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The Convergence of Energy Use from Renewable Sources in the European Countries: Spatio-Temporal Approach

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Abstract: This article presents the analysis of the convergence of energy use from renewable sources among chosen European countries using a spatio-temporal approach. The high energy dependence of European countries on the economies of other continents makes the development of the use of renewable sources for energy production an important factor of their economic and social progress. The economic growth of every country is determined, among other factors, by an increase in the energy inputs. Therefore, in order to avoid excessive degradation of the environment, the use of renewable energy sources is increasingly becoming the crucial goal of governments worldwide. The analysis was conducted using data for 32 selected European countries in the years 1995–2019. In order to check progress in the case of the homogenization of renewable energy use, the β-convergence models for pooled cross-sectional and time-series data (TSCS) and also spatio-temporal β-convergence models were estimated. Absolute and conditional convergence was considered. Based on the literature review, the gross domestic product (GDP) per capita level and CO_2 emissions per capita level as processes conditioning the convergence in the case of the renewable energy use were chosen. Moreover, the spatial dependencies between neighboring countries were included in the models, and the neighborhood was defined in two ways. The neighborhood was quantified using the connection matrices: (1) based on the common border criterion (geographical neighborhood) and (2) based on the well-being level similarity (economic neighborhood based on the HPI index values).

Keywords: convergence; energy consumption; energy dependence; renewable sources; spatial models; spatio-temporal models

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1. Introduction

The economic growth of every country is associated with the ceaseless increase in energy demand [1–5]. An expansion in the case of obtaining energy from renewable sources is a topic often considered by the government of most countries worldwide nowadays. The production of energy using Earth's natural sources, such as sun, wind or water, causes states to become less independent on energy produced by others. Simultaneously, to a certain degree, the problem of limited resources for unlimited human needs is lessened [6–8].

Moreover, increasing the level and share of energy consumption from renewable sources contributes to environmental protection by reducing greenhouse gas emissions to the atmosphere [9–13].

Among other things, the concept of sustainable development was created for this purpose, which assumes economic growth with no degradation of the natural environment [14,15]. Moreover, the aspect of environmental development, which is an integral part of the economic growth of every country, should be taken into account more widely. States' governments promote environmentally friendly solutions, among others, with financial support that allows them to build photovoltaic and wind parks. Lucchi et al. [16] focused on the use of solar energy. They considered two types of systems that produce energy from the sun. They highlighted the guidelines for renewable energy systems' (RES) integration in historical buildings and sites.

Most of the European countries are very strongly energy-dependent on other economies [17,18]. The levels of imports of crude oil, solid fuels, electricity and natural gas, excluding a few cases (e.g., Norway), are very high. The share of the net energy export in total energy use is also worth emphasizing because it shows the energy dependence of states.

Figure 1 presents the level of the energy dependence of the chosen European countries in the years 2000 and 2019. The group of countries does not include Norway, which in both years was characterized by strong energy independence. The energy dependence rate was −723.023% in 2000 and −575.26% in 2019, respectively.

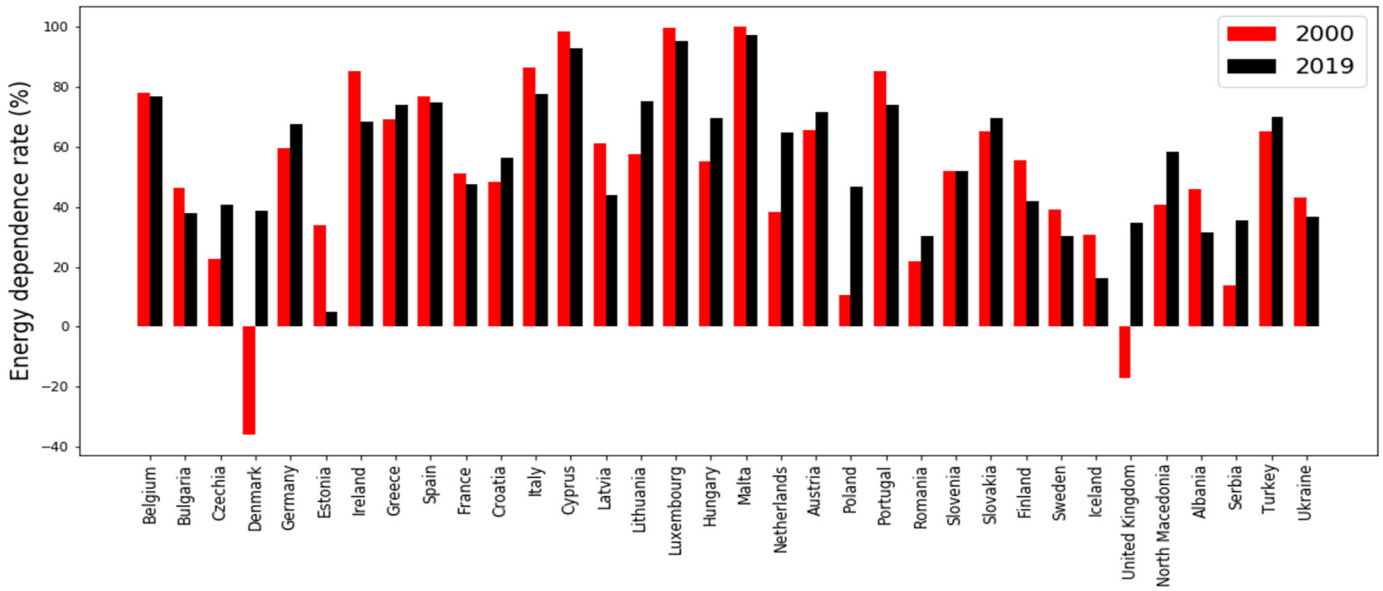


Figure 1. Energy dependence rate of the selected European countries in the years 2000 and 2019.

The most energy-dependent countries in both considered years were Cyprus, Luxembourg and Malta. Nevertheless, the values of the analyzed process decreased in 2019 compared to 2000. Denmark, Lithuania, the Netherlands, Poland, North Macedonia and the United Kingdom are among the countries with the highest increase in the share of imported energy. The highest decrease in values in 2019 compared to 2000 was noted in Estonia. Observing the graph, the fact that many countries recorded an increase in energy imports is worrying. It indicates that in order to record economic growth, they must use an increasing amount of non-renewable energy from trading partners.

Based on the official data, presented by Eurostat, the European Union countries (constituting most of the continent) imported energy mainly from Russia (solid fuels–46.7%, natural gas–41.1% and crude oil–21.1%). Partner countries also included the United States, Australia, the countries of the Arabian Peninsula and African countries (South Africa, Algeria and Nigeria). Chen et al. [19] pointed out that European countries import almost 50% of the global natural gas import (mostly via pipelines). They show that the Netherlands and Norway are the countries that have the highest European natural gas export rates. Siddi [20], in his research, also focused on the high energy dependence of European countries on Russia. Moreover, Bouwmeester and Oosterhaven [21] indicated an increase in the dependence of Europe on non-EU gas flow. Although most of the energy in the EU is imported, its energy prices are not higher in comparison to their partner countries. This is the result, among other reasons, of using different governmental policy instruments to support energy development in countries [22].

The high energy dependence of European countries on other states has instilled in them the importance of the development of renewable energy use. This fact was the main motivation for conducting this research. The aim of this analysis is to verify

whether the homogenization of renewable energy use level is occurring in the European continent, considering the spatial dependencies simultaneously. Moreover, the paper determines whether the relationship between countries that are well-being similar influence on the convergence process in renewable energy consumption. Therefore, the impact of behavior related to changes in renewable energy consumption from neighboring countries is analyzed. The neighborhood between economies is defined in two ways. Firstly, units are neighbors when they have a common land border (geographical neighborhood), and secondly, when they are similar in the case of well-being (economic neighborhood). The analysis was conducted for 32 selected European countries for the years 1995–2019. In order to evaluate the considered process, the models of the spatio-temporal absolute and conditional β-convergence are used.

In this research the following hypothesizes are investigated: (1) in the European continent the homogenization of renewable energy consumption occurs, (2) economic growth has a significant influence on the convergence process in the case of renewable energy consumption and (3) spatial dependency is an important factor in standardizing the level of renewable energy consumption.

2. Literature Review

In previous studies authors focused mainly on convergence in the case of total energy consumption [23–26]. Most of them pointed out equalizing levels of energy consumption between states. Many publications present an analysis on the convergence of energy use from renewable sources as well. This occurrence is due to, among other reasons, governmental approaches to renewable energy policies. This is due to the fact that governments follow a tendency towards adopting similar policies for renewable sources [27]. However, Grafström [28] showed the significant divergence of technological solutions for renewable energy source use. His conclusion was formulated based on research conducted on 13 of the 15 first European Union member states. However, the work of Strunz et al. [27] showed the widening of the gap between subsidies for research and development in order to achieve the goals in the scope of renewable energy sources.

Despite the differences resulting from the technological possibilities of the world countries, researchers have pointed out on the homogenization of the level and the shares of energy use from renewable sources. Kasman and Kasman [29] in their study, based on the data for EU-15 in the years 1990–2018, showed the convergence of renewable energy consumption per capita. They used the β- and σ-convergence models, estimating them for three appointed clusters. The same process was considered in other studies as well [30–32]. Butnaru et al. [30] took into account the level of renewable energy use in the EU countries in the period of 1960–2015. Payne et al. [31] conducted their study on the US in the period of 1970–2012, using, among other methods, unit root tests for time series with structural breaks. However, Zhang et al. [32] included the level of renewable energy use to build the Malmquist–Luenberger productivity index and an analysis of its convergence in Latin American countries. In turn, Reboredo [33] considered the convergence of the loading coefficient, which compares the relation of the share of renewable energy in every country to its panel average. The stochastic convergence approach in the analysis of renewable energy consumption unification as presented in the study of Solarin et al. [34]. They focused on the renewable energy consumption of 27 OECD countries in the period of 1965–2014.

Amongst the studies focusing on the convergence of the share of renewable energy use for total energy consumption, the research conducted by Dog and Pan [35] is worth pointing out. They concluded that homogenization occurred in the case of Belt and Road Initiative (BRI) countries in the period of 2004–2018. Presno and Landajo [36] pointed to its convergence in clubs of the EU countries. Convergence within the EU was also considered in a study conducted by Berk et al. [37]. The convergence of the share of renewable energy to the widest spatial extent known (176 countries in the period 1990–2018) was demonstrated by Bigerna et al. [38]. They estimated the β-convergence models in absolute and conditional versions. They considered gross domestic product (GDP) per capita and

the life expectancy at birth in the processes of determining the homogenization process in the field of renewable energy.

Most of the studies also investigated the energy efficiency convergence. Cheng et al. [39] considered the process of equalizing the level of energy efficiency in China provinces in the period of 1997–2016. They provided a study based on the spatial convergence approach using spatial autoregressive and spatial error panel data models. In order to estimate spatial models, they constructed a spatial weight matrix considering the geographical distance between provinces. Moreover, they concluded that the convergence process occurs. Han et al. [40] presented a similar approach in their study. Nonetheless, they defined the spatial weight matrix based on the economic distance between spatial units, considering the trade flows between them. They focused on the catch-up effect in the energy efficiency between selected countries. Panel data models for an analysis on the convergence of energy efficiency were also used by Huang et al. [41]. They concluded a unification process in China had occurred based on the club convergence approach. Liddle and Sadorsky [42] verified the energy efficiency convergence for 81 selected countries using a σ-convergence approach. Their study embraced the countries that account for almost 90% of total energy consumption in the world.

In studies about renewable energy resources, an aspect of energy intensity has been raised as well [43–45]. The problem of technological solutions' diffusion between states [33,46] and also between the territorial units inside them [47] is an important process from a development point of view in the case of renewable energy consumption. Therefore, changes in the production and consumption of energy from renewable sources are determined by their changes in other countries. For this reason, implementing the spatial dependencies analysis is justified, which is used in this context by a few authors. In the literature, one of the approaches used to consider dependencies in space is unit clustering in the homogenous sets using cluster analysis [48–51]. The weakness of this approach is that the strength of the influence of some economies on others is not able to be determined. This is possible in an analysis with the use of spatial and spatio-temporal models. Fontanella et al. [52] considered the problem of the convergence of renewable energy use, using a classic spatial autoregressive (SAR) model. They defined neighborhood states as states that share a common land border. Their research was conducted for 28 chosen European countries in the years 1995–2010. While Hille and Lambert [53] focused on the aligning level of energy use from renewable sources in the Korean provinces. As an analyzing tool they used the spatial lag of X (SLX) model for panel data. In the SLX model, as opposed to the SAR model, the spatial lag of the dependent variable is not included. The authors pointed out the influence of processes such as the income of economies and economic openness both in the considered territorial unit and neighboring units on their renewable energy use.

There are a few researchers who have used spatial methods for renewable energy consumption convergence analysis. However, there is no research considering the connections between countries with similar wealth and well-being levels. In this study, spatial models are used to estimate the dependence of renewable energy consumption of certain countries on energy consumption by other countries with similar well-being. This allows us to better understand the formation of renewable energy use in the considered area because wealth and well-being are significant factors in renewable energy market development. Therefore, the spatial approach to β-convergence analysis is presented.

3. Methodology

3.1. Spatial Structure of the Processes

This research was conducted in light of the concept of pooled time series and cross-sectional (TSCS) data modeling. Based on this concept the heterogeneity of spatial units is characterized using spatial and spatio-temporal trends, as opposed to panel data modeling. The evaluation of the deterministic spatio-temporal trend presence (which shows long-term dependencies) was also used to eliminate non-stationarity in the average of the process.

Therefore, in the first step of the investigation the models of the spatial and spatio-temporal trend for all considered processes were estimated and verified. The general form of the spatial trend model is as follows [54,55]:

$$Y(\boldsymbol{s}_i) = \sum_{k=0}^{p} \sum_{m=0}^{p} \theta_{km} u_{1,i}^{k} u_{2,i}^{m}, \tag{1}$$

where $\boldsymbol{s}_i = [u_{1,i}, u_{2,i}]$ is the vector of the geographic location coordinates of the spatial units, $i = 1, 2, \ldots, N$ denotes the spatial unit number and $k + m \leq p$. Likewise, the spatio-temporal tendency can be described with the use of a polynomial function in the form of [56]:

$$Y(\boldsymbol{s}_i, t) = \sum_{k=0}^{p} \sum_{m=0}^{p} \sum_{l=0}^{p} \theta_{kml} u_{1,i}^{k} u_{2,i}^{m} t^{l}, \tag{2}$$

where $\boldsymbol{s}_i$, i is as defined above, t is the time variable and $k + m + l \leq p$.

With the evaluation of the spatial trend presence, the global spatial autocorrelation occurrence, which is responsible for the significance of the connections between neighbors, was investigated. To study the global spatial autocorrelation occurrence, a few statistics were defined. The spatial autocorrelation measure used in this research is Moran's I statistic, given by the following formula [57], p. 22:

$$I = \frac{n}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}} \cdot \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} [y(\boldsymbol{s}_i) - \overline{y}] [y(s_j) - \overline{y}]}{\sum_{i=1}^{n} [y(\boldsymbol{s}_i) - \overline{y}]^2} = \frac{n}{S_0} \cdot \frac{\boldsymbol{y}^T \boldsymbol{W} \boldsymbol{y}}{\boldsymbol{y}^T \boldsymbol{y}}, \tag{3}$$

where $y(\boldsymbol{s}_i)$ is the realization of the spatial process $Y(\boldsymbol{s})$ in the ith spatial unit, $\overline{z}$–= is an average value of the process, $\boldsymbol{y}$ is a column vector with the elements in the form of $y_i = y(\boldsymbol{s}_i) - \overline{y}$ and $S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}$ is a sum of all the elements of the spatial weights matrix.

In the analysis, two types of spatial connection matrices between territorial units were considered. The first of them quantifies the neighborhood by the land common border criterion (**W**). It is classical and the most often used spatial weights matrix in the spatial analyses. The second spatial connection matrix was constructed on the basis of the economic distance between units (**D**). The process, characterizing the economic similarity of the spatial units, is the Happy Planet Index (HPI), which shows the level of their well-being. The distance matrix (**D**) was constructed in the following steps (see: [10], pp. 4–5): (1) Evaluation of the distance between spatial units using the values of the Happy Planet Index. (2) Determination of the borderline level g of the units' similarity. (3) Appropriate conversion of the non-zero elements of the matrix. (4) Standardization to the unity of the elements by rows.

For the analysis in the spatio-temporal dimension, two blocked matrices of the cross-sectional and time connections were created (1) according to the common border criterion and (2) between well-being levels of the different countries.

After filtering out the processes from the long-term dependencies, represented by the spatio-temporal deterministic trend, the presence of the stochastic trend (in the variance of the process) was checked using the Levin–Lin–Chu test [58].

3.2. β-Convergence Approach

The concept of convergence was created by Solow [59] based on the neoclassical economic growth model. Next, this concept was developed, among others, by Baumola [60]. In most of the research papers, the income convergence hypothesis is tested [61,62]. However, the analyses of social convergence or convergence in the case of consumption are applied more often [63,64]. The concept of β-convergence is based on the idea of poorer economies catching up to wealthier ones [65].

In this investigation, the β-convergence idea was used in order to verify whether a convergence process of renewable energy use levels in Europe can be observed. Initially, the spatio-temporal absolute β-convergence model was estimated in the form of [65]:

$$ln(RE)_{i,t}{}^{f} = \alpha_o + (1+\beta)ln(RE)_{i,t-1}{}^{f} + \varepsilon_{i,t}, \quad (4)$$

where $ln(RE)_{i,t}{}^{f}$ denotes the energy use from renewable sources per capita process reduced to stationarity. Additionally, α_o and β are the structural parameters of the model, whereas ε is a random component. Convergence is considered to occur if the evaluation of the parameter β is negative and simultaneously, the parameter is statistically significant.

Next, the conditional convergence model, supplementing the model (6) with additional explanatory variables, was estimated given as:

$$ln(RE)_{i,t}{}^{f} = \alpha_o + (1+\beta)ln(RE)_{i,t-1}{}^{f} + \gamma_1 ln(GDP)_{i,t}{}^{f} + \gamma_2 ln(CO_2)_{i,t}{}^{f} + \varepsilon_{i,t}, \quad (5)$$

where $ln(RE)_{i,t}{}^{f}$ is as defined above, but $ln(GDP)_{i,t}{}^{f}$ and $ln(CO_2)_{i,t}{}^{f}$ are the reduced to stationarity GDP per capita and CO_2 emissions per capita processes, α_o, β, γ_1, γ_2 are the structural parameters of the model and ε is the random component. Process choice influenced by the convergence of renewable energy use is based on the mostly confirmed dependencies between renewable energy use, GDP level and CO_2 emissions presented in the literature [66–71].

In order to determine the significance of the implementation of spatial effects to the models given as (4) and (5), base and robust versions of Lagrange multiplier tests (LM) were used [72], pp. 37–39. Then, spatio-temporal models supplemented by dependencies between neighbors were estimated and took the following form:

$$ln(RE)_{i,t}{}^{f} = \alpha_o + (1+\beta)ln(RE)_{i,t-1}{}^{f} + \rho \sum_{i \neq j} w_{ij,t} \ln(RE)_{j,t} + \varepsilon_{i,t}, \quad (6)$$

$$\begin{gathered} ln(RE)_{i,t}{}^{f} = \alpha_o + (1+\beta)ln(RE)_{i,t-1}{}^{f} + \eta_{j,t}, \\ \eta_{j,t} = \lambda \sum_{i \neq j} w_{ij,t}\eta_{j,t} + \varepsilon_{i,t}, \end{gathered} \quad (7)$$

$$\begin{gathered} ln(RE)_{i,t}{}^{f} = \alpha_o + (1+\beta)ln(RE)_{i,t-1}{}^{f} + \gamma_1 ln(GDP)_{i,t}{}^{f} + \gamma_2 ln(CO_2)_{i,t}{}^{f} + \\ + \rho \sum_{i \neq j} w_{ij,t} ln(RE)_{j,t} + \varepsilon_{i,t}, \end{gathered} \quad (8)$$

$$\begin{gathered} ln(RE)_{i,t}{}^{f} = \alpha_o + (1+\beta)ln(RE)_{i,t-1}{}^{f} + \gamma_1 ln(GDP)_{i,t}{}^{f} + \gamma_2 ln(CO_2)_{i,t}{}^{f} + \eta_{j,t}, \\ \eta_{j,t} = \lambda \sum_{i \neq j} w_{ij,t}\eta_{j,t} + \varepsilon_{i,t}, \end{gathered} \quad (9)$$

where models (6) and (8) are the spatial autoregressive models, which include the influence of the dependent variable from the neighboring countries. However, models (7) and (9) are the spatial error models, including the influence of the variables not included in the model and random processes from the neighboring units.

The β parameter serves to calculate the t_{hl} (half-life statistics) value, which presents the time needed to reduce the difference by half. It is expressed as follows [73], p. 11:

$$t_{hl} = \frac{\ln(2)}{b}, \quad (10)$$

where: $b = -\ln(1+\beta)$ expresses the convergence rate.

4. Data

In this research data the level of renewable energy use per capita (RE), GDP per capita, CO_2 emissions per capita and the Happy Planet Index measure are considered. Data were taken from the three following databases: (1) RE and CO_2 from the Our World in Data website (https://ourworldindata.org/ (accessed on 2 October 2021)); (2) GPD from the World Bank (https://data.worldbank.org/ (accessed on 2 October 2021)); (3) HPI from the

Happy Planet Index website (http://happyplanetindex.org/ (accessed on 2 October 2021)). All calculations were made with the use of R software (version 4.1.1). Figures were made with the R and Python software.

Figure 2 shows the spatial decomposition of energy use from renewable sources values in the years 1992 and 2019 (parts (a) and (b)), and also its growth rate in the period of 1995–2019 (part (c)). The values of the processes are categorized into four groups using positional measures of descriptive statistics as follows: (1) very low values—below median reduced by quarter deviation, (2) low values—between median reduced by quarter deviation and median, (3) high values—between median and median increased by quarter deviation, (4) very high values—more than median increased by quarter deviation. In both extreme years of the study, most of Middle Eastern European countries were characterized by relatively low levels of renewable energy use. Moreover, low values of the considered process were observed in the Benelux countries. In 2019 the formation of the values in space divided Europe into two quite consistent areas. The first includes the Central and Eastern European countries (with low values of energy use), but the second includes units in the western and southern parts of the continent (excluding Benelux countries). It should be noted that most of the countries with lower values of energy use from renewable sources were characterized by a high growth rate in the period of 1995–2019. Hence, we can suppose that the convergence process of renewable energy use levels among European countries occurs.

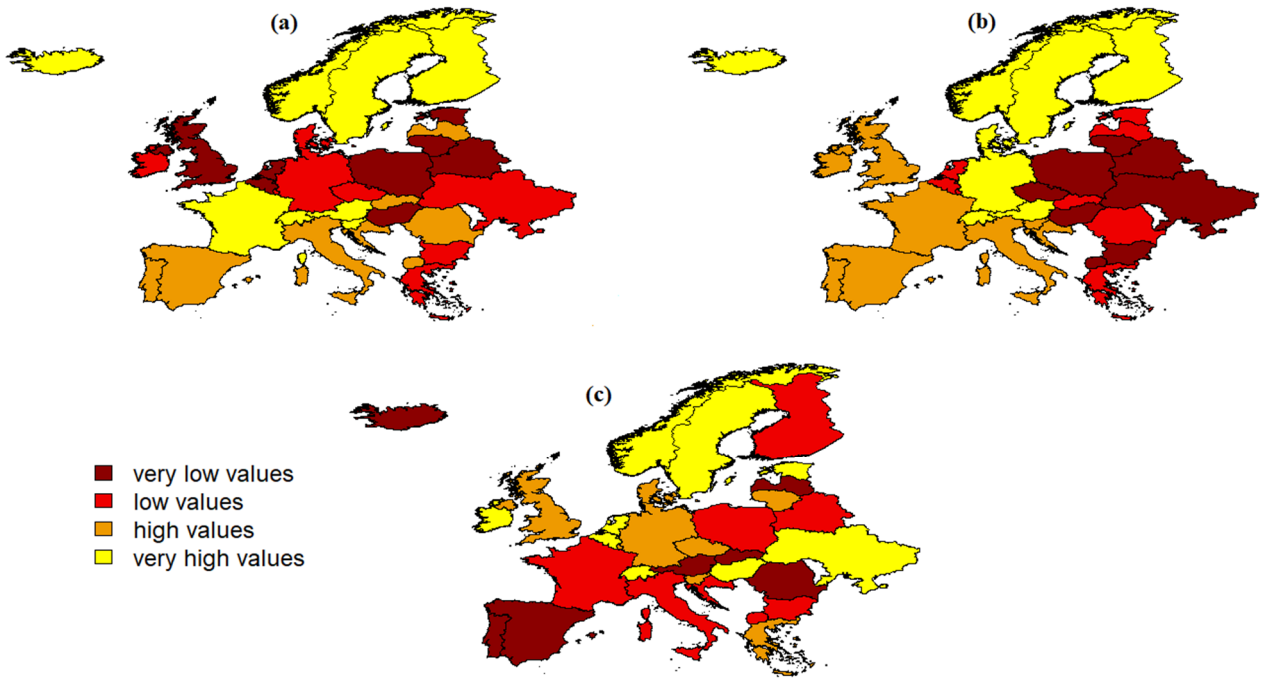


Figure 2. Spatial differentiation of the renewable energy use per capita in the years 1995–part (**a**) and 2019–part (**b**) and its growth rate in the period of 1995–2019–part (**c**).

In turn, Figure 3 shows the spatial decomposition of the gross domestic product per capita values in the years 1995 (part (a)) and 2019 (part (b)). A certain tendency can be observed. In both years, the considered region was shared by two consistent areas. The first was represented by the Central and Eastern European countries, which were characterized by a low level of GDP per capita. The remaining part of the continent was dominated by relatively rich countries (excluding Portugal). Comparing the distributions showed in Figures 2 and 3, we can suppose that there is a high correlation between the level of GDP per capita and energy use from renewable sources in Europe.

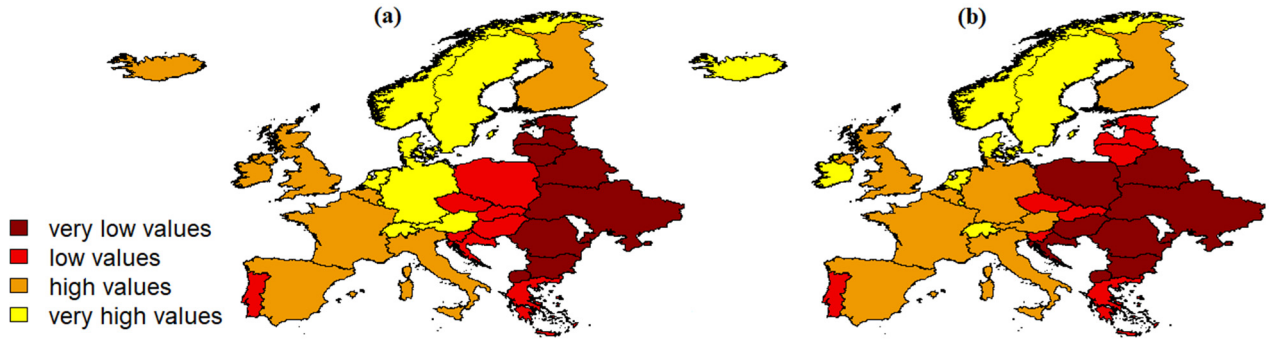


Figure 3. Spatial differentiation of the gross domestic product (GDP) per capita in the years 1995–part (**a**) and 2019–part (**b**).

Figure 4 contains maps with the spatial differentiation of the CO_2 emissions level per capita for the considered area in the extreme years of the study. In both years, most of the countries of Southern Europe, Sweden, Lithuania and Latvia had a low level of the analyzed process. The most polluted states (based on CO_2 emissions levels) were states in Central Europe. It should be observed that the distributions presented in Figure 4 are different than those in Figures 2 and 3. Therefore, we can expect no relation between the considered processes.

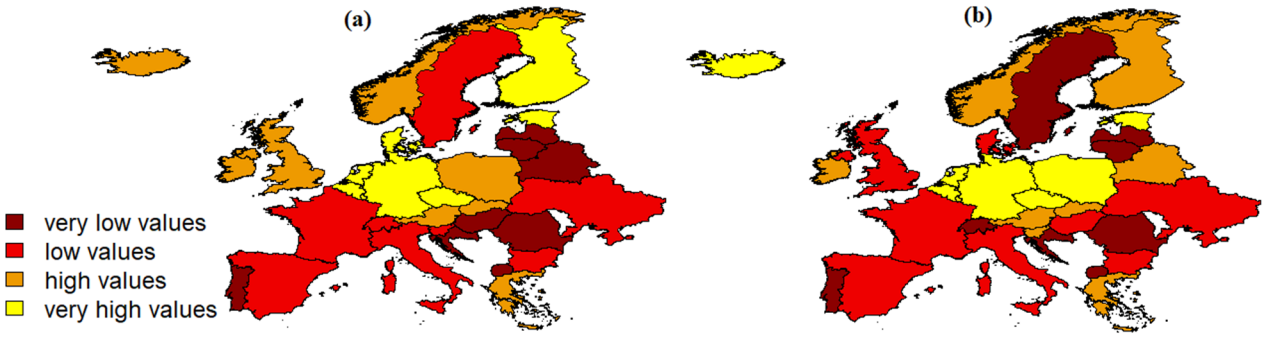


Figure 4. Spatial differentiation of the CO_2 emissions per capita in the years 1995–part (**a**) and 2019–part (**b**).

5. Empirical Results

At the beginning of the empirical analysis, the spatio-temporal structure of renewable energy use (*RE*), GDP per capita (*GDP*) and CO_2 emissions (CO_2) were investigated in order to evaluate the long-term tendency towards their formation. Hence, in the first step, the spatial trend models in the period of 1995–2019 were estimated (see Appendix A). In the whole period of the analysis, the second-degree spatial trend for variables *RE* and *GDP* was observed; however, in the second case, the trend plane was better fitted (in the light of R^2 values). Moreover, in only a few cases, the connections between neighboring units were characterized by statistical significance (but mainly for the distance matrix **D**). In turn, for the CO_2 variable, a spatial trend was observed, but not for all the years of the study. If it occurred, it was a first-degree trend. It is worth noting that, besides 1995, the connections between neighbors described using distance matrix **D** were statistically significant.

Next, based on the results of the spatial trend models, the spatio-temporal models were estimated. The results of estimation and verification of the models for all considered processes are shown in Table 1.

Table 1. The results of the estimation and verification of the spatio-temporal tendency towards the considered processes.

Parameter	Renewable Energy Use (*RE*)		GDP per Capita (*GDP*)		CO_2 Emissions (CO_2)	
	Estimate	*p*-Value	Estimate	*p*-Value	Estimate	*p*-Value
θ_{000}	49.6688	0.0000	16.5668	0.0000	1.5354	0.0000
θ_{100}	0.2172	0.0000	0.0116	0.0000	−0.0095	0.0000
θ_{010}	−1.7600	0.0000	−0.3242	0.0000	0.0145	0.0000
θ_{001}	0.0645	0.0000	0.1063	0.0000	−0.0104	0.0000
θ_{200}	−0.0040	0.0000	−0.0036	0.0000	-	-
θ_{110}	−0.0035	0.0000	-	-	-	-
θ_{020}	0.0180	0.0000	0.0037	0.0000	-	-
θ_{002}	-	-	−0.0021	0.0000	-	-
R^2	0.5893		0.8104		0.1884	
Moran's test (**W**)	−0.0991 (0.0010)		0.0892 (0.0022)		0.0481 (0.0595)	
Moran's test (**D**)	−0.1869 (0.0000)		0.1503 (0.0000)		−0.3184 (0.0000)	

Note: figures in brackets refer to *p*-values.

Table 1 consists of models after a posteriori elimination of the statistically insignificant variables. It should be noted that the positive estimate of the parameter θ_{001} denotes an average growth of the energy use level from the renewable sources demonstrated in the period of 1995–2019. In the same period, the CO_2 emissions level decreased on average (negative estimate of the parameter θ_{001}) and the GDP per capita level increased on average, but it was an expiring increase (positive estimate of the parameter θ_{001} and negative estimate of the parameter θ_{002}). In the analysis of the formation of all considered processes, the connections between neighbors played a significant role, quantified using distance matrix **D**. However, in the case of *RE* and CO_2 variables, neighbors are characterized by the different values of processes (negative global spatial autocorrelation was observed). In turn, in the case of GDP, its values in neighboring territorial units (in light of the HPI values) were similar. It should be noted that the connections determined on the basis of the well-being similarity of the countries turned out to be stronger than those determined on the basis of the common border criterion. Geographical neighborhood was not significant in CO_2 emissions levels.

Based on the values of the processes filtered out from the long-term dependencies, the presence of the unit root in the cross-sectional time-series using the Levin–Lin–Chu test was verified. By analyzing the results of testing the presence of the unit root, shown in Table 2, no unit root in the formation of the processes was noted. Therefore, in the next steps of the analysis, stationary processes, filtered out from the spatio-temporal trend, were used.

Table 2. The results of the unit root Levin–Lin–Chu test for considered processes filtered out from long-term tendency.

Levin–Lin–Chu	*RE*	*GDP*	CO_2
test statistics	−9.0939	−6.3491	−3.1566
***p*-value**	0.0000	0.0000	0.0008

The second stage of the empirical research was to verify the hypothesis about the homogenization of renewable energy use in the selected European countries. In Table 3 there are the results of the estimation and verification of the absolute and conditional β-convergence models for pooled time-series and cross-sectional (TSCS) data. An estimate of the parameter that is statistically significant and less than one indicates a progressive process of convergence in the level of energy consumption from renewable sources among countries in Europe. Based on this parameter, the appointed convergence rate indicates a reduction of the existing differences between about 4.87% and 5.13% per year for absolute and conditional convergence, respectively. In effect, around 14 years and around 13.5 years are needed respectively to reduce the existing differences by half. Therefore, conditioning

countries to unify in the case of the considered process accelerates the convergence. During the verification of the hypothesis about conditional convergence, no influence from the CO_2 emissions was noted. Hence, the GDP per capita is the only process that has a significant influence on the homogenization of renewable energy use.

Table 3. The results of the estimation and verification of the pooled TSCS β-convergence models.

Parameter	Absolute		Conditional	
	Estimate	***p*-Value**	**Estimate**	***p*-Value**
α_o	−0.0069	0.3040	−0.0066	0.3268
$1+\beta$	0.9525	0.0000	0.9500	0.0000
γ_1	-	-	0.0334	0.0246
R^2	0.9708		0.9709	
Moran's test	**W** matrix	**D** matrix	**W** matrix	**D** matrix
	0.4778 (0.0000)	0.1097 (0.0004)	0.4743 (0.0000)	0.0992 (0.0013)
	***LM* tests**			
LM_{err}	230.8334 (0.0000)	11.4558 (0.0007)	227.4654 (0.0000)	9.3701 (0.0022)
LM_{lag}	7.8218 (0.0052)	0.7861 (0.3752)	6.2027 (0.0128)	0.1682 (0.6817)
RLM_{err}	223.9022 (0.0000)	10.6980 (0.0011)	222.838 (0.0000)	9.2693 (0.0023)
RLM_{lag}	0.8907 (0.3453)	0.0284 (0.3453)	1.5754 (0.2094)	0.0674 (0.7952)
	Convergence characteristics			
b	0.0487		0.0513	
t_{hl}	14.2432		13.5226	

The results of Moran's test for the models' residuals show the significance of the connections between neighbors, quantified using both considered neighborhood matrices according to the common border criterion (**W**) and according to similarity of the well-being level criterion (**D**). Based on the results of the LM tests in the basic and robust version, the validity of the estimation of the spatial autoregressive model (SAR) and spatial error model (SE) for **W** matrix as well as the spatial error model for **D** matrix should be noted.

In Table 4 the results of the estimation and verification of the spatio-temporal absolute β-convergence models are presented. The estimate of the parameter value implies that the influence of the lagged dependent variable ($1 + \beta$) does not differ much from its estimate as shown in Table 3. The statistical significance for the parameters responsible for an influence of the dependent variable changes (ρ) and variables not included in the model or random processes (λ) from neighboring countries was observed. It should be noted that connections quantified using distance matrix **D** have a positive impact on the convergence process because the convergence speeds up. In turn, including the geographical connections makes homogenization slower. Therefore, imitation of the operations of countries with a similar well-being level, as measured with the HPI index, is advantageous in terms of the homogenization of renewable energy use. In light of the Akaike criterion, spatial error models are better than the spatial autoregressive model, whose residuals exhibit a spatial autocorrelation.

In turn, Table 5 contains the results of the estimation and verification spatio-temporal conditional β-convergence models. Just as in the case of absolute convergence, the estimate of the $1 + \beta$ parameter does not differ significantly from its estimate shown in Table 3. However, the inclusion of the impact of changes in the values of dependent processes and processes not included in model or random processes from the neighboring units causes a slight slowdown of homogenization in the case of renewable energy use. The convergence rate fluctuates between 4.52% and 5.1% per year according to the estimated model. Moreover, a decrease in the impact of GDP per capita level was observed. This is evidenced by the lack of statistical significance of the parameter γ_1.

Table 4. The results of the estimation and verification of the spatio-temporal absolute β-convergence models.

Parameter	Model					
	SAR_W		SE_W		SE_D	
	Estimate	*p*-Value	Estimate	*p*-Value	Estimate	*p*-Value
α_o	−0.0083	0.2157	−0.0078	0.4835	−0.0074	0.3297
$1+\beta$	0.9555	0.0000	0.9567	0.0000	0.9520	0.0000
ρ	0.0284	0.0050	-	-	-	-
λ	-	-	0.5375	0.0000	0.1200	0.0014
pseudo-R^2	0.9711		0.9810		0.9713	
$Log-l$	203.5137		318.3293		204.6790	
AIC	−399.0300		−628.6600		−401.3600	
Moran's test	0.4617 (0.0000)		−0.0068 (0.4331)		−0.0144 (0.3480)	
Convergence characteristics						
b	0.0455		0.0443		0.0492	
t_{hl}	15.2262		15.6636		14.0815	

Note: $Log-l$ and AIC refer to the log-likelihood and Akaike criterion values, respectively.

Similar to the case of the absolute convergence analysis, the spatial error model is better than the spatial autoregressive model. The results of Moran's test denote the presence of spatial autocorrelation in the SAR model residuals, as opposed to the SE models.

The results of this paper show that the convergence process of renewable energy consumption occurs, which is in line with results obtained by other authors. This study presents a new approach for verifying a relationship between neighbors in the case of renewable energy consumption. Hitherto, the authors focus on the geographical neighborhood and economic neighborhood (in light of the trade-flows). The approach, using the well-being level as a measure of similarity between countries enriches investigations of renewable energy use.

Table 5. The results of the estimation and verification of the spatio-temporal conditional β-convergence models.

Parameter	Model					
	SAR_W		SE_W		SE_D	
	Estimate	*p*-Value	Estimate	*p*-Value	Estimate	*p*-Value
α_o	−0.0079	0.2390	−0.0077	0.4854	−0.0073	0.3310
$1+\beta$	0.9531	0.0000	0.9558	0.0000	0.9503	0.0000
γ_1	0.0278	0.0620	0.0203	0.0800	0.0276	0.0625
ρ	0.0255	0.0123	-	-	-	-
λ	-	-	0.5366	0.0000	0.1111	0.0035
pseudo-R^2	0.9712		0.9810		0.9714	
$Log-l$	205.2443		319.8583		206.3818	
AIC	−400.4900		−629.7200		−402.7600	
Moran's test	0.4603 (0.0000)		−0.0064 (0.4374)		−0.0144 (0.3629)	
Convergence characteristics						
b	0.0480		0.0452		0.0510	
t_{hl}	14.4376		15.3331		13.5973	

6. Conclusions

The aim of this paper was to determine whether there is a process of equalizing the level of energy consumption from renewable sources in European countries. The analysis points out significant convergence in the case of the considered process. It is important from the point of view of the energy dependence of European countries on the economies from other continents, mainly Russia, the USA or Australia.

The estimated β-covergence models show that the economies with higher levels of renewable energy use per capita are catching up with the countries with a relatively low

level of the considered process. However, 15 years are needed in order to reduce existing inequalities by half. Moreover, significant evidence proved the relationship between CO_2 emissions and renewable energy use does not occur in the case of the convergence analysis. A positive influence on the development of renewable energy use shows the enrichment of the economies, expressed by the level of the GDP per capita.

The inclusion of the dependencies between neighboring economies in the models caused the loss of the significance of the GDP per capita impact on the convergence process. It denotes the superiority of neighboring countries' behavior over the economies' enrichment in the case of renewable energy use. Additionally, inclusion of the impact of the dependent variable in the models or other processes not included in the model on the neighboring units causes an extension of the time needed to reduce existing differences. One of the reasons for this situation could be the availability of technology needed to produce renewable energy. In other words, to produce the same level of renewable energy as their neighbors, countries need similar technology. Nevertheless, some time is necessary to obtain this. findings of this paper could motivate governments to speed up the development of the technology sector. Innovations in renewable energy sources sector would allow environmental degradation to cease.

The conducted research showed that the convergence of renewable energy use among the European countries occurs. In further analysis on this subject, distinguishing economies by their growth level and verifying the hypothesis about club convergence are topics worth considering. Moreover, the study could be enriched by the analysis of subperiods and the use of the other connection matrices. It is also worth providing an analysis on the subsets of the considered area, defining these subsets with the GDP per capita values. This would allow the differentiation of countries in terms of their wealth level.

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Appendix A

Table A1. The results of the estimation and verification of the spatial trend models for all considered processes.

Variable:		*RE*			*GDP*			CO_2	
Year	Trend	Moran *I*		Trend	Moran *I*		Trend	Moran *I*	
		W Matrix	D Matrix		W Matrix	D Matrix		W Matrix	D Matrix
1995	2	−0.1897	−0.2954	2	−0.0196	−0.0012	-	−0.0167	−0.3435
1996	2	−0.1760	−0.2807	2	−0.0542	−0.0137	-	−0.0241	−0.3699
1997	2	−0.1934	−0.3015	2	−0.0962	−0.0205	-	−0.0783	−0.3894
1998	2	−0.2429	−0.3109	2	−0.1235	−0.0001	-	−0.0650	−0.3960
1999	2	−0.2080	−0.2431	2	−0.1409	0.0069	1	−0.0937	−0.3602
2000	2	−0.2101	−0.2650	2	−0.1409	−0.0028	1	−0.0876	−0.3600
2001	2	−0.1465	−0.2562	2	−0.1657	−0.0056	1	−0.0915	−0.3421
2002	2	−0.1711	−0.2072	2	−0.1838	−0.0200	1	−0.1076	−0.3204
2003	2	−0.1989	−0.2342	2	−0.1994	−0.0311	1	−0.1245	−0.3387
2004	2	−0.1588	−0.2337	2	−0.2063	−0.0457	1	−0.1365	−0.3365
2005	2	−0.1358	−0.2005	2	−0.2120	−0.0589	1	−0.1575	−0.3376
2006	2	−0.1600	−0.1596	2	−0.2172	−0.0556	-	−0.1510	−0.3120
2007	2	−0.0990	−0.1861	2	−0.2166	−0.0432	-	−0.2103	−0.3735
2008	2	−0.0666	−0.1458	2	−0.2421	−0.0470	-	−0.2074	−0.3668
2009	2	−0.0263	−0.0485	2	−0.2348	−0.0179	-	−0.1794	−0.3326

Table A1. *Cont.*

Variable:		*RE*			*GDP*			CO_2	
Year	Trend	Moran *I*		Trend	Moran *I*		Trend	Moran *I*	
		W Matrix	D Matrix		W Matrix	D Matrix		W Matrix	D Matrix
2010	2	−0.0283	−0.0213	2	−0.2097	−0.0461	1	−0.1674	−0.3544
2011	2	−0.0127	−0.0130	2	−0.1661	−0.0447	-	−0.1709	−0.3823
2012	2	−0.0102	−0.0394	2	−0.1371	−0.0537	-	−0.1744	−0.3754
2013	2	−0.0512	−0.0832	2	−0.1205	−0.0424	1	−0.1723	−0.3904
2014	2	−0.0068	−0.1257	2	−0.1286	−0.0112	1	−0.1802	−0.4046
2015	2	−0.0741	−0.0768	2	−0.1429	0.0128	-	−0.1783	−0.3775
2016	2	−0.0864	−0.0714	2	−0.1471	0.0165	1	−0.1978	−0.4039
2017	2	−0.0322	−0.0214	2	−0.1719	0.0061	-	−0.1865	−0.4071
2018	2	−0.0935	−0.0570	2	−0.1861	0.0092	-	−0.1705	−0.3549
2019	2	−0.0680	−0.0704	2	−0.1896	−0.0068	-	−0.1188	−0.2768

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