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RESEARCH ARTICLE

Renewable, non-renewable energy consumption and economic growth nexus in G7: fresh evidence from CS-ARDL

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Abstract

This study investigates the effects of renewable energy (REN) consumption and non-renewable energy (NREN) consumption on economic growth in G7 countries with annual data covering the period 1980–2016 using a new panel data estimator that provides robust results under cross-sectional dependence, slope heterogeneity, and can be used whether series are integrated in different orders. In addition, the causality between the variables is analyzed with the panel bootstrap Granger causality method takes cross-sectional dependency and slope heterogeneity into account. According to Cross-sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) results, the coefficients of REN and NREN consumption are positive and statistically significant in both the short- and long-run. Furthermore, NREN consumption has a greater impact on enhancing economic growth than REN consumption. The panel bootstrap causality analysis reveals that the growth hypothesis (GH) is valid in REN in Canada, Italy, and the USA; neutrality is valid in REN in France, Japan, and the UK; the feedback hypothesis (FE) is valid for REN only in Germany. For NREN, the GH is valid for Canada, France, and Germany; the conservation hypothesis (CH) is valid in Italy and the UK. Finally, the FH is valid in Japan and the USA.

Keywords Renewable energy · Non-renewable energy · CS-ARDL analysis · G7 countries · Economic growth

Introduction

Energy is a vital element used in many points from production to electricity. The rapid increase in the world population, industrialization activities, technological innovations, living standards, and consumption expenditures lead to intense energy demand. Since fossil fuels are less costly, traditional fossil fuels (NREN resources) are predominantly preferred in energy production to meet the increasing demand. For instance, NREN consumption accounted for approximately 79.7% of global final energy consumption in 2017 (REN21 2019). However, fossil fuels based on NREN consumption such as oil, coal, and natural gas are accepted as the reason for a significant increase in the amount of carbon dioxide (CO_2) emission and similar greenhouse gases, which cause a significant increase in surface temperature (Destek 2017; Destek and Sinha 2020; Sharma et al. 2021). This situation causes serious global environmental issues such as global warming and climate change. In addition to the negative impacts of NREN sources on the environment, fossil fuels are seen as a serious problem in front of the sustainable growth targets of economies due to volatility in their prices and being exhaustible resources. These economic and environmental problems such as increasing energy demand and greenhouse gas emissions, volatility in the price of NREN sources, the danger of depletion of NREN sources, and dependence on foreign sources in energy have increased the interest in REN sources considered as clean and endless energy.

As REN sources do not harm the environment, they are supported by environmental organizations, and most countries, especially developed countries, aim to increase their

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production by adapting their production technologies to REN sources. Both the technologies needed for REN production and the difficulty of storing the generated energy cause REN to have a disadvantage compared to fossil fuels in terms of production cost. Despite this disadvantageous situation, demand, investment and production amount for renewable resources in the world are increasing day by day. In the 2006–2016 period, NREN consumption increased by 1.4% on average while REN consumption increased by 2.3% on average (REN21 2019). Moreover, total REN investments in the world were 45.2 billion dollars in 2004, it increased approximately 7.2 times and jumped to 325 billion dollars in 2017 (Ajadi 2019). However, due to the high production cost, it is known that the share of investments belongs to developed countries which account for 84% of global REN investment. Especially, G7 countries accounted for 29% of total electricity generation from REN sources such as wind, solar, bioenergy, geothermal, hydropower, and marine in 2014 (IRENA 2019).

After all these developments, although it is generally accepted that renewable energy is environmentally friendly, its economic efficiency is still an important topic of discussion. In the short term, high initial installation costs of some REN resources are considered as the disadvantage of REN sector development on the economic activities. On the other hand, the cost of REN sources continues to decline with the advent of technological innovations and wider REN project deployment in the long run. In addition, job-creating features of the REN sector may be accepted as the other advantage for economic indicators. Because, the number of direct or indirect employees in the REN sector is estimated to be 11 million in 2018 (REN21 2018). Therefore, it is crucial to separate the short-run and long-run impact of REN consumption on economic growth for energy policies. Based on these reasons, the main aim of this paper is to analyze the link between REN, NREN consumption, and economic growth in G7 countries using the Cross-sectionally Augmented ARDL model developed by Chudik and Pesaran (2015). There are a few advantages of this method compared to other panel data estimators. First, this method provides robust results under cross-sectional dependence. Second, it can be used whether series are integrated into different orders such as I_0, I_1, or a combination of both. Third, it gives well results in case of weak exogeneity. Forth, depending on whether slope coefficients are homogenous or heterogeneous, this method allows both pooled, mean group, and pooled-mean group estimates. Despite its advantages, there can be a negative bias in the estimations with small sample time series. Therefore, we also reported bias-corrected estimation results using the split-panel jackknife method to mitigate small sample time series bias. After the estimation of short and long-run coefficients, the direction of causality between renewable, NREN, and economic growth was also investigated to analyze the validity of feedback, conservation, neutrality, and GH with panel bootstrap Granger causality method that provides robust results under cross-sectional dependence. Due to its country-specific estimations, it is also useful while slope coefficients are heterogeneous. On the other hand, there are several reasons why we chose the sample of G7 countries in this study. G7 countries accounted for almost half of the global GDP. In addition, these countries have consumed approximately one-third of the World's energy production. G7 economies are also one of the communities with the largest share in renewable energy production (Behera and Mishra 2020). Choosing G7 countries is not only because of being the leading countries accounted for global GDP, NREN, and REN consumption, but also because of their climate change mitigation policies that strongly associated with their energy-economic growth nexus policies (Tugcu and Topcu 2018).

This study offers multiple contributions to previous empirical works. These are (i) to our best knowledge, this is the first study using the CS-ARDL method which provides more robust results compared to other panel data estimators. (ii) As Aghion and Howitt (2008) mentioned, growth models generally suffer from endogeneity problems which lead to reverse causality and are mostly ignored in previous studies. Our estimation method is robust under weak exogeneity. (iii) We provide estimates that analyze both the short and long-run effects of REN and NREN on economic growth. (iv) The causality relationship also investigated with Kónya (2006) panel causality method that considers cross-sectional dependency and gives country-specific results while slope coefficients are heterogeneous.

Literature review

Global issues such as increasing environmental concerns, volatility in fossil fuel prices, fossil fuel depletion, the security of energy supply, and dependence on imported energy show the importance of investments in REN sources. Furthermore, it is crucial for policymakers to design appropriate policies to investigate the effects of REN use on economic activities. Energy-economic growth literature starting with the study of Kraft and Kraft (1978) tested the link between total energy consumption and economic growth with Granger causality test in the US spanning a period of 1947–1974 is based on four hypotheses namely growth, conservation, feedback, and neutrality. According to GH, there is a one-way causality relationship running from energy consumption to economic growth and energy-saving policies have negative impacts on economic activities. A one-way causality relationship running from economic growth to energy consumption is called CH assuming energy-saving policies have no negative effects on economic activities. According to FH, there is a two-way causal relationship between energy consumption and economic growth and there is a mutual interaction between energy consumption and economic policies. Finally, according to the neutrality hypothesis (NH), there is no causal relationship between energy consumption and economic growth and energy-saving policies has no effect on economic growth.

In recent years, there has been a growing number of studies exploring the relationship between REN consumption and economic growth or the relationship between renewable and NREN consumption and economic growth. The summary of previous empirical studies is given in Table 1.

In the previous literature, a few studies have investigated the effects of REN consumption on economic growth in G7 countries. Chang et al. (2015) investigated the causality between REN and economic growth in G7 countries with annual data covering the period 1990–2011 utilizing the causality analysis method developed by Emirmahmutoglu and Kose (2011). The results indicate that the FH is confirmed for the overall panel. In addition to panel results, country-specific results were also reported in their analysis. These results show that the NH is valid for Canada, Italy, and the USA while the GH is supported for Japan and Germany. Finally, the CH is confirmed for France and the UK. Tugcu et al. (2012) aimed to explore the role of REN and NREN in economic growth in G7 countries for the 1980–2009 periods via bound testing analysis and Hatemi-J (2012) causality test. Estimation results for the augmented production function revealed that the FH is valid in England and Japan. The CH is confirmed in Germany. In order to fill this gap in the literature, we attempt to probe the relationship between REN, NREN consumption, and economic growth in G7 using the new method CS-ARDL providing robust results under cross-sectional dependency and also using the panel bootstrap causality method.

Model, data, and methodology

Model and data

Following the related literature, to compare the relative effects of renewable and non-renewable energy usage on economic growth, we present our model which describes the economic growth as a function of renewable energy, non-renewable energy, and capital accumulation based on Cobb-Douglas production function as follows;

$$GDP_{it} = \beta_{1i} + \beta_2 REN_{it} + \beta_3 NREN_{it} + \beta_4 GFC_{it} + \varepsilon_{it} \quad (1)$$

where GDP is measured in real GDP per capita (constant 2010 $) as a proxy for economic growth, REN is measured in billion Kwh as an indicator of renewable electricity consumption, NREN is measured in billion Kwh as a proxy for non-renewable electricity consumption and GFC is used in gross fixed capital formation share in GDP as a proxy for capital accumulation. Since all variables are used in per capita form, the labor force is excluded from the empirical model. The dataset of GDP and GFC variables are taken from World Development Indicators published by the World Bank while REN and NREN consumption indicators are taken from U.S. Energy Information Administration. The dataset is covering the period 1980–2016. All variables are turned into the logarithmic form. In the estimation of Eq. (1), panel data analysis methods are used.

Methodology

Cross-sectional dependence and slope homogeneity

Standard panel data methods assume that no dependency exists between cross-section units and slope coefficients are homogenous. However, estimators that ignore cross-sectional dependence may cause false inferences (Chudik and Pesaran 2013). In addition, the estimated coefficients may differ across cross-section units. Therefore, the existence of cross-sectional dependence and slope homogeneity will be investigated at first. The existence of cross-sectional dependence in the error term obtained from the model analyzed with Pesaran (2004) CD_{LM} and Pesaran et al. (2008) bias-adjusted LM test. These methods are valid while N>T and T>N. Therefore, CD_{LM} and bias-adjusted LM (LM_{adj}) tests found appropriate and their test statistics can be calculated as follows;

$$CD_{LM} = \left(\frac{1}{N(N-1)}\right)^{\frac{1}{2}} \sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\widehat{\rho}_{ij}^{\,2}-1\right) \quad (2)$$

$$LM_{adj} = \sqrt{\frac{2}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{(T-k)\widehat{\rho}_{ij}^{\,2}-\mu_{Tij}}{V_{Tij}} \quad (3)$$

Equation (5) shows the calculation of Pesaran (2004) CD_{LM} and Eq. (6) is Pesaran et al. (2008) bias-adjusted LM test statistic. V_{Tij}, μ_{Tij}, and $\widehat{\rho}_{ij}$ respectively represent variance, mean, and the correlation between cross-section units. The null and alternative hypothesis for both test statistics;

H_0: No cross-sectional dependence exist

H_1: Cross-sectional dependence exist

Pesaran and Yamagata (2008) developed Swamy (1970)'s random coefficient model in order to investigate parameter heterogeneity in panel data analysis.

Swamy's test statistic can be calculated as follows.

$$\widehat{S} = \sum_{i=1}^{N}\left(\widetilde{\beta}_i - \overbrace{\beta}_{WFE}\right)\frac{x_i' M_T x_i}{\widetilde{\sigma}_i^2}\left(\widetilde{\beta}_i - \overbrace{\beta}_{WFE}\right) \quad (4)$$

In Eq. (5), $\widetilde{\beta}_i$ and $\overbrace{\beta}_{WFE}$ respectively indicate the parameters obtained from pooled OLS and weighted fixed effects estimation while M_T is the identity matrix. Swamy's test

Table 1 Summary of the empirical literature

Study	Period	Sample	Methodologies	Results
Sadorsky (2009)	1994–2003	18 emerging countries	Panel FMOLS, DOLS, OLS	REN increases GDP
Apergis and Payne (2010a)	1985–2005	20 OECD countries	Panel FMOLS, Granger causality	REN↔GDP
Apergis and Payne (2010b)	1992–2007	13 Eurasia countries	Panel FMOLS, ECM	REN↔GDP
Apergis and Payne (2011a)	1990–2007	16 emerging countries	Panel FMOLS, ECM	REN↔GDP NREN↔GDP
Apergis and Payne (2011b)	1980–2006	6 Central American countries	Panel FMOLS, ECM	REN↔GDP
Apergis and Payne (2011c)	1990–2007	25 developed and 55 developing countries	Panel FMOLS, ECM	REN↔GDP NREN↔GDP
Mahmoodi and Mahmoodi (2011)	1985–2007	7 Asian developing countries	ARDL, Toda and Yamamoto	REN↔GDP (Bangladesh and Jordan) GDP→REN (India, Iran, Pakistan, and Syria)
Apergis and Payne (2012)	1990–2007	80 countries	Panel FMOLS, ECM	REN↔GDP NREN↔GDP
Ocal and Aslan (2013)	1990–2010	Turkey	ARDL; Toda-Yamamoto	GDP→REN
Pao and Fu (2013)	1980–2010	Brazil	Johansen cointegration, VECM	REN↔GDP
Kula (2014)	1980–2008	19 OECD countries	Pedroni cointegration, Panel DOLS, VECM	GDP→REN
Lin and Moubarak (2014)	1977–2011	China	ARDL, VECM	REN↔GDP
Salim et al. (2014)	1980–2011	29 OECD countries	CCEMG, PMG	REN↔GDP NREN↔GDP
Ohler and Fetters (2014)	1990–2008	20 OECD countries	Panel FMOLS, ECM	REN↔GDP
Ben Aïssa et al. (2014)	1980–2008	11 African countries	Panel OLS, FMOLS, DOLS, VECM	REN≠GDP
Shahbaz et al. (2015)	1972Q1–2011Q4	Pakistan	ARDL, VECM	REN↔GDP
Dogan (2015)	1990–2012	Turkey	ARDL, Johansen, Gregory-Hansen cointegration, VECM	REN≠GDP NREN↔GDP
Jebli and Youssef (2015)	1980–2010	69 countries	Panel FMOLS, DOLS, OLS, VECM	REN↔GDP NREN→GDP
Dogan (2016)	1988–2012	Turkey	ARDL, Johansen, Gregory-Hansen cointegration, VECM	REN↔GDP NREN↔GDP
Alper and Oguz (2016)	1990–2009	7 new EU members	ARDL, Hatemi-J (2012) causality	REN↔GDP (Bulgaria) GDP→REN (Czech Republic)
Inglesi-Lotz (2016)	1990–2010	34 OECD countries	Pedroni cointegration, Fixed effect OLS	REN increases GDP
Bhattacharya et al. (2016)	1991–2012	Top 38 countries	Pedroni cointegration, FMOLS	REN increases GDP
Ohlan (2016)	1971–2012	India	ARDL, VECM	REN↔GDP NREN↔GDP
Koçak and Şarkgüneşi (2017)	1990–2012	9 Black sea and Balkan countries	Panel DOLS, FMOLS, Dumitrescu and Hurlin causality	REN↔GDP
Shakouri and Khoshnevis Yazdi (2017)	1971–2015	South Africa	ARDL, Granger causality	REN↔GDP
Destek and Aslan (2017)	1980–2012	17 emerging countries	Bootstrap panel causality	REN→GDP (Peru) GDP→REN (Colombia and Thailand) REN↔GDP (Greece and South Korea) NREN→GDP (China, Colombia, Mexico and Philippines) GDP→NREN (Egypt, Peru and Portugal)

Table 1 (continued)

Study	Period	Sample	Methodologies	Results
				REN↔GDP (Turkey)
Rafindadi and Ozturk (2017)	1971Q1–2013QIV	Germany	ARDL, VECM	REN↔GDP
Adams et al. (2018)	1980–2012	30 SSA countries	Panel FMOLS, DOLS, Dumitrescu and Hurlin causality	REN→GDP NREN→GDP
Kahia et al. (2017)	1980–2012	11 MENA countries	Panel FMOLS, VECM	REN↔GDP NREN↔GDP
Atems and Hotaling (2018)	1980–2012	174 countries	Panel OLS, GMM	REN and NREN consumption increase GDP
Ozcan and Ozturk (2019)	1990–2016	17 emerging countries	Bootstrap panel causality	REN≠GDP (16 countries) REN→GDP (Poland)
Zafar et al. (2019)	1990–2015	16 Asia-Pacific Economic Cooperation countries	CUP-FM, CUP-BC estimators	REN and NREN increase economic growth
Rahman and Velayutham (2020)	1990–2014	South Asian countries	Panel DOLS and FMOLS estimators	REN and NREN increase GDP
Vural (2020)	1990–2015	6 Sub-Saharan African countries	Panel FMOLS estimator	REN and NREN increase GDP
Pegkas (2020)	1990–2016	Greece	ARDL	REN and NREN increase GDP
Asiedu et al. (2021)	1990–2018	26 European countries	Panel DOLS and FMOLS estimators	REN has a positive impact on GDP while NREN negative

Note: "↔", "→", and "≠" indicate bidirectional causality, unidirectional causality, and no causality respectively.

statistic is developed by Pesaran et al. (2008) with the following equations,

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S}-k}{\sqrt{2k}}\right) \quad (5)$$

$$\widetilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S}-E\left(\widetilde{Z}_{it}\right)}{\sqrt{Var\left(\widetilde{Z}_{it}\right)}}\right) \quad (6)$$

where $\widetilde{S}$ is the Swamy test statistic and k is a number of explanatory variables. $\widetilde{\Delta}_{adj}$ is a bias-adjusted version of $\widetilde{\Delta}$. $\widetilde{Z}_{it}$ =k and $Var\left(\widetilde{Z}_{it}\right) = 2k(T-k-1)/T+1$. The null and alternative hypothesis for both test statistics is given below.

$H_0 : \beta_i = \beta$

$H_1 : \beta_i \neq \beta$

The rejection of the null hypothesis shows the heterogeneity of slope coefficients in panel data models. After these preliminary analyses, stationarity levels of the variables will be examined with Cross-sectionally Augmented Dickey-Fuller (CADF) test.

Panel unit root test

Pesaran (2006) suggested a factor modeling approach which is simply adding the cross-section averages as a proxy of unobserved common factors into the model to prevent the problems caused by cross-sectional dependence. Following this approach Pesaran (2007) proposed a unit root test. This method is based on augmenting the Augmented Dickey-Fuller (ADF) regression with lagged cross-sectional mean and its first difference to deal with cross-sectional dependence (2008). This method considers the cross-sectional dependence and can be used while N>T and T>N. The CADF regression is;

$$\Delta y_{it} = \alpha_i + \rho_i^* y_{i,t-1} + d_0 \overline{y}_{t-1} + d_1 \Delta \overline{y}_t + \epsilon_{it} \quad (7)$$

$\overline{y}_t$ is the average of all N observations. To prevent serial correlation, the regression must be augmented with lagged first differences of both y_{it} and $\overline{y}_t$ as follows;

$$\Delta y_{it} = \alpha_i + \rho_i^* y_{i,t-1} + d_0 \overline{y}_{t-1} + \sum_{j=0}^{p} d_{j+1} \Delta \overline{y}_{t-j} + \sum_{k=1}^{p} c_k \Delta y_{i,t-k} + \epsilon_{it} \quad (8)$$

After this, Pesaran (2007) averages the t statistics of each cross-section unit ($CADF_i$) in the panel and calculates $CIPS$ statistic as follows;

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \quad (9)$$

The null hypothesis of this test is the existence of a unit root in the panel in question. If the CIPS statistic exceeds the critical value, the null of unit root will be rejected.

Cross-sectionally augmented ARDL model

In the analysis of long- and short-run coefficients, we estimated a Cross-sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model developed by Chudik and Pesaran (2015). The main advantages of the CS-ARDL estimator are providing robust results whether series co-integrated or not and repressors are I_0, I_1 or a combination of both (2017). Since it is an ARDL version of Dynamic Common Correlated Estimator that is based on the individual estimations with lagged dependent variable and lagged cross-section averages, it considers cross-sectional dependency (Chudik and Pesaran 2015). It allows mean group estimations while slope coefficients are heterogeneous. The mean group version of CS-ARDL model is based on the augmentation of the ARDL estimations of each cross-section with cross-sectional averages which are proxies of unobserved common factors and their lags (Chudik et al. 2017). This method also performs well under the weak exogeneity problem that occurs while the lagged dependent variable added to the model. The authors claimed that augmenting the model with lagged cross-section averages is mostly prevent the endogeneity problem. The CS-ARDL estimation is based on the following regression.

$$y_{it} = \alpha_i + \sum_{l=1}^{p_y}\lambda_{l,i}y_{i,t-l} + \sum_{l=0}^{p_x}\beta_{l,i}x_{i,t-l}\sum_{l=0}^{p_\varphi}\varphi_{i,l}^{'}\overline{z}_{i,t-l} + \varepsilon_{it} \quad (10)$$

In Eq. (10), $\overline{z}_{t-l}$ refers to lagged cross-sectional averages $[\overline{z}_{t-l} = (\overline{y}_{i,t-l}, \overline{x}_{i,t-l})]$. The long-run coefficient of mean group estimates are

$$\widehat{\theta}_{CS-ARDL,\ i} = \frac{\sum_{l=0}^{p_x}\widehat{\beta}_{l,i}}{1-\sum_{l=0}^{p_y}\widehat{\lambda}_{l,i}}, \widehat{\theta}_{MG} = {}^{1}/_{N}\sum_{i=1}^{N}\widehat{\theta}_i \quad (11)$$

where $\widehat{\theta}_i$ denotes individual estimations of each cross-section. The error correction form of the CS-ARDL method is

$$\Delta y_{it} = \varnothing_i\left[y_{i,t-l} - \widehat{\theta}_i x_{i,t}\right] - \alpha_i + \sum_{l=1}^{p_y-1}\lambda_{l,i}\Delta_l y_{i,t-l}$$
$$+ \sum_{l=0}^{p_x}\beta_{l,i}\Delta_l x_{i,t-l}\sum_{l=0}^{p_\varphi}\varphi_{i,l}^{'}\Delta_l\overline{z}_{i,t-l} + u_{it} \quad (12)$$

where $\varnothing_i$ denotes error correction speed of adjustment. According to Chudik and Pesaran (2013), CCE mean group estimator with lagged augmentations performs well in terms of bias, size, and power. However, when T<50 the authors observed a negative bias. To mitigate that small sample time series bias, Chudik and Pesaran (2015) suggested the split-panel jackknife method developed by Dhaene and Jochmans (2015). The jackknife method is based on the following equation.

$$\widetilde{\pi}_{MG} = 2\widetilde{\pi}_{MG} - {}^{1}/_{2}\left(\widehat{\pi}_{MG}^{a} + \widehat{\pi}_{MG}^{b}\right) \quad (13)$$

In Eq. (13), $\widehat{\pi}_{MG}^{a}$ denotes the CCEMG estimation with the first half of time dimension (t = 1, 2, 3, . . . , (T/2)) and $\widehat{\pi}_{MG}^{b}$ denotes estimation with second half of time dimension (t = (T/2)+1, (T/2)+2, . . . , T). In this study, our time dimension is 37 (T<50). Therefore, the bias-corrected results of CS-ARDL estimation will be reported. After the estimation of the CS-ARDL model, we performed panel causality analysis to determine long-run causal relationships.

Panel bootstrap Granger causality analysis

In the analysis of causality between variables, the panel bootstrap Granger causality method proposed by Kónya (2006) is used. This method is based on the estimations with seemingly unrelated regressions (SUR) that prevent the cross-sectional dependency problem. This method also does not require any preliminary analysis of unit root and co-integration (Kónya 2006; Kar et al. 2011). The panel causality analysis of Kónya (2006) is based on the estimation of the following equation systems:

$$GDP_{1t} = \alpha_{11} + \sum_{l=1}^{p_1}\lambda_{11l}GDP_{1t-l} + \sum_{l=1}^{p_1}\beta_{11l}REN_{1t-l} + \varepsilon_{11t} \quad (14)$$

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$$GDP_{Nt} = \alpha_{1N} + \sum_{l=1}^{p_1}\lambda_{1Nl}GDP_{Nt-l} + \sum_{l=1}^{p_1}\beta_{1Nl}REN_{Nt-l} + \varepsilon_{1Nt}$$

$$GDP_{1t} = \alpha_{11} + \sum_{l=1}^{p_1}\lambda_{11l}GDP_{1t-l} + \sum_{l=1}^{p_1}\beta_{11l}NREN_{1t-l} + \varepsilon_{11t} \quad (15)$$

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$$GDP_{Nt} = \alpha_{1N} + \sum_{l=1}^{p_1}\lambda_{1Nl}GDP_{Nt-l} + \sum_{l=1}^{p_1}\beta_{1Nl}NREN_{Nt-l} + \varepsilon_{1Nt}$$

$$REN_{1t} = \alpha_{11} + \sum_{l=1}^{p_1}\lambda_{11l}REN_{1t-l} + \sum_{l=1}^{p_1}\beta_{11l}GDP_{1t-l} + \varepsilon_{11t} \quad (16)$$

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$$REN_{Nt} = \alpha_{1N} + \sum_{l=1}^{p_1}\lambda_{1Nl}REN_{Nt-l} + \sum_{l=1}^{p_1}\beta_{1Nl}GDP_{Nt-l} + \varepsilon_{1Nt}$$

$$NREN_{1t} = \alpha_{11} + \sum_{l=1}^{p_1}\lambda_{11l}NREN_{1t-l} + \sum_{l=1}^{p_1}\beta_{11l}GDP_{1t-l} + \varepsilon_{11t} \quad (17)$$

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$$NREN_{Nt} = \alpha_{1N} + \sum_{l=1}^{p_1}\lambda_{1Nl}NREN_{Nt-l} + \sum_{l=1}^{p_1}\beta_{1Nl}GDP_{Nt-l} + \varepsilon_{1Nt}$$

where N is the number of cross-sections (i=1,…,N), t is the time period (t=1,…,T) and l is the lag length. If calculated country-specific Wald statistics exceed the bootstrap critical value, the null of no causality will be rejected. Since this method makes country-specific estimates, it provides robust results while slope coefficients are heterogeneous.

Empirical findings

In the first step of empirical analysis, we should examine both the cross-sectional dependency and homogeneity assumptions to choose more robust estimations. Based on this, we first employ the tests that Pesaran (2004) CD_{LM} and Pesaran et al. (2008) bias-adjusted LM tests for cross-sectional dependence and slope homogeneity test of Pesaran and Yamagata (2008) and the findings are given in Table 2. According to results, the null of no cross-sectional dependency is rejected for both CD_{LM} and bias-adjusted LM tests at 1%. In addition, the null of homogeneity is also rejected at 1% level. Regarding these results, the methods that allow cross-sectional dependence and slope heterogeneity will be used in the continuation of the analysis.

In the second step, the stationarity properties of the variables are investigated with the CIPS unit root test and the results are given in Table 3. In the testing procedure, constant and trend terms are both considered at level form of variables while only constant term is taken into account in the first differenced estimations. The results show that the null of unit root is rejected at 1% for the GDP, NREN, and GFC in the first differenced forms. However, REN is found trend stationary in level form. Fortunately, the used methodology is suitable for the subsequent step because the CS-ARDL approach can be used in case of different orders of stationary.

The preliminary analysis shows different orders of stationarity, cross-sectional dependence, and slope heterogeneity. The CS-ARDL approach was found appropriate for our analysis because of its robustness under cross-sectional dependency and different orders of stationarity. We also estimated a mean group CS-ARDL model to deal with country-specific coefficients. Optimum lag structure is determined via F joint test from general to particular. We also reported the bias-corrected CS-ARDL estimation by using the split-panel jackknife method. The results of the estimation are summarized in Table 4. According to the results, REN consumption has a positive impact on GDP per capita growth and this effect is significant at 10% and 5% according to CS-ARDL and its bias-corrected estimation respectively. A 1% improvement in REN use increases economic growth 0.12%. The impact of NREN use is positive as well. However, its effect is higher and more significant. A 1% improvement in NREN use increases growth 0.19 and 0.17% while bias correction is used. These results show that NREN consumption results in faster economic growth. The effect of gross-fixed capital formation which was added as a control variable into the model is positive and significant at 1% according to both estimation results. The short-run coefficients are provided similar results with long-run coefficients. The coefficients of renewable, non-renewable consumption, and gross fixed capital formation variables are positive in the short run. NREN consumption results in faster economic growth in the short-run compared to REN consumption. Finally, the error correction terms

Table 2 Cross-sectional dependence and slope homogeneity

Test	Statistics	p-value
$\mathbf{CD_{LM}}$	4.62***	0.000
$\mathbf{LM_{adj}}$	20.94***	0.000
$\tilde{\Delta}$	15.985***	0.000
$\tilde{\Delta}_{adj}$	17.153***	0.000

***Denotes the rejection of the null hypothesis at 1%

Table 3 CIPS unit root test results

	Level	1^{st} difference	Results
GDP	−2.342	−2.601***	I_1
REN	−3.156	-	I_0
NREN	−1.320	−5.256***	I_1
GFC	−1.842	−3.993***	I_1

***Denotes the rejection of the null hypothesis at 1%

Table 4 CS-ARDL estimation results

	$CS\text{-}ARDL$ (2, 1, 1, 1)		$CS\text{-}ARDL_{JK}$ (2, 1, 1, 1)	
	coefficient	*t-statistics*	*coefficient*	*t-statistics*
Short run				
ΔGDP_{t-1}	0.2964	4.84***	0.3846	4.45***
ΔREN	0.0680	2.21**	0.0544	3.75***
ΔNREN	0.1235	4.93***	0.0870	3.54***
ΔGCF	0.1620	3.13***	0.1350	2.40**
Long run				
REN	0.1243	1.66*	0.1249	2.10**
NREN	0.1946	3.80***	0.1726	2.59***
GFC	0.2531	3.06***	0.2094	3.15***
Error correction	−0.7035	−11.48***	−0.6153	−7.12***
F statistics		4.60***		5.66***
Adjusted R^2		0.56		0.64

***, **, and * indicate the rejection of the null hypothesis at 1, 5, and 10%, respectively of CS-ARDL and its bias-corrected version are negative and significant at 1%. This result refers to an equilibrium process in the long run. The speed of adjustment is 70% in one period while it is 61% according to bias-corrected estimation.

The results of the short- and long-run estimations show consistency with the results of Zafar et al. (2019), Rahman and Velayutham (2020), Vural (2020), and Pegkas (2020). The authors similarly concluded that both renewable and non-renewable energy consumption has a positive impact on economic growth. Our results show inconsistency with Destek (2016) and Asiedu et al. (2021). Their empirical results show that renewable energy consumption has a positive impact on growth while non-renewable energy consumption has a negative impact. In contrast, we concluded that non-renewable energy consumption is more effective to accelerate economic growth compared to renewable energy.

In addition to CS-ARDL estimation, we determined the long-run causal relationship via Kónya (2006) bootstrap Granger causality analysis. This method was found appropriate due to cross-sectional dependency and slope heterogeneity in our model. It also provides robust results whether the variables stationary or not. The other advantage of this methodology is that using this test allows observing the country-specific causal connections. In the analysis of causality, the maximum lag level is determined as 3 and the optimum lag level is determined via Schwarz Information Criterion. The critical values are obtained from 10,000 bootstrap replications.

According to the results given in Table 5, there is a significant unidirectional causality from REN to GDP per capita in Canada, Germany, Italy, and the USA at 1% level. The relationship is two-way only in Germany. The causality from NRE consumption to GDP per capita is significant at 10% in Germany, 5% in Canada, France, and the USA, and 10% in Germany. There is causality from GDP to NRE use in the UK at 10% and Italy at 1%. Finally, there is a bidirectional causality in Japan and the USA. The results of panel causality analysis in the context of growth, conservation, feedback, and NH are summarized in Table 6.

Table 6 Summary of causality results

	REN-GDP	NREN-GDP
Canada	Growth	Growth
France	Neutrality	Growth
Germany	Feedback	Growth
Italy	Growth	Conservation
Japan	Neutrality	Feedback
UK	Neutrality	Conservation
USA	Growth	Feedback

The panel causality results show that the GH is valid in REN in Canada, Italy, and the US while neutrality is valid in France, Japan, and the UK. The FH is valid for REN only in Germany. For NREN, the GH is valid for Canada, France, and Germany and the CH is valid in Italy and the UK. Finally, the FH is valid in Japan and the USA.

Concluding remark

The aim of this study is to examine the impacts of REN and NREN consumption on economic growth in G7 countries for the period spanning from 1980 to 2016. In the estimation of short- and long-run effects, the CS-ARDL approach is employed. In addition, Kónya (2006) bootstrap Granger

Table 5 Panel causality test results

	REN⇏GDP				GDP⇏REN				NREN⇏GDP				GDP⇏NREN			
		Bootstrap critical values				Bootstrap critical values				Bootstrap critical values				Bootstrap critical values		
	Wald stat.	1%	5%	10%	Wald stat.	1%	5%	10%	Wald stat.	1%	5%	10%	Wald stat.	1%	5%	10%
Canada	0.979***	0.557	0.323	0.223	1.346	14.207	8.390	6.436	0.247**	0.362	0.193	0.129	1.896	6.532	4.759	3.814
France	0.224	2.456	1.823	1.518	2.092	13.247	10.776	9.352	1.230**	1.740	0.847	0.577	0.306	7.040	4.170	3.128
Germany	0.763***	0.756	0.488	0.372	4.686*	8.633	5.408	3.693	1.307*	2.427	1.380	0.990	0.125	8.365	5.483	4.418
Italy	5.992***	2.864	2.474	2.175	5.324	24.573	17.476	14.080	0.356	4.323	3.435	3.101	7.716***	7.331	4.431	3.313
Japan	0.242	4.945	4.533	4.288	1.517	13.635	8.517	5.684	5.190***	1.357	1.162	1.070	5.887**	6.212	3.014	2.163
UK	0.362	4.036	3.545	3.123	0.061	10.370	6.670	5.080	2.954	12.248	11.456	1.070	2.135*	6.407	2.905	1.962
USA	9.097***	1.085	0.740	0.596	1.927	15.212	9.363	6.979	2.146**	2.294	1.845	1.645	3.217*	7.475	4.434	3.064

***, **, and * indicate the rejection of the null hypothesis at 1, 5, and 10% respectively causality method is utilized to probe the causality link between the variables.

The findings obtained from CS-ARDL estimation refers that REN and NREN uses are both positively related to economic growth in the long- and short-run. On the other hand, as the coefficients of these two variables are compared it is concluded that the impact of NREN use on economic growth is higher and statistically more significant. Within the framework of these results, NREN is more effective in increasing economic growth compared to REN consumption in the short- and long-run. Our findings support the evidence of Adams et al. (2018) and Tugcu et al. (2012). Despite the rise in investments in REN sources in the G7 countries, the costs are still higher compared to NREN use. Due to these high costs, the increase in the use of REN in production has a decreasing effect on competitiveness. Although the effect of REN use on economic growth is lower, it can be said that it will be a more rational choice than NREN use to make economic growth sustainable. Considering the positive environmental effects of REN, it is thought that the growth to be realized by scaling up the use of REN will be more sustainable. Furthermore, the cost disadvantages of REN use are expected to decrease due to the increase in REN investments and technological developments. In addition to short and long-run estimation results, the causality analysis shows that the GH is proven for RE in Canada, Italy, and the USA; neutrality is proven for REN in France, Japan, and the UK; the FH is proven for REN only in Germany. In the case of NREN, the GH is proven for Canada, France, and Germany; the CH is proven in Italy and the UK. Finally, the FH is proven in Japan and the USA. Concerning these results, in Canada, Germany, Italy, and the USA it is seen that the economic benefits of RE investments are started to emerge. However, in France, Japan, and the UK, there is no causal link between REN consumption and economic growth. Therefore, REN policies in France, Japan, and the UK are economically inefficient. However, these countries should continue to invest in REN sources because of their environmental benefits. Our additional findings show that gross fixed capital formation which added to the model as a control variable also positively affects economic growth in both the short- and long-run.

According to empirical results of the analysis, this study presents useful insights for policymakers to formulate energy-growth nexus policies in G7 countries. The crucial policy implication of this paper claims that G7 countries should utilize both NREN and REN to reach their targeted economic growth rate. Although the positive impact of NREN consumption on economic growth has been greater than REN consumption, G7 countries should increase investment in renewable energy sources by taking into account the negative environmental externalities of NREN. To combat climate change and achieve the Sustainable Development Goals (SDGs), these countries may change the industrial structure from NREN to REN sources. Furthermore, G7 members should invest more in renewable energy sources, technologies, and energy infrastructure to increase efficiency and decrease high energy production costs.

Author contribution MAD initiated and designed the study. İO reviewed the literature and collected the dataset. AEG carried out the empirical analysis. AEG and İO have jointly interpreted the empirical findings, revised and completed the manuscript. All authors read and approved the final manuscript.

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