prices around 1985–1986. These events are important for energy market and prices, and the USA economy.

Although the results from the Gregory-Hansen cointegration test are reliable, we also apply the ARDL approach to cointegration (Pesaran et al. 2001) to further confirm the results shown in Table 3. The bounds testing for cointegration is constructed based on the standard log-linear functional specification. Following Pesaran and Pesaran (2009, pg. 318), we propose the following ARDL model for testing cointegration among the analyzed variables:

$$\begin{aligned}\Delta CO2_t = {} & \alpha_0 + \gamma D_{2006} + \sum_{i=1}^{2} \alpha_i \Delta CO2_{t-i} \\ & + \sum_{i=1}^{2} \vartheta_i \Delta GDP_{t-i} + \sum_{i=1}^{2} \delta_i \Delta GDP2_{t-i} \\ & + \sum_{i=1}^{2} \beta_i \Delta REC_{t-i} + \sum_{i=}^{2} \rho_i \Delta NREC_{t-i} + \phi_1 CO2_{t-i} \\ & + \phi_2 GDP_{t-i} + \phi_3 GDP2_{t-i} + \phi_4 REC_{t-i} \\ & + \phi_5 NREC_{t-i} + \varepsilon_t \end{aligned} \quad (4)$$

where Δ is the first difference parameter; α_0 is a constant parameter; D_{2006} is the dummy variable that takes the value of zero before the break date and the value of one after; α, β, ρ, ϑ, and δ are the coefficient parameters; ε is a normally distributed error term; the maximum lag length is 4, considering the time length. The joint F-statistic is used to investigate the significance of possible existence of a long-run relationship (cointegration) among CO_2 emissions, GDP, GDP^2, REC, and NREC. The null hypothesis of no cointegration, $H_o: \varnothing_1 = \varnothing_2 = \varnothing_3 = \varnothing_4 = \varnothing_5 = 0$, is tested against the alternative hypothesis of cointegration, $H_a: \varnothing_1 \neq \varnothing_2 \neq \varnothing_3 \neq \varnothing_4 \neq \varnothing_5 \neq 0$. More precisely, the null hypothesis of no cointegration cannot be rejected if the computed F-statistic is smaller than the lower critical bound; on the contrary, the null hypothesis of no long-run relationship can be rejected in favor of the alternative hypothesis if the computed F-statistic is greater than the upper critical bound.

Table 3 Gregory-Hansen cointegration test with structural break

Test	Statistic	BD	5% critical value
ADF	−7.10**	2005	−6.84
Z_t	−7.34**	2006	−6.84

The Gregory-Hansen cointegration test is estimated for the model $f(CO_2/GDP, GDP^2, REC, NREC)$

**Stands for the statistical significance at 5% level

Table 4 indicates the F-statistic obtained from the bounds testing for cointegration in the presence of structural change. We have enough evidence to reject the null hypothesis of no cointegration in favor of the alternative hypothesis of cointegration among the analyzed time-series data at 5% level of significance since the tabulated F-statistic is greater than 95% critical value. In light of the reports from the two cointegration tests in the presence of structural break, we can assert that there is a long-run relationship among carbon emissions, GDP, quadratic GDP, REC, and NREC for the USA.

Long-run estimates and discussions

Once the existence of long-run relationship is detected between the non-stationary time-series data, long-run estimates become statistically and economically meaningful, reliable, and accurate. In order to estimate long-run coefficients on GDP, GDP^2, and renewable and non-renewable energy for CO_2 emissions, we apply the ARDL procedure on the EKC model given in Eq. 2.

The coefficients on GDP, GDP^2, renewable energy consumption, and non-renewable energy consumption for CO_2 emissions are reported in Table 5. The estimated coefficients are equivalent to the elasticities of carbon emissions with respect to the analyzed variables since the time-series data are transformed into their natural logarithms. As expected, increases in the use of renewable energy negatively affect the levels of emissions; on the other hand, increases in non-renewable energy consumption trigger the air pollution.

Table 4 Bounds testing for cointegration with structural break

Model	F-statistic	BD	95% lower bound	95% upper bound
$f(CO_2/GDP, GDP^2, REC, NREC)$	7.63**	2006	3.90	5.25

BD is the known break date adopted from the Gregory-Hansen cointegration test. The critical value bounds are calculated by stochastic simulations using 20,000 replications because the actual critical values for different sample sizes and for models that use dummy variables can differ from those posted in Pesaran et al. (2001)

**Stands for the statistical significance at 5% level

More precisely, a 1% rise in REC decreases CO_2 emissions by 0.09%, and a 1% increase in NREC increases the pollution by 1.04%. The findings are consistent with Koirala and Mysami (2015), Chiu and Chang (2009), Sulaiman et al. (2013), Shafiei and Salim (2014), Lopez-Menendez et al. (2014), Al-Mulali et al. (2015a, b), Boluk and Mert (2015), Bilgili et al. (2016), Bento and Moutinho (2016), Dogan and Seker (2016b, c), and Jebli et al. (2016). An obvious action towards the low levels of emissions is to increase the use of energy from renewable sources and decrease the use of energy from non-renewable sources in energy mix in the USA. In addition, regulatory policies should be implemented to fight for the pollution such that buildings, institutions, firms, factories, and electricity power companies should be forced by regulations to meet some portion of their energy needs from renewable sources, and to gradually increase its portion in the future. The US government should publicly share that the intention of this legislation is for better environment and to leave a cleaner world for the next generations. Hence, creation of public awareness of renewable energy and clean environment plays a significant role in this matter.

The signs of elasticity of CO_2 emissions with respect to GDP and the square of GDP are negative and positive, respectively, indicating that the EKC hypothesis is not valid for the USA. More precisely, the (partial) marginal effect of GDP on CO_2 is calculated by $\beta_1 + 2*\beta_2*GDP$ $(-4.66 + 2*0.08*GDP)$, and thus the (partial) marginal effect of GDP on carbon emissions is clearly negative at the earlier stages of economic growth; but, it increases and eventually becomes positive as the USA shifts to higher stages. In other words, increases in the levels of production lead to environmental degradation after some threshold level. This is consistent with Soytas et al. (2007), and Dogan and Turkekul (2016) which analyze the validity of the EKC hypothesis for the USA using the aggregate energy consumption. In addition, lack of the EKC hypothesis in the present study is in line with those focused on several different cases; Ozturk and Acaravci (2010) for Turkey, Pao et al. (2011) for Russia, Du et al. (2012) for China, Chandran and Tang (2013) for ASEAN, Boluk and Mert (2014) for the EU, Lopez-Menendez et al. (2014) for the EU, Dogan et al. (2015) for the OECD countries, Al-Mulali et al. (2015b) for Vietnam, Ajmi et al. (2015) for Italy, Farhani and Ozturk (2015) for Tunisia. Obviously, the use of renewable energy and the adoption of environmentally friendly technologies in production processes are important for a cleaner environment. In addition, given the fact that generating energy from renewable sources currently costs more than that from non-renewable sources, the US government should also encourage and financially support the institutions, universities, and researchers to work on reducing the cost of producing energy from all types of renewable sources, and on the application of the methods of environmental protection.

The results and policy implications are robust and accurate because the proposed model passes several diagnostic tests. First, the goodness of fit of the specification ($R^2 = 0.98$) is very close to one that is preferred in econometric analysis as the adjustment of the model in Eq. 2 is fairly perfect. Second, a statistically significant F-statistic (60.75) suggests the joint significance of the analyzed variables in the given model. Third, the Durbin-Watson (DW) statistic is around 2, indicating that residuals are not correlated. In addition to the DW-statistic, the LM test of residual serial correlation also suggests that we cannot reject the null hypotheses of no serial correlation and homoscedasticity at 5% level of significance since the

Table 5 Long-run estimates from ARDL model

Regressor	Coeff.	T-ratio	*p* value
GDP	−4.66*	−1.93	0.07
GDP2	0.08**	1.96	0.07
REC	−0.09***	−7.93	0.00
NREC	1.04***	16.13	0.00
C	80.35**	2.21	0.04
DB	−0.01**	−2.41	0.03
F-stat	60.75***		0.00
R^2	0.98		
DW-stat	2.13		
	LM-stat	*p* value	
Serial correlation	0.46	0.49	
Heteroscedasticity	1.56	0.21	
Normality	0.39	0.82	

The ARDL model (2,4,4,1,1) is selected based on the Akaike Information Criteria

*Stands for the statistical significance at 10% level

**Stands for the statistical significance at 5% level

***Stands for the statistical significance at 1% level associated *p* value (0.49 and 0.21) is far greater than 0.05. Last, the null hypothesis of normality based on a test of skewness and kurtosis of residuals cannot be rejected at 5% level of significance.

Conclusions and policy implications

The USA has joined neither the Kyoto protocol nor an international framework dealing with increased carbon emissions even though it is the second largest producer of carbon emissions, the second largest consumer of energy, and the largest economy in the world. The aim of this study is to guide the US government in this matter. Hence, the current study analyzes the influence of the real income, renewable energy consumption, and non-renewable energy consumption for the USA in the EKC model. The findings are:

- The Zivot-Andrews and the Clemente-Montanes-Reyes unit root tests with structural break report that the analyzed variables become stationary at first-differences.
- The Gregory-Hansen cointegration test with structural break and the bounds testing for cointegration in the presence of structural break show that the real income, the quadratic real income, and renewable and non-renewable energy consumption are cointegrated.
- The long-run estimates obtained from the ARDL model indicate that increases in renewable energy consumption mitigate carbon emissions whereas increases in non-renewable energy consumption contribute to CO_2 emissions. In addition, the EKC hypothesis is not valid for the USA since the signs of coefficients on the real income and the quadratic income are negative and positive, respectively.

Based on the conclusions that we reach, possible policy implications are:

- The use of energy from renewable sources should be increased while the use of energy from non-renewable sources should be decreased.
- Regulatory policies play an important role to handle the increased CO_2 emissions. Alternatively, public and private buildings, firms and factories, and electric power industry should be forced by regulations to gradually increase the share of renewable sources in energy mix in the near future. The US government should publicly share that the intention of this legislation is for better environment.
- The creations of public awareness of renewable energy and clean environment play significant roles in lower levels of emissions.
- The adoptions of renewable energy sources and environmentally-friendly technologies in each step of production processes are important for environmental improvements.
- Projects on the application of the methods of environmental protection should be further supported.

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