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Solar energy-economic growth nexus in top 10 countries with the highest installed capacity

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ABSTRACT

This paper investigates the relationship between solar energy production and economic growth for top 10 countries with the highest installed solar energy production capacity as of 2017 (China, the USA, Japan, Germany, Italy, India, the UK, France, Australia, and Spain, respectively) using data over the period 1999–2015. For this purpose, the paper employs panel cointegration and causality methods that are robust to cross-sectional dependence. The findings imply that the coefficient of solar energy is insignificant in the empirical model and that there is no causality between solar energy and GDP, indicating the neutrality hypothesis prevails for solar energy. Theoretical and practical implications are also discussed.

KEYWORDS

Renewable energy; solar energy; economic growth; cross-sectional dependence; panel cointegration; panel causality

1. Introduction

Energy is an essential factor of production as all production activities depend on the utilization of energy. For this reason, energy demand rapidly increases especially in periods when economies grow. International Energy Agency (2020, hereafter IEA) data show that energy consumption increased by 49.7% over the period 1990–2015. This figure does not pose a problem by itself. However, the high share of fossil energy sources, namely coal, oil, and natural gas, in energy consumption[1] results in serious problems and concerns all over the world: (i) concerns about the exhaustion of fossil sources as they are nonrenewable (Chapman 2014), (ii) energy supply shocks and high volatility of energy prices (Kruyt et al. 2009), and (iii) environmental problems, such as air pollution, global warming, and climate change. Because of these concerns and problems, policy makers have further begun to pay attention to renewables which are clean energy sources in the last decades. Principal renewable energy sources are biomass, hydro, solar, wind, and geothermal. Policy makers expect renewable energy to meet energy needs for sustainable economic growth and to decrease environmental problems (Fang 2011).

Solar energy is the energy of solar radiation which is observed in the form of heat and light and is received from the greatest energy source on Earth, the Sun (Prvulovic et al. 2018). Hence, solar energy is considered to be the largest renewable energy sources (Aman et al. 2015; Sahu 2015). The quantity of solar rays arriving at the earth's surface each hour is higher than all energy needs every year (Center for Climate and Energy Solutions 2017; Prvulovic et al. 2016). In addition, solar energy has lots of great advantages over fossil energy sources. Accordingly, solar energy (i) emits no greenhouse gases, (ii) improves land and the quality of water sources, (ii) expands energy supply, (iv) provides energy security and independence, and (v) results in rural population's access to electricity in developing economies (Solangi et al. 2011). Last but not least, electricity is produced from solar energy during the

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[1]In the world, the share of fossil sources in total energy consumption was 80.4% in 2015 (World Bank 2020).

hours when electricity is the most expensive during a day (Dusonchet and Telaretti 2010). Solar energy technology has two elements: concentrating solar power (CSP) technologies and solar photovoltaic (PV) cells. PV cells directly convert sunlight to electricity, while CSP technologies utilize mirrors to gather the sun's rays and to transform these rays into heat, which in turn spins a steam turbine that generates electricity (Aman et al. 2015). The PV cells' costs have diminished remarkably in the past years because of new investments and technological progress in the solar energy industry. Accordingly, the cost of a PV cell per watt diminished from 76.67 USD to 0.74 USD over 1977–2013 period (Economist 2013). This huge decrease encourages investments in solar energy and solar energy systems are stimulated by many countries in the world (Aman et al. 2015; Liu 2018). Therefore, solar energy investments have increased especially since the last decade in the world, and solar energy's share in total renewable electricity generation began to increase. For instance, in the world, while the share of solar PV energy in renewable electricity generation was 0.5% in 2009, it reached 2.2% in 2012 and was 4.6% in 2015 (IEA 2020).

Based on these advantages and developments for solar energy, this paper investigates the relationship between solar energy production and economic growth for top 10 countries with the highest installed capacity in 2017 over the period 1999–2015 by employing some advanced panel data techniques which are robust to cross-sectional dependence. The paper focuses on a group of countries considering their progress in the establishment of solar energy installations and their installed solar energy capacities instead of a group of countries with similar economic performances or geographical proximity. This paper contributes to the energy economics literature in some aspects. First, one can notice from the energy economics literature that there exists a continuously growing empirical literature on the renewable energy-growth nexus. He/she can also notice that a greater part of these papers examines this relationship using aggregated data and does not investigate the specific effects of different types of renewable energy on economic growth. In doing so, they obtain findings and present policy proposals for renewable energy sources as a whole. This paper argues that examining the specific effects of different types of renewable energy sources on economic growth can help policy makers further while they are designing energy policies. The paper, therefore, searches for the influence of solar energy on economic growth considering there is a research gap on this topic. Second, to our knowledge, Ewing, Sari, and Soytas (2007), Ohler and Fetters (2014), Armeanu, Vintila, and Gherghina (2017), Bilgili et al. (2019), and Bulut and Apergis (2020) examine the particular effects of solar energy production and/or consumption on economic growth. Accordingly, Ewing, Sari, and Soytas (2007), Bilgili et al. (2019), and Bulut and Apergis (2020) examine this relationship for the USA, while Ohler and Fetters (2014) and Armeanu, Vintila, and Gherghina (2017) investigate the related relationship using a panel data framework. Even though Ohler and Fetters (2014) consider cross-sectional dependence while examining the renewable energy-economic growth nexus, their empirical model does not include some important determinants of economic growth, namely capital, and labor. Therefore, their findings may have been exposed to the omitted variable bias. Besides, Armeanu, Vintila, and Gherghina (2017) do not take cross-sectional dependence into consideration, which may lead to biased and inefficient findings. However, this paper sets up an empirical model including capital and labor which are considered to be important determinants of economic growth and performs panel unit root, cointegration, and causality methods which are robust to cross-sectional dependence. Hence, we believe that our paper is able to present more efficient and unbiased findings compared to the findings of the previous studies in the existing literature.

The remaining of the paper is organized as follows: Section 2 presents the empirical literature on the economic growth-renewable energy nexus. Section 3 gives model and data while estimation methodology is exhibited in Section 4. Findings are reported in Section 5. Section 6 concludes the paper.

2. Literature review

In the energy economics literature, researchers use four hypotheses to test the energy-economic growth nexus (Ozturk 2010). These hypotheses are as follows: (i) the growth hypothesis is supported when there is a unidirectional causal relationship from energy to economic growth, (ii) the feedback hypothesis dominates if there exists a bidirectional causal relationship between economic growth and energy, (iii) the conservation hypothesis prevails when there is a unidirectional causal relationship from economic growth to energy, and (iv) the neutrality hypothesis dominates if there are not any causal relationships between energy and economic growth.

Nowadays a continuously increased number of renewable energy-growth studies become involved in the investigation of economic growth and renewable energy, but fewer of them deal with specific-disaggregated forms of renewable energy, namely they aim to study separately the contribution of the various forms of renewable energy in the economic growth. Nevertheless, there are some studies that examine the relationship between economic growth and different kinds of renewable energy in the extant literature. Besides, some of them focus on solar energy production/consumption and its effect on economic growth. Examples of the aforementioned scant studies have been produced by Ewing, Sari, and Soytas (2007), Ohler and Fetters (2014), Armeanu, Vintila, and Gherghina (2017), Bilgili et al. (2019), and Bulut and Apergis (2020) and can be collectively seen in Table 1. While Ohler and Fetters (2014) and Armeanu, Vintila, and Gherghina (2017), respectively, examine this nexus for OECD and European Union countries, others focus on this relationship for the USA. Besides, Ewing, Sari, and Soytas (2007), Bilgili et al. (2019), and Bulut and Apergis (2020) find evidence in favor of the growth hypothesis, whereas Ohler and Fetters (2014) and Armeanu, Vintila, and Gherghina (2017), respectively, yield the conservation hypothesis and the neutrality hypothesis prevail. Other studies include economic growth through proxies, e.g., Marques, Fuinhas, and Menegaki (2016) include industrial production as a proxy for economic growth. Inspired by the new economics movement, recently a new strand of studies has emerged in the energy-growth nexus field. This new strand uses sustainable economic growth instead of GDP growth and has generated new studies which use renewable energy as a variable of interest but cannot be directly compared with the studies in Table 1. Such studies are Menegaki and Tugcu (2018) for renewable energy and nonrenewable energy in Asian countries, Menegaki and Tiwari (2017) for nonrenewable and renewable energy in American countries.

Following the empirical literature on the renewable energy-economic growth nexus, we observe that the bulk of studies has dealt with the total renewable energy-growth nexus instead of the nexus between specific types of renewable energy and growth so far. Since renewable energy disaggregates into many different types of renewable energy such as hydro, solar, biomass, waste, geothermal, wind, etc., this reveals the range of potential studies that are needed to gauge the gap.

Table 1 presents the empirical literature on the relationship between economic growth and renewable energy.

3. Model and data set

Within the scope of a panel data analysis, this paper utilizes a Cobb–Douglas production function to investigate the influence of solar PV electricity production on economic growth for top 10 countries with the highest total installed solar energy capacity in the world as of 2017 (China, the USA, Japan, Germany, Italy, India, the UK, France, Australia, and Spain, respectively). Hence, the empirical model in the paper includes solar energy together with capital and labor. The log-linear form of the production function in the analysis is specified as the following:

$$\ln Y_t = \delta_0 + \delta_1 \ln K_t + \delta_2 \ln L_t + \delta_3 \ln S_t + \varepsilon_t \quad (1)$$

where ln, Y, K, L, S, and ε, respectively, stand for GDP (constant 2010 USD), gross capital formation (constant 2010 USD), employment to population ratio for 15+ (%), solar PV electricity generation (GWh), and the error term. As solar PV electricity generation began in 1999 for the UK, the data set in the paper covers the period 1999–2015. While data for GDP, capital, and labor are extracted from the World Bank (2020), solar energy production data are taken from IEA (2020).

Table 1. Empirical literature on the economic growth-renewable energy nexus.

Studies	Country or Countries	Data-span	Method	RE type	Covariates	Evidence for hypotheses
Ewing, Sari, and Soytas (2007)	USA	2001–2005	Generalized forecast error variance decomposition	RE, H, S, W, CRW	L, FE	Growth
Payne (2009)	USA	1949–2006	Causality	RE	K, L, NRE	Neutrality
Bowden and Payne (2010)	USA	1949–2006	Causality	CRE, IRE, RRE	K, L	Neutrality
Menyah and Wolde-Rufael (2010)	USA	1960–2007	Causality	RE	CO_2	Conservation
Apergis and Payne (2011b)	6 Central American countries	1980–2006	Cointegration Causality	RE	K, L	Feedback
Payne (2011)	USA	1949–2007	Causality	B	K, L	Growth
Shahbaz, Zeshan, and Afza (2012)	Pakistan	1972–2011	Cointegration	RE	K, L, NRE	Feedback
Tugcu, Ozturk, and Aslan (2012)	G7 countries	1980–2009	Cointegration Causality	RE	NRE, K, L, E	Mixed
Yildirim, Sarac, and Aslan (2012)	USA	1949–2010	Cointegration Causality	RE, B, H, G	L, I	Neutrality, Growth
Bildirici and Ozaksoy (2013)	10 European countries	1960–2010	Cointegration	B	None	Conservation, Growth, Feedback
Ocal and Aslan (2013)	Turkey	1990–2010	Cointegration Causality	CRW	K, L	Conservation
Pao and Fu (2013)	Brazil	1980–2009	Cointegration	H, RE	K, L, TE, NRE	Conservation, Growth
Ohler and Fetters (2014)	OECD countries	1990–2008	Cointegration Causality	B, G, H, S, W, CRW	NRE	Conservation
Pao, Li, and Fu (2014)	MIST emerging economies: Mexico, Indonesia, South Korea, and Turkey	1990–2010	Panel cointegration Panel causality	RE	K, L, FE	Growth
Caraiani et al. (2015)	5 Emerging European countries: Bulgaria, Hungary, Poland, Romania, and Turkey	1980–2013	Causality	RE	None	Conservation
Chang et al. (2015)	G7 countries	1990–2011	Causality	RE	None	Mixed findings
Omri, Mabrouk, and Sassi-Tmar (2015)	17 developed & developing countries	1990–2011	Simultaneous equation modeling	RE	K, L, CO_2, OP, OC	Growth, Feedback
Ozturk and Bilgili (2015)	51 SSA countries	1980–2009	Cointegration	B	O, P	Growth
Bhattacharya et al. (2016)	Top RES consuming 38 countries	1991–2012	Cointegration	RE	K, L	Conservation
Menegaki (2016)	BRIC countries	1992–2008	Dynamic fixed effects	RE	CO_2, O, K, L	Feedback
Menegaki and Ozturk (2016)	MENA countries	1997–2009	Dynamic fixed effects	RE	R, PS, L, FE	Feedback
Armeanu, Vintila, and Gherghina (2017)	European Union countries	2003–2014	Cointegration and causality	B, G, H, S, W	A, L, GHG	Neutrality
Bilgili et al. (2017)	USA	1982–2011	Causality	B	None	Growth
Bulut and Muratoglu (2018)	Turkey	1990–2015	Cointegration Causality	RE	NRE, A, K, L, D	Neutrality
Aydin (2019a)	BRICS countries	1992–2013	Cointegration Causality	B	K, L	Mixed findings

(*Continued*)

Table 1. (Continued).

Studies	Country or Countries	Data-span	Method	RE type	Covariates	Evidence for hypotheses
Aydin (2019b)	OECD countries	1980–2015	Time domain and frequency domain causality	RE	NRE	Neutrality (time domain) Feedback (Frequency domain)
Bilgili et al. (2019)	USA	1989–2019	Wavelet coherence	B, S, W, G	None	Growth
Bulut and Inglesi-Lotz (2019)	USA	2000–2018	Cointegration	RE	NRE	Growth
Charfeddine and Kahia (2019)	MENA region	1980–2015	Panel vector autoregressive (VAR)	RE	K, L, CO_2, FD	Growth
Diaz et al. (2019)	134 countries	1960–2010	Generalized method of moments	RE	EI, N, INF, O, etc.	Growth
Mohamed, Jebli, and Youssef (2019)	France	1980–2015	Cointegration Causality	RE	FE, O, T	Growth
Ozcan and Ozturk (2019)	17 emerging countries	1990–2016	Causality	RE	None	Neutrality except Poland
Zafar et al. (2019)	Asia-Pacific economic cooperation countries	1990–2015	Cointegration Causality	RE	A, K, NRE, O	Feedback
Bulut and Apergis (2020)	USA	1984–2018	Cointegration	RE, S	K, L	Growth
Chen, Pinar, and Stengos (2020)	103 countries	1995–2015	Generalized method of moments	RE	K, L, NRE	Growth (OECD) Neutrality (Non-OECD)

A: Technology, K: capital, L: labor, FE: fossil energy, CO_2: CO_2 emissions, O: trade openness, P: population, FD: financial development, TE: total energy, RE: renewable energy, NRE: nonrenewable energy, CRE: commercial renewable energy, IRE: industrial renewable energy, RRE: residential renewable energy, CRW: combustible renewables and waste, H: hydroelectric power, S: solar energy, INF: inflation, W: wind energy, G: geothermal energy, B: biomass energy, EI: energy intensity, N: nuclear energy, GHG: greenhouse gas emissions, D: democracy, E: education, T: terrorism, I: investment, OP: oil price, OC: oil consumption, PS: political stability, R: rents.

Table 2. Descriptive statistics and correlation matrix for the variables.

Descriptive statistics				
	lnY	lnK	lnL	lnS
Mean	28.655	27.233	4.011	5.754
Median	28.527	27.067	4.042	5.667
Maximum	30.445	29.087	4.320	10.719
Minimum	27.373	25.848	3.741	0.000
Std. deviation	0.779	0.812	0.132	2.869
Observations	170	170	170	170
Correlation matrix				
lnY				
lnK	0.947			
lnL	0.365	0.459		
lnS	0.419	0.395	−0.007	

Table 2 reports descriptive statistics and correlation matrix for the variables in the empirical model. Accordingly, all descriptive statistics except the standard deviation of lnY are greater than those of lnK, lnL, and lnS. Besides, lnY is positively correlated with all variables. Time plots for the variables are exhibited in Figure 1. As is seen, electricity production from solar PV has rapidly increased for all countries in the panel data set. Descriptive statistics and time plots provide one with some initial analysis for the variables under consideration. Yet, researchers should consider some econometric techniques to obtain more efficient output about the relationships between variables.

4. Research methodology

4.1. Preliminary analysis: cross-sectional dependence and unit root tests

In a panel data model, researchers first should search for cross-sectional dependence because a shock in one country can be transmitted to other countries in the panel. To test for the null hypothesis of no

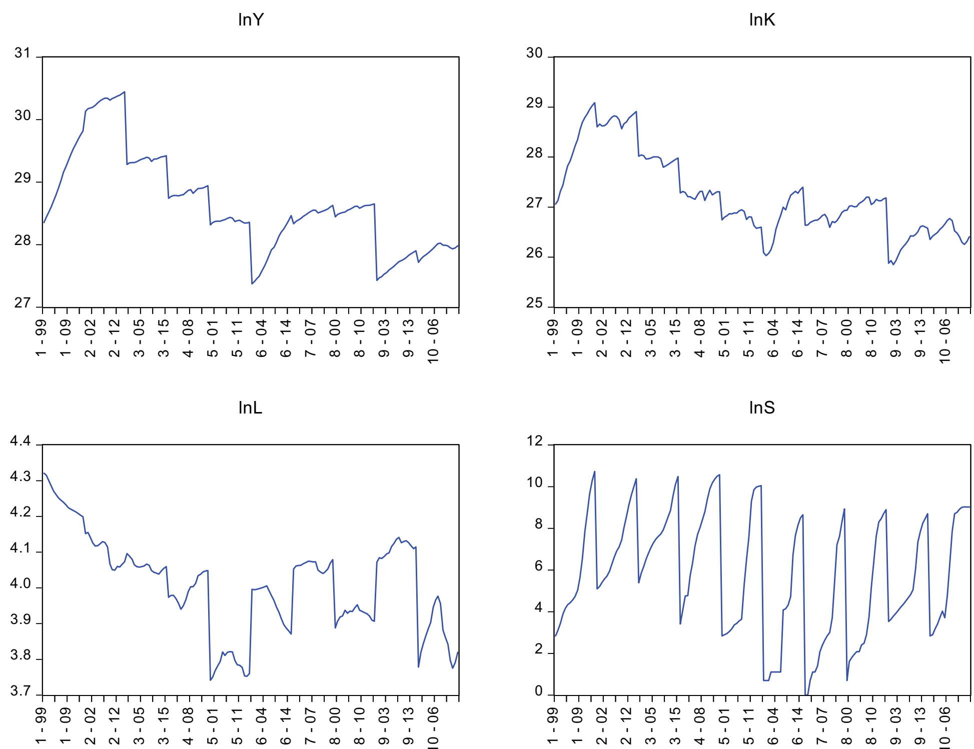

Figure 1. Time plots for the variables.

cross-sectional dependence, the paper employs the LM test of Breusch and Pagan (1980), CD and CD_{lm} tests of Pesaran (2004), and LM_{adj} test of Pesaran, Ullah, and Yamagata (2008). Then, they should test the stationarity levels of the variables to avoid the possible spurious regression problem. To test for the null hypothesis of non-stationarity, the paper performs the cross-sectionally augmented Dickey–Fuller (henceforth CADF) panel unit root test propounded by Pesaran (2007).

4.2. Westerlund (2008) panel cointegration test

If all variables are found to be stationary at first difference in a panel data model, the long-run relationship between the variables in the model should be examined through a panel cointegration test. Westerlund (2008) develops a panel cointegration test which is robust to cross-sectional dependence. He begins with using the data generating process defined as below:

$$y_{it}=\alpha_i+\beta_i x_{it}+u_{it} \tag{2}$$

$$x_{it}=\delta_i x_{i,t-1}+\varepsilon_{it} \tag{3}$$

The variable x is not stationary when $\delta_i = 1$, whereas it is stationary when $\delta_i < 1$. The disturbance term, namely u_{it}, meets the following conditions:

$$u_{it}=\lambda_i' F_t+e_{it} \tag{4}$$

$$F_{jt}=p_j F_{jt-1}+w_{jt} \tag{5}$$

$$e_{it}=\varphi_i e_{it-1}+v_{it} \tag{6}$$

where F is a-dimensional vector of common factors and λ_i represents a vector of factor loadings. The null hypothesis of no cointegration is H_0: $\varphi_i = 1$ for all i, whereas the alternative hypothesis is H_1: $\varphi_i = 1$ for at least some i. To test for the null hypothesis, Westerlund (2008) uses Durbin–Hausman test statistics, namely DH_g and DH_p.

4.3. CCEMG and AMG estimators

If there exits cointegration between variables in a panel data model with cross-sectional dependence, the long-run parameters could be estimated via either the common correlated effects mean group (CCEMG) estimator suggested by Pesaran (2006) or the augmented mean group (AMG) estimator propounded by Eberhardt and Teal (2010).

Pesaran (2006) first considers the following model:

$$y_{it}=\alpha_i d_t+\beta_i x_{it}+e_{it} \tag{7}$$

where d_t denotes a n x 1 vector of observed common effects and x_{it} stands for a k x 1 vector of regressors. The errors have the multifactor structure demonstrated as

$$e_{it}=\gamma_i f_t+\varepsilon_{it} \tag{8}$$

where f_t is the m x 1 vector of unobserved common effects and ε_{it} indicates the errors. After defining, Pesaran (2006) augments Equation (7) and re-describes it as the following:

$$y_{it}=\alpha_i+\beta_i X_{it}+d_{1i}\overline{y}_t+d_{2i}\overline{X}_t+e_{it} \rightarrow \widehat{b}_{CCEMG}=N^{-1}\sum_{i=1}^{N}\widehat{b}i \tag{9}$$

where the cross-section means and stand for a proxy for f_t, and is the long-run parameter of the related variable.

Eberhardt and Teal (2010) proposed a two-stage procedure defined as

$$\Delta y_{it} = b' \Delta X_{it} + \sum_{t=2}^{T} c_t D_t + e_{it} \rightarrow \widehat{c}_t = \widehat{\mu}_t^o \quad (10)$$

$$y_{it} = a_i + b_i' X_{it} + |c_i t + d_j \widehat{\mu}_t^o + e_{it} \rightarrow \widehat{b}_{AMG} = N^{-1} \sum\nolimits_{i=1}^{N} \widehat{b}_i \quad (11)$$

A standard pooled first difference regression with T-1 dummies, which are redefined as, is estimated at the first stage. At the second stage, this variable is incorporated in N standard unit regressions. The long-term coefficient of a variable is indicated by the panel.

4.4. Dumitrescu and Hurlin (2012) panel causality test

The last step is to investigate the causality between variables in a panel data model. This is also essential for an analysis that examines the energy-economic growth nexus to detect which hypothesis prevails. Dumitrescu and Hurlin (2012) propound a panel causality test that (i) takes cross-sectional dependence into account and (ii) is based on the individual Wald statistics. They use the following models:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \gamma_i^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \beta_i^{(k)} x_{i,t-k} + \varepsilon_{i,t} \quad (12)$$

$$x_{i,t} = \delta_i + \sum_{k=1}^{K} \theta_i^{(k)} x_{i,t-k} + \sum_{k=1}^{K} \lambda_i^{(k)} y_{i,t-k} + \varepsilon_{i,t} \quad (13)$$

They posit lag orders K are identical across all cross-section units in the panel and the panel is balanced. The null hypothesis of no causality for all cross-section units is tested against the alternative hypothesis that there is a causal relationship for a subgroup of cross-section units.

In this context, they propose to utilize the average of individual Wald statistics for the test of the non-causality hypothesis for units i = 1, …, N. The average statistic $W_{N,T}^{Hnc}$ associated with the null Homogeneous Non-Causality (HNC) hypothesis is exhibited as the following:

$$W_{N,T}^{Hnc} = \frac{1}{N} \sum_{i=1}^{N} W_{i,T} \quad (14)$$

where $W_{i,T}$ denotes the individual Wald statistics for the ith cross-section unit.

5. Findings

Table 3 depicts the results of the cross-sectional dependence, unit root, and cointegration tests. The outputs of the cross-sectional dependence tests are reported in panel A of the table. As is seen, the null hypothesis of no cross-sectional dependence is rejected at 1% significance level by all cross-sectional dependence tests, implying a shock which appears in one country in the sample is conducted to other countries. After detecting the existence of cross-sectional dependence in the empirical model, panel B of the table exhibits the findings of the CADF panel unit root test. Accordingly, the null hypothesis of a unit root cannot be rejected at level, whereas it can be rejected at first difference for all variables in the empirical model. Hence, the CADF panel unit root test implies that all variables are stationary at first difference, meaning the cointegration relationship in the model can be examined through the Westerlund (2008) panel cointegration test. Panel C of the table demonstrates the results of the Westerlund (2008) panel cointegration test. Accordingly, the null hypothesis of no cointegration can be rejected with regard to the DH_g statistic at 1% level. This finding indicates the long-term coefficients of lnK, lnL, and lnS can be estimated.

Table 3. Cross-sectional dependence, unit root, and cointegration tests.

Panel A: Cross-sectional dependence tests		
Test		Statistic
LM		105.937* (0.000)
CD		5.920* (0.000)
CD_{lm}		6.423* (0.000)
LM_{adj}		6.403* (0.000)
Panel B: Pesaran (2007) panel unit root test		
Variable		
lnY	Level	0.075
	1st difference	−2.500*
lnK	Level	0.823
	1st difference	−2.075**
lnL	Level	0.602
	1st difference	−2.021**
lnS	Level	0.279
	1st difference	−2.227**
Panel C: Westerlund (2008) cointegration test		
Test		
DH_g		3.311*
DH_p		−1.212

* and ** respectively indicate 1% and 5% statistical significance levels.

Table 4. CCEMG and AMG estimators.

	CCEMG		AMG	
Variable	Coefficient	Prob. value	Coefficient	Prob. value
lnK	0.164*	0.000	0.258*	0.000
lnL	−0.176	0.571	0.103	0.833
lnS	−0.005	0.264	−0.003	0.309

* indicates 1% statistical significance level.

Table 4 presents the results obtained from the CCEMG and AMG estimators. The CCEMG estimator indicates that lnK, lnL, and lnS have the estimations of 0.164, −0.176, and −0.005, respectively. Besides, the coefficient of lnK is significant at 1% level, whereas the coefficients of lnL and lnS are statistically insignificant. The AMG estimator yields that lnK, lnL, and lnS are related to the estimations of 0.258, 0.103, and −0.003, respectively. Additionally, while the coefficient of lnK is significant at 1% level, the coefficients of lnL and lnS are statistically insignificant. Hence, the CCEMG and the AMG estimators give the same results in terms of the signs and statistical significance of the coefficients.

The positive and statistically significant coefficient of capital is compatible with the neoclassical growth model suggested by Solow (1956) and the conventional macroeconomic theory. Accordingly, capital is the main determinant of economic growth as capital is utilized in the production activities and so indicates an economy's production capacity (Acemoglu 2009). Besides, the statistically insignificant coefficient of labor implies that most of countries in the sample are developed economies, meaning they have capital-intensive production structures. Finally, the CCEMG and the AMG estimators indicate that solar energy has no statistically significant influence on economic growth for the countries in the panel data set.

Table 5. Panel causality test.

Null hypothesis	Statistic	Prob. value
lnS does not Granger cause lnY	2.050	0.132
lnY does not Granger cause lnS	0.304	0.738

Table 5 illustrates the results of the Dumitrescu and Hurlin (2012) panel Granger causality test. As is seen, the null hypotheses that lnS does not Granger cause lnY and that lnY does not Granger cause lnS cannot be rejected at any significance levels, meaning there is no causality between solar energy and GDP.

Hence, this paper yields evidence in favor of the neutrality hypothesis for solar energy in top 10 countries with the highest installed solar energy production capacity. Therefore, the findings of this paper concur with those of Ohler and Fetters (2014) and Armeanu, Vintila, and Gherghina (2017), who, respectively, find evidence in favor of the conservation and the neutrality hypotheses, as these papers discover solar energy has no impact on economic growth. Typically, the neutrality hypothesis is generally confirmed in very high-income countries and very low-income countries. The former occurs because rich countries do not rely on energy consumption for their wealth achievements. On one hand, they have advanced technologies which enable energy efficiency and on the other hand they have reached a saturation point in their economic development which stabilizes to a low level, because those countries have aging populations and mature capital infrastructure. On the other hand, low-income countries which are mainly agricultural economies also may exhibit support for the neutrality hypothesis because energy consumption is either beyond their reach or beyond the technological knowledge. Imagine, for example, a small rural economy with a basic barter economy. Energy is useful for cooking and heating and no other productive activities. Thus, its consumption does not contribute to economic growth. Of course, we do not have such countries in our sample, but India could be regarded as a low-income country. On the other hand, the rest of the countries are either G7 countries or other highly developed countries. Thus, the evidence of neutrality hypothesis does not come to surprise. On the contrary, it is justified.

However, in this paper, we do not deal with the investigation of total energy consumption in the energy-growth nexus of the sampled countries, but we specify on solar energy production only. Thus, we are interested in the knowledge of the neutrality hypothesis in the renewable energy-growth nexus which has also been confirmed in previous research work. The sample in this paper is innovative and concerns a grouping of countries not based on geographic terms or economic performance but rather on their progress in the establishment of solar energy installations and the penetration of solar energy in their economies. Thus, our study is unique and not directly comparable with others such as Banday and Aneja (2020) in which India has evidence for the growth hypothesis. However, Chang et al. (2015) have also found support for the neutrality hypothesis for Canada, Italy, and the USA but not for France and UK. In the country sample where India is part of in Destek (2016) the neutrality hypothesis is not supported for India. Menegaki (2011) has found evidence for the neutrality hypothesis in the renewable energy-growth nexus, but still, there are not separate results for each type of renewable energy such as the solar energy which is the focus of the current paper. Various other studies have dealt with the relationship between renewable energy and economic growth, but no other has found support for the neutrality hypothesis. Menyah and Wolde-Rufael (2010) have found evidence for the conservation hypothesis for the USA. Some other papers found other hypotheses except the neutrality hypothesis prevailed, namely Apergis et al. (2012) for developed and developing countries, Apergis and Payne (2011a) for emerging economies, Tugcu, Ozturk, and Aslan (2012) for G7 countries, Apergis and Payne (2012) for developed and developing countries, Apergis and Payne (2010a) for Eurasian countries, Apergis and Payne (2010b) for OECD countries, Sadorsky (2009) for emerging economics and Apergis and Payne (2011b) for Central America, etc. This underlines the importance of the current study once more.

6. Conclusion

This paper investigates the impact of solar energy production on economic growth in top 10 countries with the highest installed capacity in 2017 for the period 1999–2015. After carrying out cross-sectional dependence tests and detecting the presence of cross-sectional dependence, the paper performs some panel data techniques which are robust to cross-sectional dependence. The paper finds that solar energy production does not affect GDP and that there is no causality between solar energy production and GDP. Therefore, the paper explores that the neutrality hypothesis prevails for solar energy in the case of top 10 countries with the highest installed capacity.

The validity of the neutrality hypothesis means that solar energy production and economic growth do not affect each other in the countries in the sample. In the energy economics literature, it is denoted that the neutrality hypothesis can especially dominate in countries whose production structures shift from the manufacturing sector to the service and information sectors, which are not energy-intensive sectors (Ghali and El-Sakka 2004). As most of the countries in the sample are advanced and information-based economies, the empirical findings of the paper appear to be not surprising.

Hence, the empirical findings imply that solar energy is not a considerable determinant of economic growth for these countries. These findings, therefore, present evidence that solar energy is not a complementary of capital and a crucial component of economic growth. Put differently, additional volumes of solar energy won't enhance GDP in these countries and solar energy-saving policies and solar energy supply shocks do not have negative influences on the growth rates of these economies.

In Sections 1–2 of the paper, it was stated that the empirical literature mostly investigated the relationship between economic growth and renewable energy using aggregated data. For this reason, this paper argues that future research should focus on the particular effects of other renewable energy sources on economic growth in these countries. If these papers explore other renewable energy types have impacts on economic growth, then policy makers in these countries can contemplate other renewable energy sources. If not, these countries should reallocate their sources in favor of considerable determinants of economic growth, such as technology, physical capital, and human capital, etc. On the other hand, it is with no doubt that policy makers in these countries should not ignore the merit of solar energy in decreasing environmental problems.

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Disclosure statement

The authors declare that they have no conflict of interest.

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