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Taxonomic Analysis of the Diversity in the Level of Wind Energy Development in European Union Countries

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Abstract: In this paper, the development of the wind energy sector in 28 European Union countries in 2017 is described. By means of taxonomic methods—i.e., Ward’s method and the Wrocław taxonomic methods—clusters of countries similar in terms of their potential and level of development of the wind energy sector in the EU are distinguished. The main purpose of the paper is to separate and cluster EU countries due to the current development potential of the wind energy sector and determinants stimulating the development of this sector. By means of the ranking methods of linear ordering (Technique for Order of Preference by Similarity to Ideal Solution—TOPSIS method), a ranking of EU countries that defines their position in the development of this very important wind energy sector was determined. The results show that the research hypothesis of a great diversity of EU countries considering the development potential of the wind energy sector is justified. The countries of the former European Union, which have focused for a long time on the development of wind energy in their energy policy and have had favorable climate and natural conditions, as well as a large social acceptance of programs supporting the acquisition of energy from renewable sources, have primacy in the development ranking of the energy sector. Additionally, new members of the union, in spite of some delays associated with the development of “green” energy, are trying to increase their energy potential in this area. The research may be extended to include further analyses regarding other renewable energy sources and take into account other European and world countries.

Keywords: renewable energy; wind energy development; cluster analysis; TOPSIS method

1. Introduction

Large population growth and scientific and technical revolutions contribute to an increase in energy demand. The primary production of energy in the world reached 13.79 billion toe (tonnes of oil equivalent) in 2015. Between 2005 and 2015, the world primary production of energy increased by 19.4% [1]. This created new challenges for humanity related to the future of the energy sector.

Nowadays, the main task is an introduction of countermeasures including both saving energy and replacing its traditional carriers with others that do not cause significant environmental degradation. Therefore, intensive works on the use of renewable energy sources (RES) were conducted. For instance, the primary production of energy in the EU-28 decreased from 862.9 Mtoe in 2007 to 758.2 Mtoe in 2017 (a 12.1% decrease in production). During this time, the primary production from renewable sources increased by 65.6%, from 136.8 Mtoe in 2007 to 226.5 Mtoe in 2017. As a result of these changes, renewable energy sources (29.9%) [2] had the largest share in 2017 in the primary energy production in the EU-28.

Renewable energy sources are ones that replenish (or renew) themselves naturally [1]. Wind energy is one of the basic renewable energy sources. In 2018, wind energy accounted for 19.0% of the global balance of energy generated from renewable sources [3]. In 2017, the EU-28 share was 13.8% [4]. Wind energy is of solar origin, but its direction is also influenced by the globe's rotational motion (Coriolis force) and sea currents. Therefore, the resultant air mass movement is caused by the combined action of various factors, as a result of which the wind is characterized by different directions and intensities [5]. Wind conditions vary across Europe. The most favorable conditions prevail on the Atlantic coasts, the North Sea, and the Baltic Sea [6].

The last 20 years have seen a very rapid increase in the share of renewable energy in energy production (and thus consumption) in the European Union. This is particularly noticeable in the production of wind energy. Even in 2000, the share of wind energy in the total volume of energy produced coming from various also conventional sources in EU countries was 0.1%; in 2010, it was 0.7%; and in 2018, it increased to 1.9% [7].

In 2017, wind energy for the first time reached the largest share among RES in generating electricity in the EU-28. The amount of electricity produced in 2017 from wind turbines was 362.4 TWh, and this was 3.5 times larger than in 2007. As a result, in 2017 the share of wind energy in the total amount of electricity generated in the EU-28 from renewable energy sources increased to 37.2% [4].

Offshore wind energy will have an increasing share in the energy market. Offshore wind farms are located at the sea, and although they require more investment they are more efficient, and provide up to 40% more energy than similar onshore farms [5,8]

The above-mentioned data that describe the growing importance of wind energy constituted the main motivation to undertake the research presented in this paper. The EU, made up of 28 independent states, is naturally internally diverse. This diversity is clearly visible in various comparative statistical studies and also applies to the energy sector, in particular the wind energy sector.

The aim of the paper is to isolate clusters of EU countries similar to each other in terms of the current level of development of the wind energy sector. The research hypothesized that, in spite of large variations in wind energy development in the EU-28 countries, there are clusters of similar countries in the area studied.

The level of wind energy development can be described by many variables. Some of them are strongly correlated with each other. Only variables that were not correlated (do not contain the same statistical information) and describe the sector in its various aspects were selected for the study. Statistical methods of cluster analysis were used in the research: the Ward method [9,10] and the Wroclaw taxonomy method [11,12]. These methods are commonly used by many researchers to group objects described by many quantitative traits. In addition, using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) ranking methods [13], a ranking of EU countries was also developed due to the development of wind energy.

It is easy to see which country dominates in terms of one feature selected. However, when the analyses relate to objects described by many features, then the matter is not so obvious. Taxonomic methods were created to study multi-feature objects. Taxonomic methods allow grouping objects similar to each other in terms of features selected for research. They guarantee homogeneity within the formed clusters and differentiation between them. They allow one not only to isolate clusters but also to analyze and assess which features dominate in the resulting clusters. The Wroclaw method makes it possible to identify countries departing from the others. It can also be divided into groups. Taxonomic methods also allow analyzing the structure of the community, not just indicating extreme cases. The use of the ranking enables us to order countries in terms of the features adopted from the worst to the best and confirms the correctness of the grouping carried out.

The research on the grouping of territorial units due to the similarity in renewable energy is relatively rarely conducted [14–17]. When analyzing online databases of scientific publications, we did not come across publications about our research.

Statistical data from sources such as IRENA (International Renewable Energy Agency) [18], Windeurope.org [19], TheWindPower.net website [20], and Eurostat databases [21] were used. The analyses used computer packages and programs such as Excel spreadsheet, Statistica and R.

The following points of the paper include an analysis of the current literature related to wind energy, the research methods and data sources used, the research results, and the most important conclusions.

2. Literature Review

Information relating to renewable energy comes from many sources; its importance in the period of global climate change, the reduction in conventional energy sources, and the possibility of its use to increase the energy potential of countries were widely discussed for several decades and are often discussed in the world literature. Many countries have announced their own long-term strategies and defined tasks and policies for successively increasing the share of renewable energy (including wind energy) in their overall energy production. At the same time, the methods of obtaining energy from classic sources have gradually been diminished and modernized, which reduces the impact of conventional energy on the environment. Many publications discuss the problems of the strategic planning and development of renewable energy (including wind) in EU countries and worldwide. The papers [22] deal with the issues related to the effective implementation of EU energy goals regarding the introduction and wider use of renewable energy sources as one of the means of increasing energy security, reducing greenhouse gases, and improving the competitiveness of EU economies in the world. The most important mechanisms supporting the functioning of the energy market in individual EU countries were analyzed, and it was stated that the development of the renewable energy sector would not take place as long as there were various unified mechanisms supporting it. The issues regarding the current state, an analysis of development perspectives, the characteristics of road maps, and sustainable development strategies for the energy sector from renewable sources in individual branches of the economy in EU countries and other selected countries of the world were discussed, for example, in the papers [23–27].

The selection of appropriate power supply and storage capacity plays an important role in the operation and profitability of the entire energy system. The aim of paper [28] was to present the possibility of the estimation of appropriate power supply based on the renewable energy sources in the context of the whole energy system in the annual balance, taking into account the technical and economic optimization strategies.

A discussion of the impact of various economic, social, and environmental conditions on the current energy transformation in the world can be found in the study [29]. Research is also conducted on the institutional determinants of renewable energy use in various countries and over time. For example, the work [30] presents the impact of factors such as labor market regimes, national stock markets, and merger and acquisition (M&A) activity among other “doing business” conditions on the use of renewable energy in EU countries. It also confirmed the positive impact of the EU’s 2009 Directive in promoting an increase in the share of energy from renewable sources. Eventie and Hills [31] conducted a very detailed analysis of 69 publications of authors from various EU regions published until 2011 and raising issues related to renewable energy development in EU countries and the implementation of the European policy for the sustainable energy development of countries. Many (145) different categories of problems were identified in these works. They concerned a number of aspects, such as technical and economic issues, effective management problems, and environmental aspects, as well as social aspects affecting the current state and development of the renewable energy sector. The separation and division of the works into homogeneous clusters was performed due to the problems of the aspects considered in them using statistical methods which apply the Principal Component Analysis (PCA). The clusters of publications received by the authors can be characterized as follows: Cluster 1 included works where problems relating mainly to the local specificity of countries, management problems, and social issues and their impact on the development of the renewable energy sector were considered. Cluster 2 dealt with the works that discussed cross-sectional issues and reflected the complexity of

many subjects related to the introduction of projects, supporting the implementation of renewable energy sources and the multitude of factors analyzed, such as local opposition to the installation of the projects, the complexity of processes affecting the implementation of these projects, and the sustainable relationship of economic and environmental goals. Cluster 3 included the publications related the issues on technological challenges and various types of technological problems in the scope of satisfying the demand for electricity, as well as the issues of innovation. The works from the 4th cluster were dominated by environmental problems such as environmental protection in the process of obtaining energy, environmental uncertainty (threat to the environment), as well as researching the positive relationship between entrepreneurship and sustainable energy policy. The last cluster of the works was related to issues on the economic possibilities of the development of the renewable energy sector, aspects of competitiveness, the impact of the development of subsidies and local renewable energy sources, etc.

Similarly, the work [32] analyzes in detail the issues of scientific papers on the renewable energy sector from 1979 to 2009 published by various institutions and research centers in the world. It was observed that, in 2009, the publications on renewable energy from biomass accounted for 56%, solar energy accounted for 26%, wind energy accounted for 11%, and the remaining 7% were on hydropower and geothermal energy. In recent years, a significant increase in the number of such publications has been observed (e.g., regarding wind energy in 2009, as many as 2000 publications were registered).

Many publications concern the analysis and development of the renewable energy sector, in particular wind energy in a region of the world or for individual countries. Noteworthy are the works on the analysis of the development of the renewable wind energy sector in individual countries—e.g., Turkey [33–37], Romania [38,39], Malta [40], the Czech Republic [41], Spain [42,43], Poland [44], Lithuania [45], Italy [46]—as well as for the whole region: e.g., the Balkans [47], EU countries [48], and globally [49].

Some publications discuss specific aspects connected with the development of wind energy in Europe and in the world in detail. The publication [50] presents the characteristics of the technologies used in acquiring wind energy, such as the process of designing wind turbines, the characteristics of major wind energy suppliers, the specificity of onshore and offshore turbines. The predicted wind energy development scenarios and current statistical data on the current state and perspectives of wind energy development in the world were characterized. A detailed review on the characteristics of selected wind energy storage systems and their practical applications was carried out (wind farms, wind parks, smart grids). The main economic strategies supporting the development and promotion of the wind energy sector were discussed, and the most important challenges facing this sector were pointed out.

The development of wind energy brings not only positive effects. Some aspects of the negative impact of wind energy development and improper location of wind farms on tourism development in Czech tourist regions are discussed in the paper [51]. The publication [52] also presents the negative effects of wind energy development, which is widely considered as clean and environmentally friendly. However, some problems resulting mainly from installation technology and the operation of wind turbines may have a negative impact on the environment. The publications present the current state of wind energy development in the leading countries in the world, divided into offshore and onshore wind energy, and characterize their potential and the challenges they face. The negative impact of wind energy turbines on the environment resulting from noise, light effects, the impact on animals and birds, and climate change was also discussed and characterized.

The work [53] characterizes the evolution of wind energy in a recent period of time (1996–2009). The publication presents the very visible high-growth dynamics of the total energy capacity and the amount of energy generated from wind turbines installed both in Europe and in the world. The percentage structure of global wind energy production per world regions was discussed. In Europe, a significant increase in the share of wind energy production can be observed over the years (in 1990

it was only 19%, while in 2007 it increased to 61%). Some aspects of financing the construction of typical wind farms and prospects for wind energy development in selected EU countries by 2020 are also discussed.

An analysis of the efficiency and profitability of small wind turbines in wind farms in five European Union countries (France, Germany, Italy, Spain, and the Netherlands) is discussed in the paper [54]. It analyzes the profitability model of small wind turbines (SWT) based on an analysis of the Net Present Value (NPV) cash flows, which was used to assess the effectiveness of their operation. The analysis uses several basic parameters that most affect the performance of wind turbines and various costs of their installation and operation. A similar issue for offshore wind farms operating in the northern Europe is discussed in [55].

The problem of analyzing employment in the wind energy sector in EU countries is discussed in the paper [56]. Based on surveys, the employment structure in the wind energy sector was analyzed in enterprises related to the production and distribution of this type of energy and operating in the wind energy market. The results show that in the wind energy sector there was a significant increase in employment in recent years, with a simultaneous decrease in other energy sectors. However, a shortage of specialized management staff—e.g., managing directors, project managers, specialized engineers—was observed.

The study of the impact of potential climate change on the volume of wind energy production is an important problem in the analysis of renewable wind energy acquisition. The publication [57] presents simulation models (ENSEMBLES climate modelling) for predicting production capacity depending on evolutionary climate changes. Additionally, correlations and production dependencies in the volume of onshore wind energy produced in individual EU countries were examined. The research results can be used to better integrate the European energy transmission system through the better integration of cross-border energy transmission lines.

Another very important issue is the proper, environment-friendly, and population-friendly location of wind turbines. The publication [58] developed a model for the optimal location of wind turbines using multi-criteria decision analysis and GIS (Geographical Information System), which was used to plan the location of wind turbines in Poland (Low-Silesian Province—Wroclaw). The computer software developed on the basis of the model supports decision-making and allows better decision-making flexibility (e.g., setting priorities—weights for criteria) and improving efficiency in the decision-making process regarding wind turbine locations, compared to the use of multiple single-criteria assessments for potential location scenarios.

A similar issue concerning the use of methods of Multi-criteria Decision Analysis (MCDA) in problems of supporting various decisions in the energy sector (renewable energy, including wind energy) is devoted to the work [59]. The use of this type of methodology in various practical applications stressed in the publication is aimed at the greater promotion and improvement of the effectiveness of the process of implementing the sustainable energy development policy of EU countries. The publication [60] presents a review and multifaceted characteristics of their subject matter and the scope of research for 105 published scientific articles in 2004–2017 regarding the use of MCDA methods in the planning and implementation of the sustainable development of renewable energy.

In the research on the renewable energy market in the context of sustainable energy development, various research approaches are used, including advanced statistical methods, such as multidimensional statistical analysis methods, cluster analysis methods, and ranking methods. The publication [14] uses cluster analysis methods (Ward's method) to isolate clusters of similar countries in terms of the energy potential of renewable sources in the new EU member states in 2016 compared to 2004. Similar taxonomic methods were used in [61], where an analysis of the efficiency of crop residue utilization in the process of renewable energy production was carried out on the example of agricultural regions of Ukraine. In the process of isolating clusters similar in terms of the largest energy consumption and energy potential of renewable energy production from cereal residues, cluster analysis methods—the so-called single binding—were used.

3. Materials and Methods

3.1. Data Sources

The main sources of research data acquisition were:

- International Renewable Energy Agency (IRENA) [18];
- The windeurope.org website [19];
- TheWindPower.net—number of wind farms and number of turbines in the farm [20];
- Eurostat—demographics [21].

On the basis of the original data, indicators constituting a set of potential explanatory variables were determined. Some of these indicators were obtained by referencing the original data to the number of residents.

3.2. Taxonomic Methods

Multidimensional comparative analysis and cluster analysis (Ward's method and the Wrocław taxonomic methods) were used to study the differences in the level of wind energy development in the European Union. This term was introduced by R. Tryon [9] and then developed by R. Cattelle [10]. The methods enable a clear and precise division of the surveyed units (in this case, EU countries) characterized by many features into clusters (clusters) of objects similar to each other in terms of the features adopted for the study. The cluster analysis is used in many scientific areas. Thanks to the methods applied, it is possible to check to what extent EU countries differ in terms of wind energy production and its use. Before starting the basic taxonomic analysis, the input data were normalized (standardized—according to the Formula (8)).

3.2.1. Ward's Method

One of the agglomerative clustering methods—Ward's method—was used in the analysis. This method uses the variance analysis approach in its procedures [62]. It aims to minimize the sum of squares of deviations of any two clusters that can be formed at any stage of the study. This is one of the most effective clustering methods. The order of conduct in Ward's method is similar to that in other agglomeration methods. Significant differences occur in the parameters used in the formula. The procedure is as follows: it begins with determining the taxonomic matrix of dimensions $n \times n$, which contains the distance of each pair of objects. The matrix is symmetrical about the main diagonal, which only zeros constitute. Next, pairs of objects (and further clusters) are searched for, where the mutual distance is the smallest. The objects are designated as " p " and " q ", with $p < q$. Subsequently, the " p " and " q " merge into one new cluster that occupies the position with the number " p ". At the same time, the object (cluster) with the number " q " is deleted, and the cluster numbers with the number higher than it are reduced by one. In this way, the matrix dimension is reduced by 1. Next, the distance of the new cluster from each remaining cluster is determined by the formula:

$$D_{pr} = a_1 \cdot d_{pr} + a_2 \cdot d_{qr} + b \cdot d_{pq}, \quad (1)$$

where: D_{pr} —distance of the new cluster from the cluster number " r "; d_{pr} —distance of the original cluster " p " from the cluster " r "; d_{qr} —distance of the original cluster " q " from the cluster " r "; d_{pq} —mutual distance of the original clusters " p " and " q "; a_1, a_2, b —parameters which in Ward's method are calculated on the basis of the following formulas:

$$a_1 = \frac{n_p + n_r}{n_p + n_q + n_r}, \quad a_2 = \frac{n_q + n_r}{n_p + n_q + n_r}, \quad b = \frac{-n_r}{n_p + n_q + n_r}. \quad (2)$$

n_p, n_q, n_r —denote the number of individual objects in individual clusters.

Cluster average methods were used to describe the clusters. For the clusters obtained, an analysis of cluster means was carried out, which aims to indicate the indicators (diagnostic features) dominating in a given cluster. The arithmetic means of the indicators studied were calculated for the numerical data matrix, marked as $\overline{W}_i$. Then, the arithmetic means of the indicators in the obtained were calculated, and were marked as $\overline{w}_i$. The indicator of the structure of each cluster is the quotient $\overline{w}_i/\overline{W}_i$. The maximum value of the structure indicator shows the dominance of a given feature in the received cluster. The average level of the phenomenon is valued as 1. The values above 1 are indicators that have values higher than the average, and those below 1 are indicators for which the level in individual clusters is less than the average.

3.2.2. The Wrocław Taxonomic Methods

The dendrite methods belong to the cluster of hierarchical taxonomic procedures, based on concepts from graph theory [63], which are constructed on the basis of the distance matrix between classified units. At the stage of graph construction, the dendrite methods are agglomeration procedures, while when analyzing them they have the character of division procedures. The criterion that distinguishes the dendritic methods from other clustering procedures, including hierarchical ones, is the possibility of presenting the classification results in the form of a dendrite defined as a coherent graph (the graph is consistent if each two different of its vertices are connected by an unbroken string (chain)), and open (open graph) is a graph without loops and cycles, with the cycle being a finite series of connected edges in which the initial vertex of the first edge is also the end vertex of the last edge.

The Wrocław taxonomy was used to identify countries that significantly differ in terms of the features adopted for an analysis from the rest of the objects studied. The aim of the analysis was to obtain the shortest coherent graph called the “optimal coherent dendrite” [64]. The ordering procedure is as follows [12]. Each of the rows of the distance matrix has an element with the minimum value. This element indicates a pair of objects, a model and a shadow. These objects are combined, and the connections obtained in this way usually form an inconsistent graph, which is called the first-degree dendrite. Then, in the first-degree dendrites, a pair of objects (belonging to different sub-graphs) with a minimum distance is sought. When combining them, one receives a second-degree dendrite. Under given conditions, a coherent graph connecting all objects is created. This creates an optimal graph of minimum distances. To obtain homogeneous clusters, a specific division criterion should be adopted [62]. A set of units is divided in a “natural” way into k parts, if $w_k < w_{k-1}$, where:

$$w_i = \frac{\widetilde{d}_{i-1}}{\widetilde{d}_i} \quad (i = 2, \dots, n), \quad (3)$$

where $\widetilde{d}_i$ is a descending order of the length of the dendrite edge. Of the several possible natural divisions, the best is the one that provides the largest decrease in dendrite ligament length. The “strong” Perkal [11] dendrite division is based on cumulants ordered in the descending length of the links:

$$s_{i+1} = s_i - \widetilde{d}_i, \quad (i = 1, \dots, n-1), \quad (4)$$

where s_i is the sum of the lengths of all dendrite links.

The set of units is divided in a “strong” way into k parts if $w_{k-1} > w_k > w_{k+1}$, where:

$$w_i = \frac{s_{i-1}}{s_i}, \quad (i = 2, \dots, n). \quad (5)$$

There is another method of dividing dendrites, which is based on a certain threshold value d^* (see Hellwig [65]), where, in dendrite, all links longer than the critical value d^* should be rejected:

$$d^* = \overline{d} + 2s_d, \quad (6)$$

where $\bar{d}$ and s_d is the arithmetic mean and standard deviation of the dendrite edge length.

3.3. Ranking Methods—TOPSIS Method

In the ranking analyses, statistical decision-making methods of linear ordering of multi-feature objects were used. A modified TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was used in the study (see Hwang and Yoon [13]) with the distance metric Generalized Distance Measure (GDM) from Jajuga et al. [66]. It is assumed that the input matrix of decision (diagnostic) variables is given as X_{ij} , $i = 1, \dots, m$; $j = 1, \dots, n$, where n is the number of diagnostic variables, m is the number of ranked (ordered) statistical objects (EU countries), and the determined weight vector for diagnostic variables is $w_j \in [0, 1]$, $\sum_{j=1}^n w_j = 1$. In the decision-making process of ranking EU countries in terms of wind energy development, the following procedure was applied:

1. It is assumed that all diagnostic variables X_j will be treated as stimulants or de-stimulants. The values of features that are nominative are transformed into the corresponding stimulant values by means of transformation:

$$X_{ij} = \frac{\min\{nom_j; X_{ij}^N\}}{\max\{nom_j; X_{ij}^N\}}, \quad (7)$$

where X_{ij}^N —value of the j -th denominator observed for the j -th object; nom_j —the nominal value of the j -th variable.

2. Determination of the normalized data matrix using the standardization procedure according to the formula:

$$Z_{ij} = \frac{X_{ij} - \bar{X}_j}{S_j}, \quad (8)$$

where $\bar{X}_j$ is the mean value of j -th primary variable, while S_j is the deviation of the standard j -th variable.

3. Determining the coordinate values for the standard vector a^+ (ideal solution) for the optimal values of diagnostic variables and coordinates of the anti-template vector a^- (anti-ideal solution) for the worst values of diagnostic variables according to the formulas:

$$a^+ = (a_1^+, a_2^+, \dots, a_n^+) \left\{ \left(\max_{i=1, \dots, m} Z_{ij} \mid j \in J_S \right), \left(\min_{i=1, \dots, m} Z_{ij} \mid j \in J_D \right) \right\}, \quad (9)$$

$$a^- = (a_1^-, a_2^-, \dots, a_n^-) \left\{ \left(\min_{i=1, \dots, m} Z_{ij} \mid j \in J_S \right), \left(\max_{i=1, \dots, m} Z_{ij} \mid j \in J_D \right) \right\}, \quad (10)$$

where J_S is a set of stimulants, and J_D is a set of de-stimulants.

4. Calculation of the distance of the i -th examined object from the GDM_i^+ and anti-pattern GDM_i^- . The Generalized Distance Measure (GDM) was used in the calculations:

$$GDM_i^+ = \frac{1}{2} - \frac{\sum_{j=1}^n w_j (Z_{ij} - a_j^+) (a_j^+ - Z_{ij}) + \sum_{j=1}^n \sum_{l=1, l \neq i, l \neq i_+}^m w_j (Z_{ij} - Z_{lj}) (a_j^+ - Z_{lj})}{2 \left[\sum_{j=1}^n \sum_{l=1}^m w_j (Z_{ij} - Z_{lj})^2 \cdot \sum_{j=1}^n \sum_{l=1}^m w_j (a_j^+ - Z_{lj})^2 \right]^{\frac{1}{2}}}, \quad (11)$$

$$GDM_i^- = \frac{1}{2} - \frac{\sum_{j=1}^n w_j (Z_{ij} - a_j^-) (a_j^- - Z_{ij}) + \sum_{j=1}^n \sum_{l=1, l \neq i, l \neq i_-}^m w_j (Z_{ij} - Z_{lj}) (a_j^- - Z_{lj})}{2 \left[\sum_{j=1}^n \sum_{l=1}^m w_j (Z_{ij} - Z_{lj})^2 \cdot \sum_{j=1}^n \sum_{l=1}^m w_j (a_j^- - Z_{lj})^2 \right]^{\frac{1}{2}}}, \quad (12)$$

where i_+ is the index (number) of the pattern object, and i_- is the index (number) of the anti-pattern object.

5. Determination of the aggregate measure (ranking factor) determining the degree of similarity of the examined objects to the ideal solution in accordance with the formula:

$$TOPSIS (GDM)R_i = \frac{GDM_i^-}{GDM_i^- + GDM_i^+}. \quad (13)$$

For $i = 1, \dots, m$, where $0 \leq R_i \leq 1$.

6. Determination of the final ranking for the examined objects (EU countries) depending on the value of the measure R_i . The higher the values of the calculated synthetic index, the higher the ranking country in the ranking.

4. Research Results

4.1. Diagnostic Variables Used—Determinants of the Wind Energy Sector Development

Many variables could be accepted for the research. The initial set of potential variables included 21 indicators. The analysis of variability and correlation enabled the selection of seven indicators that are characterized by the required properties (high variability and weak correlation correlation). The final set of indicators included:

- X1—Wind farms per 100 thous. people;
- X2—Number of turbines per one wind farm;
- X3—Renewable (wind offshore) electricity capacity (MW) per 100 thous. people;
- X4—Renewable (wind onshore) electricity capacity (MW) per 100 thous. people;
- X5—Wind cumulative capacity growth rate—% 2017/2013;
- X6—Renewable (wind) electricity generation (GWh) per 100 thous. people;
- X7—Share of renewables in gross inland energy consumption of which: wind power (2017) [%].

The indicators adopted for the study were characterized by descriptive statistics, which are included in Table 1.

Table 1. Basic descriptive statistics of the selected variables.

	Mean	Median	Min	Max	C ₂₅	C ₇₅	SD	V _z [%]	K
X ₁	3.1	1.6	0.00	30.7	0.6	2.9	5.8	188.2	20.4
X ₂	8.2	6.2	0.00	20.1	4.1	11.6	5.5	67.7	−0.3
X ₃	2.03	0.0	0.00	22.5	0.0	0.9	4.8	240.4	11.5
X ₄	24.9	18.7	0.00	73.5	11.8	34.3	21.6	86.9	0.1
X ₅	0.51	0.35	−0.20	3.57	0.01	0.67	0.70	137.4	13.7
X ₆	61.9	43.8	0.11	257.1	22.9	81.5	60.4	97.7	2.9
X ₇	1.6	1.2	0.001	6.9	0.6	2.1	1.6	99.3	3.5

The first feature in the analysis was the number of wind farms per 100,000 residents (Figure 1). The average quantity for EU countries is just over three farms. Denmark stands out against the background of other countries, where per 100,000 inhabitants there are nearly 31 wind farms. The diversity of the countries in terms of the number of wind farms is very large, as evidenced by the coefficient of variation, which is at the level of 188%. The asymmetry is right-sided, which means that the vast majority of countries have less than three wind farms per 100,000 residents.

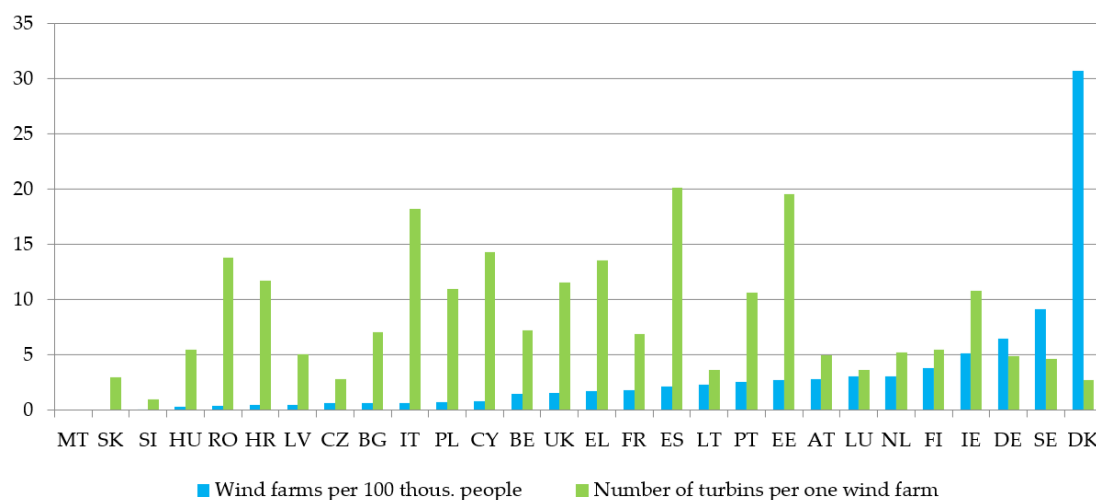


Figure 1. Wind farms per 100 thous. people and the number of turbines per wind farm.

The second variable that characterizes wind farms is the number of turbines per farm (Figure 1). The average for EU countries is slightly above eight, and the highest values occur in Spain, Estonia, and Italy—around 20. The negative kurtosis value and high coefficient of variation show a significant diversity of countries in terms of the average number of turbines in farms.

The electrical power from wind farms located at sea and on the coast (Figure 2), calculated per 100,000 residents, is also the largest in Denmark (22.5 MW per 100,000 inhabitants). In addition to Denmark, such installations have in the EU only: Belgium, Germany, Ireland, the Netherlands, Finland, Sweden, and the United Kingdom. In other countries, only onshore farms operate. Therefore, the coefficient of variation for this feature is very high—240%.

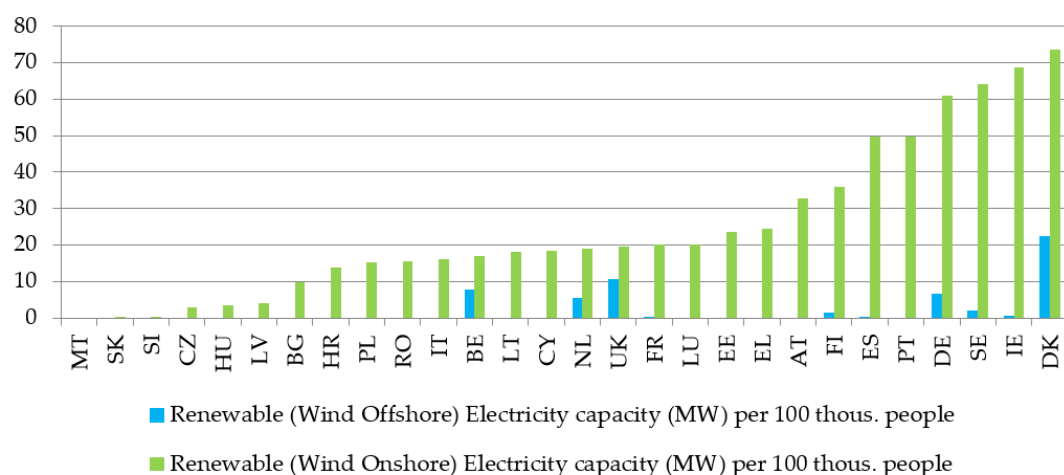


Figure 2. Renewable (wind offshore) electricity capacity (MW) per 100 thous. people and renewable (wind onshore) electricity capacity (MW) per 100 thous. people.

Additionally, the electric power from onshore wind farms (Figure 2) is the highest in Denmark (73.5 MW per thousand hybrids), while it is the lowest in Slovakia and Slovenia (0.07 MW and 0.24 MW per thousand inhabitants), excluding Malta, which does not have such farms at all. The average value per country is about 25 MW per thous. residents.

The fifth of the analyzed features determines the dynamics of changes in the installed capacity of wind farms from 2013 to 2017 (Figure 3). The largest increase in installed capacity, at 357%, occurred in Finland. In one country, Slovakia, a 20% decrease was recorded, and the average value of the indicator for EU countries was 51%. The average value of electricity generated by wind farms per 100,000

residents for EU countries is 62 GWh. The most was produced in Denmark at just over 257 GWh, and the least (excluding Malta) was in Slovakia (0.11 GWh).

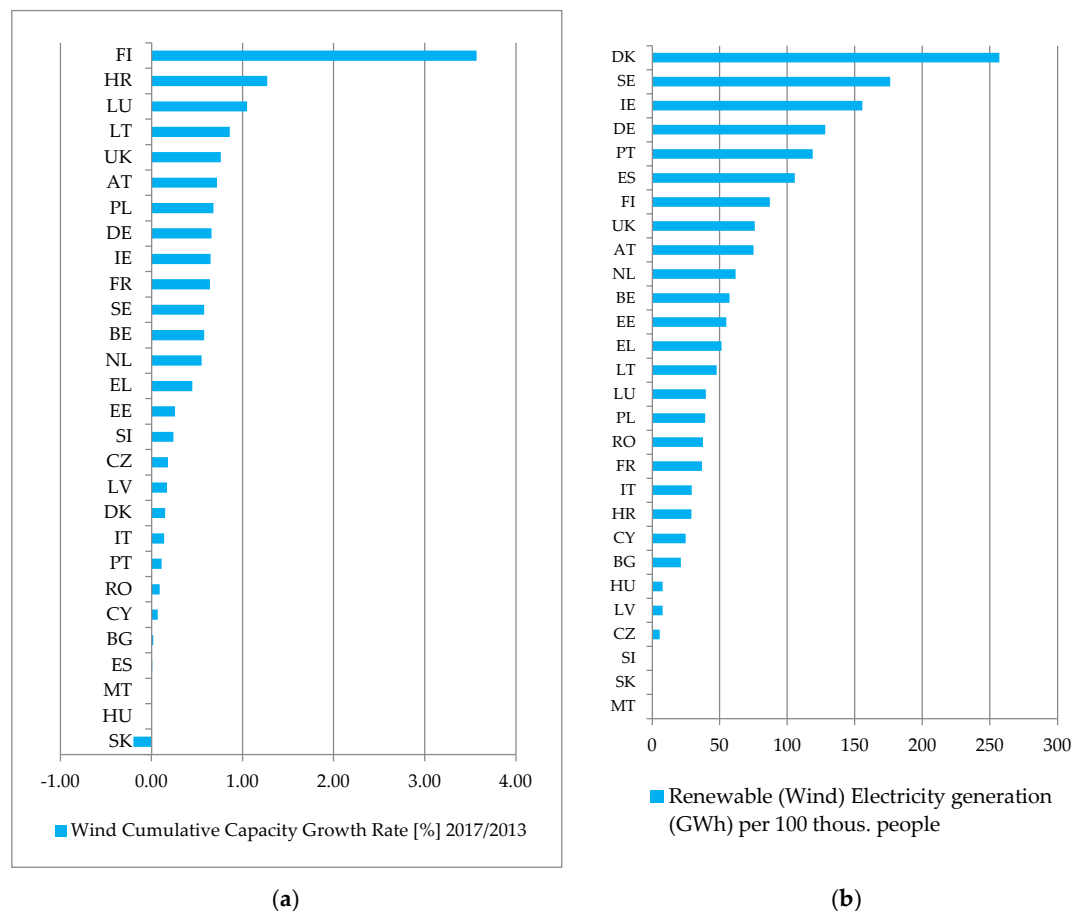


Figure 3. (a) Wind cumulative capacity growth rate—2017/2013 [%]; (b) renewable wind electricity generation (GWh) per 100 thous. people.

The last variable adopted for research is the share of wind energy in the total energy consumption (Figure 4). The average share for the countries surveyed is 1.6%. Denmark has the highest share at 6.9%, and the lowest is in Malta, Slovakia, and Slovenia.

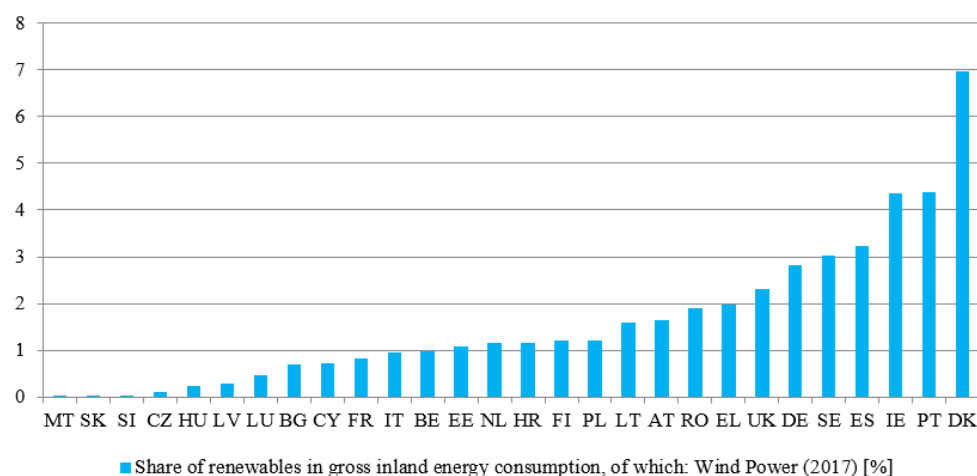


Figure 4. Share of renewables (wind energy) in the gross inland energy consumption (2017) [%].

For all the features analyzed, their distribution is characterized by right-sided asymmetry, which means that most EU countries achieve the value of the studied indicators below the global average. On the other hand, high values of the volatility indexes show a large diversity of countries in terms of the examined features.

4.2. Grouping Results Using the Wroclaw and Ward's Taxonomy Methods

The variables selected for research that characterize the level of development and potential of wind energy in the EU countries were subjected to the grouping procedure using the Wroclaw method. Grouping has identified countries that in a distinctive way distinguish themselves from others.

At the beginning, based on the Euclidean distance matrix, a table was prepared with the minimum distances between the countries examined, and then they were ordered from the largest to the smallest (Table 2). For distance, the mean value and the standard deviation were calculated, which were 1.14 and 1.08, respectively. Based on the statistics calculated, a critical value $d^* = 3.31$ was given. It allows cutting off the longest connections between countries and thus identifying the ones most different from the others in terms of energy potential and the level of wind energy development.

Table 2. Elements of the Wroclaw dendrite—minimum Euclidean lengths between the countries studied.

No.	Countries	Link Length (d_1)	No.	Countries	Link Length (d_1)
1	DK-SE	6.32 *	19	RO-CY	0.79
2	FI-HR	3.79 *	20	LU-LT	0.78
3	ES-EL	2.14	21	LT-LU	0.78
4	ES-PT	1.87	22	CY-IT	0.75
5	SE-IE	1.64	23	RO-EL	0.74
6	IE-PT	1.40	24	EL-RO	0.74
7	PT-IE	1.40	25	EE-IT	0.72
8	UK-BE	1.35	26	IT-EE	0.72
9	DE-SE	1.33	27	BG-NL	0.65
10	SE-DE	1.33	28	NL-BG	0.65
11	NL-FR	1.29	29	HU-SK	0.60
12	LV-FR	1.22	30	SK-CZ	0.58
13	PL-EL	0.88	31	BG-HU	0.55
14	AT-LT	0.88	32	CZ-SI	0.39
15	HR-PL	0.87	33	MT-SI	0.39
16	FR-LT	0.85	34	SI-MT	0.39
17	PL-FR	0.84	35	LV-HU	0.26
18	FR-PL	0.84	36	HU-LV	0.26

$\bar{x} = 1.14$; $\sigma = 1.08$; $d^* = 3.31$ —critical value for the link length (* denotes length $d_1 > d^*$).

Based on the distances contained in the table, the first-order graph was constructed, and then the second-order graph so that it is consistent. The connection graph is presented in Figure 5. Using the critical value d^* , two countries were cut off, for which the connection distances were greater than the critical value adopted, $d^* = 3.31$. Table 2 and Figure 5 show that these countries are: Finland (FI) and Denmark (DK).

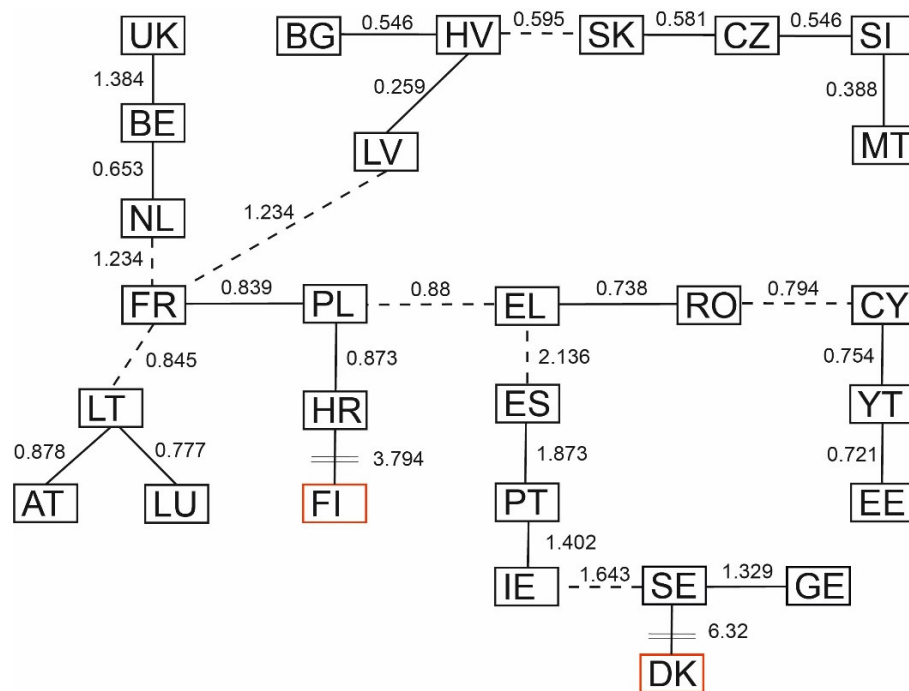


Figure 5. The Wrocław dendrite—division of countries into clusters.

The next step in the research was subjecting the data to a clustering procedure using Ward's method. The results of the clustering are presented in Figure 6. Two clustering lines were proposed. The initial division was on a line of eight units of linkage distance, which divided the countries into four groups: A, B, C, and D.

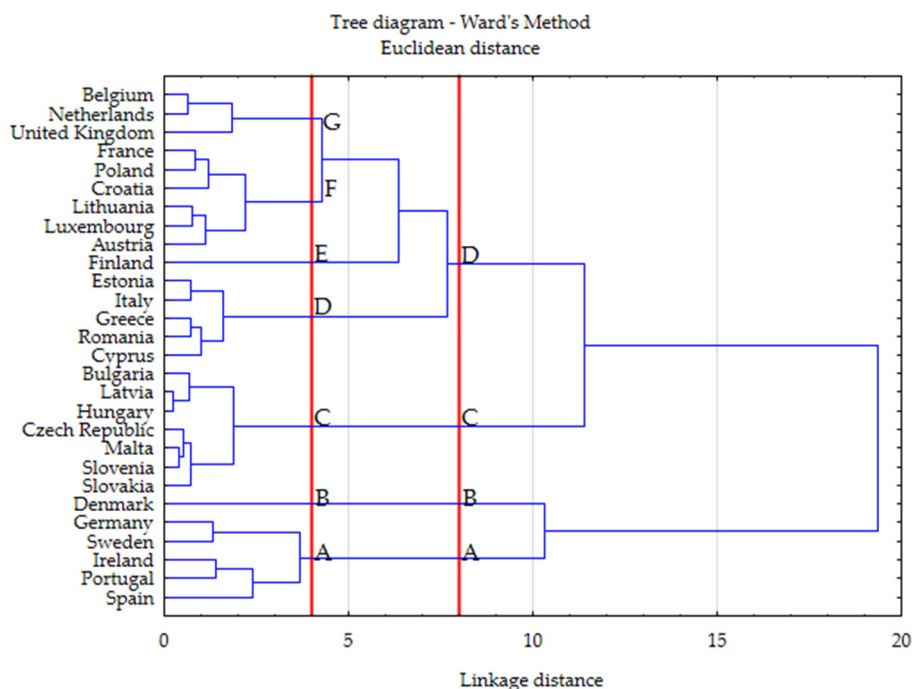


Figure 6. Tree diagram—division of the EU countries into clusters.

This division seemed to be the most optimal, but taking into account previous analyses (the Wrocław taxonomy), Denmark and Finland should form separate clusters. In addition, it was also checked whether all the features show statistically significant differences between the clusters.

The results of the variance analysis test (ANOVA) showed that one of the features was not differentiated between clusters—wind cumulative capacity growth rate (% 2017/2013).

The analysis of the group means in individual clusters showed that the “D” group was somewhat flattened (averaged) and includes countries of different characteristics; therefore, taking into account the previous indications, the final course of the clusters was carried out on a line of four units of linkage distance.

Thus, the previous cluster “D” was divided into four smaller ones, where one can see the difference in the resulting clusters. This is also confirmed by the test of variable variance analysis in the resulting clusters (Table 3).

Table 3. ANOVA test results. Selected features divided into 4 and 7 clusters.

	Division into	
	4	7
	<i>p</i> -Value	
Wind farms per 100 thous. people	0.00000 ***	0.00000 ***
Number of turbines per one wind farm	0.02872 *	0.001120 *
Renewable (Wind Offshore) Electricity capacity ([MW] per 100 thous. people)	0.00000 ***	0.00000 ***
Renewable (Wind Onshore) Electricity capacity ([MW] per 100 thous. people)	0.00000 ***	0.00000 ***
Wind Cumulative Capacity Growth Rate [%] (2017/2013)	0.13327	0.00000 ***
Renewable (Wind) Electricity generation ([GWh] per 100 thous. people)	0.00000 ***	0.00000 ***
Share of renewables in gross inland energy consumption, of which: Wind Power (2017) [%]	0.00000 ***	0.00000 ***

* $p < 0.05$ —statistically significant, *** $p < 0.001$ —statistically highly significant. Source: own elaboration based on the analyzed data.

The final division into clusters is shown in Table 4. The most numerous is cluster C, which brings together as many as seven countries. There are also two one-element clusters, which are Denmark (B) and Finland (E).

Table 4. Division of the EU countries into clusters similar to each other in terms of development level and wind energy potential.

Cluster	Countries
A	Spain, Portugal, Ireland, Sweden, Germany,
B	Denmark,
C	Slovakia, Slovenia, Malta, the Czech Republic, Hungary, Latvia, Bulgaria,
D	Cyprus, Romania, Greece, Italy, Estonia,
E	Finland,
F	Austria, Luxembourg, Lithuania, Croatia, Poland, France
G	The United Kingdom, the Netherlands, Belgium.

Source: own elaboration based on the analyzed data.

4.3. Ranking of EU Countries Using Linear Ordering Methods

Using the TOPSIS linear ordering method with a synthetic measure of the degree of similarity to the pattern (13), a ranking of the studied EU countries in terms of energy potential and the level of wind energy development was determined. All the diagnostic variables adopted for the study were stimulant. The same weight system was adopted for the ranking for all the diagnostic variables whose values were normalized using the standardization procedure (8). The results for the measures

of the distance of all tested objects (EU countries) from the standard and anti-template, the value of the TOPSIS R_i synthetic measure, and their ranking is presented in Table 5.

Table 5. Ranking of EU countries using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method.

Country	GDM (Pattern)	GDM (Anti-Pattern)	TOPSIS Measure R_i	Ranking
Denmark (DK)	0.108	0.629	0.853	1
Ireland (IE)	0.222	0.528	0.704	2
Sweden (SE)	0.239	0.460	0.658	3
Germany (DE)	0.229	0.421	0.648	4
Finland (FI)	0.282	0.475	0.628	5
Spain (ES)	0.330	0.474	0.589	6
Portugal (PT)	0.318	0.419	0.568	7
The United Kingdom (UK)	0.289	0.341	0.541	8
Estonia (EE)	0.443	0.327	0.424	9
Greece (EL)	0.442	0.248	0.359	10
Italy (IT)	0.517	0.257	0.332	11
Croatia (HR)	0.472	0.229	0.327	12
Austria (AT)	0.444	0.184	0.293	13
Belgium (BE)	0.432	0.174	0.287	14
Romania (RO)	0.521	0.197	0.274	15
Poland (PL)	0.510	0.163	0.242	16
The Netherlands (NL)	0.444	0.139	0.239	17
Cyprus (CY)	0.559	0.175	0.239	18
Lithuania (LT)	0.508	0.118	0.189	19
Luxembourg (LU)	0.526	0.120	0.186	20
France (FR)	0.540	0.101	0.158	21
Bulgaria (BG)	0.640	0.043	0.064	22
Latvia (LV)	0.671	0.022	0.032	23
Hungary (HU)	0.683	0.021	0.029	24
The Czech Republic (CZ)	0.686	0.010	0.015	25
Slovenia (SI)	0.701	0.008	0.012	26
Slovakia (SK)	0.721	0.005	0.007	27
Malta (MT)	0.720	0.002	0.002	28

Source: own elaboration based on the data analyzed.

Denmark took the best position in the ranking. The next positions were taken by Ireland and Sweden, and the worst places went to countries such as Malta, Slovakia, Slovenia, the Czech Republic, Hungary, Latvia, and Bulgaria.

The individual rows in Table 5 are marked with different colors that correspond to the clusters shown in Table 4.

5. Discussion

As a result of the research into EU countries in terms of energy potential and the level of wind energy development, seven clusters of countries were distinguished, whose profile regarding wind energy differs significantly.

By far, Denmark has the best conditions in terms of the features analyzed; it is the leader of wind energy in the EU. It creates a one-element cluster marked as “B”, and in the ranking it comes first. It has the most wind farms per 100,000 residents, but the smallest indicator is responsible for the number of turbines per one farm, so there are many small farms. Denmark also has a high ratio responsible for the renewable (wind offshore) electricity capacity (MW) per 100,000 people. The indicator for renewable (wind onshore) electricity capacity (MW) per 100,000 people is also very high. Denmark has the smallest increase for the wind cumulative capacity growth rate (%) calculated from 2013 to 2017. This results from the very good use of wind energy resources for many years. In Denmark, the indicators for renewable (Wind) electricity generation (GWh) per 100,000 people are the highest, as well as the share of renewables (from wind power) in the gross inland energy consumption in (2017) (%) (Figure 7). Denmark has a very good geographical location for wind energy. At a height of 10 m, the average

wind speed is approximately 4.9–5.6 m/s. The best locations for building wind farms are in the west of the country and on the coasts in the east of Denmark. In Denmark’s territorial waters, there are many shallows with a depth of 5–10 m, where at a height of 50 m the winds reach 8.5–9 km/h. These areas are good locations for building offshore wind farms. Denmark is also a leader in wind turbine production [67].

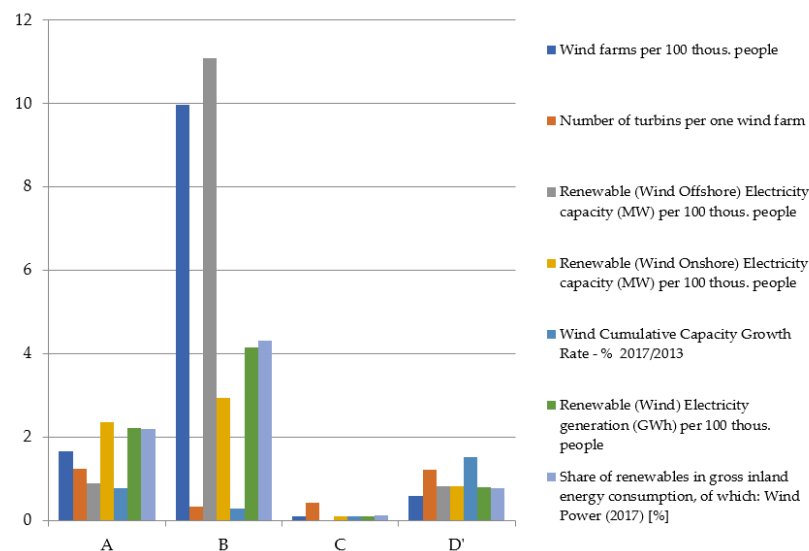


Figure 7. Group means for the 4 clusters formed.

The second largest wind energy development is the “A” cluster, which includes Spain, Portugal, Ireland, Sweden, and Germany. For years, these countries have been leaders in the introduction and development of wind energy. These countries have a significant number of wind farms (above the average for Europe), and the farms are quite large. Well above average are the indicators responsible for renewable (wind) electricity generation (GWh) per 100,000 people and share of renewables (from wind power) in the gross inland energy consumption in (2017) (%) (Figure 7). Floating wind farms appeared on the Portuguese coast, and wind energy in Ireland is developing most dynamically among other RES sources, although most farms wind farms are located in Ireland on land and the development of offshore farms is still planned. Sweden has made great progress in the field of wind energy in recent years. From a capacity of below 4 GW in wind energy in 2012, it has already reached 8 GW. Wind currently meets 14% of Sweden’s electricity demand, and an additional 4.2 GW is already under construction.

Finland is in good condition in terms of energy potential and the level of development of energy generating energy from renewable wind energy sources—it forms a one-element cluster marked “E”. The largest in Finland is the indicator for growth (wind cumulative capacity growth rate—% 2017/2013). Figure 8. This means that Finland is investing and developing this branch of renewable energy. The indicator regarding the number of wind farms is above the global average, so farms are more than average in EU countries, but they are not large. The indicator responsible for renewable (wind onshore) electricity capacity (MW) per 100,000 people is also above the average level, and therefore Finland definitely receives the greater part of energy from onshore wind farms. The renewable (wind) electricity generation (GWh) ratio is also high per 100,000 people. (Figure 8)

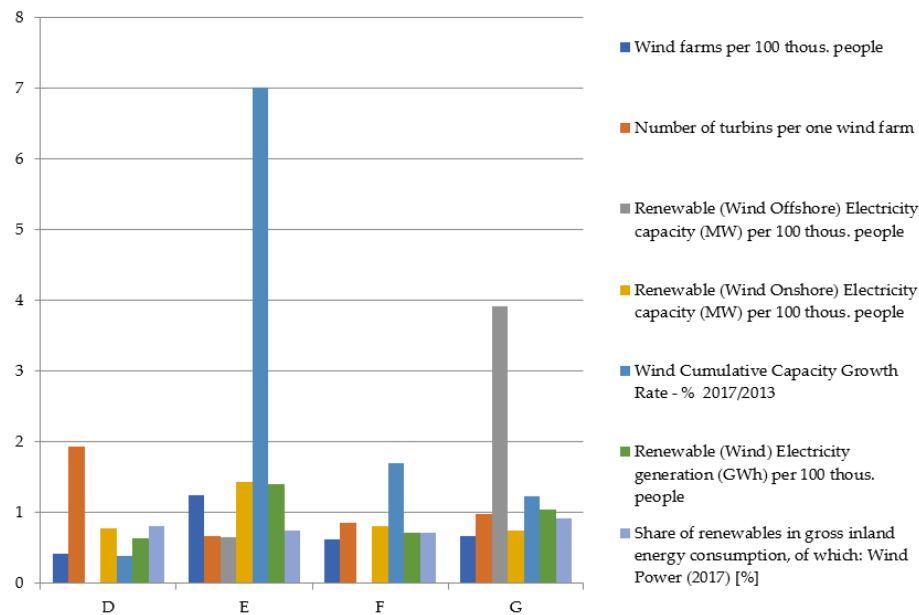


Figure 8. Group means for clusters included in cluster D from Figure 7.

The next cluster consists of three countries: the United Kingdom, the Netherlands, and Belgium. This is the cluster marked “G”. They also have a strong position considering the energy potential and the level of development of energy generating wind energy. The renewable (wind offshore) electricity capacity (MW) ratio per 100,000 people is dominant in this cluster, because these countries have chosen mostly offshore farms. Above the average global level, there are also two indicators regarding renewable (wind) electricity generation (GWh) per 100,000 people and wind cumulative capacity growth rate (% 2017/2013), which means that these countries are still expanding their wind energy resources (see Figure 8).

The next two clusters “D” and “F” are at a medium level of wind energy development. The “D” cluster includes Cyprus, Romania, Greece, Italy, and Estonia. They do not have many wind farms, but they are relatively large. In addition, all the renewable (wind) energy indicators are below the EU average (see Figure 8).

The “F” cluster covers six countries: Austria, Luxembourg, Lithuania, Croatia, Poland, and France. These countries gathered in one cluster due to the high value of the indicator responsible for growth (wind cumulative capacity growth rate—% 2017/2013). There is a chance that by investing in wind energy, these countries will change their position in the ranking for the better. Other indicators responsible for energy potential and the level of wind energy development are below the global average (see Figure 8).

The last and also the worst cluster in terms of energy potential and the level of development of the wind energy sector is the cluster marked as “C”. Seven countries were found in it: Slovakia, Slovenia, Malta, the Czech Republic, Hungary, Latvia, and Bulgaria. This cluster includes Malta, which does not have a single wind farm, and there are almost no wind farms in the other countries included in this cluster (see Figure 7). All the indicators responsible for energy potential are, therefore, at a minimal level compared to other clusters. These countries are investing in other renewable energy sources. Slovakia, Latvia, Hungary, and Bulgaria invest mainly in hydroelectric power plants, while Hungary and Malta also invest in solar energy. In Hungary, the average annual number of sunny hours is around 1800 h, and in Malta it is 3000 h.

It is quite difficult to compare the results presented in the paper with the results of similar studies, as they have not been conducted so far. There has been taxonomic research on broadly understood renewable energy, but not solely on wind energy. In the work [14], on the share of energy from renewable sources, only the new EU member states were classified. In the work [15], using the k-means

method, 28 EU countries were grouped in terms of the share of renewable energy in the total energy produced and the country's energy dependences. Similarly, in the work [17], the k-means method was used to classify EU countries in terms of their photovoltaic (PV) energy production. The country classifications obtained in the cited studies do not coincide with the classification presented in this study. The fact that different cluster analysis results were obtained there is not surprising, as they relate to completely different aspects of the renewable energy sector and take into account other variables for research. For this reason, the results presented in the study constitute a new contribution to the current of research on understanding the state of the renewable energy sector in EU countries.

6. Conclusions

As a result of the analysis, it can be concluded that, in spite of the significant diversity of EU countries due to the development of wind energy, there are groups of similar countries. A taxonomic analysis identified seven such groups (Figure 9). This confirms our research hypothesis.

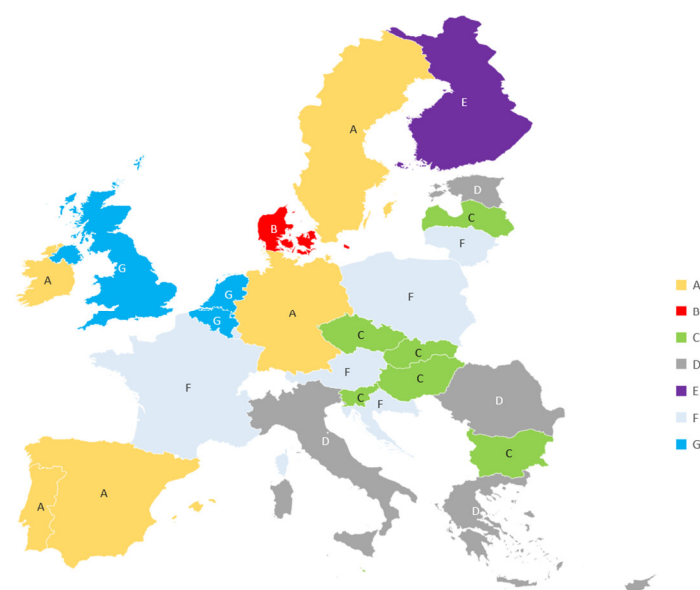


Figure 9. Division of the EU countries into clusters.

Clusters A and B form the countries with the highest level of wind energy development, which is confirmed by their top positions in the ranking. Denmark (cluster B) is the undisputed leader, as it clearly occupies the first place in the individual rankings of five out of the seven selected features. It is distinguished from cluster A by a significantly larger number of wind farms, but with smaller wind farms and a larger share of offshore installations. The countries from clusters A and B were characterized by a lower than average growth rate of capacity installed in the years 2013–2017.

Cluster C consists of the countries with the least and slowest developed wind energy in the European Union in 2013–2017. They occupy the last seven places in the ranking.

Other countries have wind power developed at an average level, as evidenced by their middle positions in the ranking. There are also some differences between them that allow them to be divided into four clusters—D, E, F, and G.

Cluster E is made up of Finland, which was distinguished in the EU by its exceptionally high wind cumulative capacity growth rate in the years 2013–2017. With such high dynamics maintained in the following years, Finland will soon join Cluster A. In turn, the countries from Cluster G, taking advantage of the good geographical location on the North Sea, are characterized by a high share of offshore installations in acquiring wind energy.

Cluster D is distinguished by the largest average number of turbines in one wind farm, while cluster F is relatively high, second only to Finland in terms of the dynamics of the increase in capacity installed in 2013–2017. Other values of indicators used in the analysis were below the EU average in these clusters.

The research may be extended to include further analyses on other renewable energy sources and may also include other European and world countries. They can also contribute to further in-depth research and analysis regarding the impact of various factors (e.g., economic, social, legislative, environmental, political, etc.) on the structure of the clusters. Conducting similar research in the future will allow determining if there are any changes in the structures of separate clusters.

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