Environmental Science and Pollution Research (2022) 29:30134–30144
https://doi.org/10.1007/s11356-021-17684-z

RESEARCH ARTICLE

Renewable energy-economic growth nexus revisited for the USA: do different approaches for modeling structural breaks lead to different findings?

Umit Bulut[1] · Muhammad Shahbaz[2,3] · Xuan Vinh Vo[4]

Received: 14 September 2021 / Accepted: 18 November 2021 / Published online: 8 January 2022

Abstract
It can be observed from the existing energy literature the previous papers investigating the influence of renewables consumption on GDP for the USA commonly ignore structural breaks in the US economy. Hence, the purpose of this paper is to examine the impact of renewable energy consumption on economic growth for the USA using quarterly data over the period 1977Q1-2019Q3 through unit root and cointegration methods based on different approaches in modelling structural breaks. Our empirical evidence confirms that all unit root tests give similar outputs and show all the variables become stationary at 1st differences. Besides, cointegration tests show highly different results in terms of the statistical significance of the coefficients. For instance, the cointegration test without structural breaks indicates that renewable energy consumption has no impact on economic growth. With sharp structural breaks in the cointegration approach, there is no cointegration between the variables. The empirical findings of the cointegration test with sharp and gradual breaks imply that renewable energy consumption has positive effects on economic growth. This paper discusses the implications of the empirical findings.

Keywords Renewable energy · Economic growth · US economy · Structural breaks · Sharp breaks · Gradual breaks

Introduction

To stress the role of energy in economic activities, Shahbaz (2018) uses an illuminating metaphor and notes that "energy consumption drives the wheels of economic growth." In this statement, energy, as a crucial input for economic activities, can feed economic growth along with other factors of production, namely capital and labor (Menegaki 2018). Therefore, reasonable energy prices, availability of energy sources, and sustainability of energy supply are strongly associated with the welfare level of the society (Inglesi-Lotz 2018). As a result of this relationship, the expansion of economic activities, increasing population along with rapid urbanization, has resulted in increases in energy utilization since the 1950s (Bilgili et al. 2016; Menegaki 2018). For instance, British Petroleum (2019, hereafter BP) data exhibit that energy consumption grew by 18.5% from 2008 to 2018 in the world. Then, it becomes crucial for economies whose sources will be exploited to meet this huge energy demand. The data on this topic show that the shares of fossil energy, nuclear energy, and renewable energy in primary energy consumption were, respectively, about 85%, 4%, and 11% by 2018 (BP 2019). This high dependence on fossil energy sources results in important problems in the world: depletion of fossil energy sources (Chapman 2014), concerns for the continuous availability of fossil energy at reasonable prices (IEA 2019), and serious environmental problems, i.e., air

Responsible Editor: Roula Inglesi-Lotz

Umit Bulut
ubulut@ahievran.edu.tr

Muhammad Shahbaz
muhdshahbaz77@gmail.com

Xuan Vinh Vo
vxvinh@yahoo.com

1 Department of Economics, Faculty of Economics and Administrative Sciences, Kirsehir Ahi Evran University, Kirsehir, Turkey

2 School of Management and Economics, Beijing Institute of Technology, Beijing, China

3 Institute of Business Research, University of Economics, Ho Chi Minh City, Vietnam

4 Institute of Business Research and CFVG, University of Economics, Ho Chi Minh City, Vietnam

pollution, climate change, and global warming, stemming from the combustion of fossil fuels (Bilgili et al. 2017; Bulut and Muratoglu 2018; Danish and Ulucak 2020). These problems, especially concerns for environmental degradation arising from the employment of fossil sources, have led policymakers to discuss how the dependency on fossil energy sources can be reduced. Therefore, many meetings have been organized to reduce environmental threats since the 1970s. For instance, Rio de Janeiro Earth Summit (1992), the Kyoto Protocol (1997–2005), and the United Nations Climate Change Conference (2015) can be considered as the most important attempts to decrease the use of fossil energy sources (Menegaki and Tsani 2018). As a result of these meetings, there has been a great policy emphasis on the adoption of technologies stimulating renewable and clean energy sources, namely hydroelectric, biomass, solar, wind, and geothermal (Diemuodeke and Briggs 2018; Koengkan et al. 2020). Energy policies which are capable of decreasing the high dependence on fossil sources are crucial for sustainable development (Uzar 2020). Therefore, in policy debates for sustainable development, there exists a consensus for the transition towards renewable energy sources by speeding up the development and the diffusion of renewable energy technologies (Strachan et al. 2015; Tabrizian 2019). In other words, the development of renewable energy sources is considered as the main way to reduce the problems and concerns created by the use of fossil energy sources in a global perspective (Lu et al. 2020). Thus, many countries are actively encouraging renewable energy production and consumption via various policies, and renewable energy is considered as a crucial policy tool for sustainable development today. On the other hand, energy conservation policies have remained in the background as governments do not want to sacrifice economic growth for improving environmental quality. Therefore, investments in renewable energy sources have resulted in a great decrease in renewable energy technologies' costs in recent years (Diemuodeke and Briggs 2018; Kocaarslan and Soytas 2019). Decreases in costs led to a feedback mechanism and stimulated more investments in renewable energy technologies.

Within this scope, policymakers have two main expectations about renewables: to decrease environmental degradation and to meet energy needs for economic growth (Fang 2011). In the empirical energy literature, the former is usually tested via the environmental Kuznets curve hypothesis.[1] Besides, the latter is related to the research field focusing on the renewable energy-economic growth nexus. While the energy-economic growth nexus has been examined in the empirical energy literature since the 1970s energy crisis (Hajko et al. 2018), the renewable energy-economic growth nexus has gained attraction since the meetings and efforts denoted above.

When one examines the empirical literature on the energy-economic growth relationship, he/she will notice that researchers tend to follow a panel data analysis at investigating this nexus as they usually have many observations through a panel data model (Tiwari et al. 2018; Tugcu 2018). Put differently, panel data analysis is more popular compared to time series analysis in the energy literature. This leaning may lead to two considerable problems that researchers may be exposed to while they are discussing empirical findings. First, findings for the whole panel are likely to conceal specific features and internal dynamics of countries in the panel data set (Menyah et al. 2014). In such a case, it is likely that a policy proposal based on the empirical findings are not proper for some countries in the sample. Second, researchers usually ignore the existence of structural breaks that can change the interactions between energy and economic growth in time. Put differently, they commonly employ estimation methods which do not consider structural breaks, whereas these breaks may have serious economic and social influences.

To determine whether renewable energy is able to provide energy requirements for economic activities, this paper examines the impact of renewable energy consumption on economic growth for the USA using quarterly data from 1977Q1 to 2019Q3. The contributions of the paper to the existing literature are fourfold. First, contrary to the major part of the empirical literature, this paper follows a time series analysis as relatively long time series data are publicly available for the USA. Second, the USA is the largest economy in the world and is a great energy consumer (Danish and Ulucak 2021a). Accordingly, as per World Bank (2020), the share of the US economy in total world GDP (constant 2010 USD) was about 21.6% in 2018. Besides, with regard to Energy Information Administration (henceforth EIA 2020a) data, the share of the USA in total world primary energy consumption was about 17% in 2018. Hence, positive and/or negative shocks in the US economy and changes in energy demand of the USA can affect other countries in the world. Therefore, the paper's empirical findings are crucial for not only the USA but also the rest of the world. Third, to avoid the possible omitted variables bias, the paper uses a Cobb–Douglas production function including capital, labor, renewable energy consumption, and fossil energy consumption. Thus, the paper makes a comparative analysis of the influences of fossil and renewable energy consumption on the US economic growth as well. Last but most important, this paper makes a methodological contribution to the existing energy literature. Previous papers on the effect of renewable consumption on output

[1] See Shahbaz and Sinha (2019) for details about the curve and the literature.

for the USA employ different estimation methodologies, such as causality tests (Aslan 2016; Bilgili et al. 2017; Bowden and Payne 2010; Payne 2009; Troster et al. 2018; Tugcu and Topcu 2018; Yildirim et al. 2012), the generalized variance decomposition method (Ewing et al. 2007), cointegration tests (Bulut and Apergis 2021; Bulut and Inglesi-Lotz 2019), a wavelet coherence approach (Bilgili 2015; Bilgili et al. 2019), and the Markov switching methodology (Bildirici and Gokmenoglu 2017). However, none of these regards different approaches to model structural breaks. This paper employs time series methods that use different approximations in modelling structural breaks by paying attention to breaks. Accordingly, the paper first employs the autoregressive distributed lag (ARDL) cointegration test without structural breaks. Then, the paper relaxes the assumption of no breaks and performs the cointegration test of Hatemi-J (2008), which assumes the structural breaks occur instantaneously. Finally, the paper carries out the cointegration test propounded by Tsong et al. (2016) that posits structural breaks may arise instantaneously or gradually. While the Hatemi-J (2008) cointegration test regards only sharp breaks, Tsong et al. (2016) cointegration test takes not only sharp but also gradual breaks into account. In this way, this paper also investigates whether different ways in modelling structural breaks induce different findings. It should be noted that the paper follows the same way in unit root testing and employs unit root tests based on different approximations in modelling breaks.

All unit root tests present evidence all the variables are stationary at first differences, whereas the cointegration tests signify different empirical findings in terms of the impact of renewable energy consumption on the US economic growth. Accordingly, (i) the ARDL cointegration test yields that renewable energy consumption has no effect on economic growth, (ii) the Hatemi-J (2008) cointegration test's results imply that there is no cointegration and so long-run parameters cannot be estimated, and (iii) the empirical findings of Tsong et al. (2016) cointegration test indicate economic growth is positively linked with renewable energy consumption.

The remainder of the paper is as the following: The empirical literature is given in Sect. 2. Section 3 introduces model and data set. Section 4 reveals the methodology. Section 5 demonstrates empirical results. Section 6 concludes the paper.

Literature review

There is an expanding empirical literature on the relationship between renewable energy consumption and economic growth for the USA, yet the number of empirical studies is still limited. This paper presents the empirical literature focusing on the influence of renewable energy consumption on economic growth for the USA.[2] For instance, Ewing et al. (2007) utilize disaggregated renewable energy data for the 2001–2005 period and carry out the generalized variance decomposition method. They detect hydroelectric, solar, waste, wind, and wood energy's consumption increase GDP. Payne (2009) utilizes data for the period 1949–2006 and finds there is not any causality between GDP and total renewable consumption. Bowden and Payne (2010) examine the renewables consumption-economic growth nexus for some sectors over the period 1949–2006. They determine that only residential energy consumption causes GDP. Yildirim et al. (2012) use disaggregated renewable energy data from 1949 to 2010. They find that biomass-waste-derived energy consumption causes GDP. Bilgili (2015) yields that industrial production is positively related to renewable energy consumption through the wavelet coherence methodology and data spanning the period 1981–2013. Aslan (2016) analyses the effect of biomass energy consumption on GDP by applying cointegration and causality approaches over the period 1961–2011. The empirical findings indicate that biomass energy consumption not only increases but also causes GDP. Bildirici and Gokmenoglu (2017) exploit data for the period 1961–2013 and use the Markov switching vector autoregressive approach to investigate the effect of the consumption of hydropower energy on economic growth. Their findings imply that GDP is positively associated with hydropower energy consumption. Bilgili et al. (2017) examine the causal relationship between bioenergy consumption and GDP for the period 1982–2011 and found that biomass energy consumption causes GDP. Tugcu and Topcu (2018), utilizing data for the period 1980–2014 and exploiting cointegration and causality analyses, detect that GDP is positively associated with renewable energy consumption. Troster et al. (2018) investigate the nexus between renewable energy consumption and industrial production for the 1989–2016 period by applying Granger causality in a quantile regression methodology. They find that a bidirectional causality exists between renewable energy consumption and industrial production at the lowest quantiles of the distribution. There is also a unidirectional causal relationship running from renewable energy consumption to industrial production at the higher quantiles of distribution. Bilgili et al. (2019) use the disaggregated renewable energy data for the period 1989–2016 and perform the continuous wavelet methodology. They determine all types of renewables have a positive impact on industrial production. Bulut and Inglesi-Lotz (2019),

[2] Bilgili et al. (2019) provide a broad empirical literature on the renewable energy consumption-economic growth nexus for other countries and country groups in the world.

Table 1 Literature review

Author(s)	Period	Method	Finding
Ewing et al. (2007)	2001–2005	The generalized variance decomposition method	REC increases GDP
Payne (2009)	1949–2006	Causality test	No causality between REC and GDP
Bowden and Payne (2010)	1949–2006	Causality test	Only residential REC causes GDP
Yildirim et al. (2012)	1949–2010	Causality test	Only biomass-waste-derived EC causes GDP
Bilgili (2015)	1981–2013	The wavelet coherence methodology	IP is positively linked with REC
Aslan (2016)	1961–2011	Cointegration and causality methods	Biomass EC increases GDP Biomass EC causes GDP
Bildirici and Gokmenoglu (2017)	1961–2013	The Markov switching vector autoregressive approach	GDP is positively associated with hydropower EC
Bilgili et al. (2017)	1982–2011	Causality test	Biomass EC causes GDP
Tugcu and Topcu (2018)	1980–2014	Cointegration and causality methods	REC increases GDP
Troster et al. (2018)	1989–2016	Granger-causality in a quantiles regression methodology	REC causes IP
Bilgili et al. (2019)	1989–2016	The wavelet coherence methodology	REC increases IP
Bulut and Inglesi-Lotz (2019)	2000–2018	Cointegration test	REC increases IP
Bulut and Apergis (2021)	1984–2018	Cointegration test	REC increases GDP

EC, energy consumption; REC, renewable energy consumption; IP, industrial production.

using data during the period 2000–2018 and running an asymmetric cointegration test, discover that industrial production is positively related to renewable energy consumption. Finally, Bulut and Apergis (2021) examine the impact of renewable energy consumption on economic growth throughout 1984–2018 by applying cointegration test containing sharp and gradual structural breaks. They discovered that GDP is positively associated with renewable energy consumption.

Table 1 presents the empirical literature focusing on the effect of renewables consumption on GDP in the USA. From the empirical literature, some points have merit to be denoted here. First, the findings of previous papers differ according to the period, types of renewables, and estimation methodologies. In other words, previous papers do not present clear-cut evidence for the relationship between renewable energy and economic growth. Second, only Bulut and Apergis (2021) consider structural breaks when investigating the influence of renewable energy consumption on the US economic growth. Thus, there is a research gap about the impact of renewable energy consumption on economic growth in the presence of structural breaks.

Model and data set

This paper investigates the effect of renewables on GDP in the USA. Besides, the paper compares renewable energy consumption and fossil energy consumption in terms of their effects on economic growth. This paper utilizes a Cobb–Douglas–type production function, and the empirical model includes renewable and fossil energy consumption, capital, and labor. Hence, the production function of the paper can be depicted as:

$$Y = K^{\beta_1} L^{\beta_2} F^{\beta_3} R^{\beta_4} e^{u} \quad (1)$$

where Y is output; K describes capital; L stands for employment; F denotes fossil energy consumption; R is renewable energy consumption; and e is the error term. In Eq. (1), the returns to scale are indicated by β parameters in the model. This paper prefers to use a log-linear version of this model since the nonlinear specification is not capable of helping policymakers to plan policies related to energy production (Shahbaz et al. 2015; Shahbaz 2018). Thus, the log-linear version of the production function is established as below:

$$\ln Y_t = \beta_0 + \beta_1 \ln K_t + \beta_2 \ln L_t + \beta_3 \ln K_t + \beta_4 \ln R_t + u_t \quad (2)$$

where Y stands for real GDP (billions of chained 2012 USD), K defines gross fixed capital formation (billion USD), L denotes employment level (thousands of people), F is fossil energy consumption (trillion Btu), R stands for renewable energy consumption (trillion Btu), and u is the error term. All series are seasonally adjusted. The quarterly data spanning from 1977Q1 to 2019Q3 are used. GDP, capital, and labor data are taken from the Federal Reserve Bank of St.

Louis (2020). Energy consumption data are obtained from EIA (2020b).

Estimation methodology

Unit root tests

In a time series analysis, the first step is to carry out unit root tests for the variables in the empirical model to avoid the possible spurious regression problem. Otherwise, traditional t-statistic and/or F-statistic exhibited by the ordinary least squares (OLS) estimates for nonstationary series produce inefficient and biased output. Therefore, this paper performs unit root tests to determine whether the series under consideration are stationary. Accordingly, we first apply ADF unit root test propounded by Dickey and Fuller (1981) without structural breaks. Then, we apply N-P unit root test produced by Narayan and Popp (2010) with two sharp structural breaks. Finally, we apply E-L unit root test developed by Enders and Lee (2012). This test is capable of presenting efficient output irrespective of the number and form, namely sharp or gradual, of structural breaks.

Cointegration tests

ARDL cointegration test

Researchers should detect whether there exists cointegration before estimating parameters when series are I(d), where d is not equal to 0, to avoid the inefficient results about t-statistic and F-statistic for a time series analysis. The ARDL methodology is widely used in econometric analyses to investigate cointegration between nonstationary variables. Accordingly, first, the null hypothesis implying no cointegration is tested via the bounds testing approach propounded by Pesaran et al. (2001). Second, if there exists cointegration, long-run parameters are estimated via the model developed by Pesaran and Shin (1999). This model is illustrated as:

$$Y_t = \alpha + \sum_{i=1}^{p} \alpha_i Y_{t-i} + \sum_{i=0}^{q} \beta_i X_{t-i} + u_t \tag{3}$$

Using the model in Eq. (3), one is able to compute long-run coefficients. After the calculations of long-run parameters, the short-run relation in the empirical model is estimated via the error correction model, which can be defined as follows:

$$\Delta Y_t = \theta_0 + \theta_1 EC_{t-1} + \sum_{i=1}^{p} \delta_i \Delta Y_{t-i} + \sum_{i=0}^{q} \lambda_i \Delta X_{t-i} + u_t \tag{4}$$

The parameter for the one-period lagged value of the error correction (θ_1) indicates how much deviation in the short run is mended in the long run. Hence, if this coefficient is found as statistically significant and negative, then cointegration is confirmed.

Hatemi-J (2008) *cointegration test with regime shifts*

The ARDL cointegration test is commonly used in the existing literature to examine the cointegration relationship in an empirical model. This method supposes that there is no change in long-run parameters over time. In other words, it posits that there exist no regime shifts/breaks, namely structural breaks in the slope coefficient(s) and intercept, during the observed period. Yet, parameters can be affected by some important events in the economy, such as radical changes in economic policies, economic crisis, natural disasters, and wars; thus they may change over time. Hence, researchers likely explore inefficient findings for cointegration if they use cointegration techniques that do not pay attention to structural breaks. While the cointegration tests of Gregory and Hansen (1996) and Westerlund and Edgerton (2007) assume a single structural break, Hatemi-J (2008)'s cointegration test considers two structural breaks. Hatemi-J (2008) first uses the equation below to suggest a cointegration test with two structural breaks:

$$y_t = a + \beta x_t + u_t, t = 1, 2 \cdots, n \tag{5}$$

where y, x, and u are the dependent variable, independent variable(s), and the error term, respectively. To consider the impacts of the breaks on the slope coefficient(s) and intercept, namely two regime shifts, Eq. (5) can be stated as follows:

$$y_t = \alpha_0 + \alpha_1 D_{1t} + \alpha_2 D_{2t} + \beta_0 x_t + \beta_1 D_1 x_t + \beta_2 D_2 x_t + u_t \tag{6}$$

where y, x, α_0, α_1, α_2, D_1, D_2, β_0, β_1, β_2, and u, respectively, denote the independent variable, explanatory variable, constant until the first break, the change in constant after the first break, the change in constant after the second break, the first dummy variable, the second dummy variable, the parameter of the explanatory variable until the first break, the change in the parameter of the explanatory variable after the first break, the change in the parameter of the explanatory variable after the second break, and the error term. One can notice that structural breaks are captured by the dummy variables. To model the structural breaks, Hatemi-J (2008) defines the dummy variables as follows:

$$D_{1t} = \begin{cases} 0 \text{if} t \leq [n\tau_1] \\ 1 \text{if} t > [n\tau_1] \end{cases}$$

$$D_{2t} = \begin{cases} 0 \text{if} t \leq [n\tau_1] \\ 1 \text{if} t > [n\tau_2] \end{cases}$$

with the unknown parameters $\tau_1 \epsilon (0,1)$ and $\tau_2 \epsilon (0,1)$ which express the relative timing of the regime change point. The integer part is denoted by the bracket. To test the null hypothesis of the nonexistence of cointegration, Hatemi-J (2008) utilizes the augmented Dickey-Fuller (ADF) test of Engle and Granger (1987) along with Z_α and Z_t tests of Phillips (1987). Hatemi-J (2008) produces new critical values via Monte-Carlo simulations since these test statistics have nonstandard distributions. If the statistics are greater than critical values, the null hypothesis of no cointegration can be rejected, and long-run coefficients are estimated.

Tsong et al. (2016) *cointegration test with gradual breaks*

Hatemi-J (2008) cointegration test can present efficient results when there exist two sharp structural breaks in definite periods. Using the Fourier methodology, Tsong et al. (2016) produce a cointegration test which is able to present efficient and unbiased findings regardless of the form, i.e., sharp or gradual, and the number of structural breaks. Another important advantage of this cointegration test is that it allows researchers to test whether or not the Fourier component must be in the empirical model. Put differently, researchers can determine whether they need to use this test before investigating the presence of cointegration. Tsong et al. (2016) use the equation below:

$$y_t = d_t + x_t'\beta + \eta_t, \eta_t = \gamma_t + \upsilon_{1t}, \gamma_t = \gamma_{t-1} + \upsilon_{1t}, x_t = x_{t-1} + \upsilon_{2t} \quad (7)$$

In Eq. (7), d_t can be described as $d_t = \delta_0 + \delta_1 t + f_t$. In this model, the Fourier function is captured by f_t and is defined as the following:

$$f_t = \alpha_k \sin\left(\frac{2k\pi t}{T}\right) + \alpha_k \cos\left(\frac{2k\pi t}{T}\right) \quad (8)$$

where k denotes the Fourier frequency, t stands for time trend, and T indicates the number of observations. The null hypothesis of cointegration and the alternative hypothesis of no cointegration can be illustrated as:

$$H_0 : \sigma_u^2 = 0 \text{versus } H_1 : \sigma_u^2 > 0 \quad (9)$$

where σ_u^2 is the variance of u_t in Eq. (7). To test the null hypothesis of cointegration, the model can be redescribed as the following:

Table 2 Results for the unit root tests

Variable	ADF	N-P[a]	E-L
lnY	−1.423	−2.424 (1990:Q3, 2008:Q3)	−1.843
lnK	−2.256	−3.609 (2008:Q4, 2010:Q1)	−2.128
lnL	−1.544	−3.197 (1999:Q4, 2008:Q4)	−1.740
lnF	−1.294	−1.181 (1989:Q4, 2008:Q2)	−3.904
lnR	−2.060	−2.820 (2000:Q4, 2009:Q3)	−3.226
ΔlnY	−9.173[b]	−7.321[b]	−9.412[b]
ΔlnK	−7.490[b]	−6.139[b]	−7.909[b]
ΔlnL	−5.711[b]	−7.481[b]	−9.225[b]
ΔlnF	−8.144[b]	−7.775[b]	−8.321[b]
ΔlnR	−10.083[b]	−10.910[b]	−6.050[b]

[a]Break dates are reported in parentheses.

[b]Indicates 1% significance.

$$y_t = \sum_{i=0}^{m} \delta_i t^i + \alpha_k \sin\left(\frac{2k\pi t}{T}\right) + \beta_k \cos\left(\frac{2k\pi t}{T}\right) + x_t'\beta + \upsilon_{1t} \quad (10)$$

Using this model, the cointegration test statistic can be calculated as:

$$CI_f^m = T^{-2}\hat{\omega}_1^{-2}\sum_{t=1}^{T} S_t^2 \quad (11)$$

where $S_t = \sum_{t=1}^{T} \hat{\upsilon}_{1t}$ is the partial sum of the OLS residuals in Eq. (10) while $\hat{\omega}_1^2$ denotes the consistent estimator of the long-run variance of υ_{1t}. Tsong et al. (2016) perform the dynamic OLS (DOLS) estimator of Saikkonen (1991) when the independent variables are not strictly exogenous. Last but not least, Tsong et al. (2016) test whether this testing procedure should be used for the empirical model. Accordingly, they use F-test to test the null hypothesis of the nonpresence of the Fourier component.

Empirical results and discussion

Table 2 reports the findings of unit root tests for the variables in the model. Accordingly, all unit root tests show that for all variables in the model, the null hypothesis of unit root is not rejected at level, but it is rejected at the first difference form. Put differently, the results of unit root tests imply all variables are integrated of order one. Besides, the 2007/2008 global financial crisis accounts for most of the break dates indicated by N-P unit root test. After determining all variables have a unit root and are integrated of order one, the

Table 3 Results of the cointegration tests for the model[a]

Panel A: ARDL cointegration test[b]			
Panel A1: Results for the bounds test			
Test statistic		6.804[d]	
Panel A2: Long-run coefficient			
Variable	Coefficient	Std. error	t-statistic
lnK	0.347[e]	0.153	2.271
lnL	0.922	0.652	1.413
lnF	– 0.057	0.194	– 0.294
lnR	0.003	0.072	0.049
Panel B: Hatemi-J (2008) cointegration test			
Panel B1: Results for the cointegration test[c]			
	ADF statistic	Phillips (Z_t) statistic	Phillips (Z_α) statistic
Regime shift model	– 6.309 (2002:Q1) (2004:Q3)	– 6.209 (2002:Q1) (2004:Q3)	– 60.923 (1991:Q2) (1995:Q4)
Panel C: Tsong et al. (2016) cointegration test			
Panel C1: Results for the cointegration test			
Frequency	Min SSR	Test statistic	F-statistic
1	0.028	0.047	5.544[e]
Panel C2: DOLS results			
Variable	Coefficient	Std. error	t-statistic
lnK	0.464[e]	0.180	2.573
lnL	– 0.035	0.725	– 0.048
lnF	0.484[d]	0.166	2.908
lnR	0.162[e]	0.067	2.406

[a]For critical values of the cointegration tests, see Pesaran et al. (2001: 300), Hatemi-J (2008:501), and Tsong et al. (2016: 1091).

[b]To save space, short- and long-run models of the ARDL cointegration test are not presented in the paper. It must be noted that the coefficient of the one-period lagged error correction term is negative and significant in the short-run model, supporting the presence of cointegration relationship in the model.

[c]Break dates are depicted in parentheses.

[d]Indicates 1% statistical significance.

[e]Indicates 5% statistical significance.

next step is to examine whether there occurs cointegration in the model.

Table 3 depicts the findings of cointegration tests for the empirical model. Panel A of Table 3 reports the output for the ARDL cointegration test without structural breaks. Accordingly, the null hypothesis of no cointegration can be rejected at 1% level, meaning the long-run coefficients can be estimated. The long-run parameters of lnK, lnL, lnF, and lnR are, respectively, 0.347, 0.922, – 0.057, and 0.003, respectively. Besides, the coefficient of lnK is significant, but other coefficients are statistically insignificant. Hence, the empirical findings of the ARDL test discover that only capital has statistically significant influences on GDP. Panel B of Table 3 reports the results for the regime shift model of Hatemi-J (2008) cointegration test. Accordingly, the null hypothesis of no cointegration isn't rejected at any significance levels as test statistics seem to be lower than critical values. As the findings obtained from this test indicate no cointegration, the long-run parameters are not estimated. Finally, Panel C of Table 3 presents the results of Tsong et al. (2016) cointegration test. The null hypothesis of the absence of the Fourier component in the empirical model can be rejected at 5% level of significance, meaning that Tsong et al. (2016) cointegration test must be utilized for the estimation of the empirical model. In addition, the null hypothesis of the presence of cointegration is not rejected, implying the existence of a cointegration relationship in the empirical model and that the long-run parameters could be estimated via the DOLS methodology. Accordingly, lnK, lnL, lnF, and lnR, respectively, appear to have the estimations of 0.464, – 0.035, 0.484, and 0.162, and only the coefficient of lnL is not statistically significant. Thus, the findings of Tsong et al. (2016) cointegration test provide evidence that GDP is positively associated with capital, fossil energy consumption, and renewable energy consumption in the USA.

The empirical findings of cointegration tests imply that considering structural breaks play a crucial role while investigating the influence of renewable energy consumption on economic growth. The empirical findings also indicate that different approximations in modelling structural breaks lead to highly different findings. Accordingly, while the ARDL cointegration test's results illustrate renewable energy consumption does not have any influences on economic growth, Tsong et al. (2016) test's results explore renewable energy consumption has positive effects on economic growth. Moreover, the output of Hatemi-J (2008) cointegration test discovers that the long-run parameter of renewable energy consumption cannot be estimated as there is no cointegration in the model. This paper primarily considers the results of Tsong et al. (2016) cointegration test as this test seems to be more feasible for economic data and the empirical findings of this test indicate the Fourier component should be included in the empirical model. Accordingly, the statistically significant and positive coefficient of capital confirms the conventional macroeconomic theory because capital is used to produce services and goods and so signifies the production capacity of an economy (Acemoglu 2009). This output also concurs with the neoclassical growth model produced by Solow (1956). Additionally, the findings for labor might mean that the US economy has a capital-intensive economic structure. Furthermore, the findings yield that fossil energy and renewables consumption have statistically significant and positive impacts on the US GDP growth rates. Therefore, the findings explore that fossil and renewable energy are crucial components for the growth of the US economy (Apergis and Payne 2009). Put differently, increases in fossil and renewable energy consumption enlarge GDP of the USA and energy-saving policies and/or energy supply shocks will limit the US economic growth. Besides, the findings indicate fossil energy appears to be more influential than renewable energy as the coefficient of fossil energy consumption is greater than that of renewable energy consumption.

Hence, the findings of the present paper for total renewable energy conform to empirical findings discovered by Bilgili (2015), Tugcu and Topcu (2018), Troster et al. (2018), and Bulut and Inglesi-Lotz (2019), while they contradict with output explored by Payne (2009).

Conclusion and policy implications

This paper examines the influence of renewable energy consumption on GDP for the USA using quarterly data covering the period 1977Q1-2019Q3 through a production function, including capital, labor along with fossil energy consumption. While doing that, the paper performs time series methods with different approximations in modelling structural breaks. Accordingly, the paper employs time series tests without breaks, with sharp breaks, and with both sharp and gradual breaks. All unit root tests' results indicate all variables in the empirical model are stationary at their first differences, indicating that the possible cointegration relation in the empirical model could be checked. The paper first performs the ARDL cointegration test without breaks. This test confirms cointegration and explores that fossil and renewable energy consumption have no effects on GDP. Then, the paper employs the Hatemi-J (2008) cointegration test with two sharp breaks and discovers that there is no cointegration in the empirical model, implying the long-run parameters of the independent variables in the model could not be estimated. Finally, the paper carries out the Tsong et al. (2016) test, taking both sharp and gradual breaks into account. This test affirms the presence of cointegration and yields that (i) fossil and renewable energy consumption have positive impacts on GDP and (ii) the influence of fossil energy consumption on GDP is greater than the impact of renewable energy consumption on GDP. These empirical findings provide policymakers and researchers with two crucial inferences. First, both fossil and renewable energy consumption stimulate economic growth of the US economy. Hence, fossil and renewable energy sources are important components of economic growth and energy supply shocks and/or energy-saving policies have negative influences on economic growth. Second, fossil energy consumption has greater impacts on the US economic growth compared to renewable energy consumption.

Bilgili et al. (2019) also point out that the replacement of fossil energy sources with renewable energy sources was very low until the early 2000s in the USA. For instance, in January 2000, the shares of fossil and renewable energy consumption in total primary energy consumption were 86% and 5.65%, respectively. Afterwards, policymakers in the USA began to put many policies into action, such as production tax credits and investment tax credits, to encourage the use of renewable energy both nationally and federally. All states provide many policies and incentives for the utilization of renewable energy sources in the USA today. Figure 1 illustrates the number of renewable energy policies and incentives for the top ten states with the highest GDP in the USA (NC Clean Energy Technology Center 2020). States implement many incentives and policies toward renewable energy. While all states stimulate almost all kinds of renewable energy, each state concentrates on some of the renewable energy sources further. Accordingly, (i) solar energy technologies are especially supported in California, Florida, Illinois, and Pennsylvania; (ii) production and consumption of solar and wind energy are particularly stimulated in New Jersey, Ohio, and Texas; (iii) Georgia becomes prominent in promoting bioenergy; (iv) hydroelectric along with wind energy technologies are encouraged in Washington; and (v) many kinds of renewable

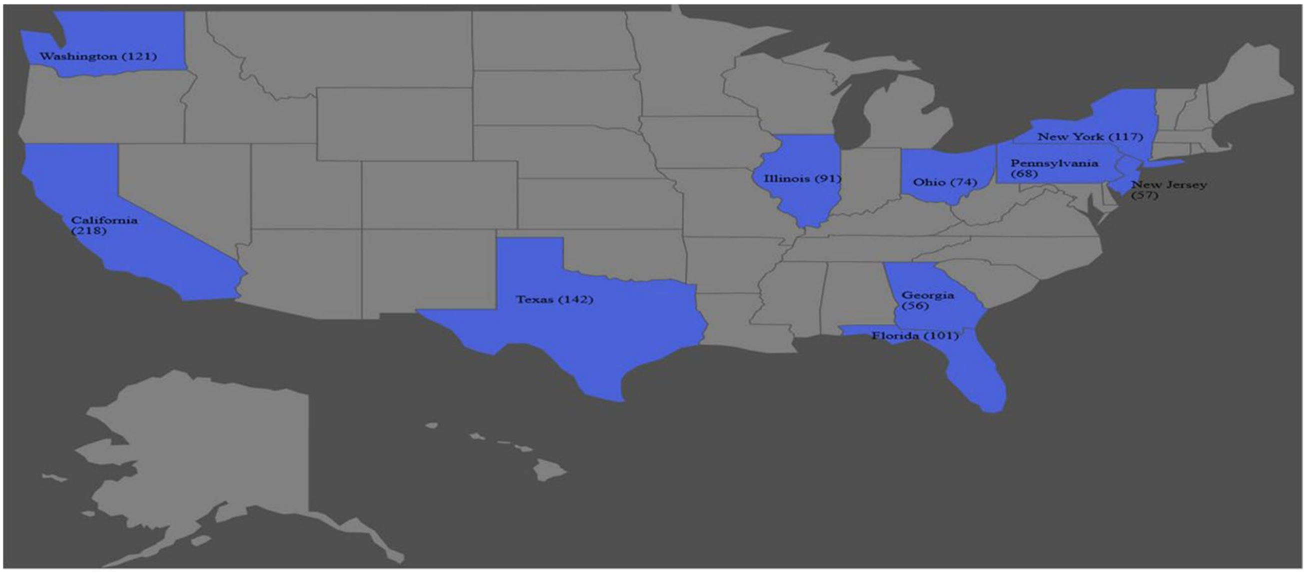

Fig. 1 The number of renewable energy policies and incentives for states with the highest GDP in the USA by the third quarter of 2019. Source: NC Clean Energy Technology Center (2020)

energy sources, namely wind, solar, hydroelectric, and biomass, are actively supported in New York (The Renewable Energy Hub USA 2020). As a result of these incentives and policies, the share of renewable energy sources in total primary energy consumption reached 12.62% in June 2019 (EIA 2019).

Renewable energy significantly contributes to the US economic growth due to these supportive policies (Energy Information Administration 2017; Union of Concerned Scientists 2013). For instance, the biomass industry has had 100 billion USD direct and indirect impact of the US economy by 2014 (The US Department of Energy 2014). Besides, biofuels technologies are expected to create a stable domestic energy supply that can decrease oil import of the USA. Hence, it is anticipated that biomass energy is capable of improving the current account balance of the US economy. The US Department of Energy (2020) denotes that wind energy is affordable compared to coal and natural gas of which prices are volatile as agreements for wind energy generation usually provide fixed prices for 20 years. Additionally, wind energy is expected to save consumers 280 billion USD by 2050. Solar Energy Industries Association (2019) states that the USA had more than 2 billion solar photovoltaic installations and solar energy was more than a 17-billion USD industry by May 2019. Besides, the forecasts show that the USA will have 3 and 4 million installations in 2021 and 2023, respectively. Therefore, the contributions of solar energy technologies to the US economy are likely to increase in the following years. In addition, geothermal energy industry contributed to the US economy with 20 billion USD in 2015 (Think Geoenergy 2017) and is expected to add 85 billion USD to the US economy within the next two decades (Geothermal Resources Council, 2012). Developments in renewable energy industries along with the more efficient use of energy also make energy cheaper for households and firms in the USA. In the USA, the ratio of energy expenditures to GDP was 5.6% in 2016, which is the lowest value since 1970 (EIA 2018).

As denoted in the first part of the paper, fossil energy contradicts with the goal of sustainable development as the utilization of fossil energy results in many concerns and problems. Therefore, even though the empirical findings provide evidence that fossil energy consumption has greater positive impacts on the US economic growth compared to renewable energy consumption, this paper contends policymakers in the USA should go on promoting renewable energy technologies without ignoring the effects of these supports on federal and national budget balance. The substitution of dirty technologies with clean and environmentally friendly technologies should be accelerated by the government through more policies and incentives (Fotis and Polemis 2018). Put differently, as Danish et al. (2019) and Danish and Ulucak (2021b) remark, more renewable energy should be included in the energy mix of the USA to decrease the dependence on fossil energy sources. As these incentives proceed, the impact of renewable energy consumption on economic activities can expand, and the substitution level of fossil energy with renewable energy can increase.

Finally, this paper suggests that future papers take structural breaks into account while determining the influence of energy consumption on GDP as different approaches for modelling structural breaks may lead to different findings as in the present paper.

Author contribution Umit Bulut: conceptualization, formal analysis, methodology, project administration, writing—original draft. Muhammad Shahbaz: conceptualization, data curation, investigation, writing—original draft. Xuan Vinh Vo: supervision, validation, writing—original draft.

Data availability The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

References

Acemoglu D (2009) Introduction to modern economic growth. Princeton University Press, New Jersey

Apergis N, Payne JE (2009) Energy consumption and economic growth in Central America: evidence from a panel cointegration and error correction model. Energy Econ 31:211–216

Aslan A (2016) The causal relationship between biomass energy use and economic growth in the United States. Renew Sustain Energy Rev 57:362–366

Bildirici M, Gokmenoglu SM (2017) Environmental pollution, hydropower energy consumption and economic growth: evidence from G7 countries. Renew Sustain Energy Rev 75:68–85

Bilgili F (2015) Business cycle co-movements between renewables consumption and industrial production: a continuous wavelet coherence approach. Renew Sustain Energy Rev 52:325–332

Bilgili F, Ozturk I, Kocak E, Bulut U, Pamuk Y, Mugalolgu E, Baglitas HH (2016) The influence of biomass energy consumption on CO_2 emissions: a wavelet coherence approach. Environ Sci Pollut Res 23:19043–19061

Bilgili F, Kocak E, Bulut U, Kuskaya S (2017) Can biomass energy be an efficient policy tool for sustainable development? Renew Sustain Energy Rev 71:830–845

Bilgili F, Kuskaya S, Toguc N, Mugaloglu E, Kocak E, Bulut U, Baglitas HH (2019) A revisited renewable consumption-growth nexus: a continuous wavelet approach through disaggregated data. Renew Sustain Energy Rev 107:1–19

Bowden N, Payne JE (2010) Sectoral analysis of the causal relationship between renewable and non-renewable energy consumption and real output in the US. Energy Source Part B Econ Plan Policy 5:400–408

BP (2019) BP statistical review of world energy. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf. Accessed 14 Feb 2020.

Bulut U, Muratoglu G (2018) Renewable energy in turkey: great potential, low but increasing utilization, and an empirical analysis on renewable energy-growth nexus. Energy Policy 123:240–250

Bulut U, Inglesi-Lotz R (2019) Which type of energy drove industrial growth in the US from 2000 to 2018? Energy Rep 5:425–430

Bulut U, Apergis N (2021) A new methodological perspective on the impact of energy consumption on economic growth: time series evidence based on the Fourier approximation for solar energy in the USA. GeoJ 86:1969–1980

Chapman I (2014) The end of peak oil? Why this topic is still relevant despite recent denials. Energy Policy 64:93–101

Danish ZJ, Wang B, Latif Z (2019) Towards cross-regional sustainable development: the nexus between information and communication technology, energy consumption, and CO_2 emissions. Sustain Dev 27:990–1000

Danish, Ulucak R (2020) The pathway toward pollution mitigation: does institutional quality make a difference? Bus Strategy Environ 29:3571-3583

Danish, Ulucak R (2021a) A revisit to the relationship between financial development and energy consumption? Is globalization paramount? Energy 227:1-8

Danish, Ulucak, R (2021b) Renewable energy, technological innovation and the environment: a novel dynamic auto-regressive distributed lag simulation. Renew Sustain Energy Rev 150:1-11

Dickey DA, Fuller WA (1981) Likelihood ratio statistics for autoregressive time series with a unit root. Econometrica 49:1057–1072

Diemuodeke EO, Briggs TA (2018) Policy pathways for renewable and sustainable energy utilisation in rural coastline communities in the Niger delta zone of Nigeria. Energy Rep 4:638–644

Enders W, Lee J (2012) The flexible Fourier form and Dickey-Fuller type unit root tests. Econ Lett 117:196–199

Energy Information Administration (2017) US energy and employment report. https://www.energy.gov/sites/prod/files/2017/01/f34/2017%20US%20Energy%20and%20Jobs%20Report_0.pdf. Accessed 25 Mar 2020.

Energy Information Administration (2018) In 2016, U.S. energy expenditures per unit GDP were the lowest since at least 1970. https://www.eia.gov/todayinenergy/detail.php?id=36754. Accessed 25 Mar 2020.

Energy Information Administration (2020a) What is the United States' share of world energy consumption? https://www.eia.gov/tools/faqs/faq.php?id=87&t=1. Accessed 24 Mar 2020.

Energy Information Administration (2020b) Petroleum and other liquids. https://www.eia.gov/totalenergy/data/monthly/index.php. Accessed 15 Mar 2020.

Engle RF, Granger CW (1987) Co-integration and error correction: representation, estimation, and testing. Econometrica 55:251–276

Ewing BT, Sari R, Soytas U (2007) Disaggregate energy consumption and industrial output in the United States. Energy Policy 35:1274–1281

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

Federal Reserve Bank of St. Louis (2020) Federal reserve economic data. https://fred.stlouisfed.org/. Accessed 15 Mar 2020.

Fotis P, Polemis M (2018) Sustainable development, environmental policy and renewable energy use: a dynamic panel data approach. Sustain Dev 26:726–740

Geothermal Resources Council (2012) Geothermal basics: O&A. https://www.geothermal.org/PDFs/Geothermal_Basics_QandA.pdf. Accessed 25 Mar 2020.

Gregory AW, Hansen BE (1996) Residual-based tests for cointegration in models with regime shifts. J Econom 70:99–126

Hajko V, Sebri M, Al-Saidi M, Balsalobre-Lorente D (2018) The energy-growth nexus: history, development, and new challenges.

In: Menegaki A (ed) The economics and econometrics of the energy-growth nexus. Elsevier Inc., United Kingdom, pp 3–48
Hatemi-J A (2008) Tests for cointegration with two unknown regime shifts with an application to financial market integration. Empir Econ 35:497–505
IEA (2019) Energy security. https://www.iea.org/areas-of-work/ensuring-energy-security. Accessed 14 Feb 2020.
Inglesi-Lotz R (2018) The role of potential factors/actors and regime switching modelling. In: Menegaki A (ed) The economics and econometrics of the energy-growth nexus. Elsevier Inc., United Kingdom, pp 113–139
Kocaarslan B, Soytas U (2019) Asymmetric pass-through between oil prices and the stock prices of clean energy firms: new evidence from a nonlinear analysis. Energy Rep 5:117–125
Koengkan M, Fuinhas JA, Santiago R (2020) The relationship between CO_2 emissions, renewable and non-renewable energy consumption, economic growth, and urbanisation in the southern common market. J Environ Econ Policy 9:383–401
Lu J, Ren L, Yao S, Rong D, Skare M, Streimikis J (2020) Renewable energy barriers and coping strategies: evidence from the Baltic states. Sustain Dev 28:352–367
Menegaki AN (2018) Introduction. In: Menegaki A (ed) The economics and econometrics of the energy-growth nexus. Elsevier Inc., United Kingdom, pp xv–xxv
Menegaki AN, Tsani S (2018) Critical issues to be answered in the energy-growth nexus (egn) research field. In: Menegaki A (ed) The economics and econometrics of the energy-growth nexus. Elsevier Inc., United Kingdom, pp 141–184
Menyah K, Nazlioglu S, Wolde-Rufael Y (2014) Financial development, trade openness and economic growth in African countries: new insights from a panel causality approach. Econ Model 37:386–394
Narayan PK, Popp S (2010) A new unit root test with two structural breaks in level and slope at unknown time. J Appl Stat 37:1425–1438
NC Clean Energy Technology Center (2020) Find policies & incentives by state. https://www.dsireusa.org/. Accessed 15 Feb 2020.
Payne JE (2009) On the dynamics of energy consumption and output in the US. Appl Energy 86:575–577
Pesaran MH, Shin Y (1999) An autoregressive distributed lag modelling approach to cointegration analysis. In: Strom S (ed) Econometrics and econometric theory in the 20th century: the Ragnar Frisch centennial symposium. Cambridge University Press, Cambridge, pp 371–413
Pesaran MH, Shin Y, Smith RJ (2001) Bounds testing approach to the analysis of level relationships. J Appl Econom 16:289–326
Phillips PC (1987) Time series regression with a unit root. Econometrica 55:277–301
Saikkonen P (1991) Asymptotically efficient estimation of cointegration regressions. Econom Theo 7:1–21
Shahbaz M, Loganathan M, Zeshan M, Zaman K (2015) Does renewable energy consumption add in economic growth? An application of auto-regressive distributed lag model in Pakistan. Renew Sustain Energy Rev 44:576–585
Shahbaz M (2018) Current issues in time series analysis for the energy-growth nexus EGN; asymmetries and nonlinearities case study: Pakistan. In: Menegaki A (ed) The economics and econometrics of the energy-growth nexus. Elsevier Inc., United Kingdom, pp 229–253
Shahbaz M, Sinha A (2019) Environmental Kuznets curve for CO_2 emissions: a literature survey. J Econ Stud 46:106–168
Solar Energy Industries Association (2019) United States surpasses 2 million solar installations. https://www.seia.org/news/united-states-surpasses-2-million-solar-installations. Accessed 25 Mar 2020.
Solow RM (1956) A contribution to the theory of economic growth. Quart J Econ 70:65–94
Strachan PA, Cowell R, Ellis G, Sherry-Brennan F, Toke D (2015) Promoting community renewable energy in a corporate energy world. Sustain Dev 23:96–109
Tabrizian S (2019) Technological innovation to achieve sustainable development-renewable energy technologies diffusion in developing countries. Sustain Dev 27:537–544
The Renewable Energy Hub USA (2020) Renewable energy incentives by state for the United States of America. https://www.renewableenergyhub.us/renewable-energy-incentives-for-the-usa.html. Accessed 15 Feb 2020.
The US Department of Energy (2014) Biomass fueling America's growing clean energy economy. https://www.energy.gov/eere/articles/biomass-fueling-america-s-growing-clean-energy-economy. Accessed 25 Mar 2020.
The US Department of Energy (2020). Wind vision: a new era for wind power in the United States. https://www.energy.gov/eere/wind/wind-vision. Accessed 25 Mar 2020.
Think Geoenergy (2017) Geothermal providing system flexibility for America's energy system and economy. https://www.thinkgeoenergy.com/geothermal-providing-system-flexibility-for-americas-energy-system-and-economy/. Accessed 25 Mar 2020.
Tiwari AK, Forte A, Garcia-Donato G, Menegaki AN (2018) Practical issues on energy-growth nexus data and variable selection with Bayesian analysis. In: Menegaki A (ed) The economics and econometrics of the energy-growth nexus. Elsevier Inc., United Kingdom, pp 187–227
Troster V, Shahbaz M, Uddin GS (2018) Renewable energy, oil prices, and economic activity: a Granger-causality in quantiles analysis. Energy Econ 70:440–452
Tsong CC, Lee CF, Tsai LJ, Hu TC (2016) The Fourier approximation and testing for the null of cointegration. Empir Econ 51:1085–1113
Tugcu CT (2018) Panel data analysis in the energy-growth nexus (EGN). In: Menegaki A (ed) The economics and econometrics of the energy-growth nexus. Elsevier Inc., United Kingdom, pp 255–271
Tugcu CT, Topcu M (2018) Total, renewable and non-renewable energy consumption and economic growth: revisiting the issue with an asymmetric point of view. Energy 152:64–74
Union of Concerned Scientists (2013) Renewable electricity standards deliver economic benefits. https://www.ucsusa.org/resources/renewable-electricity-standards-deliver-economic-benefits#.WoN7lq5l-Ul. Accessed 25 Mar 2020.
Uzar U (2020) Is income inequality a driver for renewable energy consumption? J Clean Prod 255:1–11
Westerlund J, Edgerton DL (2007) New improved tests for cointegration with structural breaks. J Time Ser Anal 28:188–224
World Bank (2020) World Bank open data. https://data.worldbank.org/. Accessed 24 Mar 2020.
Yildirim E, Sarac S, Aslan A (2012) Energy consumption and economic growth in the USA: evidence from renewable energy. Renew Sustain Energy Rev 16:6770–6774

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.