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Persistence of shocks on non-renewable and renewable energy consumption: evidence from 15 leading countries with Fourier unit root test

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Abstract

This paper investigates the persistence of shocks on non-renewable and renewable energy consumption for 15 leading countries by renewable energy consumption, over the period 1980–2018. For this aim, we apply Christopoulos and Leon-Ledesma (J Int Money Finance 29(6):1076–1093, 2010) Fourier ADF unit root test which structural breaks are included by using a trigonometric function to allow for smooth temporary mean changes rather than jump functions. In application, we do not need to specify the numbers, locations and the forms of the structural breaks a priori. The results give that shocks on non-renewable energy consumption per capita are persistent for 13 countries except Sweden and the United States; shocks on renewable energy consumption per capita are persistent for 12 countries except Canada, Sweden and the United Kingdom. Overall, we conclude that persistent policy implications on non-renewable energy consumption are more effective tool than transitory policy stances for 13 countries except Sweden and the United States whereas persistent policy implications on renewable energy consumption are more effective for 12 countries except Canada, Sweden and the United Kingdom. In other words, since the energy consumption returns to its trend path quickly, any policy will not be effective on non-renewable energy consumption for Sweden and the United States, and also on renewable energy consumption for Canada, Sweden and the United Kingdom.

Keywords Non-renewable energy consumption · Renewable energy consumption · Fourier unit root test · Persistent shocks · Transitory shocks

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1 Introduction

Energy, which is characterized as the basic input for economic and social development, is needed more and more every day with the effects of rapid population growth, urbanization and industrialization. Energy sources, that satisfy this demand, are classified as non-renewable and renewable energy sources. The resources such as petroleum, coal, natural gas that are limited and non-continuous in nature are known as non-renewable energy resources (namely fossil fuels) while resources such as solar, wind, geothermal, hydropower, ocean and biomass that are continuous and unrestricted in nature are known as renewable energy resources (Ali et al., 2017). Renewable energy sources are natural energy sources that are less harmful to human and the environment compared to non-renewable energy sources (Alrikabi, 2014).

In the last two centuries, fossil fuels have been widely used due to the advanced and cheap production technologies. But the damage caused by the energy obtained from these fuels to the environment and the knowledge that these fuels will run out in the near future have led countries to find alternative energy sources (Figueroa, 2013). Especially, with the oil crisis in 1973, an insecurity atmosphere about energy resources has emerged. At the same time, in addition to economic problems, the emergence of "sustainable development" in socio-economic terms and "global warming and climate change" in terms of environmental awareness accelerated the steps in the field of energy.

In addition, the countries that accepted the Climate Change Framework Convention, which was announced in 1992 and entered into force in 1994, have approved to decrease their greenhouse gas emissions and to support developing countries in this regard technologically and financially. The Kyoto Protocol, signed in 1997 within the framework of this convention, considered greenhouse gases, especially carbon dioxide emissions, as the main reasons of global warming. This protocol stated that carbon dioxide emissions were the most polluting gas and were responsible for 58.8% of the greenhouse gases worldwide and required countries to reduce the carbon amount, they emitted to the atmosphere to the levels in the year 1990 (International Energy Agency, 2011). In this way, it has been understood more clearly by both developed and developing countries that environmental cleaning and sustainability are important. This protocol came into force only in 2005. The reason for the delay is that the emissions of the countries that have ratified the protocol in 1990 must reach 55% of the total emissions on earth for the protocol to enter into force. This rate is only reached at the end of 8 years with the participation of Russia. These developments have led to an intense interest in renewable energy sources and investments in these energy sources have gradually increased around the world. With renewable energy, it is possible for countries to meet their increasing energy needs with natural energy sources, reducing their dependence on foreign sources, increasing sustainable energy use and minimizing environmental pollution (Stern & Stern, 2007).

This paper examines the persistent behaviour of shocks on non-renewable and renewable energy consumption over the 1980–2018 period for 15 leading countries by renewable energy consumption based on the 2019 report data of British Petroleum (BP) Statistical Review of World Energy (alphabetically Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, South Korea, Spain, Sweden, Turkey, the United States, the United Kingdom). Based on the reports of BP, it is reported that renewable energy consumption increased by 2.9 *exajoules*. The annual growth rate is 9.7% which is below the 10-year average but the absolute increase in energy terms is in-line with 2017, 2018 and 2019 and the largest increase for any fuel in 2020. In Fig. 1, we can see

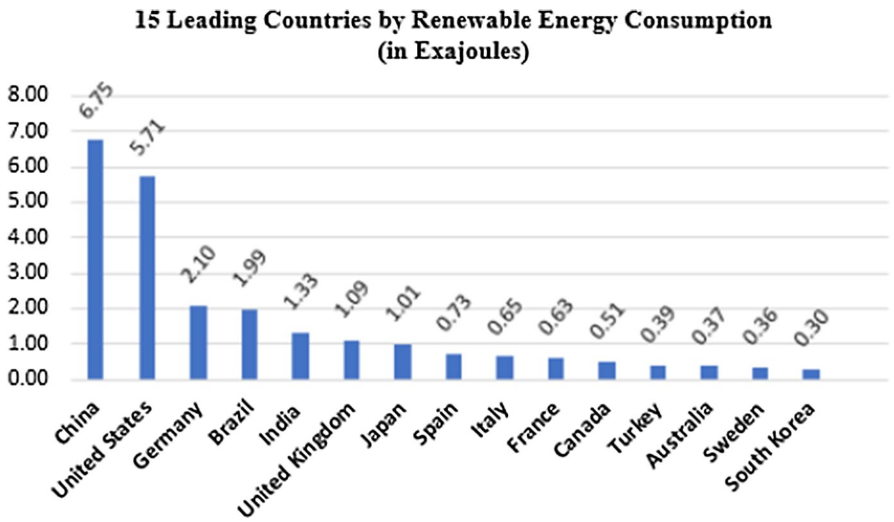

Fig. 1 15 leading countries by renewable energy consumption (in exajoules). *Source*: BP Statistical Review of World Energy

15 leading countries by renewable energy consumption (in exajoules) based on the 2019 report of BP Statistical Review of World Energy.

The figure clearly indicates that China is the largest contributor to renewable energy consumption, followed by the United States, then Germany, Brazil, India, the United Kingdom, Japan, Spain, Italy, France, Canada, Turkey, Australia, Sweden and South Korea. In our paper, by taking into account these countries, we analyse the persistence of the shocks on non-renewable and renewable energy consumptions.

Investigating time series behaviour of energy consumption gives special information to researchers, academicians and policy-makers. When energy consumption exhibits a stationary behaviour, shocks on energy consumption have transitory effects. This stationary behaviour gives information about the future of energy consumption according to past behaviour and leads policy makers in policy decisions of future (Mishra et al., 2009). On the other hand, shocks on energy consumption have persistent effects, when energy consumption follows a unit root process (Lee and Chang, 2007). Measuring the persistent effects of the shocks on energy consumption provides foresights in the implementation, organisation and effectiveness of environmental policies (Belbute & Pereira, 2017).

In application of our paper, we use Fourier Augmented Dickey Fuller (FADF) unit root test of Christopoulos and Leon-Ledesma (2010). The advantage of this test is that structural breaks are considered by using a trigonometric function which takes into account smooth temporary mean changes rather than jump functions and we do not need to specify the numbers, locations and the forms of the structural breaks a priori (Christopoulos and Leon-Ledesma, 2010). The contributions of this study to the literature are twofold. First, this paper explores the persistence of shocks by considering both non-renewable energy consumption and renewable energy consumption together. In this way, non-renewable and renewable energy consumptions for 15 countries are analyzed simultaneously, allowing researchers and policy makers to compare countries by energy source types. Second, to the best of our knowledge, there is no paper in the literature that directly analyzes the persistence of shocks on non-renewable and renewable energy consumption by using Christopoulos and Leon-Ledesma (2010) unit root test.

This paper is organised as follows: Sect. 2 gives the review of the literature, Sect. 3 outlines the methodology of Christopoulos and Leon-Ledesma (2010) unit root test, Sect. 4 describes the data and give the empirical results. Section 5 concludes and reports policy implications, finally.

2 Literature review

The motivation for investigating the persistent or transitory behaviour of the shocks on the energy consumption, is started based on the findings by Narayan and Smyth (2017). They consider the shocks on the primary energy consumption for 182 countries over the 1979–2000 period by using Augmented Dickey Fuller (ADF) and panel data unit root tests. Their findings from ADF unit root test show that the null of unit root hypothesis is rejected in 56 countries. Since univariate unit root tests have low power with short data, they apply panel unit root test and conclude that energy consumption is stationary and shocks to energy consumption per capita are transitory. Following Narayan and Smyth (2017), several papers analyze the effects of the shocks on the different non-renewable energy consumption data by using different methods for different countries, different time periods and obtain mixed results. From methodological perspective, some papers based on non-renewable energy consumption use panel unit root tests (Apergis et al., 2010; Chen & Lee, 2007; Hsu et al., 2008; Magazzino, 2016; Zhu & Guo, 2016), univariate unit root tests with structural breaks (Kula et al., 2012; Narayan et al., 2010; Shahbaz et al., 2014), both univariate and panel unit root tests (Ozcan, 2013; Ozturk & Aslan, 2011), nonlinear unit root tests (Aslan, 2011; Hasanov & Telatar, 2011), both univariate unit root tests with structural breaks and nonlinear unit root tests (Aslan & Kum, 2011; Ozturk & Aslan, 2015), subsampling confidence interval methods (Fallahi et al., 2016), Fourier unit root tests (Yilanci & Tunali, 2014), fractional integration methods (Caporale et al., 2019), both Fourier and fractional unit root tests (Bozoklu et al., 2020). The details of these papers on the persistence of shocks for non-renewable energy consumption, is tabulated in Table 1, chronologically.

Since it is well understood that renewable energy are less harmful to human and the environment compared to non-renewable energy sources, several papers in the literature are focused on the persistence of shocks for different renewable energy consumption data. When we classify these papers based on their methodology, it is seen that some papers use fractional integration methods (Apergis & Tsoumas, 2011; Barros et al., 2012, 2013), Fourier stationarity and unit root tests without and with structural breaks (Aydin & Pata, 2020; Cai & Menegaki, 2019; Lee et al., 2021; Shahbaz et al., 2018; Tiwari & Albulescu, 2016), univariate unit root tests with structural breaks (Demir & Gozgor, 2018; Gozgor, 2016), mixed univariate structural break unit root tests, panel unit root test and Fourier unit root test (Wang et al., 2016). The detailed information about related papers on the persistence of shocks for renewable energy consumption is reported in Table 2, chronologically.

Table 1 The literature on the persistence of shocks for non-renewable energy consumption

Authors	Type of energy	Period	Countries	Methodology	Findings
Narayan and Smyth (2017)	Primary energy consumption per capita	1979–2000	182 countries	Univariate and panel unit root tests	ADF unit root test: transitory shocks for 56 countries Panel unit root test: transitory shocks
Chen and Lee (2007)	Energy consumption per capita	1971–2002	104 countries with 7 geographical groups	Panel unit root test of Carrion-i-Silvestre et al. (2005)	Transitory shocks for all regional-based panel
Hsu et al. (2008)	Energy consumption	1971–2003	84 countries in five regions	Panel *seemingly* unrelated regressions Augmented Dickey Fuller (SURADF) unit root test of Breuer et al. (2001)	Stationarity is affected by the differences between five regions
Apergis et al. (2010)	Coal consumption	1982–2007	50 US states	Panel stationarity and unit root tests with structural breaks	Transitory shocks
Narayan et al. (2010)	Energy consumption	1973–2007	Australia, its six states, one territory	Lee and Strazicich (2003) unit root test with two structural breaks	Transitory shocks
Aslan (2011)	Natural gas consumption	1960–2008	50 US states	Nonlinear unit root test of Kapetanios et al. (2003)	Persistent shocks for 27 US states, transitory shocks for 23 US states
Aslan and Kum (2011)	Energy consumption	1970–2006	Turkish disaggregates	Lee and Strazicich (2003) unit root test with two structural breaks and non-linear unit root test of Kruse (2011)	Lee and Strazicich (2003) unit root test: transitory shocks for residential, industrial and agricultural sectors Kruse (2011) unit root test: persistent shocks for transportation, non-energy uses and other, final energy consumption, cycle and energy consumption of energy sector's

Table 1 (continued)

Authors	Type of energy	Period	Countries	Methodology	Findings
Hasanov and Telatar (2011)	Primary energy consumption per capita	1980–2006	178 countries	Kapetanios et al. (2003) and Sollis (2004) unit root tests with nonlinear adjustments and structural breaks	Transitory shocks for most of the countries
Ozturk and Aslan (2011)	Energy consumption	1970–2006	7 sectors for Turkey	Lagrange Multiplier (LM) univariate and panel unit root tests without and with one structural break	Univariate LM unit root test without break: persistent shocks in "transportation, agriculture, industrial, non-energy field, final energy consumption and circuit and energy sector" Univariate LM unit root test with one structural break: transitory shocks for all disaggregate energy sectors Panel LM unit root tests without and with one structural break: transitory shocks
Ozcan (2013)	Total primary energy consumption per capita	1980–2009	17 Middle East countries	Lee and Strazicich (2003, 2004) univariate LM unit root tests with structural breaks and Im et al. (2005) panel LM unit root test	Univariate LM unit root tests with structural breaks: transitory shocks for most of the Middle East countries Panel LM unit root test: transitory shocks
Kula et al. (2012)	Electricity consumption per capita	1960–2005	23 High-income Organisation for Economic Cooperation and Development (OECD) countries	Lee and Strazicich (2003, 2004) LM unit root tests	Transitory shocks for 21 OECD countries
Shahbaz et al. (2014)	Coal consumption per capita	1965–2010	47 developed and developing countries	Lee and Strazicich (2003, 2004) LM unit root tests	Transitory shocks in all the analyzed countries

Table 1 (continued)

Authors	Type of energy	Period	Countries	Methodology	Findings
Yilanci and Tunali (2014)	Energy consumption per capita	1960–2011	109 countries	Fourier LM unit root test of Enders and Lee (2012)	Transitory shocks for 25 countries
Ozturk and Aslan (2015)	Electricity consumption per capita	1960–2005	23 OECD countries	Univariate linear LM unit root test and Kruse (2011) nonlinear unit root test	Persistent shocks for 12 OECD countries
Fallahi et al. (2016)	Energy consumption per capita	1971–2011	107 countries	Subsampling confidence interval methods	Transitory shocks for 39 countries
Magazzino (2016)	Energy consumption per capita	1960–2013	19 Eurozone member countries	First and second generation panel unit root tests	Persistent shocks for the specification with constant and trend, transitory shocks for the alternative specification with constant
Zhu and Guo (2016)	Nuclear energy consumption per capita	1991–2013	27 countries	Panel unit root test with structural breaks	Transitory shocks for the overal sample, persistent shocks in two sub-samples
Caporale et al. (2019)	Energy consumption per capita	1980–2014	Gulf Cooperation Council (GCC) countries	Fractional integration methods	Transitory shocks in the case of Bahrain and Qatar
Bozoklu et al. (2020)	Aggregate energy consumption per capita	1960–2014	113 countries	ADF unit root test, the efficient Wald test for fractional unit-roots and the Fourier ADF test proposed by Enders and Lee (2012)	ADF unit root test: transitory shocks for 10 countries The efficient Wald test for fractional unit-roots: transitory shocks for 21 countries Fractional Fourier unit root test: transitory shocks for 29 countries

Table 2 The literature on the persistence of shocks for renewable energy consumption

Authors	Type of Energy	Period	Countries	Methodology	Findings
Apergis and Tsoumas (2011)	Disaggregated solar, biomass energy and geothermal consumption	1989–2009	Residence, industrial, transportation, electric power and commercial sectors in the US	Fractional integration tests in the presence of structural breaks	Transitory shocks
Barros et al. (2012)	Total renewable energy consumption	1981:1–2010:10	US	Fractional integration and autoregressive models	Persistent shocks
Barros et al. (2013)	Disaggregated renewable energy consumption (hydro-power, solar, wind, geothermal, wood, waste and biofuels)	1994:2–2011:10	US	Fractional integration and autoregressive models	Persistent shocks in the hydropower, solar, wind, waste, and biofuels
Gozgor (2016)	Renewable energy consumption	1971–2014	Three large developing economies: Brazil, China and India	Lee and Strazicich (2003, 2004), Narayan and Poop (2010) and Carrion-i-Silvestre et al. (2009) unit root tests	Persistent shocks for Brazil; transitory shocks for China and India
Tiwari and Albulescu (2016)	Renewable-to-total electricity consumption ratio	1980–2011	90 countries	Flexible Fourier stationarity test of Becker et al. (2006) and the Fourier ADF unit root test of Enders and Lee (2012)	Flexible Fourier stationarity test: transitory shocks for 65 countries Fourier ADF unit root test: transitory shocks for all cases, except the United Kingdom
Wang et al. (2016)	Non-fossil energy consumption: hydropower, solar energy nuclear energy, other renewables (including geothermal, wind, biomass), and non-hydro renewables	1965–2011 for nuclear energy consumption and hydropower consumption 1990–2011 for solar energy, other renewables and non-hydro renewables consumption	Japan	Univariate LM unit root tests of Lee and Strazicich (2003, 2004), panel LM unit root test of Im et al. (2005) and Fourier LM test of Enders and Lee (2012)	Persistent shocks for nuclear energy; transitory shocks for other renewable energy consumption series

Table 2 (continued)

Authors	Type of Energy	Period	Countries	Methodology	Findings
Demir and Gozgor (2018)	Renewable energy consumption	1971–2016	54 countries	Narayan and Poop (2010) unit root test with two breaks	Persistent shocks only for 9 countries
Shahbaz et al. (2018)	Renewable energy consumption	1800–2008	9 countries	Structural break unit root tests of Leybourne et al. (1998) and Enders and Lee (2012) and also a newly proposed test	Transitory shocks
Cai and Menegaki (2019)	Clean energy consumption	1965–2016	8 emerging economies	Fourier quantile unit root test of Bahmani-Oskooee et al. (2018) without and with smooth breaks	Fourier quantile unit root test without smooth breaks: transitory shocks for Brazil and Philippines Fourier quantile unit root test with smooth breaks: transitory shocks for China, Pakistan and Thailand
Aydin and Pata (2020)	Renewable energy consumption (hydropower, geothermal, solar, wind, wood, waste, biofuels, total biomass and total renewable energy consumption)	1973:01–2019:09	US	A new suggested wavelet-based Fourier unit root test and wavelet-based ADF unit root test	Wavelet-based Fourier unit root test: transitory shocks for biofuels; persistent shocks for geothermal, waste, and wind energy Wavelet-based ADF unit root test: transitory shocks for hydropower energy consumption; persistent shocks for solar, wood, total biomass, and total renewable energy consumption

Table 2 (continued)

Authors	Type of Energy	Period	Countries	Methodology	Findings
Lee et al. (2021)	Renewable energy consumption	1960–2017	The US economy and the 50 states plus the District of Columbia	Quantile unit-root test with smooth breaks of Bahmani-Oskooee et al. (2018)	Transitory shocks for the US and for 32 of the 51 states/district

3 Econometric methodology

Due to the unit root tests which consider either breaks or non-linear adjustment seperately, have low power and give the results over acceptance of the null hypothesis of nonstationarity, Christopoulos and Leon-Ledesma (2010) propose "Fourier unit root tests" which account structural breaks and non-linear adjustment. In the construction of the tests, structural breaks are taken into account by using a trigonometric function which allows smooth temporary mean changes rather than jump functions, as well as nonlinear adjustment is modeled by smooth transition functions. The basic advantage of the tests is that we do not need to specify the numbers, locations and the forms of the structural breaks a priori (Christopoulos and Leon-Ledesma, 2010).

For a stochastic variable y_t, Christopoulos and Leon-Ledesma (2010) consider the following model:

$$y_t = \delta(t) + v_t \tag{1}$$

here $\delta(t)$ refers to a time varying deterministic component and $v_t \sim N(0, \sigma)$. To consider the unknown number of breaks with unknown form of $\delta(t)$, following Fourier series expansion is used as Becker et al. (2004), Becker et al. (2006) and Enders and Lee (2004):

$$\delta(t) = \delta_0 + \sum_{k=1}^{G} \delta_1^k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{G} \delta_2^k \cos\left(\frac{2\pi kt}{T}\right) \tag{2}$$

where k means the frequency number for the Fourier function, t refers to trend term, T means the size of the sample and $\pi = 3.1416$. When the appropriate frequency number k is known, we can use Eq. (1) in order to test presence of unknown structural breaks. But, the value of k is unknown. In this respect, Ludlow and Enders (2000) report that, in approximating the Fourier expansion for applications, a single frequency is enough. Following their statement, Eq. (2) is updated as follows:

$$\delta(t) = \delta_0 + \delta_1 \sin\left(\frac{2\pi kt}{T}\right) + \delta_2 \cos\left(\frac{2\pi kt}{T}\right). \tag{3}$$

Becker et al. (2004) state that Eq. (3) has more power than the multiple breaks tests of Bai and Perron (2003), in detecting smooth breaks for unknown form in the case of intercept. The basis of this statement is that incorporating structural breaks to improve the performance of the tests may not be a proper specification of the deterministic component. Changes can occur smoothly rather than suddenly. Bierens (1997) points out that Chebyshev polynomials might be a better mathematical approximation of the time functions since Chebyshev polynomials are bounded and orthogonal. Chebyshev polynomials are cosine functions of time and can be very flexible to apprioximate deterministic trends. Bierens (2001) presents unit root tests by using this context. As on other contribution, Cuestas and Gil-Alana (2016) employ Chebyshev polynomials in time to describe the deterministic part of the model and assume that the detrended series displays long memory behavior.

In our application of Christopoulos and Leon-Ledesma (2010) Fourier unit root test, we complete the following three steps:

Step 1 Because the value of k is unknown, this first step includes calculating the optimal frequency k^*. For this purpose, the following model is estimated by Ordinary Least Square (OLS) method for each integer k value in the interval from 1 to 5 and the value of k that gives the minimum residual sum of squares is chosen:

$$y_t = \delta_0 + \delta_1 \sin\left(\frac{2\pi kt}{T}\right) + \delta_2 \cos\left(\frac{2\pi kt}{T}\right) + v_t. \tag{4}$$

Then, the residuals from OLS are computed as:

$$\hat{v}_t = y_t - \left[\hat{\delta}_0 + \hat{\delta}_1 \sin\left(\frac{2\pi k^* t}{T}\right) + \hat{\delta}_2 \cos\left(\frac{2\pi k^* t}{T}\right)\right]. \tag{5}$$

Step 2 As a second stage, a unit root test is applied on the OLS residuals of stage one. For Fourier ADF test called by Christopoulos and Leon-Ledesma (2010), the following model is constructed:

$$\Delta v_t = \alpha_1 v_{t-1} + \sum_{j=1}^{p} \beta_j \Delta v_{t-j} + u_t \tag{6}$$

here u_t is white noise error term. The unit root hypothesis $H_0 : \alpha_1 = 0$ is tested against $H_1 : \alpha_1 \neq 0$. As stated by Becker et al. (2006), the asymtotic distribution of the calculated test statistics depends on the Fourier series' frequency (k). The critical values for different k values in the interval 1–5 can be obtained from Table 1 of Christopoulos and Leon-Ledesma (2010). If we reject the null hypothesis, the third step of the test can be applied.

Step 3 When the null hypothesis of a unit root is rejected in the second step, we test the null hypothesis of $H_0 : \delta_1 = \delta_2 = 0$ against the alternative $H_0 : \delta_1 = \delta_2 \neq 0$ in (4) by applying F test $\left(F_\mu\left(\tilde{k}\right)\right)$. The critical values for F test can be found in Becker et al. (2006). It is very important to remind that F statistic has low power in the existence of nonstationarity, it can be used only when the unit root null hypothesis is rejected. The rejection of the related hypothesis means that the considered variable follows a stationary behaviour around a breaking deterministic function.

4 Data and empirical results

To investigate the persistence of shocks on non-renewable and renewable energy consumption, this paper uses annual non-renewable and renewable energy consumption per capita series over the period 1980–2018 for 15 leading countries by renewable energy consumption worldwide in 2019 (alphabetically Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, South Korea, Spain, Sweden, Turkey, the United States, the United Kingdom). The non-renewable and renewable energy consumption data set, measured in quadrillion British thermal unit (BTU), is provided by the US Energy Information Administration (EIA) (https://www.eia.gov/international/data/world/total-energy/total-energy-consumption). To obtain per capita series, we divide non-renewable and renewable energy consumption by the total population of each countries obtained from the World Development Indicators database of the World Bank (https://databank.worldbank.org/source/world-development-indicators#). We convert all the data to natural logarithms before the analysis and label them as LNREC and LREC for logarithmic non-renewable energy consumption per capita and logarithmic renewable energy consumption per capita, respectively. As a first step in our analysis, we apply traditional ADF (Dickey & Fuller, 1979), PP (Philips & Perron, 1988) and Dickey Fuller Generalised Least Squares (DF-GLS) (Elliot et al., 1996) unit root tests and report their results in Table 3.

The ADF, PP and DF-GLS test results indicate that we are unable to reject the unit root null hypothesis for LNREC and LREC series in the majority of the countries. For

Table 3 The results of traditional unit root tests

Countries	LNREC			LREC		
	ADF	PP	DF-GLS	ADF	PP	DF-GLS
Australia	−0.181(0)	−0.014[1]	−0.602(0)	−1.297(0)	−0.994[7]	−1.512(0)
Brazil	−3.116(2)	−3.324[1]*	−2.875(2)	−1.953(0)	−1.963[2]	−1.666(0)
Canada	−3.846(1)**	−3.857[1]**	−2.707(1)	−3.146(0)	−2.958[5]	−2.499(0)
China	−1.819(1)	−1.825[3]	−1.752(1)	−0.759(0)	−0.660[2]	−1.505(3)
France	−2.248(0)	−2.552[4]	−1.655(0)	−2.612(0)	−2.353[3]	−2.462(0)
Germany	−1.956(2)	−1.682[2]	−2.071(2)	−4.374(1)***	−3.278[24]*	−2.786(2)
India	−2.507(0)	−2.645[3]	−2.085(0)	−1.789(0)	−1.607[4]	−1.840(0)
Italy	−0.902(1)	−0.617[2]	−1.147(1)	−2.395(0)	−2.451[1]	−2.260(0)
Japan	−0.799(0)	−1.099[2]	−1.584(1)	−3.228(0)*	−3.151[2]	−3.169(0)*
South Korea	−0.286(0)	−0.543[3]	−1.624(3)	−0.892(1)	−2.352[3]	−2.645(0)
Spain	−0.704(0)	−1.135[4]	−1.881(3)	−1.860(2)	−4.244[4]***	−1.437(2)
Sweden	−2.601(0)	−2.863[3]	−1.932(0)	−4.924(0)***	−4.858[3]***	−4.878(0)***
Turkey	−2.290(0)	−2.050[2]	−2.367(0)	−3.223(0)*	−3.181[1]	−3.283(0)**
United States	−1.640(0)	−1.795[3]	−2.257(3)	−0.932(0)	−1.018[2]	−1.217(0)
United Kingdom	0.340(1)	0.142[1]	−1.492(3)	−3.238(3)*	−4.246[18]***	−0.794(3)

(***), (**) and (*) show rejection of the unit root null hypothesis at the 1%, 5% and 10% significance levels, respectively. The numbers in parantheses indicate the lag orders in the ADF and DF-GLS. The lags are decided on the Schwarz (SC) criterion. The truncation lags for the Newey–West correction of the PP test are in brackets

LNREC series, the only exceptions are Canada based on ADF, Brazil and Canada based on PP and there is no rejection based on DF-GLS unit root test. For LREC series, the number of rejections increases to five (Germany, Japan, Sweden, Turkey and the United Kingdom) based on ADF, increases to four (Germany, Spain, Sweden and the United Kingdom) based on PP and increases to three (Japan, Sweden and Turkey) based on DF-GLS unit root test. When these results are interpreted in general, it can be concluded that shocks on non-renewable energy consumption per capita have transitory effects only for Brazil and Canada, and persistent effects for other 13 countries. On the other hand, shocks to renewable energy consumption per capita are transitory for Germany, Japan, Spain, Sweden, Turkey and the United Kingdom, and persistent for remaining countries in the analysis.

To obtain more reliable results, we need a better unit root test and apply Fourier ADF test of Christopoulos and Leon-Ledesma (2010). For this purpose, we follow a three step procedure mentioned in the previous section. Since there is no a priori information about the numbers, locations and the shape of the structural breaks, we first estimate Eq. (4) for our each series and determine the optimal frequency k^* which minimizes the sum of squared residuals (SSR) for each integer (k) from 1 to 5. The second and third columns in Table 4 give the minimum SSR and optimal frequency (k^*) for LNREC series, respectively. On the other hand, the sixth and seventh columns of Table 4 present the minimum SSR and optimal frequency (k^*) for LREC series, respectively.

Table 4 The results of Christopoulos and Leon-Ledesma Fourier ADF test

Countries	LNREC				LREC			
	SSR	k^*	FADF	$F_\mu(\tilde{k})$	SSR	k^*	FADF	$F_\mu(\tilde{k})$
Australia	0.0419	1	−2.952(0)	108.489^{I}	0.7748	1	−1.214(0)	9.480^{I}
Brazil	1.0016	1	−0.915(0)	25.133^{I}	0.6943	1	−1.839(0)	22.497^{I}
Canada	0.0460	1	−2.695(0)	43.082^{I}	0.0316	1	−3.959(0)**	24.432^{I}
China	3.7404	1	−1.396(1)	40.776^{I}	12.1296	1	−0.584(1)	26.767^{I}
France	0.2726	2	−1.927(0)	7.196^{I}	0.8633	1	−3.510(1)	21.998^{I}
Germany	0.3277	1	−1.009(0)	31.485^{I}	7.9373	1	−1.335(1)	42.538^{I}
India	3.1375	1	0.168(1)	23.998^{I}	1.7675	1	−0.869(0)	21.039^{I}
Italy	0.0828	1	−2.377(0)	87.140^{I}	1.4313	1	−1.364(1)	19.255^{I}
Japan	0.1080	1	−1.725(0)	38.360^{I}	1.0782	1	−1.721(0)	18.879^{I}
South Korea	3.6076	1	−0.557(0)	29.732^{I}	6.9121	1	−0.688(1)	8.737^{I}
Spain	0.1318	1	−2.249(0)	135.290^{I}	2.2353	1	−2.660(1)	35.599^{I}
Sweden	0.6224	1	−3.642(0)*	7.167^{I}	0.2360	5	−5.469(0)***	3.414
Turkey	2.4072	1	−1.082(0)	23.689^{I}	3.9334	2	−2.401(0)	10.891^{I}
United States	0.0638	1	−4.327(0)**	24.540^{I}	0.2670	1	−2.360(0)	19.786^{I}
United Kingdom	0.2669	1	−1.437(0)	21.908^{I}	53.390	1	−4.541(1)***	5.487^{V}

(***), (**) and (*) show rejection of the unit root null hypothesis at the 1%, 5% and 10% significance levels, respectively. The corresponding critical values can be found in Table 1 of Christopoulos and Leon-Ledesma (2010). Numbers in parantheses indicate the optimal lag length based on Schwarz (SC) criterion

(^{I}) and (^{V}) denote rejection of the null of linearity at the 1% and 5% significance levels, respectively. Under the null hypothesis, the $F_\mu(\tilde{k})$ test is distributed as an F statistic with 2 degrees of freedom. The critical values for F statistics are obtained from Table 1 of Becker et al. (2006)

It is clearly seen that the optimal frequency is 1 for all cases except LNREC series of France ($k^* = 2$) and LREC series of Sweden ($k^* = 5$) and Turkey ($k^* = 2$). The LNREC and LREC series for each countries are plotted against the related fitted Fourier functions in Figs. 2 and 3, respectively.

The plots of the LNREC and LREC series against the fitted Fourier functions exhibit that the estimated Fourier functions fit well to the large swings in the LNREC and LREC series.

After finding optimal frequencies for each series of the each countries, we obtain the OLS residuals from the related model estimations and proceed to the second step of the test procedure by applying ADF test (known as FADF). In this point, we need to give our attention to the fourth and eight columns of Table 4 for FADF test results of LNREC and LREC series, respectively. These results indicate that the unit root null hypothesis is rejected for Sweden and the United States in the case of LNREC; and also for Canada, Sweden and the United Kingdom in the case of LREC. It is clear that we cannot reject the unit root null hypothesis for majority of the countries in both cases of LNREC and LREC series.

The testing significance of the breaks by applying F test $\left(F_\mu(\tilde{k})\right)$, is the final step for our analysis. Although these results are presented in the fifth column of the Table 4 for LNREC series and in the last column of the Table 4 for LREC series for all countries, it has to be noted that, we can proceed to the third step of the test only when the unit root null hypothesis is rejected. For the cases which we cannot reject the null hypothesis, we cannot comment in favor of the presence of the breaks. On the other hand, the rejection of the

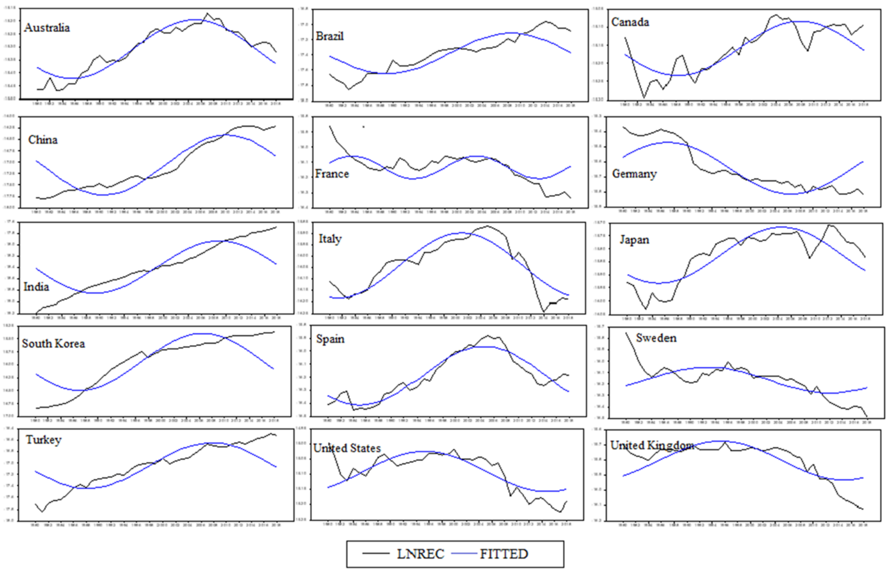

Fig. 2 LNREC series and fitted Fourier functions

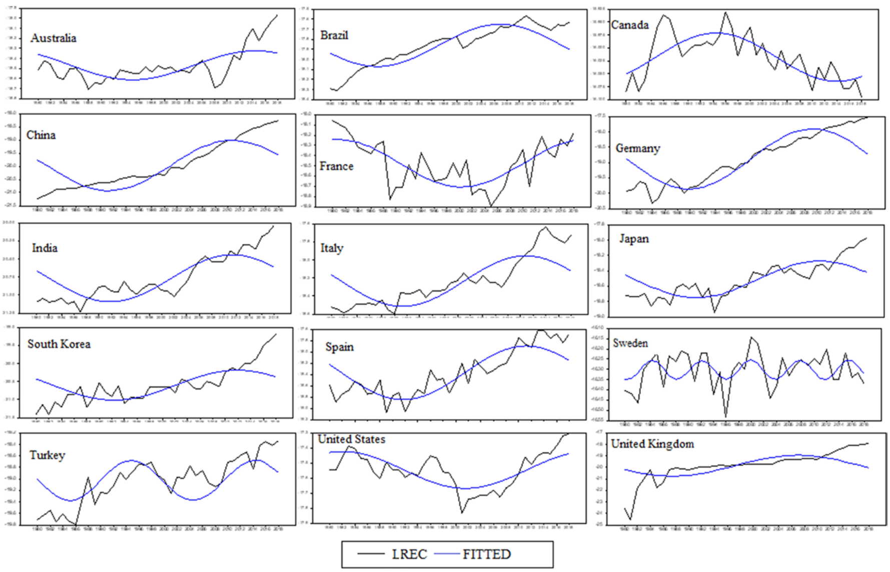

Fig. 3 LREC series and fitted Fourier functions

null hypothesis means stationarity around a breaking deterministic function. The relevant $F_{\mu}(\tilde{k})$ statistics in the fifth and last columns of the Table 4 show that the null hypothesis ($H_0 : \delta_1 = \delta_2 = 0$) is rejected for all cases except LREC series of Sweden with (3.414) statistic value. In other words, the significant $F_{\mu}(\tilde{k})$ statistics mean that the trigonometric terms should be added to all estimated models except LREC series of Sweden. For the

LREC series of Sweden, the result of ADF unit root test is valid which refers to stationarity. When all of these Fourier ADF unit root test results are interpreted in terms of shocks on non-renewable and renewable energy consumption per capita, we conclude that shocks on non-renewable energy consumption per capita are transitory only for Sweden and the United States and persistent for remaining 13 countries; shocks on renewable energy consumption per capita are transitory only for Canada, Sweden (according to ADF unit root test) and the United Kingdom and persistent for other 12 countries. When we compare our results for non-renewable energy consumption by country with the results of other studies in the literature, we see that Bozoklu et al. (2020) find transitory shocks for aggregate energy consumption per capita of Sweeden and the United States and support our results partially for these countries. Also, Yilanci and Tunali (2014) support our result for the United States and find for the United States that shocks to energy consumption per capita are transitory. Based on our results for renewable energy consumption by country, Demir and Gozgor (2018) obtain the same results for Canada, Sweden and the United Kingdom and find that shocks on renewable energy consumption are transitory. Moreover, Shahbaz et al. (2018) find transitory shocks for renewable energy consumption of Canada and Sweden like us.

When the energy literature is examined, there are some claims on the main reasons of finding stationarity in energy consumption, in other words, transitory shocks on energy consumption. According to Hsu et al. (2008), these reasons are as follows: (i) abundance of energy resources, (ii) less energy consumption, (iii) middle-income level, (iv) new environmental laws. On the other hand, Hasanov and Telatar (2011) refer energy consumption per capita to be stationary in developed and high-income countries. Furthermore, Mishra et al. (2009) claim that less volatility in energy consumption may be a reason to stationarity and transitory shocks. Our results based on non-renewable and renewable energy consumption coincide with the reason of Hasanov and Telatar (2011) and two reasons (abundance of energy sources and new environmental laws) of Hsu et al. (2008). In our paper, the countries with stationary non-renewable and renewable energy consumption per capita are developed and high-income countries which have abundant energy resources and apply strong environmental laws.

5 Conclusions and policy ımplications

In this paper, we examine the persistence of shocks on non-renewable and renewable energy consumption for 15 leading countries by renewable energy consumption, over the period 1980–2018, by using Fourier ADF unit root test of Christopoulos and Leon-Ledesma (2010). As reported about this test before, structural breaks are included by using a trigonometric function to allow for smooth temporary mean changes rather than jump functions and we do not need to specify the numbers, locations and the forms of the structural breaks a priori. The results give that non-renewable energy consumption per capita is stationary only for Sweden and the United States. When we give our attention to the renewable energy consumption per capita, it is seen that renewable energy consumption per capita is stationary for Canada, Sweden and the United Kingdom and nonstationary for other countries in the analysis. These results indicate that that shocks on non-renewable energy consumption per capita are transitory only for Sweden and the United States; shocks on renewable energy consumption per capita are transitory only for Canada, Sweden and the United Kingdom. In other words, it can be said that shocks on non-renewable energy consumption per capita and renewable energy consumption per capita are persistent for majority of the analyzed countries. When we give our attention to the countries with stationary non-renewable and renewable energy consumption per capita, we see that these developed and high income countries have abundant energy resources and strong environmental laws. These properties support Hasanov and Telatar (2011) and two reasons (abundance of energy sources and new environmental laws) of Hsu et al. (2008).

Our empirical results on the non-renewable energy consumption and renewable energy consumption provide significant policy implications:

First, policy changes have transitory effects on the non-renewable energy consumption in Sweden and the United States, but they have persistent effects on the non-renewable energy consumption in Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, South Korea, Spain, Turkey and the United Kingdom. In other words, the transitory policy stances can be more succesful in Sweden and the United States; persistent policy implications are more effective tool than transitory policy stances for other 13 countries analyzed. On the other hand, the policy changes on the renewable energy consumption have transitory effects only in Canada, Sweden and the United Kingdom; persistent effects in others. Since the energy consumption returns to its trend path quickly, any policy will not be effective on non-renewable energy consumption for Sweden and the United States, and also on renewable energy consumption for Canada, Sweden and the United Kingdom.

Second, there is potential of shock spillover from the non-renewable energy consumption to other economic variables (e.g., employment, economic growth, inflation, real exchange rate, foreign direct investment) in Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, South Korea, Spain, Turkey and the United Kingdom; from the renewable energy consumption to macroeconomic variables in Australia, Brazil, China, France, Germany, India, Italy, Japan, South Korea, Spain, Turkey and the United States. Similarly, the possible relationships between non-renewable energy consumption, renewable energy consumption and other economic variables can be investigated by using cointegration methods for the related countries.

Third, since non-renewable energy consumption exhibits a stationary process in Sweden and the United States, renewable energy consumption exhibits a stationary process in Canada, Sweden and the United Kingdom, forecasting the future of the non-renewable and renewable energy consumption is possible in related countries. However, this issue is impossible for other countries which non-renewable and renewable energy consumptions have a unit root process.

The future papers on the persistence of shocks on energy consumption can investigate the sub-components of both non-renewable (petroleum, coal, natural gas) and renewable (solar, wind, geothermal, hydropower, ocean and biomass) energy sources in different sectors by using recently developed Fourier unit root tests that consider structural breaks, nonlinearity and long memory together.

Data availability The datasets analysed during the current study are available in the database of US Energy Information Administration (EIA) (https://www.eia.gov/international/data/world/total-energy/total-energy-consumption) and in the database of World Development Indicators of the World Bank (https://databank.worldbank.org/source/world-development-indicators#).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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