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Comparative Analysis of the Diffusion of Innovations in Wind Energy in European Countries

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ABSTRACT

Objective: The aim of this article is to compare the diffusion processes of innovations in wind energy among selected European countries.
Research Design & Methods: The study used the Bass model, with parameters estimated separately for each country, and then, based on the obtained parameter estimates, a taxonomic analysis of the compared countries was carried out. This enabled the identification of regularities between the obtained indicators of innovation, imitation and market potential. Ward's method, using Euclidean distance, was applied in the cluster analysis, and the contribution of variables to differentiating the resulting groups of countries was assessed using ANOVA.
Findings: The results of the taxonomic analysis enabled the isolation of the diffusion profiles of innovations in wind energy technologies. In particular, it has been proven that innovators are large countries with strong economies, high levels of GDP and a high share of spending on research and development. The imitators of such technologies are primarily countries in Central, Eastern and Southern Europe, where the level of expenditure on research and development is lower than in Western Europe.
Implications/Recommendations: The results presented in the article may support the development of an energy system with a high share of renewable energy sources. Moreover, they

can be helpful in assessing the effectiveness of the actions of individual countries' governments in decarbonising their economies.

Contribution: The research results presented in this article fill the research gap in the field of comparative analysis of innovation diffusion profiles in wind energy in European countries.

Article type: original article.

Keywords: renewable energy, wind energy, Bass model, learning curves, Ward's method.

JEL Classification: Q42, Q55, C38.

1. Introduction

The energy transition aimed at decarbonising economies is one of the most important challenges the world will face in the near future. The urgency of this process arises, on one hand, from adverse climate changes caused by greenhouse gas emissions, and on the other hand, from limited resources of traditional energy raw materials. The need to move away from the use of fossil fuels and replace them with renewable energy sources has long been postulated by governments of many countries, international organisations and associations. This is reflected in international agreements and declarations obliging signatory countries to take specific actions. It is worth recalling here the so-called Paris Agreement concluded by UN member states (Markard, Geels & Raven, 2020) or the European Green Deal, which obliges EU countries to achieve climate neutrality by 2050 (Vela Almeida *et al*., 2023). As part of a package of policy initiatives, the European Commission has developed an EU financing mechanism for the Green Deal to support EU member states in achieving their individual and collective goals in the energy transition (Sikora, 2021). Implementing the assumptions of the Green Deal requires, among other things, intensified innovative activities aimed at developing modern technologies supporting renewable energy sources, increasing their efficiency, availability and reducing the costs of their implementation. An important element of these activities is the development of wind energy. In the EU, in 2022, energy from renewable energy sources accounted for nearly 23% of the total energy consumed, with the share of electricity from wind accounting for approximately 38% of the energy generated from renewable sources. This means that wind is the most significant source of renewable energy in the EU (Eurostat, 2024). There are many indications that this type of energy has significant and still untapped potential. To fully utilise it, innovations and appropriate energy policy are needed, including, for example, legal regulations regarding the location of wind farms, and appropriate public education reducing fears about the construction of wind energy infrastructure (Bin Abu Sofian *et al*., 2024). Technological innovations in this area are multidirectional and include materials used in the construction of wind turbines, improvements in the design of wind turbine blades and rotors, automation of wind energy control using artificial intelligence solutions (Bin Abu Sofian *et al*., 2024; Machado & Dutkiewicz, 2024). An important challenge for the industry is also the construction of increasingly larger wind turbines, including turbines resistant to extreme weather conditions floating on seas and oceans (Bošnjaković *et al*., 2022).

Wind energy, as a sustainable energy source, is gaining recognition among environmentalists and decision-makers. Nevertheless, like other infrastructure projects, wind farms face challenges related to environmental protection, landscape change and visual impact (Avila, 2018; Dhar *et al*., 2020). Solving these problems is essential for the continued development and wide acceptance of wind energy.

Innovations in wind energy technologies, like other renewable energy sources, undergo diffusion, i.e. spreading throughout the economy. According to Rogers' diffusion model (Rogers, 2003), different groups of people adopt innovations at different rates, and the innovation adoption process includes five stages: knowledge, persuasion, decision, implementation, confirmation. Many studies confirm that diffusion typically follows an S-shaped curve over time, although the pace of this phenomenon and its overall characteristics may differ between the economies of different countries (Söderholm & Klaassen, 2007; Skoczkowski, Bielecki & Wojtyńska, 2019).

This may be due to differences in the market potential of countries, as well as different levels of absorption of new technologies, the availability of locations for this type of investment, and different priorities in the energy policy of individual countries. The diffusion of renewable energy technologies based on wind energy may be influenced by, for example, the availability of winds at appropriate speeds (which is influenced by the topography, length of the sea coastline, barometric conditions), the condition of the existing energy infrastructure, administrative and legal regulations regarding the construction of wind farms, social acceptance for such ventures. Comparative studies on the diffusion of wind technologies are therefore important from the point of view of assessing the effectiveness of actions aimed at creating zero-emission economies in accordance with the guidelines of the European Green Deal. Despite the relatively frequent approach to this issue by researchers, there is a research gap in the literature in this area. There is a lack of research that comprehensively compares the processes of innovation diffusion in wind energy technologies in European countries. However, there are many studies relating to specific countries or regions (Murugesha & Prasanna Kumar, 2012; Zhang *et al*., 2024).

The aim of this article is to compare the diffusion processes of innovations in wind energy among selected European countries. The Bass model was used to achieve this goal. Based on the estimation results of this model, regularities were determined between the obtained indicators of innovation, imitation and market potential for the studied countries. Additionally, the author conducted a taxonomic analysis of these countries using quantitative characteristics of innovation diffusion processes in wind technologies.

2. Literature Review

Several trends can be identified in the literature on renewable energy research, namely the analysis of technological changes, the study of the diffusion of innovations, the economic and environmental effects of the implementation of renewable energy sources, as well as the psychosocial aspects of innovation in renewable energy technologies (Zhou *et al*., 2020; Omri, Chtourou & Bazin, 2022). The initial research stream employs exogenous and endogenous models. Exogenous models are used to examine, among others, effectiveness of technological solutions, while endogenous models are used to analyse the costs of a standard product within one company (learning curve) or the costs of non-standard products at the global, regional or national level (experience curve) (Horsky & Simon, 1983). When examining the diffusion of renewable energy technologies, one diagnoses technological cycles and innovation saturation levels. Models reflecting S-shaped curves are mainly used here, such as the Bass model, the logistic function, the Gomertz model and others (Meade & Islam, 2006; Zhang *et al*., 2020; Zhou *et al*., 2020). In wind energy research, learning curves and innovation diffusion models are often used, as well as a combination of these tools with the analysis of factors determining or limiting the development of wind turbine technology. There are numerous publications devoted to the Asian wind energy market. Hayashi, Huenteler and Lewis (2018) used learning curves to examine how the accumulation of experience and knowledge of wind farm developers and turbine manufacturers contributed to productivity growth in the Chinese wind energy industry. They showed that the efficiency, turbine size and unit costs in Chinese wind farms depend little on the accumulation of experience and knowledge.

Learning curves were also used by Zhang *et al*. (2024) in a study of the main factors influencing onshore wind energy in China, which made it possible to identify ways to reduce the costs of producing such energy. The diffusion of wind technology also in China was studied by She *et al*. (2019). The authors examined eight wind farm bases in China in terms of innovation diffusion and presented projections for them to increase the use of wind energy by 2030. They showed that a poorly developed energy network is the greatest obstacle to the development of wind energy in regions with large resources and poor developed economy, while subsidies are a key factor in the diffusion of wind energy in developed regions (She *et al*., 2019). The logistic curve was applied in studying the diffusion of wind energy technology in Pakistan and in the forecasting of wind energy consumption by Harijan *et al*. (2011).

Studies also link the diffusion of technological innovations with specific technological parameters of installed wind turbines, such as the height of the rotor hub, wind energy generation capacity and others. Murugesha and Prasanna Kumar (2012) conducted an extensive study of this type in the Indian state of Karnataka. Due to the cointegration of the time series they used, they used vector error correction models. A quantitative analysis of innovation diffusion in the European wind energy sector (for Denmark, Germany, Spain and the UK) was carried out by Söderholm and Klaassen (2007). Using a learning curve model based on dynamic cost reduction, the authors showed, among others, that reductions in investment costs (resulting from, among others, educational activities and public research and development support) were important determinants of the increased dissemination of wind energy. In turn, Dalla Valle and Furlan (2011) used the Generalised Bass Model (GBM), standard Bass model (BM), logistic model, and Gompertz model to analyse the diffusion of wind energy technologies in some European and US markets in connection with the effects of local incentive policies. They also made short-term estimates and forecasts of wind energy life cycles. Dubarić *et al*. (2011) used S-shaped curves in modelling the diffusion of wind energy technology (in terms of power supply technology, rotor form, regulation and pitch adjusting) using panel data. The authors demonstrated that, particularly in regulation technology, there is a strong relationship between the increase in the number of patents and market changes. In the study conducted by Garsous and Worack (2022), barriers to the diffusion of wind energy technologies are examined. The authors argue that some foreign trade instruments that may limit access to markets for key environmental technologies may be used to inhibit the development of wind turbine technologies. The authors further argue that industrial policy should be shaped in such a way that domestic companies specialising in wind turbine technologies can apply their specific potential to new opportunities in global industries.

Hernandez-Negron, Baker and Goldstein (2023) use experience curves as a basis for examining the development of new wind technology for wind turbines located at sea in relation to farms located on land (using mature technology), and hybrid solutions are also examined. By focusing on the levelised cost of electricity obtained from offshore wind energy, the authors show the importance of its connection with onshore wind energy. An intriguing study on the diffusion of innovations in wind energy technologies in European countries using learning curves created on the basis of the Cobb-Douglas model was shown by Grafström and Lindman (2017). Additionally, they used econometric models for panel data, thanks to which they assessed the significance of the impact of various factors on the development of wind energy in Europe. They showed, among others, that the price of steel is an important determinant of the costs of wind energy, and investment costs are an important factor determining the amount of power installed in wind energy.

Thompson (2023) used meta-analysis to prove that renewable energy sources do not replace fossil fuels, but increase energy demand, which results in increased greenhouse gas emissions. According to her, the development of renewable energy, including wind energy, is not possible without billions of dollars in subsidies to support the investment process, it will be insufficient and will not fulfil its fundamental role, i.e., it will not eliminate the use of fossil fuels. A less pessimistic vision of the development of wind energy and its role in improving energy security is presented by Wheatley (2024). She argues that the leading share of renewable energy sources in the energy mixes of individual countries is possible thanks to sustainable technological progress supported by innovation and inter-sectoral and international cooperation. She believes that the transformational potential of these technologies is enormous; thanks to which they will reduce carbon dioxide emissions and improve energy security. Lindman and Söderholm (2012) conducted a comprehensive meta-analysis based on the results of 35 studies that used learning curves. Using the concept of an extended learning curve, they showed, among others, that in the case of wind energy, integrating the effects of public research and development results in lower learning rates than those generated by the so-called single-factor learning curves. A review of the barriers and factors influencing the global imbalance in the diffusion of wind energy in developing countries was performed by Zwarteveen *et al.* (2021). They identified 59 factors influencing the diffusion of wind energy and then grouped them into eight categories, the key of which are: economic, environmental, technical, technological, social, regulatory, political potential, as well as a set of other factors. Lacerda and Van den Bergh (2014) studied the impact of various actions on the diffusion of innovations in wind energy in three large markets: China, Germany and the USA. They demonstrated that policy support for environmental innovations can help create competitive advantages in the wind energy market. Using the examples of China and Germany, they demonstrated a strong relationship between political support and diffusion.

Skoczkowski, Bielecki and Wojtyńska (2019) used logistic curves to describe the diffusion of innovations and based on them, presented forecasts for the development of wind energy until 2100. However, their research was performed for all EU countries jointly, so a detailed comparative analysis between specific countries is not possible here. This article attempts to fill this research gap. Although the issue of diffusion of innovations in wind energy is relatively popular in scientific research, it rarely compares the diffusion of this phenomenon in a larger number of countries. Meanwhile, this type of research is necessary to assess the progress of various countries in the processes of economic decarbonisation. The author of this article met these expectations and compared the diffusion of innovations in wind technologies in 32 European countries. Data for calculations come from the database available under an open licence: Our World in Data (2024). The basis for building models of the diffusion of innovations in wind technologies were the time series of annual energy production (in TWh) covering the years 1985–2023.

3. Methodology

The Bass model was employed to study the spread of wind energy technology. This model is relatively often used in the analysis of the diffusion of innovations, including those related to wind energy technologies. In analysing the diffusion of this type of technology, Bass's model was used by, among others, She *et al*. (2019) and Dalla Valle and Furlan (2011). It is also worth emphasising that BM is characterised by simplicity, traceability and ease of interpretation of the obtained parameters. The basic form of this model is presented as follows (Bass, 1969, 2004; Guidolin, 2023):

$$\frac{dN(t)}{dt} = \left[p + q\frac{N(t)}{M}\right][M - N(t)], \tag{1}$$

where:

$N(t)$ – total number of users of the innovation in time t,
M – number of potential and current users of the innovation,
p – innovation coefficient,
q – imitation coefficient.

The p parameter indicates the percentage of users who will adopt the innovation. In turn, the component $q\frac{N(t)}{M}$ in formula (1) denotes the percentage share of users of the innovation, scaled by the imitation coefficient q.

Solving the differential equations (1) we obtain the following function:

$$N(t) = M\frac{1 - \exp(-(p+q)t)}{1 + \frac{q}{p}\exp(-(p+q)t)}, \quad t > 0. \tag{2}$$

Its graph is an S-shaped curve, and its derivative showing the immediate process of innovation diffusion can be written as follows:

$$N'(t) = M\frac{p(p+q)\exp(-(p+q)t)}{[p + q\exp(-(p+q)t)]^2}, \quad t > 0. \tag{3}$$

Diffusion models were constructed for each of the analysed countries and then, based on the parameter estimates in the Bass model, the countries were grouped using the Ward method. Ward's method was chosen due to its popularity and effectiveness confirmed in numerous studies (Sokołowski, 1992). Ward's method belongs to hierarchical methods of cluster analysis and uses an approach based on the analysis of variance to estimate the distance between clusters. Its assumption is to minimise the sum of squares of any two clusters that can be formed at individual stages of the agglomeration procedure. Thanks to this, it is possible to obtain the effect of homogeneity within clusters and heterogeneity between clusters. Ward's method is flexible in data exploration and avoids many problems typical of other hierarchical methods. By using it, one can avoid, for example, the "chain" effect, consisting in the creation of very elongated and uneven clusters. This undesirable effect is typical of many other agglomeration hierarchical methods (e.g., single linkage, average linkage), and does not occur in Ward's method, because it favours groups of similar size, which prevents the formation of clusters resembling a "chain." The grouping of countries using Ward's method was performed in the STATISTICA package.

4. Results and Discussion

The Bass model was estimated for 25 EU and 7 non-EU European countries. The study included only countries with available data on annual energy production from wind turbines for the years 1985–2023. The estimation results of model (1) for European countries are presented in Table 1. The asymptotic standard errors of the parameter estimates are given in parentheses, and the coefficients of determination are given in the last column.

Table 1. Results of Estimation of Parameters *p*, *q* and *M* in the Bass Model

Country	Symbol	Parameters			R^2
		p	*q*	*M*	
Austria	AUT	0.0020 (0.0007)	0.2209 (0.0610)	127.5310 (58.4092)	0.9991
Bulgaria	BLR	0.0001 (0.0000)	0.2194 (0.0965)	160.7375 (59.6336)	0.9962
Belgium	BEL	0.0001 (0.0000)	0.3266 (0.1114)	17.7803 (8.3212)	0.9996
Belarus	BGR	0.0012 (0.0003)	0.4830 (0.2106)	21.2182 (8.1902)	0.9988
Czech Republic	CZE	0.0007 (0.0003)	0.7391 (0.1966)	10.6650 (3.4341)	0.9769
Denmark	DNK	0.0032 (0.0007)	0.1268 (0.0569)	544.7865 (233.7134)	0.9842
Estonia	EST	0.0007 (0.0001)	0.7765 (0.4069)	70.7565 (28.1611)	0.9784
Finland	FIN	0.0031 (0.0011)	0.3832 (0.1813)	927.0251 (214.1428)	0.9829
France	FRA	0.0062 (0.0026)	0.3220 (0.1633)	430.7368 (130.9440)	0.9797

Table 1 cnt'd

Country	Symbol	Parameters			R^2
		p	*q*	*M*	
Germany	DEU	0.0080 (0.0010)	0.1757 (0.0803)	2963.0164 (1345.2094)	0.9924
Greece	GRC	0.0002 (0.0001)	0.6008 (0.0631)	50.3106 (16.2503)	0.9944
Hungary	HUN	0.0010 (0.0003)	0.7355 (0.2111)	101.9395 (38.0234)	0.9801
Ireland	IRL	0.0043 (0.0007)	0.4746 (0.1011)	22.4051 (4.2122)	0.9760
Italy	ITA	0.0079 (0.0010)	0.2431 (0.1133)	1534.6216 (214.8470)	0.9863
Latvia	LVA	0.0003 (0.0001)	0.6771 (0.1598)	302.6631 (127.4212)	0.9968
Lithuania	LTU	0.0006 (0.0002)	0.6317 (0.1870)	18.5520 (9.3873)	0.9980
Luxembourg	LUX	0.0001 (0.0000)	0.1834 (0.0638)	412.3438 (48.6566)	0.9871
Netherlands	NLD	0.0003 (0.0001)	0.1841 (0.0865)	1224.1204 (561.8713)	0.9843
North Macedonia	MKD	0.0001 (0.0000)	0.4185 (0.1276)	1.8211 (0.4134)	0.9890
Norway	NOR	0.0031 (0.0017)	0.3212 (0.0864)	82.8061 (41.2374)	0.9781
Poland	POL	0.0046 (0.0016)	0.3446 (0.0872)	902.0218 (343.6703)	0.9899
Portugal	PRT	0.0003 (0.0001)	0.2474 (0.0576)	225.4201 (54.5517)	0.9838
Romania	ROU	0.0012 (0.0004)	0.7645 (0.3387)	80.9809 (22.8366)	0.9927
Russia	RUS	0.0001 (0.0000)	0.3168 (0.0716)	1564.2958 (528.7320)	0.9954
Slovakia	SVK	0.0003 (0.0001)	0.6004 (0.2384)	1.9522 (0.7477)	0.9909
Slovenia	SVN	0.0002 (0.0001)	0.1875 (0.0958)	0.0838 (0.0219)	0.9831
Spain	ESP	0.0034 (0.0005)	0.1920 (0.0666)	2199.1364 (888.4511)	0.9900
Sweden	SWE	0.0036 (0.0014)	0.2947 (0.1314)	2380.7366 (630.8952)	0.9837

Table 1 cnt'd

Country	Symbol	Parameters			R^2
		p	q	M	
Switzerland	CHE	0.0002 (0.0001)	0.2705 (0.0995)	192.1953 (77.6469)	0.9772
Ukraine	UKR	0.0001 (0.0000)	0.5480 (0.2066)	161.6696 (31.8489)	0.9936
Great Britain	GBR	0.0058 (0.0032)	0.2868 (0.1259)	3039.7893 (556.2814)	0.9855
Croatia	HRV	0.0004 (0.0001)	0.6316 (0.2248)	27.8272 (6.5116)	0.9856

Source: own study.

To facilitate comparison of the results obtained between countries, the next three figures present 2-dimensional summaries of the values of all pairs of parameters of the BM. This facilitates the identification of countries with similar diffusion of innovations in wind energy and indication of possible regularities between the parameters of the Bass model in different groups of countries. Figure 1 illustrates the values of the p and q parameters for the compared European countries.

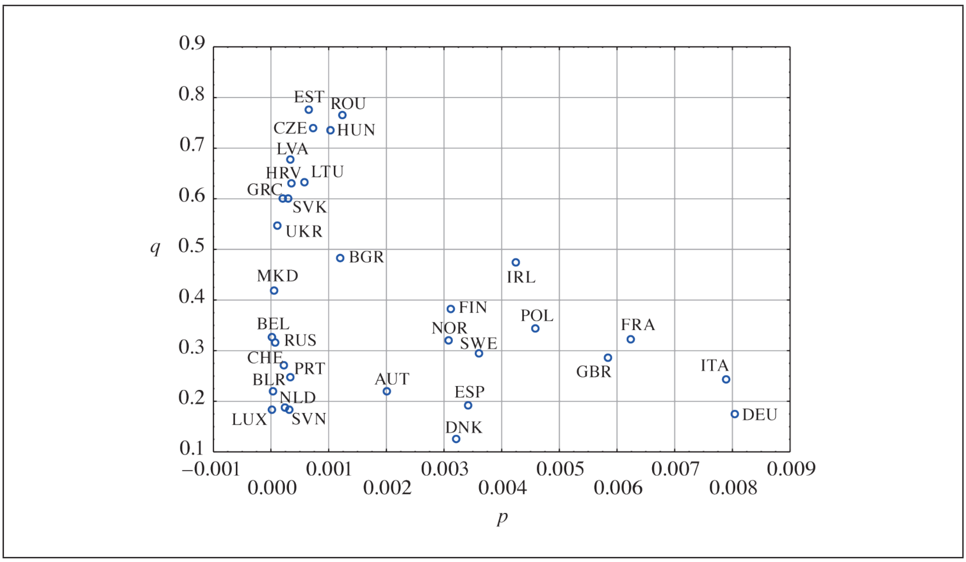

Fig. 1. Summary of the Values of Parameters p and q in the Bass Model Describing the Diffusion of Innovations in Wind Energy in European Countries

Source: own study.

Figure 1 shows that most countries are characterised by a low innovation rate and a low imitation rate. These include Central and Eastern European countries such as Ukraine, Russia, Bulgaria, Belarus, North Macedonia, but also Portugal, Switzerland and Belgium.

Their innovation index does not exceed 0.002, and their imitation index is lower than 0.5. Some of the countries mentioned supply their internal energy sector with nuclear energy (e.g., Russia, Ukraine), which may reduce the need to invest in renewable energy there. Noteworthy is the presence of Switzerland in this group of countries, where well-known wind turbine manufacturers operate. However, in this Alpine country, the key source of renewable energy is water (coming from melting glaciers) and investing in hydroelectric power plants is a priority there.

Another clearly distinguishable group of countries are imitators, characterised by low innovation and high imitation index levels. These include: Lithuania, Latvia, Estonia, Romania, Czech Republic, Hungary, Croatia, and Greece. Therefore, this group mainly includes the countries of Central and Eastern Europe, where expenditure on research and development is clearly lower than in the richer countries of Western Europe.

Countries considered innovators in wind technology with a high innovation index ($p > 0.002$) and a low level of imitation index are: Germany, France, Italy, Spain, Norway, Sweden, but also Poland. It is worth noting that these are mainly Western European countries, generally with a high level of GDP and a high share of research and development expenditure in relation to GDP. Each of them also has access to the sea, which enables the development of offshore wind energy, which is characterised by particularly high efficiency.

Figure 2 presents market potential indicators (M) of European countries and innovation indicators (p).

As shown in Figure 2, among the compared countries, the dominant ones are those with a low market potential index ($M < 1{,}500$) and late adopters of wind technologies ($p < 0.002$). These are mainly Central European countries and the Benelux countries. We also have a group of countries with low market potential but a high innovation rate. They included France, Norway, Ireland, Denmark and Austria. Among the compared countries, Great Britain, Sweden and Spain stand out with a clearly higher market potential ($M > 1{,}500$) and at the same time are pioneers of innovation in wind turbine technologies. Russia has high market potential but low innovation in the field of wind energy technology.

Figure 3 presents market potential indicators (M) of European countries and imitation indicators (q).

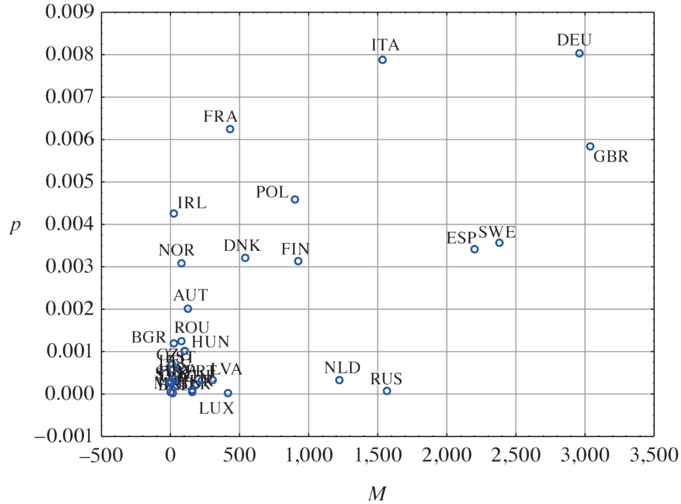

Fig. 2. Summary of the Values of Parameters *M* and *p* in the Bass Model Describing the Diffusion of Innovations in Wind Energy in European Countries

Source: own study.

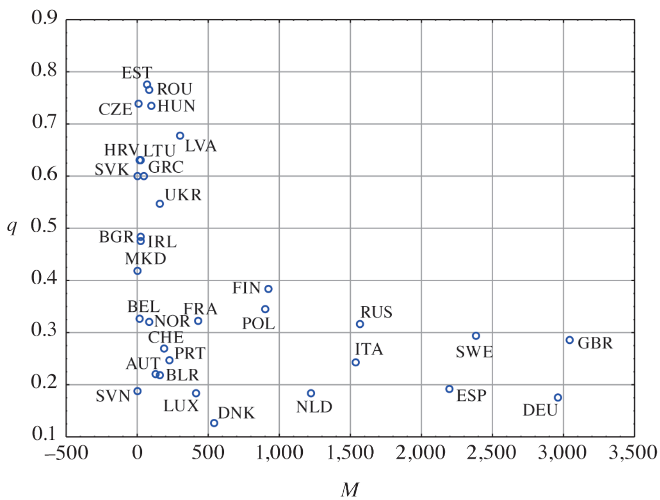

Fig. 3. Summary of the Values of Parameters *M* and *q* in the Bass Model Describing the Diffusion of Innovations in Wind Energy in European Countries

Source: own study.

Based on Figure 3, it can be concluded that the leading imitators of wind energy technology are countries with low market potential, such as Lithuania, Latvia, Estonia, the Czech Republic, Slovakia, Ukraine and Romania. Countries with high market potential ($M > 1,500$) are only small imitators of innovations in wind technologies ($q < 0.4$): Great Britain, Spain, Sweden, Germany, Italy, Russia. The dominant group consists of countries with low market potential and a low imitation index, including: the Benelux countries, Slovenia, Denmark, the Netherlands, Switzerland, Ireland, North Macedonia and Poland.

Using the the p, q and M parameters obtained in the Bass model, the compared countries were grouped. For this purpose, the Ward method with Euclidean distance was used, thanks to which clusters of countries with the most similar innovation diffusion profiles in wind energy technologies were identified. The results of this grouping are shown in Figure 4.

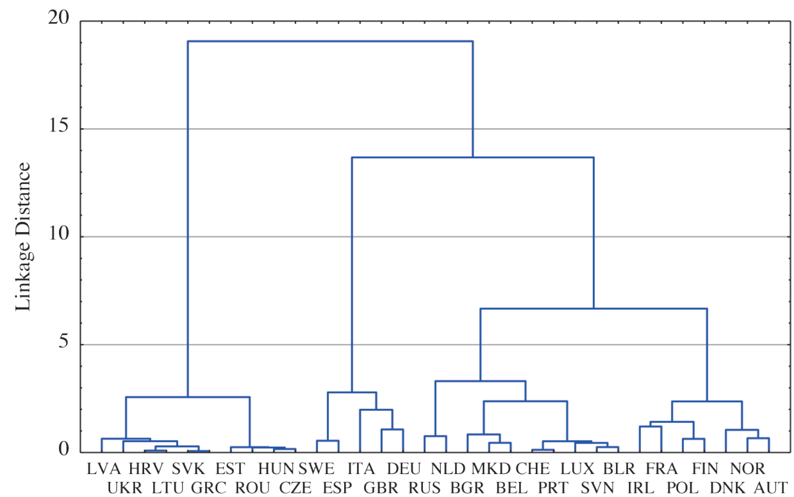

Fig. 4. Results of Grouping European Countries Using the Ward Method According to the Values of Parameters p, q and M Obtained from the Bass Model

Source: own study.

Using the criterion of the first clear increase in agglomeration distance, the dendrogram was cut off at the height of link 5 and as a result, four homogeneous clusters of countries with the following compositions were obtained:

– group one: Austria, Denmark, Finland, France, Ireland, Norway, Poland,

– group two: Czech Republic, Estonia, Greece, Croatia, Hungary, Lithuania, Latvia, Romania, Slovakia, Ukraine,

– group three: Germany, Spain, Great Britain, Italy, Sweden,

– group four: Belgium, Bulgaria, Belarus, Switzerland, Luxembourg, North Macedonia, the Netherlands, Portugal, Russia, Slovenia.

The first group consists of countries with low market potential that are late adopters. All of the countries in this group, except Austria, have access to the sea, which provides them with favourable conditions for the development of offshore wind energy. Denmark, Norway, France, Finland and Ireland benefit from this in particular. The second group consists of leading imitators with limited market potential. This is a rather heterogeneous group of countries with diverse geographical, climatic, socio-political conditions and different availability of financing sources for wind energy sector development projects. Baltic countries and Balkan countries with a sea coastline have good wind conditions, so they invest more in wind energy development. Inland countries (e.g., Czech Republic, Hungary, Slovakia) have worse wind conditions and greater social resistance to the development of the wind energy sector. The third group comprises countries with significant market potential that are pioneers in the wind energy technology market. All countries in this group are investing in modern wind technologies and developing innovations in the area of building large turbines and offshore farms. Wind energy in this group of countries plays a key role in their energy mix. The fourth group consists of countries with low market potential, low innovation in wind turbines, and low imitation rates. These are countries that are less interested in developing wind energy. These countries, however, are very diverse in terms of wind energy development, as they include technologically advanced leaders such as Belgium, the Netherlands and Portugal, as well as countries less interested in developing wind energy, such as Belarus, Russia, Slovenia and Macedonia. Government support for this sector in group four is also very different, depending on the energy policy pursued by the governments of individual countries.

To determine which parameters significantly contributed to the differentiation of the resulting clusters, a one-way ANOVA was used. The obtained results showed that at the significance level of 0.001, all parameters (p, q, M) significantly differentiate the resulting clusters, and the greatest contribution to the differentiation of country clusters is made by the imitation index (q), for which the value of the F statistic = = 40.8946, and market potential had the smallest contribution (F = 35.6851).

5. Conclusions

Wind energy is undoubtedly a promising renewable energy sector, contributing increasingly to the decarbonisation of the economy in many countries. Modern wind energy employs technology with a beneficial impact on the environment, and its current disadvantages are gradually being eliminated and, most importantly, the costs of obtaining energy from wind are systematically reduced. Increasing the share of this sector requires substantial investment and appropriate energy policy, which is often not possible without the support of government programmes or support from the EU. Creating a system for synchronisation and coordination of policies and actions towards the transformation of the power system requires detailed analyses in each country. The research results presented in this article address the research gap in comparative analysis of innovation diffusion profiles in wind energy across European countries. The innovators were identified as large countries with strong economies, high GDP, and a significant spending on research and development. The imitators, on the other hand, are primarily countries in Central, Eastern and Southern Europe, where the level of expenditure on research and development is lower than in Western Europe. Although it is challenging to formulate universal recommendations for the energy policy directions of all countries that entered the individual groups based on the obtained results, it seems that countries with low innovation and imitation indicators in many cases have a chance to improve their position in the progress of energy transformation. Typically, these countries should focus on technology transfer (import), simplifying regulations, expanding financial support systems and adapting solutions to local conditions. This can be achieved, among other things, by simplifying investment procedures, ensuring long-term predictability of legal provisions and administrative regulations, importing modern technologies through international cooperation, creating joint consortia with foreign companies and research institutes, expanding the package of incentives for the private sector interested in investing in wind energy. In many cases, modernisation of transmission networks and construction of energy storage facilities will also be indispensable. Increasing social acceptance of wind energy is also crucial, which can be achieved through appropriate ad hoc actions and educational programmes, but also through systemic changes in curricula at school or university level.

The diffusion process of innovations in wind energy technologies in European countries, as presented in this article, is confirmed by other researchers' results (Söderholm & Klaassen, 2007; Dalla Valle & Furlan, 2011; Skoczkowski, Bielecki & Wojtyńska, 2019). However, generally, other authors rarely conduct comprehensive comparative analyses allowing the identification of groups and profiles of countries with similar characteristics of the diffusion of innovations in wind energy. The presented research proposal, based on learning curves, has its limitations. The choice of model in innovation diffusion research is always a controversial issue. Moreover, the adopted method for describing the diffusion of innovations does not consider many factors that may influence the pace and size of this process, such as legal regulations, environmental conditions, price conditions and others. Therefore, future research may also consider endogenous models capable of forecasting wind energy development in individual countries, assuming different energy market development scenarios.

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Conflict of Interest

The author declares no conflict of interest.

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