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Does Renewable Energy Drive Sustainable Economic Growth? Multivariate Panel Data Evidence for EU-28 Countries

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Abstract: Energy is crucial to economic progress, but the contemporary worldwide population increase that demands greater energy generated from conventional exhaustible resources, an energy price upsurge, and environmental concerns, imperils sustainable economic growth. Nevertheless, switching to renewable energy produced from naturally replenished resources promotes energy security, likewise addressing issues such as global warming and climate change. This paper aims at exploring the influence and causal relation between renewable energy, both overall and by type, and sustainable economic growth of European Union (EU)-28 countries for the period of 2003–2014. We notice that the mean share of renewable energy in the gross final energy consumption is 15%, while the mean share of renewable energy in transport fuel consumption is 3%, which are below the thresholds of 20% and 10%, respectively, as set by the EU Directive 2009/28/EC. By estimating panel data fixed-effects regression models, the results provide support for a positive influence of renewable energy overall, as well as by type, namely biomass, hydropower, geothermal energy, wind power, and solar energy on gross domestic product per capita. However, biomass energy shows the highest influence on economic growth among the rest of renewable energy types. In fact, a 1% increase of the primary production of solid biofuels increases GDP per capita by 0.16%. Besides, cointegrating regressions set on panel fully modified and dynamic ordinary least squares regressions confirm the positive influence related to the primary production of renewable energies on economic growth. A 1% increase in primary production of renewable energies increases GDP per capita by 0.05%–0.06%. However, the results of Granger causality based on panel vector error correction model indicate both in short-run and long-run a unidirectional causal relationship running from sustainable economic growth to the primary production of renewable energies, being supported the conservation hypothesis.

Keywords: renewable energy; sustainable economic growth; fixed-effects regression; cointegration; panel vector error correction model; Granger causality

1. Introduction

Energy represents a vital factor for achieving sustainable economic growth [1], but the contemporary economic welfare is endangered by circumstances such as increased energy demand driven by the increase of world population which has entailed the quick consumption of traditional energy resources such as oil, coal, and natural gas, besides energy price rises, and discharging of harmful gases to the atmosphere. In fact, the lack of access to energy indicates a deficient situation as regards lowering poverty and accelerating development [2], but climate change issues have emerged due to greenhouse gas emissions caused by burning fossil fuels [3]. Therefore, a longer dependence on such fuels in order to overtake an upward energy demand will merely speed up environmental degradation [4]. For instance, the U.S. Energy Information Administration (EIA) [5] indicated a 48% intensification in world energy consumption by 2040; hence, the need for low carbon is obvious. Substitutes for fossil fuels, which are detrimental for the environment, are renewable energy resources that fulfill the main energy requests actual economies are confronted with, specifically regular renewal, less pollution, decreasing reliance on imported sources [6], enhanced employment [7], no security or safety concerns [8].

As long as common energy is produced from limited resources, governments should take into account a suitable utilization of it. Growth is regarded as sustainable if the existing population's desires are fulfilled without undermining the ability of upcoming generations to meet their own necessities. A sustainable economy relies on the flow of resource usage and the value of externalities being created [9] and comprises three pillars: environmental, economic and social dimensions [10]. Thus, when assessing sustainable development, also nature impairment, as well as social welfare must be considered. Sustainable economic growth reveals the key to solving the ecological disasters, weather modifications, social and the economic crises affecting most nations [11,12]. In fact, a measure like the Index of Sustainable Economic Welfare [11–15] was developed to address such concerns.

Renewable energy contributes to energy resilience through its decentralized structure that lessens the effect caused by potential technical failures or extremist assaults which might significantly damage the national electricity grid, therewith redirecting oil profits that can run to governmentally insecure states [16]. In the context of outward migration noticed within rural regions, the operation of bioenergy factories may have positive effects on related rural labor markets [17]. According to Fang [18], an increase of renewable energy consumption by 1% drives a growth of real gross domestic product (GDP) by 0.120%, GDP per capita by 0.162%, per capita annual income of rural households by 0.444%, and per capita annual income of urban households by 0.368%. Bölük and Mert [19] proved that the greenhouse gas emissions in EU countries are reduced by approximately 1/2 per unit of renewable energy consumed over fossil energy consumption. However, Vass [20] contended that renewables can support the emissions reduction goal in 2050 by roughly 8.2%, which is better relative to the forest sector with a 5.3% share, but renewables cannot surpass forest carbon sequestration without government aid.

Renewable energy technologies are grouped into mainstream energy technologies (hydropower, wind energy, solar energy, biomass, biofuels, and geothermal energy) and emerging energy technologies (marine energy, concentrated solar photovoltaic, enhanced geothermal energy, cellulosic ethanol, and artificial photosynthesis) [21]. In order to be sustainable, a renewable resource should be boundless, but without harming the environment, whereas a sustainable energy should be inexpensive over an extended period, while satisfying the community desires and fitting with actual and future civil rules [22]. Pahle et al. [23] mentioned that renewable distribution may lead to short-term socio-economic benefits that supports the robust green growth since the renewable energy segment is crucial for the shift to a green economy [24] and Foster et al. [25] discussed the interplay amongst renewable energy diffusion and the value chains of fossil fuels. In this framework, the green paradox theory of Sinn [26] argues that a policy wishing for global warming reduction may actually hasten the usage of fossil fuels for the reason that holders will want to pull out and sell more fossil fuels whilst they are still expensive. Fourth, the carbon leakage theory [27] claims that if there is not a set of worldwide harmonized climate change directives, the manufacture of goods and services reliant on fossil fuels will shift to states with less severe environmental policies, in this manner balancing emission savings accrued elsewhere.

The Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources [28] is enforced through two European Union (EU) compulsory goals, namely a 20% share of energy consumption from renewable sources and a 10% share of energy from renewable sources in transport, both by 2020. Notwithstanding, Jäger-Waldau [29] revealed structural impediments against the implementation of renewable energies, such as dependency on national conventional sources of energy and their supply network, combined with high primary investment. Thereby, Woo et al. [30] revealed geographical disparities on the topic of environmental efficiency, respectively considerable environmental efficiency related to the Organisation for Economic Co-operation and Development (OECD) American countries relative to high standard deviation of OECD European states. Also, Reboredo [31] advocated discrepancy and contradictory temporal shapes in the share of renewable energies to the energy supply. Chontanawat et al. [32] noticed that energy is neutral as regards its influence on economic growth in the developing countries as compared to developed states. Howbeit, even if Chien and Hu [33] found that OECD economies registered higher technical efficiency than non-OECD economies, a higher share of renewable energy was uncovered in the total energy supply non-of OECD economies compared to OECD ones.

Moreover, even though renewable energy fits properly in several opportunity fields like socioeconomic progress, energy access, energy security, and climate change alleviation [34], the sustainability appraisal of energy technologies should not be overlooked [35]. The adverse effects of renewable energy threaten the wellbeing of inhabitants in the environs of the renewable energy sources facilities [36] via sound from wind turbines [37] or through the risk of glare by mirroring of straight sunlight from photovoltaic unit areas [38]. The research focus is here is twofold. First, the aim of the current study is to explore the influence of renewable energy, both overall and by type, on the sustainable economic growth of the 28 EU countries for the period spanning from 2003 to 2014. Subsequently, an empirical approach will address the causal relationship between primary production of renewable energies, energy dependence, and gross domestic product per capita. The literature on the relationship between renewable energy consumption and economic growth is quite extensive [7,8,18,19,39–58], studies on the link between biomass energy and economic growth also exist [59–62], as well as hydroelectricity consumption and economic growth [63,64]. Yildirim et al. [58] considered several renewable energy types, but for the case of U.S. Nevertheless, the current manuscript differs from previous research to some extent. Particularly, the novelty of this research ensues from the investigation of the effect related to every type of renewable energy, respectively biomass, hydropower, geothermal energy, wind power, and solar energy on gross domestic product per capita. Thereby, this paper also provides insights on the causal linkage between renewable energy production, energy dependence, and economic growth at the EU-28 level, instead of renewable energy consumption, gross fixed capital formation, and labor force as in previous studies [18,41–46,48,49,52,55,56,59,63,65].

The remainder of the article is organized as follows: Section 2 reviews the empirical literature on the renewable energy consumption-economic growth nexus. Section 3 describes the employed dataset and econometric methodology. Section 4 discusses the empirical results. The final section provides concluding remarks.

2. An Overview of Literature on Renewable Energy Consumption-Economic Growth Nexus

The causal relationship between renewable energy consumption and economic growth takes the form of four testable hypotheses, respectively feedback (bidirectional causality between energy consumption and economic growth), conservation (unidirectional causality from economic growth to energy consumption), growth (unidirectional causality from renewable energy consumption to economic growth), and neutrality (the lack of causality between energy consumption and economic growth) [42]. In addition, the environmental Kuznets curve (EKC) advises that environmental degradation rises with growing income up to a boundary stage over which ecological quality straighten with greater income per capita. Nevertheless, there was not achieved any unanimity towards energy-economic growth association [44] inasmuch as selected samples, explored states' features, employed variables, and applied quantitative methods were varied [66].

Based on the estimation of a panel vector error correction model (PVECM) for twenty OECD countries over the period 1985–2005, Apergis and Payne [41] found both short-run and long-run bidirectional causality between renewable energy consumption and economic growth, being supported the feedback hypothesis. Similarly, analogous findings were exposed for six Central American countries over the period 1980–2006 [42], as well as 80 countries over the period 1990–2007 [43]. Bidirectional Granger causality between economic growth and renewable energy consumption was also noticed for Brazil, Russia, India, China, and South Africa (BRICS countries) over the period 1971–2010 [54], likewise for China for 1977–2011 [50]. By means of vector error correction model (VECM) Granger causality, Shahbaz et al. [55] confirmed the feedback effect in Pakistan for 1972Q1–2011Q4. The feedback hypothesis was supported withal for MENA Net Oil Importing Countries over 1980–2012 [48]. Likewise, Amri [40] reinforced the feedback connection in the case of 23 developed countries and 49 developing countries over 1990–2012. Koçak and Şarkgüneşi [49] for nine Black Sea and Balkan countries also proved the two-way causality link between renewable energy consumption and economic growth in 1990–2012 period.

Lise and Van Montfort [67] provided evidence for conservation hypothesis for the case of Turkey over the period 1970–2003, whereas also for Turkey over 1990–2010, based on the autoregressive distributed lag (ARDL) method and Toda-Yamamoto causality tests, Ocal and Aslan [52] revealed the conservation hypothesis for the link between renewable energy consumption and economic growth. Similarly, Sadorsky [53] exposed for 18 emerging countries over 1994–2003 that growth in real per capita income exhibits a positive and statistically significant effect on per capita renewable energy consumption. For the U.S. case for 1960–2007, Menyah and Wolde-Rufael [51] ascertained a unidirectional causality running from GDP to renewable energy consumption.

Bhattacharya et al. [44] supported the growth hypothesis forasmuch as within 57% of 38 top renewable energy consuming states over 1991–2012, renewable energy consumption exerted a positive impact on economic growth. In the same vein, Inglesi-Lotz [46] showed for 34 OECD countries a positive and statistically significant influence of renewable energy consumption to economic growth.

By employing the Toda-Yamamoto causality tests on U.S. data for the period 1949–2006, Payne [65] pointed out the lack of Granger-causality between renewable and non-renewable energy consumption and real GDP and claimed the neutrality hypothesis. The irregular and sparse use of renewable energy within Europe over 1997–2007 was established by Menegaki [8] since the estimated panel error correction model indicated the lack of short-run, as well as long-run Granger causality from renewable energy consumption to economic growth, thereby the neutrality hypothesis being acknowledged. Also, for the Italy from 1861 to 2000, Vaona [57] supported the neutrality hypothesis.

Other studies concluded mixed results, such as Huang et al. [45], which established for 82 countries classified as low income, lower middle income, upper middle income, and high income, from 1972 to 2002, the neutrality hypothesis for the low income category and the conservation hypothesis for the middle income group. Ozturk and Acaravci [68] employed the ARDL method for 1980–2006, along with the dynamic VEC model, and revealed the feedback hypothesis for Hungary, whilst the neutrality hypothesis was set for Albania, Bulgaria, Romania. Tugcu et al. [56] employed Hatemi-J causality tests for G7 countries over 1980–2009 and noticed the neutrality hypothesis for France, Italy, Canada, and U.S., feedback hypothesis for England and Japan, conservation hypothesis for Germany. Al-Mulali [39] explored through fully modified OLS more than 108 low income, lower middle income, upper middle income, and high income countries over 1980–2009 and established the bidirectional causality within 79% of countries, neutrality causality within 19% of the sample, and unidirectional causality from growth to renewable energy within 2% of states.

With reference to the literature on the types of renewable energy, Shahbaz et al. [62] confirmed the feedback hypothesis between biomass energy consumption and economic growth over 1991Q1–2015Q4, for BRICS region. Bilgili and Ozturk [59] noticed the growth hypothesis inasmuch as biomass energy consumption showed positive effects on economic growth in G7 countries for the period 1980–2009, as well as in 51 Sub-Sahara African states over 1980–2009 [60]. Yildirim et al. [58] employed the Toda-Yamamoto procedure and bootstrap-corrected causality test for U.S. over 1949–2010 and provided evidence for a causal link between biomass-waste-derived energy consumption and economic growth (growth hypothesis) and no causal association between growth and all of the other renewable energy types. Bildirici [61] explored the link between biomass energy consumption and economic growth within ten developing and emerging states and provided evidence over 1980–2009 towards long-run bidirectional causality for Argentina, Bolivia, Nicaragua, whilst long-run unidirectional causality from biomass energy consumption to GDP for Cuba, Costa Rica, El Salvador, Jamaica, Panama. Solarin and Ozturk [63] explored seven Latin America countries over 1970–2012 and supported the long-run bidirectional causality between hydroelectricity consumption and economic growth in Argentina and Venezuela, withal long-run unidirectional causality from hydroelectricity consumption to economic growth in Brazil, Chile, Colombia, Ecuador, and Peru. For a sample of the 10 major hydroelectricity consuming states during 1965–2012, Apergis et al. [64] documented for the pre-1988 period the unidirectional causality from real GDP per capita to hydroelectricity per capita, whilst bidirectional causality for the post-1988 period.

Another strand of literature revealed inconsistent results when alternative measures for sustainable income were employed as compared with the traditional examination of energy-GDP growth nexus. For instance, Menegaki and Tugcu [13] developed an Index of Sustainable Economic Welfare Growth (ISEW) for 42 Sub-Saharan African states over 1985–2013 covering the weighted consumption, non-defensive public expenditure, net capital growth, unpaid work benefit, depletion of natural environment, and the cost from social problems. By means of panel data cointegration and Granger causality, Menegaki and Tugcu [13] supported the feedback hypothesis when ISEW was used as proxy for sustainable economic welfare, but the neutrality hypothesis in case of GDP employment. Further, for 15 emerging economies during 1995–2013, Menegaki and Tugcu [14] proposed two measures of welfare: the first (BISEW) made up of adjusted personal consumption with durables, education and health expenditure, as well as net capital growth, whilst the second (SISEW) emerged by subtracting mineral, energy, and forest depletion, as well as damage related to carbon dioxide emissions, from BISEW. However, based on Granger causality and seemingly unrelated regression, Menegaki and Tugcu [14] concluded multifarious causality results. Likewise, for G7 states, over 1995–2013, Menegaki and Tugcu [11] computed a basic ISEW covering only economic variables, as well as a solid ISEW comprising the sum of economic and environmental variables. By applying a panel ARDL model, Menegaki and Tugcu [11] revealed the conservation hypothesis for GDP or basic ISEW per capita and energy consumption, but the feedback hypothesis in case of solid ISEW per capita and energy consumption. Withal, Menegaki and Tiwari [12] computed the ISEW for 20 American countries over 1990–2013 and followed quantile regression and fixed effects with PVECM approach, thus reinforcing the feedback hypothesis in case of ISEW framework, but the neutrality hypothesis for the GDP framework. In the same vein, for twenty European countries over 1995–2014, Gaspar et al. [15] confirmed the feedback hypothesis when using ISEW and the conservative hypothesis when using GDP.

Concerning the environmental Kuznets curve, for the Tunisian case during the period 1980–2009, Jebli and Youssef [47] did not support the EKC, the same conclusion being also stated by Özokcu and Özdemir [69] for 26 OECD countries with high-income levels, as well as for 52 emerging states over 1980–2010. On the contrary, Apergis et al. [70] confirmed the EKC hypothesis, but only for ten U.S. states over 1960–2010, Ahmad et al. [71] for Croatia over 1992Q1–2011Q1, Wang et al. [72] for China over 2000–2013, and Sinha and Bhattacharya [73] for 139 Indian cities during 2001–2013. Table 1 summarizes the literature regarding the relationship between renewable energy consumption and economic growth.

In could be remarked that the studies summarized within Table 1 provide scant evidence on the renewable energy consumption-economic growth nexus in EU-28 countries. Hence, the previously mentioned gap emphasizes our motivation for current paper and the study aims to contribute to the literature in this manner.

Table 1. Previous related studies on renewable energy consumption and economic growth.

Study	Period	Dataset	Estimation Technique	Outcome
Amri [40]	1990–2012	72 countries	Two-step GMM	Feedback Hypothesis
Apergis and Payne [41]	1985–2005	20 OECD countries	PVECM	
Apergis and Payne [42]	1980–2006	6 Central American countries	PVECM	
Apergis and Payne [43]	1990–2007	80 countries	PVECM	
Kahia et al. [48]	1980–2012	MENA Net Oil Importing Countries	PVECM	
Koçak and Şarkgüneşi [49]	1990–2012	9 Black Sea and Balkan countries	Panel cointegration and heterogeneous causality	
Lin and Moubarak [50]	1977–2011	China	ARDL, Johansen cointegration, Granger causality	
Sebri and Ben-Salha [54]	1971–2010	BRICS countries	ARDL and VECM	
Shahbaz et al. [55]	1972Q1–2011Q4	Pakistan	ARDL and VECM	
Shahbaz et al. [62]	1991Q1–2015Q4	BRICS region	PVECM	
Menyah and Wolde-Rufael [51]	1960–2007	U.S.	Toda-Yamamoto causality	Conservation Hypothesis
Ocal and Aslan [52]	1990–2010	Turkey	ARDL and Toda-Yamamoto causality	
Sadorsky [53]	1994–2003	18 emerging countries	Panel cointegration	
Lise and Van Montfort [67]	1970–2003	Turkey	ECM	
Bhattacharya et al. [44]	1991–2012	38 top renewable energy consuming states	Heterogeneous panel estimations	Growth Hypothesis
Inglesi-Lotz [46]	1990–2010	34 OECD countries	Pedroni cointegration	
Bilgili and Ozturk [59]	1980–2009	G7 countries	Panel cointegration, Conventional OLS, DOLS	
Ozturk and Bilgili [60]	1980–2009	51 Sub-Sahara African	Panel cointegration, Conventional OLS, DOLS	
Menegaki [8]	1997–2007	27 European countries	Panel error correction model	Neutrality Hypothesis
Vaona [57]	1861–2000	Italy	Granger non-causality	
Payne [65]	1949–2006	U.S.	Toda-Yamamoto causality	
Menegaki and Tugcu [11]	1995–2013	G7 states	ARDL	Mixed Results
Menegaki and Tiwari [12]	1990–2013	20 American countries	Quantile regression, Fixed effects model and PVECM	
Menegaki and Tugcu [13]	1985–2013	42 Sub-Saharan African states	Panel cointegration and Granger causality	
Menegaki and Tugcu [14]	1995–2013	15 emerging economies	Granger causality and seemingly unrelated regression	
Gaspar et al. [15]	1995–2014	20 European states	Panel-corrected standard errors and Fixed effects vector decomposition estimators	
Al-mulali [39]	1980–2009	108 countries	FMOLS	
Huang et al. [45]	1972–2002	82 states	System GMM and PVAR	
Tugcu et al. [56]	1980–2009	G7 countries	ARDL and Hatemi J causality	
Yildirim et al. [58]	1949–2010	U.S.	Toda-Yamamoto and Bootstrap-corrected causality	
Bildirici [61]	1980–2009	10 developing and emerging states	ARDL and Dynamic ECM	
Solarin and Ozturk [63]	1970–2012	7 Latin America countries	VECM	
Apergis et al. [64]	1965–2012	10 major hydroelectricity consuming states	Nonlinear panel smooth transition VECM	
Ozturk and Acaravci [68]	1980–2006	Albania, Bulgaria, Hungary, Romania	ARDL and VECM	

3. Data and Methodological Framework

3.1. Sample Selection and Variable Description

This paper follows panel data of EU-28 countries for the period 2003–2014, acquired from Eurostat—European Commission and World Development Indicators (WDI)—World Bank. The multivariate framework includes gross domestic product per capita as proxy for sustainable economic growth [8,18,19,32,40,45–47,49,50,53,55,59,64,67–69,72], renewable energy measures (both overall and by type), and country-level controls, as given in Table 2.

Table 2. Exhibition of the variables.

Variables	Description	Period	Source
Variables towards sustainable economic growth (dependent variables)			
GDPC	Gross domestic product per capita (constant 2010 U.S. $), logarithmic values.	2003–2014	WDI [NY.GDP.PCAP.KD]
Variables towards renewable energy and country-level controls (explanatory variables)			
Variables towards renewable energy (overall)			
PRE	Primary production of renewable energies (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
CRE	Gross inland renewable energies consumption (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [tsdcc320]
SRE_GFEC	Share of renewable energy in gross final energy consumption (%).	2004–2014	Eurostat [t2020_31]
SRE_FCT	Share of renewable energy in fuel consumption of transport (%).	2004–2014	Eurostat [tsdcc340]
EGRS	Electricity generated from renewable sources (% of gross electricity consumption).	2004–2014	Eurostat [tsdcc330]
FEC	Final renewable energies consumption in households (% of the total consumption).	2003–2014	Eurostat [t2020_rk210]
Variables towards renewable energy (by type)			
Biomass			
SBIOFUELS	Primary production of solid biofuels, excluding charcoal (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
BGAS	Primary production of biogas (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
MW	Primary production of municipal waste, renewable (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
BGASOLINE	Primary production of biogasoline (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
BDIESELS	Primary production of biodiesels (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
OLB	Primary production of other liquid biofuels (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
Hydropower			
HYDRO	Primary production of hydropower (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
Geothermal energy			
GEOTHERMAL	Primary production of geothermal energy (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
Wind power			
WIND	Primary production of wind power (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
Solar energy			
SOLAR_T	Primary production of solar thermal energy (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
SOLAR_P	Primary production of solar photovoltaic energy (1000 tonnes of oil equivalent), logarithmic values.	2003–2014	Eurostat [ten00081]
Country-level control variables			
ED	Energy dependence of a certain country (%), assessing the level of reliance upon imports so as to achieve its energy requirements.	2003–2014	Eurostat [tsdcc310]
GGE	Greenhouse gas emissions (in CO_2 equivalent) indexed to 1990, logarithmic values.	2003–2014	Eurostat [tsdcc100]
PET	Pollutant emissions from transport, nitrogen oxides (index, 2000 = 100), logarithmic values.	2003–2014	Eurostat [t2020_rk300]
RP	Resource productivity (purchasing power standard per kilogram), as the ratio between gross domestic product and domestic material consumption.	2003–2014	Eurostat [tsdpc100]
RD	Research and development expenditure (% of GDP).	2003–2014	WDI [GB.XPD.RSDV.GD.ZS]
LF	Labor force, total, logarithmic values.	2003–2014	WDI [SL.TLF.TOTL.IN]

3.2. Econometric Approach

Primarily, our purpose is to estimate the effect of renewable energy, both overall and by type, on sustainable economic growth by means of panel data fixed-effects regression model, having the general specification as follows:

$$Y_{it} = \alpha_0 + \beta_1 X_{it} + \beta_2 Z_{it} + \varepsilon_{it} \quad i = 1,\ 2,\ \ldots,\ 28,\ t = 2003,\ 2004,\ \ldots,\ 2014 \tag{1}$$

where Y denotes the dependent variable, respectively gross domestic product per capita (logarithmic values), X signifies the explanatory variables towards renewable energy, overall and by type, Z represents the country-level control variables, α is the intercept, β_1 and β_2 are parameters, ε is the error term, i is the subscript of states, and t is the subscript of the time dimension. We have adopted a fixed-effects approach in order to overcome the omitted variable bias.

Onward, our goal is to investigate the linkages between renewable energy production (PRE), energy dependence (ED), and gross domestic product per capita (GDPC), through the Granger causality based on panel vector error correction model (PVECM), by following the procedure described in previous studies [8,41–43,46,48,53,62,67]. Therefore, we will assess the stationarity of the variables by the instrumentality of the Im, Pesaran and Shin (IPS) test developed by Im et al. [74] which allows for heterogeneous autoregressive coefficients. The equation employed in order to check for unit roots takes the following form:

$$y_{it} = \rho_i y_{it-1} + \delta_i X_{it} + \varepsilon_{it} i = 1,\ 2,\ \ldots,\ 28,\ t = 2003,\ 2004,\ \ldots,\ 2014 \quad (2)$$

where X_{it} depicts the exogenous variables comprising fixed effects or individual time trend; ρ_i signifies the autoregressive coefficients, and ε_{it} shows the stationary error terms. However, the IPS test averages the augmented Dickey-Fuller (ADF) unit root tests and grant for various orders of serial correlation:

$$\varepsilon_{it} = \sum_{j=1}^{p_i} \varphi_{ij} \varepsilon_{it-j} + u_{it} \quad (3)$$

By substituting the third equation within the second equation, there ensues the form as below:

$$y_{it} = \rho_i y_{it-1} + \sum_{j=1}^{p_i} \varphi_{ij} \varepsilon_{it-j} + \delta_i X_{it} + u_{it} \quad (4)$$

where p_i expresses the number of lags in the ADF regression. The null hypothesis supposes that each series in the panel dataset comprises a unit root, whilst the alternative hypothesis reveals that at least one of the individual series in the panel is stationary. Besides, several stationarity tests are executed, such as Levin, Lin & Chu (LLC), Augmented Dickey-Fuller (ADF), Phillips-Perron (PP).

Further, we will employ the heterogeneous panel cointegration test developed by Pedroni [75,76] that permits for cross-section interdependence with different individual effects:

$$GDPC_{it} = \alpha_i + \delta_i t + \gamma_{1i} PRE_{it} + \gamma_{2i} ED_{it} + \varepsilon_{it} i = 1,\ 2,\ \ldots,\ 28,\ t = 2003,\ 2004,\ \ldots,\ 2014 \quad (5)$$

where the parameters α_i and δ_i permit for country-specific fixed effects and deterministic trends, ε_{it} denotes the estimated residuals which depicts deviations from the long-run relationship. The null hypothesis reveals the lack of cointegration, respectively non-stationary residuals.

The next step supposes the estimation of panel fully modified OLS (FMOLS) and dynamic OLS (DOLS) as in [44,49,59,60]. Lastly, we estimate the PVECM in order to perform the Granger-causality tests. As such, we carry the two-step procedure of Engle-Granger by estimating the long-run model described by the fifth equation in order to get the estimated residuals, whereas by formulating the lagged residuals from the fifth equation as the error correction term (ECT), we estimate the following dynamic error correction model:

$$\Delta GDPC_{it} = \alpha_{1j} + \sum_{k=1}^{q} \varphi_{11ik} \Delta GDPC_{it-k} + \sum_{k=1}^{q} \varphi_{12ik} \Delta PRE_{it-k} + \sum_{k=1}^{q} \varphi_{13ik} \Delta ED_{it-k} + \lambda_{1i} \varepsilon_{it-1} + u_{1it} \quad (6)$$

$$\Delta PRE_{it} = \alpha_{2j} + \sum_{k=1}^{q} \varphi_{21ik} \Delta GDPC_{it-k} + \sum_{k=1}^{q} \varphi_{22ik} \Delta PRE_{it-k} + \sum_{k=1}^{q} \varphi_{23ik} \Delta ED_{it-k} + \lambda_{2i} \varepsilon_{it-1} + u_{2it} \quad (7)$$

$$\Delta ED_{it} = \alpha_{3j} + \sum_{k=1}^{q} \varphi_{31ik} \Delta GDPC_{it-k} + \sum_{k=1}^{q} \varphi_{32ik} \Delta PRE_{it-k} + \sum_{k=1}^{q} \varphi_{33ik} \Delta ED_{it-k} + \lambda_{3i} \varepsilon_{it-1} + u_{3it} \quad (8)$$

where Δ denotes the first-difference operator, q is the lag length set at one according to likelihood ratio tests, and u reveals the serially uncorrelated error term.

4. Empirical Findings

4.1. Descriptive Statistics, Correlation Analysis, and Stationarity Investigation

Table 3 provides summary statistics of the variables employed within the empirical study. We acknowledge that the mean share of renewable energy in gross final energy consumption is 15%, whereas the mean share of renewable energy in fuel consumption of transport is 3%, which are below the thresholds of 20%, respectively 10% as set by the EU Directive 2009/28/EC [28]. Moreover, we notice that primary production of solid biofuels, excluding charcoal, alongside primary production of hydropower register the highest mean values amongst renewable energies, whilst primary production of solar photovoltaic energy, primary production of solar thermal energy, as well as primary production of biogasoline, and primary production of other liquid biofuels reveal the lowest mean values. Consequently, EU-28 countries should consider more solar electricity production which is a sustainable and quickly accessible energy source within urban settings [77], since it represents a clean substitute of fossil fuel based electricity does not cause air or water pollution, safeness of public health, and without shocks as regards electricity price. In addition, biogasoline or "green" gasoline is low-priced and ecologically responsible [78].

Table 3. Summary statistics of the variables (raw data).

Variables	Obs	Mean	Std. Dev.	Min	Max
Variables towards sustainable economic growth					
GDPC	336	31,663.85	20,449.34	4864.61	110,001.05
Variables towards renewable energy (overall)					
PRE	336	5359.61	6653.16	0.30	36,017.90
CRE	336	5502.68	6837.68	0.30	35,406.30
SRE_GFEC	308	0.15	0.11	0.00	0.53
SRE_FCT	308	0.03	0.03	0.00	0.22
EGRS	308	0.20	0.17	0.00	0.70
FEC	334	0.19	0.14	0.00	0.52
Variables towards renewable energy (by type)					
Biomass					
SBIOFUELS	336	2720.08	2915.34	0.00	11,424.70
BGAS	333	285.51	857.35	0.00	7434.30
MW	333	262.99	488.78	0.00	3037.00
BGASOLINE	333	49.77	100.51	0.00	503.40
BDIESELS	333	230.09	503.49	0.00	3042.60
OLB	333	20.22	79.96	0.00	833.80
Hydropower, geothermal energy, wind, and solar energy					
HYDRO	336	1029.01	1576.47	0.00	6786.90
GEOTHERMAL	333	201.48	918.08	0.00	5235.00
WIND	336	419.16	890.48	0.00	4931.80
SOLAR_T	336	62.56	216.95	0.00	2400.90
SOLAR_P	335	86.95	338.69	0.00	3100.30
Country-level control variables					
ED	336	0.56	0.28	−0.50	1.04
GGE	336	92.16	30.37	40.63	171.25
PET	336	84.23	20.74	40.40	138.30
RP	336	1.48	0.72	0.47	3.52
RD	336	0.01	0.01	0.00	0.04
LF	336	8,622,532.49	10,953,756.15	159,601.00	42,755,645.00

Source: Authors' computations. Notes: For the definition of variables, please see Table 2.

Table 4. Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1) GDPC	1											
(2) PRE	0.08	1										
(3) CRE	0.11 *	1.00 ***	1									
(4) SRE_GFEC	−0.08	0.42 ***	0.40 ***	1								
(5) SRE_FCT	0.21 ***	0.38 ***	0.39 ***	0.39 ***	1							
(6) EGRS	0.08	0.47 ***	0.46 ***	0.83 ***	0.39 ***	1						
(7) FEC	−0.56 ***	0.18 **	0.15 **	0.61 ***	−0.11	0.43 ***	1					
(8) SBIOFUELS	−0.03	0.97 ***	0.96 ***	0.48 ***	0.35 ***	0.47 ***	0.26 ***	1				
(9) BGAS	0.53 ***	0.65 ***	0.67 ***	−0.04	0.41 ***	0.16 **	−0.37 ***	0.56 ***	1			
(10) MW	0.61 ***	0.58 ***	0.60 ***	0.02	0.41 ***	0.18 **	−0.44 ***	0.51 ***	0.76 ***	1		
(11) BGASOLINE	0.11 *	0.53 ***	0.53 ***	0.09	0.56 ***	0.14 *	−0.21 ***	0.50 ***	0.57 ***	0.50 ***	1	
(12) BDIESELS	0.19 ***	0.64 ***	0.65 ***	0.1	0.51 ***	0.22 ***	−0.14 *	0.59 ***	0.72 ***	0.61 ***	0.67 ***	1
(13) OLB	0.43 ***	0.36 ***	0.37 ***	0.28 ***	0.37 ***	0.32 ***	−0.18 ***	0.32 ***	0.44 ***	0.58 ***	0.25 ***	0.36 ***
(14) HYDRO	−0.03	0.75 ***	0.74 ***	0.42 ***	0.33 ***	0.57 ***	0.18 **	0.74 ***	0.42 ***	0.34 ***	0.46 ***	0.51 ***
(15) GEOTHERMAL	−0.08	0.47 ***	0.48 ***	−0.04	0.16 **	0.16 **	0.06	0.44 ***	0.33 ***	0.36 ***	0.27 ***	0.45 ***
(16) WIND	0.46 ***	0.61 ***	0.62 ***	0.08	0.34 ***	0.23 ***	−0.21 ***	0.52 ***	0.77 ***	0.68 ***	0.48 ***	0.67 ***
(17) SOLAR_T	0.37 ***	0.43 ***	0.45 ***	−0.08	0.24 ***	0.20 ***	−0.19 ***	0.27 ***	0.63 ***	0.56 ***	0.37 ***	0.54 ***
(18) SOLAR_P	0.14 *	0.35 ***	0.36 ***	−0.07	0.31 ***	0.12 *	−0.07	0.28 ***	0.52 ***	0.39 ***	0.48 ***	0.51 ***
(19) ED	0.18 ***	−0.42 ***	−0.41 ***	−0.30 ***	−0.07	−0.16 **	−0.23 ***	−0.48 ***	−0.18 **	−0.15 **	−0.1	−0.14 *
(20) GGE	0.55 ***	−0.24 ***	−0.21 ***	−0.30 ***	−0.15 **	−0.05	−0.46 ***	−0.35 ***	0.11 *	0.18 **	−0.12 *	−0.07
(21) PET	−0.40 ***	−0.28 ***	−0.30 ***	−0.22 ***	−0.41 ***	−0.19 ***	0.08	−0.19 ***	−0.52 ***	−0.48 ***	−0.34 ***	−0.43 ***
(22) RP	0.59 ***	−0.04	−0.01	−0.39 ***	0.17 **	−0.18 **	−0.56 ***	−0.14 *	0.50 ***	0.50 ***	0.25 ***	0.26 ***
(23) RD	0.67 ***	0.44 ***	0.46 ***	0.42 ***	0.44 ***	0.41 ***	−0.19 ***	0.42 ***	0.53 ***	0.68 ***	0.30 ***	0.32 ***
(24) LF	0.05	0.83 ***	0.84 ***	−0.04	0.26 ***	0.12 *	−0.17 **	0.77 ***	0.73 ***	0.63 ***	0.58 ***	0.68 ***

Variables	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
(13) OLB	1											
(14) HYDRO	0.17 **	1										
(15) GEOTHERMAL	0.15 **	0.47 ***	1									
(16) WIND	0.44 ***	0.35 ***	0.37 ***	1								
(17) SOLAR_T	0.33 ***	0.32 ***	0.44 ***	0.68 ***	1							
(18) SOLAR_P	0.27 ***	0.30 ***	0.41 ***	0.48 ***	0.58 ***	1						
(19) ED	−0.13 *	−0.04	0.08	−0.15 **	0.11 *	0.1	1					
(20) GGE	0.06	−0.06	0.04	0.17 **	0.40 ***	−0.04	0.46 ***	1				
(21) PET	−0.38 ***	−0.09	−0.05	−0.54 ***	−0.48 ***	−0.51 ***	0.07	−0.07	1			
(22) RP	0.20 ***	−0.07	0.1	0.37 ***	0.41 ***	0.43 ***	0.20 ***	0.29 ***	−0.41 ***	1		
(23) RD	0.61 ***	0.24 ***	−0.02	0.44 ***	0.25 ***	0.15 **	−0.26 ***	0.15 **	−0.49 ***	0.24 ***	1	
(24) LF	0.28 ***	0.65 ***	0.56 ***	0.67 ***	0.54 ***	0.43 ***	−0.31 ***	−0.05	−0.23 ***	0.17 **	0.22 ***	1

Source: Authors' computations. Notes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. For the definition of variables, please see Table 2.

The correlations between selected variables are disclosed in Table 4. Accordingly, we notice high correlations between the measures concerning renewable energy, but we will employ these variables within distinct panel data regression models in order to avoid the multicollinearity issue.

Table 5 reveals the output of panel unit root examination. We establish that selected variables are first order stationary. Therefore, we will inspect the cointegration relationship and if such a connection emerges then a PVECM in order to reveal the long-run association is justified [79].

Table 5. Panel unit root test results.

Variables	Level							
	Individual Intercept				Individual Intercept and Trend			
	LLC	IPS	ADF	PP	LLC	IPS	ADF	PP
GDPC	−5.75 ***	−2.83 **	84.85 **	167.04 ***	−7.61 ***	−0.51	55.05	59.46
PRE	−4.45 ***	2.11	36.52	82.96 *	−6.89 ***	−1.06	68.08	109.98 ***
CRE	−5.35 ***	0.91	49.79	102.04 ***	−4.64 ***	−0.18	57.43	80.91 *
SRE_GFEC	2.13	6.06	14.31	12.22	−4.98 ***	0.34	55.27	76.34 *
SRE_FCT	−3.12 ***	0.66	53.78	52.02	−5.43 ***	−0.68	70.27 †	56.53
EGRS	7.93	9.27	5.17	11.88	−1.93 *	2.46	30.96	59.38
FEC	−0.06	3.16	29.52	34	−4.75 ***	−0.03	52.33	108.09 ***
SBIOFUELS	−5.08 ***	−0.6	60.8	77.67 *	−3.83 ***	0.93	47.80	69.75 †
BGAS	−2.95 **	1.11	61.35	68.12	−6.05 ***	−2.49 **	94.05 **	106.34 ***
MW	−4.72 ***	−0.38	42.73	51.48 †	−5.25 ***	−0.11	39.68	54.55 *
BGASOLINE	−19.94 ***	−5.8 ***	63.79 **	43.22	−21.23 ***	−2.62 **	48.61 †	27.85
BDIESELS	−8.42 ***	−2.3 *	77.93 *	118.73 ***	−5.97 ***	0.81	43.77	83.49 **
OLB	−0.67	−0.07	22.89	39.61 *	−3.64 ***	−0.66	26.11	57.51 ***
HYDRO	−8.58 ***	−5.93 ***	133.67 ***	219.98 ***	−13.28 ***	−4.99 ***	114.73 ***	196.45 ***
GEOTHERMAL	−180.32 ***	−63.66 ***	59.11 *	64.71 **	−624.51 ***	−103.32 ***	55.83 *	49.63 †
WIND	−10.94 ***	−2.94 **	103.03 ***	177.18 ***	−5.80 ***	0.04	62.10	90.14 ***
SOLAR_T	−5.38 ***	1.1	43.11	38.78	1.47	2.87	23.41	35.75
SOLAR_P	−1.97 *	1.07	48.81	25.9	−8.56 ***	−1.82 *	75.50 *	48.84
ED	0.59	2.72	27.66	69.88	−6.11 ***	−2.85 **	92.79 **	202.50 ***
GGE	2.94	4.77	25.49	20.32	−6.41 ***	−1.11	66.33	126.22 ***
PET	−1.71 *	3.22	37.08	26.03	−8.09 ***	−1.68 *	76.01 *	106.09 ***
RP	0.25	4.63	16.12	16.95	−3.78 ***	1.16	40.34	101.25 ***
RD	−2.8 **	2.16	50.4	29.95	−4.78 ***	−0.18	58.37	86.95 **
LF	−8 ***	−1.38 †	81.55 *	116.09 ***	−5.28 ***	0.76	53.20	69.96 †
Variables	**First Difference**							
	Individual Intercept				**Individual Intercept and Trend**			
	LLC	**IPS**	**ADF**	**PP**	**LLC**	**IPS**	**ADF**	**PP**
ΔGDPC	−8.08 ***	−2.76 **	83.78 **	109.52 ***	−11.96 ***	−0.94	73.15 †	77.84 *
ΔPRE	−10.37 ***	−6.04 ***	143.00 ***	242.85 ***	−9.63 ***	−2.38 **	109.15 ***	225.42 ***
ΔCRE	−7.49 ***	−4.40 ***	117.65 ***	218.64 ***	−13.47 ***	−2.03 *	93.74 **	209.88 ***
ΔSRE_GFEC	−5.13 ***	−2.37 **	88.04**	173.95 ***	−4.75 ***	−0.09	60.77	171.06 ***
ΔSRE_FCT	−5.82 ***	−3.29 ***	99.67 ***	162.77 ***	−6.61 ***	−0.13	63.54	133.15 ***
ΔEGRS	−1.85 *	0.01	56.99	118.42 ***	−11.44 ***	−1.06	89.35 **	156.94 ***
ΔFEC	−6.54 ***	−4.05 ***	107.78 ***	251.83 ***	−4.67 ***	−0.47	63.27	213.91 ***
ΔSBIOFUELS	−5.02 ***	−3.40 ***	98.06 ***	220.83 ***	−3.41 ***	−0.32	68.32 †	247.66 ***
ΔBGAS	−11.62 ***	−7.02 ***	154.65 ***	247.18 ***	−11.78 ***	−3.11 ***	122.08 ***	225.96 ***
ΔMW	−3.10 **	−2.05 *	54.77 *	128.76 ***	−1.29 †	0.04	37.81	135.87 ***
ΔBGASOLINE	−15.92 ***	−4.13 ***	75.49 ***	96.47 ***	−11.69 ***	−1.60 †	62.84 **	137.17 ***
ΔBDIESELS	−8.42 ***	−3.85 ***	98.29 ***	194.14 ***	−16.37 ***	−3.34 ***	118.53 ***	220.86 ***
ΔOLB	−4.12 ***	−2.11 *	37.61 *	79.75 ***	−3.07 **	−0.12	22.27	71.19 ***
ΔHYDRO	−16.70 ***	−9.61 ***	194.39 ***	349.57 ***	−15.30 ***	−3.71 ***	128.82 ***	299.90 ***
ΔGEOTHERMAL	−497.95 ***	−80.40 ***	96.05 ***	147.50 ***	−306.91 ***	−31.68 ***	75.29 ***	150.37 ***
ΔWIND	−9.22 ***	−3.70 ***	97.36 ***	158.60 ***	−25.28 ***	−4.90 ***	130.67 ***	206.99 ***
ΔSOLAR_T	−1.59 †	−1.16	60.06	137.08 ***	−4.90 ***	−0.06	59.29	175.25 ***
ΔSOLAR_P	−4.47 ***	−3.66 ***	93.09 ***	115.15 ***	−4.17 ***	−1.26	80.49 **	125.95 ***
ΔED	−7.98 ***	−7.75 ***	168.48 ***	383.62 ***	−5.08 ***	−2.58 **	112.63 ***	351.12 ***
ΔGGE	−11.64 ***	−6.79 ***	154.76 ***	275.04 ***	−12.86 ***	−3.20 ***	123.94 ***	293.40 ***
ΔPET	−7.84 ***	−4.71 ***	120.33 ***	191.42 ***	−5.98 ***	−0.85	81.41 *	145.72 ***
ΔRP	−7.19 ***	−4.77 ***	120.45 ***	269.63 ***	−11.66 ***	−2.59 **	108.24 ***	261.40 ***
ΔRD	−4.90 ***	−3.24 ***	97.76 ***	187.27 ***	−4.33 ***	−0.71	72.08 †	174.11 ***
ΔLF	−2.99 **	−2.29 *	81.50 *	187.40 ***	−2.94 **	−1.02	76.83 *	243.79 ***

Source: authors' computations. Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. LLC reveals Levin, Lin and Chu t* stat. IPS reveals Im, Pesaran and Shin W-stat. ADF reveals Augmented Dickey-Fuller Fisher Chi-square. PP reveals Phillips–Perron Fisher Chi-square. LLC assumes common unit root process. IPS, ADF, and PP assumes individual unit root process. For the definition of variables, please see Table 2.

4.2. Panel Data Regression Models Results

The results of panel data regression models with reference to the influence of renewable energy (overall) on sustainable economic growth are revealed in Table 6. Hence, we notice the positive influence of renewable energy on gross domestic product per capita (Equations (1)–(5)), except for final renewable energies consumption in households (Equation (6)). Besides, the share of renewable energy in gross final energy consumption shows the highest influence on economic growth among the variables towards renewable energy (overall). As such, Equation (3) reveals that if there is an increase by 1% of the share of renewable energy in gross final energy consumption, the effect would be to increase the gross domestic product per capita by 1.61%. As regards the explanatory power of the estimated models, between 9% and 17% of the variation in the economic growth is explained by the renewable energy (overall) and country-level controls. Thereby, also renowned as eco-friendly sources of energy or green energy, such energy sources drive sustainable growth through energy and financial savings achieved by replacing non-renewable and costly energy with low-priced renewable energy sources, also leading to a lesser depletion of natural resources. Besides the fact that the negative effect on the environment does not register the similar magnitude as in case of non-renewable systems, there is revealed an enlarged job creation required for developing, setting up, and operating with renewable energy systems.

Table 6. Fixed-effects estimations towards the impact of renewable energy (overall) on sustainable economic growth.

Variables	**Equations**					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
PRE	0.08 *** (5.01)					
CRE		0.07 *** (4.45)				
SRE_GFEC			1.61 *** (5.43)			
SRE_FCT				1.27 *** (5.83)		
EGRS					0.35 * (2.14)	
FEC						0.23 (1.27)
ED	0.12 † (1.82)	0.10 (1.54)	0.09 (1.46)	0.07 (1.23)	0.07 (1.13)	0.13 † (1.93)
GGE	0.19 * (2.38)	0.20 * (2.39)	0.37 *** (4.30)	0.32 *** (3.99)	0.23 ** (2.64)	0.22 * (2.59)
PET	−0.03 (−0.82)	−0.03 (−0.88)	0.09 * (2.17)	0.03 (0.75)	0.01 (0.21)	−0.05 (−1.36)
RP	−0.01 (−0.23)	−0.00 (−0.07)	0.01 (0.40)	0.02 (1.12)	−0.01 (−0.35)	0.01 (0.48)
RD	5.68 * (2.33)	6.34 ** (2.60)	1.93 (0.80)	6.98 ** (3.25)	5.86 * (2.44)	8.43 *** (3.34)
LF	−0.29 † (−1.88)	−0.31 † (−1.96)	0.15 (1.10)	−0.07 (−0.47)	0.16 (1.11)	−0.00 (−0.03)
_cons	13.02 *** (5.78)	13.50 *** (5.75)	5.46 * (2.55)	9.40 *** (4.45)	6.44 ** (2.84)	9.21 *** (4.08)
F statistic	8.18 ***	7.36 ***	7.02 ***	7.71 ***	3.23 ***	4.45 ***
R-sq within	0.16	0.15	0.15	0.17	0.08	0.09
Obs	336	336	308	308	308	334
N Countries	28	28	28	28	28	28

Source: Authors' computations. Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Values in parentheses represent *t*-statistic. For the definition of variables, please see Table 2.

Similarly, the costs related to the production, diffusion, supply, and maintenance of renewable energy grids are reduced, whereas the multifarious supply implies a lower risk as regards a full loss of power. Therewith, due to the expansive fossil fuel based power systems within rural regions, using renewable energy sources in these areas will uphold the access to basic services as illumination, communications, or water.

Table 7 shows the effect of biomass energy on gross domestic product per capita. Therefore, we acknowledge the positive influence of every kind of biomass energy on sustainable economic growth (Equations (1–5)), apart from primary production of other liquid biofuels (Equation (6)). We notice that the primary production of solid biofuels, excluding charcoal, registers the highest influence on economic growth among biomass energy types. Equation (1) shows that for a 1% increase of the primary production of solid biofuels, the gross domestic product per capita will rise by 0.16%. Based on the values related to the coefficient of determination, the proportion of variance in the economic growth that can be explained by the biomass energy varies between 9% and 28%. Founded on living matter such as solid, vegetal, or animal waste, easily accessible in rural and urban regions, biomass energy is transformed in disposable energy kinds like methane gas or transport fuels as ethanol and biodiesel. Being a carbon neutral renewable energy, biomass does not harm the atmosphere, also showing a lower level of sulphur dioxide emanations that avoids acid rain incidence.

Table 7. Fixed-effects estimations towards the influence of biomass energy on sustainable economic growth.

Variables	Equations					
	(1)	(2)	(3)	(4)	(5)	(6)
SBIOFUELS	0.16 *** (6.77)					
BGAS		0.06 *** (8.27)				
MW			0.04 *** (5.88)			
BGASOLINE				0.02 *** (6.19)		
BDIESELS					0.02 *** (8.83)	
OLB						−0.00 (−0.33)
ED	0.07 (1.15)	0.20 ** (3.22)	0.11 † (1.72)	0.10 (1.56)	0.20 *** (3.36)	0.12 † (1.83)
GGE	0.24 ** (3.01)	0.38 *** (4.81)	0.25 ** (3.11)	0.30 *** (3.71)	0.37 *** (4.79)	0.20 * (2.33)
PET	−0.04 (−1.04)	−0.00 (−0.02)	−0.06 (−1.58)	−0.03 (−0.72)	−0.03 (−0.75)	−0.06 (−1.48)
RP	−0.02 (−0.92)	0.01 (0.30)	0.01 (0.34)	0.01 (0.44)	0.02 (0.76)	0.01 (0.51)
RD	6.60 ** (2.88)	5.59 * (2.51)	7.43 ** (3.21)	7.61 ** (3.32)	7.74 *** (3.58)	9.29 *** (3.82)
LF	−0.07 (−0.53)	0.03 (0.21)	−0.06 (−0.45)	−0.03 (−0.20)	−0.10 (−0.73)	0.01 (0.09)
_cons	9.18 *** (4.48)	7.64 *** (3.83)	9.93 *** (4.76)	9.13 *** (4.40)	9.74 *** (4.96)	9.12 *** (4.14)
F statistic	11.44 ***	14.97 ***	9.68 ***	10.27 ***	16.50 ***	4.26 ***
R-sq within	0.21	0.26	0.18	0.19	0.28	0.09
Obs	336	336	336	336	336	336
N Countries	28	28	28	28	28	28

Source: Authors' computations. Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Values in parentheses represent *t*-statistic. For the definition of variables, please see Table 2.

Biomass affords sustainable growth through decreasing financial and ecological expenditures concerning transport and contributes to national energy security by diminishing the reliance on fossil fuels. In addition, biomass lessens landfills by converting the waste that is detrimental to the environment into somewhat valuable, while the rural development is spurred by agriculture and forestry wastes. The output of panel data fixed-effects regressions as regards the influence of hydropower, geothermal energy, wind, and solar energy on sustainable economic growth are pointed out in Table 8.

Table 8. Fixed-effects estimations towards the effect of hydropower, geothermal energy, wind, and solar energy on sustainable economic growth.

Variables	Equations				
	(1)	(2)	(3)	(4)	(5)
HYDRO	0.05 † (1.94)				
GEOTHERMAL		0.02 * (2.17)			
WIND			0.04 *** (11.78)		
SOLAR_T				0.03 *** (3.90)	
SOLAR_P					−0.00 (−1.33)
ED	0.15 * (2.18)	0.14 * (2.10)	0.13 * (2.39)	0.14 * (2.09)	0.13 † (1.94)
GGE	0.22 * (2.57)	0.22 ** (2.61)	0.40 *** (5.57)	0.22 ** (2.63)	0.16 † (1.82)
PET	−0.06 (−1.55)	−0.07 † (−1.68)	0.03 (0.90)	−0.06 (−1.62)	−0.07 † (−1.76)
RP	0.01 (0.39)	0.00 (0.03)	0.00 (0.08)	−0.02 (−0.93)	0.01 (0.49)
RD	8.91 *** (3.70)	8.04 ** (3.25)	7.33 *** (3.66)	6.53 ** (2.65)	10.03 *** (4.08)
LF	0.00 (0.02)	0.03 (0.19)	0.09 (0.72)	−0.18 (−1.18)	0.03 (0.19)
_cons	8.95 *** (4.09)	8.82 *** (4.03)	6.55 *** (3.57)	11.98 *** (5.28)	9.08 *** (4.14)
F statistic	4.84 ***	4.99 ***	26.02 ***	6.63 ***	4.52 ***
R-sq within	0.10	0.10	0.38	0.13	0.10
Obs	336	336	336	336	336
N Countries	28	28	28	28	28

Source: Authors' computations. Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Values in parentheses represent *t*-statistic. For the definition of variables, please see Table 2.

We acknowledge that primary production of hydropower shows a higher influence on economic growth than geothermal energy, wind power, and solar energy. Equation (1) suggests that a 1% increase in the primary production of hydropower increases gross domestic product per capita by 0.05%. However, the estimated models explain between 10% and 38% of the variation in the economic growth. Thereby, we reinforce the positive influence of renewable energy on economic growth (Equations (1–5)), with the exception of primary production of solar photovoltaic energy (Equation (6)). Besides, amongst all renewable energy types, hydropower is the least expensive and the most trustworthy and efficient. However, hydropower is narrowed by geography, geothermal energy requires tectonic activity, whereas wind, alongside solar energy are irregular. Instead, due to their spreading and modularity [16], wind and solar energy sources are less exposed to extensive breakdowns so that a mighty climatic incident in one setting will not take off power within overall area. Green energy show more resilience towards undesirable weather circumstances than fossil fuels. Per se, wind energy, as well as solar photovoltaic systems reveals no reliance on water in order to produce electricity, consequently the risks related to water insufficiency being alleviated.

Further, as regards the influence of country-level controls, we emphasize for the most part of the estimated regressions, the positive influence of energy dependence, greenhouse gas emissions, and research and development expenditure on gross domestic product per capita. Besides, the explanatory power of the estimated models is not so high due to large variance among EU-28 states as regards renewable energy utilization.

4.3. Cointegration and Causality Examination

The cointegration examination as proposed by Pedroni [75,76] by means of two tests (panel and group) is shown in Table 9. The panel tests are founded on the within-dimension form, which comprises four statistics, respectively panel v, panel rho, panel PP, and panel ADF that pool the autoregressive coefficients across dissimilar states for the unit root checks on the estimated residuals. The group tests are established on the between dimension form which cover three statistics: group rho, group PP, and group ADF, that are set on means of the individual autoregressive coefficients related with the unit root checks of the residuals for each state in the panel [41–43,46,48]. As such, panel ADF and group ADF statistic support the cointegration relationship.

Table 9. Pedroni (Engle Granger based) test results.

Within-Dimension						
Cointegration Test	**Individual Intercept**		**Individual Intercept and Individual Trend**		**No Intercept or Trend**	
	Statistic	**Weighted Statistic**	**Statistic**	**Weighted Statistic**	**Statistic**	**Weighted Statistic**
Panel v-Statistic	−0.11	−1.11	0.65	−3.32	−3.06	−3.84
Panel rho-Statistic	2.18	1.87	4.25	4.49	−2.45 **	−2.61 **
Panel PP-Statistic	−0.48	−1.21	0.92	−1.16	−6.67 ***	−6.02 ***
Panel ADF-Statistic	−4.44 ***	−3.41 ***	−0.52	−2.44 **	−6.76 ***	−6.03 ***
Between-Dimension						
	Statistic		**Statistic**		**Statistic**	
Group rho-Statistic	4.55		6.34		−0.21	
Group PP-Statistic	−0.16		−0.76		−9.12 ***	
Group ADF-Statistic	−3.46 ***		−1.02		−7.73 ***	

Source: Authors' computations. Notes: ** $p < 0.01$, *** $p < 0.001$. Akaike Info Criterion was selected for lag length.

In addition, the output of a Kao test [80] is shown in Table 10. This test estimates the homogeneous cointegration association by pooled regression permitting for individual fixed effects [48]. Based on the ADF panel cointegration check where the vectors of cointegration are homogeneous, we notice the hypothesis of cointegration among the selected variables.

Table 10. Kao (Engle Granger based) test results.

ADF (t-Statistic)	Residual Variance	HAC Variance
−4.38 ***	0.002	0.003

Source: authors' computations. Notes: *** $p < 0.001$. Akaike Info Criterion was selected for lag length.

Also, the Johansen [81] approach with Fisher effect entitled Fisher-type panel cointegration test was performed. The outcome (Table 11) lets us reject the null hypothesis of no-cointegration. Therefore, the empirical findings from Tables 9–11 document the presence of a long-term equilibrium between primary production of renewable energies, energy dependence, and gross domestic product per capita.

Table 11. Fisher (combined Johansen) test results.

Hypothesized No. of CE(s)	Fisher Stat. (From Trace Test)	Fisher Stat. (From Max-Eigen Test)
None	579.9 ***	502.3 ***
At most 1	169.6 ***	146.7 ***
At most 2	104.6 ***	104.6 ***

Source: authors' computations. Notes: *** $p < 0.001$. Akaike Info Criterion was selected for lag length. Probabilities are computed using asymptotic Chi-square distribution.

Since the hypothesis of the presence of a long-term relationship was confirmed, the next stage involves estimating this connection. The results from Table 12 reveals that a 1 percent increase in primary production of renewable energies increases gross domestic product per capita by 0.06 percent (in case of FMOLS) or 0.05 percent (in case of DOLS).

Table 12. Ouput of panel fully modified OLS (FMOLS) and dynamic OLS (DOLS).

Variables	FMOLS	DOLS
PRE	0.06 *** (4.40)	0.05 *** (5.16)
ED	0.08 (1.05)	0.12 (1.28)
R-squared	0.99	0.99
Adjusted R-squared	0.99	0.99
S.E. of regression	0.07	0.06
Durbin-Watson stat	0.42	
Mean dependent var	10.16	10.15
S.D. dependent var	0.66	0.67
Sum squared resid	1.30	1.08
Long-run variance	0.01	0.01

Source: authors' computations. Notes: *** $p < 0.001$. Panel method: pooled. Heterogeneous variances. Akaike lag and lead method in case of DOLS estimation. Values in parentheses represent t-statistic. For the definition of variables, please see Table 2.

The direction of causal association between primary production of renewable energies, energy dependence, and gross domestic product per capita is examined by employing the PVECM Granger causality and results are conveyed in Table 13. In fact, there are showed the results of estimation of both the short- and the long-term dynamics as presented theoretically by Equations (6)–(8). With respect to Equation (6), primary production of renewable energies and energy dependence has a statistically insignificant impact on gross domestic product per capita in the short-run. In regards to Equation (7), gross domestic product per capita has a positive and statistically significant influence on primary production of renewable energies in the short-run, therefore the conservation hypothesis being supported similar [51–53,67]. Concerning Equation (8), primary production of renewable energies positively influence energy dependence in the short-run. With respect to the long-run causality, the results provide support for a unidirectional causality running from sustainable economic growth and energy dependence to the primary production of renewable energies, the conservation hypothesis being reinforced.

Table 13. Granger causality based on panel vector error correction model (PVECM).

Variables	Short-Run (or Weak) Granger Causality			Long-Run Granger Causality
	ΔGDPC	ΔPRE	ΔED	ECT
(6) ΔGDPC	-	12.56 **	4.00	−0.002
(7) ΔPRE	1.49	-	4.76 †	−0.020 **
(8) ΔED	2.83	4.20	-	0.013 ***

Source: authors' computations. Notes: † $p < 0.1$, ** $p < 0.01$, *** $p < 0.001$. ECT reveals the coefficient of the error correction term. The number of appropriate lag is two according to Schwarz information criterion. For the definition of variables, please see Table 2.

5. Concluding Remarks and Policy Implications

Energy is indispensable for life, but currently the main source of energy is still represented by fossil fuels whose supply is limited, and their extraction, conversion and transport cause substantial land and water pollution, also being responsible for global warming. However, renewable energies are limitless, the risk of climate alteration is reduced, and they also contribute to job creation. The current paper documented, by means of panel data fixed-effects regression models, for EU-28 states over the period 2003–2014, that primary production of renewable energies, gross inland renewable energies consumption, share of renewable energy in gross final energy consumption, share of renewable energy in fuel consumption of transport, and electricity generated from renewable sources, positively influence gross domestic product per capita. As well, biomass energy in the form of primary production of solid biofuels, biogas, municipal waste, biogasoline, and biodiesels positively influence sustainable economic growth. Likewise, we provide evidence for a positive influence of hydropower, geothermal energy, wind, and solar energy on sustainable economic growth. However, biomass energy revealed the highest influence on economic growth among the rest of renewable energy types. Besides, current study found a long-term relationship between primary production of renewable energies, energy dependence, and gross domestic product per capita. By estimating panel fully modified and dynamic ordinary least squares regressions, the positive influence of primary production of renewable energies on economic growth was noticed. In addition, the conservation hypothesis was acknowledged, being identified both a short-run and long-run unidirectional causal relationship running from gross domestic product per capita to the primary production of renewable energies.

Consistent with EU Directive 2009/28/EC, we acknowledge that EU-28 states did not achieve yet the targets set for the share of renewable energy in gross final energy consumption and for the share of renewable energy in transport fuel consumption. As policy implications, the cooperation mechanisms among EU-28 states, in form of statistical transfers, joint projects, or joint support schemes, should be intensified. In fact, appropriate connections among countries will mitigate the risk of electricity failures, therewith reducing the demand for setting other power plants and enhancing the management of fluctuating solar or wind renewable energies. Hence, binding the electricity framework at EU-28 level will develop a resilient energy infrastructure that could ensure the electricity supply security, as well as a better incorporation of renewable energy. Besides, reducing the increased dependence on imported fossil fuels from non-EU countries will lessen the energy price volatility and will contribute to the decarbonisation strategy. As a final point, potential venues for future research will be to expand the PVECM framework to each type of renewable energy. In addition, analyzing the renewable energy consumption-economic growth nexus by means of non-linear models will be further considered. Also, considering ISEW as an alternative measure of GDP will not be overlooked.

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