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Modelling the impact of socio-economic factors on the diffusion of wind energy in selected EU countries

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Abstract

Aim: The aim of the article was to assess the diffusion of wind energy and to identify the socio-economic factors determining the rate of this diffusion.

Methodology: A logistic model was used to analyse the diffusion of wind energy, while the econometric Error Correction Model (ECM) was used to study the impact of socio-economic factors on the rate of diffusion.

Results: In most of the surveyed countries the most important variable influencing the speed of diffusion of wind technology innovations were *energy prices*, followed by *electricity consumption per capita*, whereas the least important variable was *number of researchers in R&D*. The number of patents and *R&D expenditure* were relatively more often a statistically significant determinant of the diffusion of innovation among the old EU member states than among the member states from Central and Eastern Europe.

Implications and recommendations: The innovation of the wind energy sector in some countries is insufficient and requires appropriate stimulation. This can be achieved by, among others, increasing investment outlays on research and development in the renewable energy sector, and developing offshore energy, which is much more effective than onshore wind farms.

Originality/value: The article presents an original comparative analysis of the diffusion of wind energy in EU countries, and using ECM models, the factors determining the dynamics of this diffusion were identified. The results bring added value in terms of economic and political research in the wind energy sector.

Keywords: renewable energy sources, wind energy, logistic model, ECM

1. Introduction

Wind energy is one of the key tools to counteract climate change. Generating energy from wind is one of the cleanest and most efficient ways to obtain electricity as it does not emit carbon dioxide, and does not require the combustion of fossil fuels (Dooley & Kartha, 2018; Grubb et al., 2021). For this reason, wind energy, alongside other renewable sources, has become one of the pillars of the EU climate policy, the aim of which is to significantly reduce greenhouse gas emissions. An important issue in this context is also ensuring energy security and reducing dependence on fossil fuel imports, which is particularly important in the face of volatile commodity prices and geopolitical instability in Eastern Europe (Grubb et al., 2021). The development of wind energy, together with other renewable energy sources, is a possible remedy for these problems. Investing in wind farms built on land and at sea increases the share of renewable energy in the energy mixes of individual countries, which also stimulates economic development and creates new jobs. The efficiency of wind energy development is to be ensured by the legal regulations adopted by the EU supporting investments in renewable energy sources (Markard et al., 2020). The European Green Deal assumes climate neutrality by 2050, and EU member states have been obliged to adopt timetables for actions aimed at replacing conventional energy sources with renewable sources (Almeida et al., 2023).

Although wind energy is of great importance for the energy transformation, its development faces various barriers and challenges. Problems include the location of wind farms and their impact on the landscape and ecosystems, as well as the possible negative impact on the health of residents in the immediate vicinity of wind turbines. This gives rise to social opposition, which significantly limits the possibilities of locating further wind farms (Del Río & Tarancón, 2012). One must also remember the often overlooked costs of wind energy related to the carbon footprint of wind turbine production, the costs of subsequent disposal of used equipment, and the environmental costs (threat to birds and marine animals). Variable wind power also means that in many locations the energy sector does not provide a stable supply of electricity, which poses challenges in terms of finding effective energy storage technologies and modernising the power grid that will be fully compatible with this type of electricity source (Sisodia et al., 2016). Finally, it should be emphasised that high investment costs are a barrier to the development of this form of energy, especially in the case of offshore farms (Zwarteveen at al., 2021). Despite these problems, the development of wind energy technologies is constantly accelerating, and an appropriate energy policy based on a support system from EU governments makes wind energy one of the key elements of Europe's energy transformation (Grubb et al., 2021).

There are many reasons why wind energy and its development are a frequent subject of scientific research, among which many trends can be distinguished, both focusing on technical and technological aspects, as well as economic ones (Zwarteveen at al., 2021; Şener et al., 2018). The study of the diffusion of wind energy itself and the factors that support or limit this diffusion appears particularly interesting, and is the subject of this paper. The literature lacks comprehensive comparative studies on the rate of diffusion of wind energy innovations across EU countries, as well as a multidimensional analysis of the impact of external factors on this diffusion. This article fills this research gap, and the author focused on comparing the rate of diffusion of innovations in wind energy in EU countries, and also assessed the impact of socio-economic factors on this diffusion. For this purpose, econometric modelling using the logistic function and the Error Correction Model (ECM) was employed. The adopted research method, which combined the logistic function and the ECM model in the study of innovation diffusion factors in wind energy, is a novelty, and its use in relation to individual countries provides important opportunities for the comparative assessment of national energy policies. A significant element of this study is also the comparison of the importance of factors supporting/limiting the rate of wind energy diffusion between the countries of Central and Eastern Europe (the new EU member states) and those of Western Europe. The literature indicates that this type of comparative analysis has not been conducted up to date. This also allowed for the formulation of recommendations for decision-makers responsible for the shape of energy policy in individual countries and the entire EU.

2. Literature review

The literature on the development and diffusion of wind energy is quite extensive, although in many works this issue is combined with the study of other renewable energy sources. Researchers usually analysed these issues in relation to a single economy, e.g. Şener at al. (2023) – USA, She et al. (2019) – China, Yin & Powers (2010) – US states or an entire group of countries (cf. del Rio & Tarancón (2012) – EU Member States, Sisodia et al. (2016) – EU-27, EU-15, EU-11, Marques et al. (2010) – 24 European countries, non-EU Members), or conducted a meta-analysis of the results of other studies on renewable energy (Zwarteveen at al. 2021; Şener et al. 2018). These publications analyse the impact of single determinants on the diffusion of wind energy, or classify them and assess the impact of entire categories of factors on the development of this sector. Econometric modelling is typically used in research, for example Biresselioglu et al. (2016) employed dynamic panel data analysis using the System Generalized Method of Moments (GMM), whilst Sisodia & Soares (2015) and Sisodia et al. (2016) used simple OLS regression models, and Şener et al. (2023) applied fixed-effects panel data analysis. Note, however, that the final choice of research tool depends on the research perspective and the research goals (Zwarteveen et al., 2021).

Biresselioglu et al. (2016) analysed the influence of political, economic and environmental factors on the development of installed wind power capacity worldwide. Among the explanatory variables, they took into account, among others, GDP per capita, CO2 emissions, foreign direct investment, the degree of dependence on energy imports, the share of energy from renewable sources in the total energy production and the price of electricity. Lehtovaara et al. (2014) studied the influence of the technological, market and political environment on the diffusion of wind energy. They showed that the condition for the competitiveness of the wind industry is to obtain support from governments through the creation of an appropriate energy subsidy system and an emission trading system. Economic and infrastructural factors in relation to the Chinese economy were also the subject of the research of She et al. (2019), analysing in detail the factors that facilitate the growth of wind energy use, as well as those that constitute barriers to this growth. The study showed that subsidies were a key factor in the diffusion of wind energy in developed regions, while poor grid availability was the biggest obstacle to the development of wind energy in regions with large resources and underdeveloped economies. A wide range of factors of wind energy capacity growth was studied by del Rio and Tarancón (2012), who used variables which included electricity demand and generation costs, the share of renewable energy sources in the energy mix, types and levels of government support, administrative barriers, and the general investment climate in the country. Their results indicate that removing administrative barriers and regulatory stability have a greater impact on the increase in installed wind energy capacity than various support systems for renewable energy technologies.

Economic factors (including energy prices, GDP), environmental and political factors were also used in econometric modelling of wind energy diffusion conducted by Sisodia et al. (2016), and Sisodia and Soares (2015), showing that one of the key factors of growth in wind energy investment is building a transparent and stable regulatory system in the energy market. Sisodia et al. (2016) and Sisodia and Soares (2015) used panel data models in their research, and such tools were also used in the analysis of drivers of the renewable energy market in EU countries by Marques et al. (2010). Based on the results of their research, they formulated a number of recommendations for designing energy policy, the core of which are renewable energy sources. Similar studies using analogous econometric tools were also conducted by Yin and Powers (2010) and Carley (2009). Keeley and Ikeda (2017) analysed the determinants of foreign direct investment in wind energy in developing countries, in particular drawing attention to the importance of renewable energy support policies, and showing that they have a greater (or equivalent) effect compared to factors such as corruption level, price stability, access to finance and GDP growth. In conclusion, they drew attention to important policy implications, including the need to improve the regulatory solutions of the renewable energy sector. Keeley and Matsumoto (2018) used expert opinions to assess the importance of factors determining foreign direct investment in the wind energy sector. Their study confirmed the great importance of renewable energy policies compared to traditionally argued determinants of FDI, such as the macroeconomic environment, institutional environment and natural conditions.

The importance of political motivations, which prioritise the security of energy supply, the creation of future-oriented industries and jobs, and the reduction of greenhouse gas emissions and local pollution, was also emphasized by Ydersbond and Korsnes (2016). In view of the increasingly globalised supply chains of renewable energy, Steffen et al. (2018) studied the impact of knowledge and technology transfers between countries on the development of wind energy. It is also worth paying attention to cross-sectional reviews of the results of many studies in the field of wind energy, some of which contain extensive meta-analysis, e.g. Zwarteveen at al. (2021), Şener et al. (2018), Strantzali and Aravossis (2016). Zwarteveen at al. (2021) assessed 259 factors that can support or limit the diffusion of wind energy, and divided them into eight categories: economic, environmental, technical, technological, social, regulatory and political, and other factors. Şener et al. (2018) also conducted a systematic literature review and conducted a meta-analysis based on 60 selected qualitative and quantitative studies. Similarly to Zwarteveen et al. (2021), they classified wind energy diffusion factors into analogous categories and examined which of them are drivers or barriers to diffusion and identified factors whose impact, depending on the environmental conditions, may be in different directions. The study found, among others, that economic, environmental and social factors are drivers, while many of the political, regulatory, technical and technological factors were not classified as either drivers or barriers.

3. Methodology

In modelling the diffusion of technology in renewable energy sources, models generating S-shaped curves are often used, including the Bass, Gompertz and logistic models (Bass, 1969; She et al. 2019). In this study the logistic function was used, which has proven to be quite effective in modelling the diffusion of wind energy. It takes the following form (Lei & Zhang, 2004):

$$f(t) = A/(1 + B\exp(-Ct)), \tag{1}$$

where
A, *B*, *C* – parameters of the logistic function, *t* – time variable.

Parameter *A* is interpreted as the level of diffusion saturation. In this work the logistic function was used to model the amount of electricity produced by wind farms in TWh in selected EU countries. In assessing the dynamics of diffusion phenomena, the inflection point is important, separating the period of rapid growth of the diffusion phenomenon from the period of slower growth. In the case of the logistic function, the cutoff of this point is $\ln B/C$. The dynamics of the diffusion phenomenon can be analysed using the growth rate of the logistic function GRL, which determines its change over time in relation to the level of the logistic function itself.

The growth rate of the logistic function can be expressed using the formula:

$$GRL = C - f(t)C/A. \tag{2}$$

Growth rate (*GRL*) was adopted as a dependent variable in econometric models explaining the impact of socio-demographic factors on the diffusion of innovation. In this research, the Error Correction Model (ECM) was used (Wei & Huang, 2022). The choice of this type of model was due to the fact that the time series of variables used in this research were generally cointegrated, as confirmed by the Engle Granger test (Engle & Granger, 1987).

ECM for integrated time series consists of two equations:

– equation representing a long-run relationship (cointegrating equation):

$$\ln GRL_t = \gamma_0 + \sum_{i=1}^{7} \gamma_i \ln X_{it} + u_t, \tag{3}$$

– equation representing short-run relationship with the first differences of variables:

$$\mathrm{d\_ln}GRL_t = \alpha_0 + \sum_{i=1}^{7} \alpha_i \mathrm{d\_ln}X_{it} + \alpha_8 ECT_{t-1} + \varepsilon_t. \quad (4)$$

If autocorrelation occurs in model (4), it has been modified to the following form:

$$\mathrm{d\_ln}GRL_t = \alpha_0 + \sum_{i=1}^{7} \alpha_i \mathrm{d\_ln}X_{it} + \alpha_8 ECT_{t-1} + \sum_{i=1}^{7} \sum_{s=1}^{q} \delta_{is} \mathrm{d\_ln}X_{it-s} + \eta_t. \quad (5)$$

The models included seven explanatory variables: X_1 *– GDP per capita in $, X_2 – Annual CO_2 emissions in billion tons, X_3 – total number of patents in renewable Energy technologies, X_4 – Per capita electricity consumption [kWh], X_5 – Electricity prices for household consumers in Euro, X_6 – R&D expenditure (% of GDP), X_7 – Researchers in R&D (per million people) in renewable Energy*. Equations (4) and (5) contain the ECT component, which is responsible for adjusting short-term processes to long-term equilibrium. By estimating models (3) to (5), it is possible to indicate factors that significantly affect the diffusion of wind energy in the short term and in the long term. This allows for the formulation of constructive recommendations in the field of energy policy in the compared countries.

4. Results

The empirical research consists of two parts, which include the results of modelling the diffusion of innovations in wind energy using a logistic curve, followed by the results of modelling the impact of explanatory variables on the rate of diffusion in wind energy measured using the growth rate of the logistic function. The data for modelling come from the *Our World in Data*[1] and *Eurostat database*[2] databases. The calculations used time series of variables covering the period 2000-2023. In modelling the rate of diffusion of wind energy, variables representing socio-economic and environmental aspects in selected EU countries were used. Ultimately, only 23 EU countries were included in the research, omitting those countries for which there were significant data gaps that prevented the construction of diffusion models, and then causal models. Since the time series showed cointegration confirmed by the Engle–Granger test (Engle & Granger, 1987), causal modelling was performed using error correction mechanism regression models (Wei & Huang, 2022).

Table 1 presents the results of the innovation diffusion modelling using the logistic function (1) (*p* values are given in brackets under the parameters). The last column of this table contains the inflection points of the logistic curve (values expressed in years).

Table 1. Logistic function estimation results for the EU countries studied

Country	Parameters			Inflection point
	A	*B*	*C*	
Austria	9.330 (0.019)	16.520 (0.030)	0.331 (0.013)	8.473
Belgium	17.202 (0.041)	42.101 (0.028)	0.271 (0.041)	13.801
Bulgaria	2.936 (0.012)	30.293 (0.034)	0.405 (0.023)	8.422
Croatia	3.201 (0.062)	14.642 (0.041)	0.312 (0.007)	8.602
Czechia	0.661 (0.036)	37.611 (0.056)	0.386 (0.028)	9.397
Denmark	21.085 (0.045)	42.700 (0.026)	0.293 (0.015)	12.813

[1] https://ourworldindata.org/renewable-energy
[2] https://ec.europa.eu/eurostat/data/database

Country	Parameters			Inflection point
	A	*B*	*C*	
Estonia	1.338 (0.045)	25.559 (0.002)	0.481 (0.031)	6.738
Finland	16.363 (0.018)	29.529 (0.048)	0.271 (0.039)	12.492
France	58.550 (0.028)	44.819 (0.030)	0.226 (0.036)	16.826
Germany	158.915 (0.006)	24.674 (0.015)	0.211 (0.008)	15.193
United Kingdom	93.803 (0.002)	88.304 (0.014)	0.289 (0.081)	15.504
Greece	11.573 (0.025)	85.523 (0.029)	0.431 (0.049)	10.322
Hungary	0.752 (0.027)	23.519 (0.028)	0.456 (0.037)	6.925
Ireland	15.201 (0.036)	62.369 (0.043)	0.374 (0.032)	11.051
Italy	25.892 (0.037)	63.127 (0.033)	0.287 (0.045)	14.443
Latvia	3.521 (0.023)	8.655 (0.033)	0.299 (0.094)	7.218
Lithuania	2.915 (0.011)	46.435 (0.048)	0.566 (0.027)	6.781
Netherlands	34.516 (0.026)	55.815 (0.029)	0.484 (0.058)	8.310
Poland	21.647 (0.025)	157.670 (0.042)	0.342 (0.006)	14.797
Portugal	12.677 (0.023)	46.271 (0.002)	0.251 (0.005)	15.277
Romania	8.177 (0.130)	34.685 (0.039)	0.308 (0.026)	11.514
Spain	58.286 (0.020)	65.268 (0.034)	0.305 (0.051)	13.700
Sweden	37.376 (0.062)	88.495 (0.041)	0.334 (0.005)	13.422

Source: own study.

Based on the results presented in Table 1, it can be concluded that larger countries with stronger economies and higher demand for electricity usually have a much higher level of saturation with electricity from wind than smaller economies, e.g. Germany, France, and the United Kingdom. At the same time, the inflection points of the logistic curves for these countries indicate a longer period of intensive growth rate of innovation diffusion in wind energy compared to smaller economies such as Czechia, Hungary, and Portugal. The highest growth rate of the logistic function at the inflection point was achieved by diffusion in Lithuania (0.283), the Netherlands (0.242), and Estonia (0.241), and the lowest in Germany (0.106) and France (0.113).

Calculations of the growth rate of logistic curves in individual countries also indicate that before reaching the inflection point, the diffusion of wind energy is usually more intensive in smaller economies, but then in the second phase of diffusion in countries such as Lithuania, Hungary, the Netherlands and Estonia it falls much faster than in countries with high energy demand. This may be to some extent the effect of the inertia of economies: those with lower inertia but with a sufficiently high level of ability to absorb new technologies find it easier to adapt to changes and adopt these technologies, while in economies with high inertia this process is usually longer. Table 2 presents the results of the estimation of Error Correction Models for selected EU countries.

Table 2. Estimation results of ECM models for EU countries

Country	Const	GDP *per capita*	Annual CO_2 emissions	Number of patents	*Per capita* electricity consumption	Electricity prices	R&D (% of GDP)	Researchers in R&D	Error--correction term	R^2
		d_lnX_{1t}	d_lnX_{2t}	d_lnX_{3t}	d_lnX_{4t}	d_lnX_{5t}	d_lnX_{6t}	d_lnX_{7t}	ECT_{t-1}	
Austria	-0.034***	0.559**	0.276**	0.054**	0.105***	0.178***	0.213***	-0.098	-0.164**	0.476
Belgium	-0.034**	0.511**	-0.242	0.069***	0.220**	0.206***	0.205**	-0.125**	-0.273***	0.544
Bulgaria	-0.034***	0.652**	0.386**	-0.062*	0.096**	0.224***	0.110	-0.053	-0.094**	0.656
Croatia	-0.025**	0.495**	0.255***	0.038	0.108	0.187***	0.040**	-0.029	-0.308***	0.614
Czechia	-0.509***	0.309**	0.960**	0.102	0.971**	0.353	-0.966*	0.643	-0.047**	0.745
Denmark	-0.034**	0.511**	-0.242	0.069***	0.220**	0.206***	0.205**	0.225***	-0.273***	0.727
Estonia	-0.277***	0.235**	-0.735	0.035	0.890***	0.230***	-0.039	-0.334	-0.427**	0.489
Finland	-0.039***	0.452**	0.221***	-0.069***	0.250**	0.149***	0.127*	-0.009	-0.102***	0.441
France	-0.001	0.162**	0.055***	0.020**	0.034***	0.115***	0.152**	0.479***	-0.492**	0.581
Germany	-0.002	0.448**	0.153***	0.029***	0.067***	0.321***	0.421***	0.496**	-0.363*	0.752
United Kingdom	-0.025***	0.232***	0.391**	0.081**	0.292***	0.351**	-0.065	0.188	-0.404***	0.549
Greece	-0.044***	0.676**	-0.029**	0.083**	0.219	0.248***	0.086	0.018	-0.321	0.707
Hungary	-0.255	0.217**	-1.764*	0.032**	0.883**	0.213**	-0.473*	0.308	-0.333*	0.734
Ireland	-0.020**	0.311**	-0.044	0.049**	0.134*	0.142***	0.214**	-0.244*	-0.347***	0.559
Italy	-0.028**	0.410**	-0.099	0.057**	0.152**	0.158***	-0.229	0.264*	-0.265***	0.551
Latvia	-0.268***	0.228**	0.264**	0.034	0.987***	0.223**	-0.213	0.324	-0.553***	0.509
Lithuania	-0.307***	0.260**	-0.705	0.039**	0.899**	0.255***	0.568***	0.370	-0.408	0.733
Netherlands	-0.030***	0.431**	0.219***	0.062**	0.167***	0.157***	0.140***	-0.068	0.035	0.464
Poland	-0.002	0.124**	0.967***	-0.037	0.094**	0.073***	0.018*	-0.025	-0.619**	0.551
Portugal	-0.045***	0.951**	0.697***	0.096**	0.077	0.330***	0.273	-0.149	0.558***	0.578
Romania	-0.025***	0.464**	0.194***	0.039	0.107**	0.170***	-0.153	0.0864	-0.107**	0.560
Spain	-0.068***	0.737***	-0.111	0.124*	0.033***	0.087**	0.415**	0.430***	-0.107***	0.646
Sweden	-0.054***	0.602***	-0.0354	0.103**	0.145*	0.133***	0.348**	0.470***	-0.431*	0.714

Note: *** significance at the level of 1%, ** significance at the level of 5%, *significance at the level of 10%.

Source: own study.

Analysing the content of Table 2, it can be concluded that the explanatory variables in the equations representing short-term dependencies usually have a stimulating effect on the diffusion of wind technology innovations. In the ECM models the most significant variable influencing the rate of diffusion of wind technology innovations is *energy price* (18 countries with a significance of this variable at the level of 1% and four countries with a significance of 5%). A particularly strong and positive impact of this variable is visible in Germany and Portugal, where the value of the α_5 parameter indicates an increase in the growth rate of the logistic curve by more than 0.3% on average caused by an increase in the change in *electricity price* by 1% ceteris paribus.

Secondly, a significant determinant of the diffusion of wind energy is the *Per capita electricity consumption* (nine countries with a significance of this variable at the level of 1% and ten countries with a significance of 5%). The countries where the stimulating nature of this variable was particularly strong included Lithuania, Latvia, Estonia and Czechia, where a 1% change in electricity consumption implied an increase in the rate of change in the growth rate of the logistic function by over 0.8% on average, ceteris paribus.

Relatively often the *annual CO_2 emission* turned out to be a statistically significant stimulant of the growth rate of wind energy diffusion (eight countries with a significance level of this variable of 1% and six countries with a significance level of 5%). Its strong influence on the diffusion dynamics can be seen especially in Czechia and in Poland, where a 1% increase in *CO_2 emissions* resulted in an increase in the change in RGL by an average of over 0.8% ceteris paribus. In turn, GDP had the strongest influence on the growth dynamics of wind energy diffusion in southern European countries, e.g. in Spain, Portugal and Greece. The least significant variable turned out to be *Researchers in R&D* (the result was insignificant in 15 countries). This variable had a statistically significant and positive effect (at a significance level of 0.05 or lower) on the diffusion rate only in Germany, France, Spain, Sweden and Denmark. Moreover, in 16 countries the estimation results of the error correction mechanism parameter were negative and statistically significant at the 0.05 level of significance or lower, which indicates the adjustment of short-term changes to the long-term balance, with the fastest adjustment of short-term changes seen in France, Latvia and Poland.

Table 3 contains the parameter estimates of cointegrating models describing long-term dependencies in individual EU countries. It shows that also in the long term, the most important factor affecting the growth rate of the logistic curve diffusion was *electricity price* (a factor significant at a significance level of 0.01 in 21 countries, and significant at a significance level of 0.05 in two countries). A particularly strong influence of this variable on the rate of diffusion was visible in Czechia, Germany and Poland, where a 1% increase in price caused an increase in the rate of wind energy diffusion in the long term by an average of about 0.5% ceteris paribus.

Table 3. Estimation results of cointegrating models for EU countries

Country	Const	GDP *per capita*	Annual CO_2 emissions	Number of patents	*Per capita* electricity consumption	Electricity prices	R&D (% of GDP)	Researchers in R&D	R^2
		lnX_{1t}	lnX_{2t}	lnX_{3t}	lnX_{4t}	lnX_{5t}	lnX_{6t}	lnX_{7t}	
Austria	-0.048^{**}	0.821	0.298^{**}	0.066^{**}	0.152^{***}	0.205^{***}	0.225^{***}	0.141^{**}	0.760
Belgium	-0.046^{***}	0.696^{***}	-0.255	0.078^{***}	0.243^{**}	0.264^{***}	0.225^{**}	0.127^{***}	0.722
Bulgaria	0.010^{***}	0.232^{***}	0.081^{***}	0.036^{*}	0.053^{***}	0.051^{***}	0.099	0.067	0.651
Croatia	-0.025^{***}	0.496^{**}	0.255^{***}	0.039	0.108^{***}	0.187^{***}	0.041^{**}	-0.030	0.762
Czechia	-0.721^{***}	0.349^{**}	0.774^{**}	0.142	0.711^{***}	0.517^{***}	-1.120^{*}	-0.744	0.679
Denmark	-0.051^{***}	0.560^{**}	-0.310	0.079^{**}	0.228^{**}	0.283^{***}	0.289^{***}	0.153^{*}	0.696
Estonia	-0.277^{***}	0.235^{**}	-0.735^{***}	0.035^{***}	0.590^{***}	0.231^{***}	-0.039	-0.334	0.700
Finland	-0.053^{***}	0.532^{**}	0.277^{***}	0.097^{***}	0.343^{**}	0.157^{***}	0.168^{**}	-0.013	0.639
France	0.005	0.180^{**}	0.060^{***}	0.023^{**}	0.039^{***}	0.146^{***}	0.185^{**}	0.202^{*}	0.890
Germany	-1.260	0.177^{***}	0.109^{*}	0.016^{**}	0.098^{**}	0.514^{***}	0.690^{***}	0.558^{**}	0.678
United Kingdom	-0.038^{***}	0.047	0.455^{**}	0.060^{**}	0.369^{*}	0.013^{***}	0.091^{**}	-0.236^{*}	0.936
Greece	-0.045^{***}	0.933^{***}	-0.032^{**}	0.093^{**}	0.230	0.322^{***}	0.110	0.027^{*}	0.977
Hungary	-0.353^{***}	0.241^{**}	0.866^{**}	0.042^{***}	0.958^{***}	0.251^{**}	0.552^{*}	-0.458	0.703
Ireland	-0.022^{**}	0.346^{**}	0.057^{*}	0.072^{***}	0.184^{**}	0.167^{***}	0.313^{**}	-0.290^{*}	0.725
Italy	-0.042^{***}	0.571^{***}	-0.140	0.082^{***}	0.219^{***}	0.201^{***}	0.297^{**}	0.333^{*}	0.638
Latvia	-0.280^{***}	0.340^{***}	0.317^{**}	0.039	0.591^{***}	0.315^{***}	-0.308	0.441	0.973
Lithuania	-0.440^{***}	0.323^{***}	-0.881	0.050^{***}	0.903^{**}	0.257^{***}	0.638^{***}	0.441	0.984
Netherlands	-0.040^{***}	0.456^{**}	0.227^{***}	0.081^{***}	0.207^{***}	0.204^{***}	0.191^{***}	0.084^{**}	0.905
Poland	-0.003	0.129^{**}	0.204^{***}	-0.046	0.125^{**}	0.108^{***}	0.019^{*}	-0.034	0.933
Portugal	-0.047^{***}	1.079^{**}	0.923^{***}	0.108^{**}	0.115	0.484^{***}	-0.392^{*}	-0.156	0.734
Romania	-0.028^{***}	0.595^{***}	0.251^{***}	0.046	0.156^{***}	0.224^{***}	-0.162^{*}	0.105^{*}	0.935
Spain	-0.079^{***}	0.923^{***}	-0.145	0.134^{*}	0.034^{***}	0.087^{**}	0.616^{***}	-0.585^{***}	0.784
Sweden	-0.065^{***}	0.812^{***}	-0.055	0.160^{**}	0.159^{**}	0.193^{***}	0.555^{***}	0.738^{***}	0.739

Note: *** significance at the level of 1%, ** significance at the level of 5%, *significance at the level of 10%.

Source: own study.

The next most statistically significant factor affecting the GRL in the long term was *GDP per capita* (a factor significant at a significance level of 0.01 in 10 countries and in 11 countries at a significance level of 0.05). Similarly to the short term, GDP per capita stimulated the diffusion of innovations the most in Portugal, Greece, Spain, and in Sweden. An important stimulant of the rate of diffusion of innovations in the long term was also *energy consumption per capita* (a factor statistically significant at the 0.01 level of significance in 12 countries and at the 0.05 level of significance in eight countries). Its strongest impact can be observed in Lithuania and Hungary, where a one percent increase in *energy consumption per capita* caused an increase in GRL by approximately 0.591% and 0.958%, respectively, ceteris paribus. The number of scientists appeared to be most often an insignificant factor in the rate of innovation diffusion (this factor was statistically significant at a significance level of 0.01 only in three countries, and in four countries at a significance level of 0.05). An interesting comparative analysis is the statistical significance of the factors of growth in the diffusion of innovation between the 'new' EU members (Poland, Czechia, Slovakia, Hungary, Lithuania, Latvia, Estonia, Bulgaria, Romania, Croatia) and the 'old' member states

(Germany, France, Italy, Sweden, Spain, Portugal, Greece, Belgium, the Netherlands, Austria, Ireland, Finland, Great Britain[3]). In the long and short term, the greatest differences in the statistical significance of the impact of explanatory variables on the rate of diffusion of wind innovations between old and new EU member states occurred in relation to *the number of patents* in the renewable energy sector, *electricity consumption per capita* and the *share of R&D expenditures*. *The number of patents* and *R&D expenditures* were relatively more often a statistically significant determinant of innovation diffusion (at a significance level of 0.05) among old EU member states than in the member states of Central and Eastern Europe. In turn, *electricity consumption* in the Central European EU countries was relatively more often a statistically significant determinant of the rate of diffusion of wind technologies (at a significance level of 0.05) than in the old EU member states. However, the *number of researchers in R&D* was also relatively more often a statistically insignificant determinant of the rate of diffusion of wind energy in the countries of Central and Eastern Europe than in Western Europe.

5. Discussion and conclusions

The research results show that there is a large variation in the EU countries in terms of the demand for wind energy, the use of this form of energy potential, and the rate of wind energy diffusion. These results, showing the impact of socio-economic factors on the dynamics of wind energy diffusion, were generally consistent with similar results of other researchers (Keeley & Matsumoto, 2018). Marques et al. (2010), for example, demonstrated that the length of time countries were the EU member states was important for explaining the issue of renewable energy sources. Biresselioglu et al. (2016) study confirmed, among other things, that GDP *per capita* was a particularly important determinant of installed wind capacity development in Southern European countries, while electricity prices were a significant determinant of renewable energy sources in both Central and Western European countries. These results support the conclusions obtained by the author. This consistency was also confirmed by extensive meta-analyses covering studies on factors constituting drivers and barriers to wind energy development, as well as the development of energy powered by other renewable energy sources (Zwarteveen et al., 2021; Şener et al., 2018). In general, meta-analyses also indicate that different groups of countries have different factors influencing the diffusion of wind energy, and the leading factors determining the development of this form of energy are mainly economic and environmental factors . The determinants of energy diffusion identified in this paper are important in most of the countries studied, yet with some visible differences, especially between the countries of Central and Eastern Europe ('new' EU member states) and the countries of Western Europe ('old' EU member states).

Showing the direction and strength of the impact of individual factors on the diffusion of innovations in wind energy can provide important guidance to decision-makers responsible for shaping energy policy at both national and EU levels. This is particularly important in view of the challenges posed to humanity by global warming, caused mainly by excessive greenhouse gas emissions. Striving for zero-emission economies appears one of the rational postulates, and its key element is replacing traditional energy sources with renewable sources. Wind energy has a role to play, but its potential is still not fully exploited. The presented results allow for indicating areas where appropriate decisions can improve the use of this potential, one of those being certainly science and research in the field of renewable energy sources. This is especially visible among the new Member States, where the problem is usually the insufficient number of researchers dealing with RES and low expenditure on research and development conducted in the field of renewable energy sources (these factors turned out to be more often insignificant in this group of countries).

The result is insufficient innovation in this sector in some countries, which may result in lower efficiency of wind energy and, consequently, its smaller share in national energy systems. The situation

[3] Brexit was in 2020, but the study period included data from 2000 , so the UK was included in the analysis.

can be improved by a systemic change of national energy policies to more pro-ecological ones. Support for investors from the government is also necessary in the scope of more liberal legal regulations, which allow for the introduction of flexible regulations regarding the location of wind farms. In addition, an appropriate information policy is also necessary, the aim of which is creating positive social attitude towards green energy obtained from wind. It is also important to develop offshore energy sector, which is much more efficient than onshore wind farms. There are other areas and activities in which appropriate changes could improve the diffusion of wind energy – an example is the outdated energy infrastructure that requires modernisation in order to integrate it more effectively with renewable energy sources. Another important area is the billing system, applied tariffs for consumers and prosumers of electricity, which in many countries is not conducive to the diffusion of wind energy. These and other aspects of the problem under investigation require further detailed research, and their results may be helpful in preparing detailed plans and current actions in the area of energy policy in individual EU countries. This article also opens the door to further research on the prospects for wind energy development in the EU. Further analyses should consider a broader range of factors, including national energy policy and social factors. Future research should also consider other analytical tools, such as panel data models, and create wind energy development projections.

References

Almeida, D. V., Kolinjivadi, V., Ferrando, T., Roy, B., Herrera, H., Gonçalves, M. V., & Van Hecken, G. (2023).The "Greening" of Empire: The European Green Deal as the EU first agenda. *Political Geography*, *105*, 1-16. https://doi.org/10.1016/j.polgeo.2023.102925

Bass, F. M. (1969). A new product growth for model consumer durables. *Management Science*, *15*(5), 215-227. https://doi.org/10.1287/mnsc.15.5.215

Biresselioglu, M. E., Kilinc, D., Onater-Isberk, E., & Yelkenci, T. (2016). Estimating the political, economic and environmental factors' impact on the installed wind capacity development: A system GMM approach. *Renewable Energy*, *96*, 636-644. https://doi.org/10.1016/j.renene.2016.05.034

Carley, S. (2009). State renewable energy electricity policies: An empirical evaluation of effectiveness. *Energy Policy*, 37(8), 3071-3081. https://doi.org/10.1016/j.enpol.2009.03.062

Del Río, P., & Tarancón, M. Á. (2012). Analysing the determinants of on-shore wind capacity additions in the EU: An econometric study. *Applied Energy*, *95*, 12-25. https://doi.org/10.1016/j.apenergy.2012.01.043

Dooley, K., & Kartha, S. (2018). Land-based negative emissions: Risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, *18*, 79-98. https://doi.org/10.1007/s10784-017-9382-9

Engle, R. F., & Granger, C. W. J. (1987). Co-integration and Error Correction: Representation, Estimation, and Testing. *Econometrica*, *55*(2), 251-276. https://doi.org/10.2307/1913236

Eurostat database (2024). https://ec.europa.eu/eurostat/data/database

Grubb, M. et al. (2021). The New Economics of Innovation and Transition: Evaluating Opportunities and Risks. Economics of Energy Innovation and System Transition, University of Exeter, the Report, https://eeist.co.uk/download/557/

Keeley, A. R., & Ikeda, Y., (2017). Determinants of foreign direct investment in wind energy in developing countries. *Journal of Cleaner Production*, 161, 1451-1458. https://doi.org/10.1016/j.jclepro.2017.05.106

Keeley, A. R., & Matsumoto, K. (2018). Investors' perspective on determinants of foreign direct investment in wind and solar energy in developing economies e review and expert opinions. *Journal of Cleaner Production*, *179*, 132-142. https://doi.org/10.1016/j.jclepro.2017.12.154

Lehtovaara, M., Karvonen, M., Kapoor, R., Kässi, T. S., & Pyrhönen, J. (2014). Major factors contributing to wind power diffusion. *Foresight*, *16*(3), 250-269. https://doi.org/10.1108/FS-03-2013-0012

Lei, Y. C., & Zhang, S. Y. (2004). Features and Partial Derivatives of Bertalanffy – Richards Growth Model in Forestry. *Nonlinear Analysis: Modelling and Control*, *9*(1), 65-73. https://doi.org/10.15388/NA.2004.9.1.15171

Markard, J., Geels, F.W., & Raven, R. (2020). Challenges in the acceleration of sustainability transitions. *Environmental Research Letters*, *15*(8), 1-6. https://doi.org/10.1088/1748-9326/ab9468

Marques, A., Fuinhas, J., & Pires, J. (2010). Motivations driving renewable energy in European countries: A panel data approach. *Energy Policy*, 38(11), 6877-6885. https://doi.org/10.1016/j.enpol.2010.07.003

Our World in Data (2024). https://ourworldindata.org/renewable-energy

Şener, Ş. E. C., Anctil, A., & Sharp, J. L. (2023). Economic and environmental factors of wind energy deployment in the United States. *Renewable Energy Focus*, *45*, 150-168. https://doi.org/10.1016/j.ref.2023.03.004

Şener, Ş. E. C., Sharp, J. L., & Anctil, A. (2018). Factors impacting diverging paths of renewable energy: A review. *Renewable and Sustainable Energy Reviews*, *81*(2), 2335-2342. https://dx.doi.org/10.1016/j.rser.2017.06.042

She, Z. Y., Cao, R., Xie, B. C., Ma, J. J., & Lan, S. (2019). An analysis of the wind power development factors by Generalized Bass Model: A case study of China's eight bases. *Journal of Cleaner Production*, *231*(10), 1503-1514. https://doi.org/10.1016/j.jclepro.2019.05.255

Sisodia, G. S., & Soares, I. (2015). Panel data analysis for renewable energy investment determinants in Europe. *Applied Economics Letters*, *22*(5), 397-401. https://dx.doi.org/10.1080/13504851.2014.946176

Sisodia, G. S., Soares, I., & Ferreira, P. (2016). The effect of sample size on European Union's renewable energy investment drivers. *Applied Economics*, *48*(53), 5129-5137. https://dx.doi.org/10.1080/00036846.2016.1173176

Steffen, B., Matsuo, T., Steinemann, D., & Schmidt, T. S. (2018). Opening new markets for clean energy: The role of project developers in the global diffusion of renewable energy technologies. *Business and Politics*, *20*(4), 553-587. https://dx.doi.org/10.1017/bap.2018.17

Strantzali, E., & Aravossis, K. (2016). Decision making in renewable energy investments: A review. *Renewable and Sustainable Energy Reviews*, *55*, 885-898. https://dx.doi.org/10.1016/j.rser.2015.11.021

Wei, Z., & Huang, L. (2022). Invading the dynamics of economic growth and CO_2 emission: Panel data error correction model (ECM) approach. *Environmental Science & Pollution Research*, *29*(48). https://dx.doi.org/10.1007/s11356-024-34291-w

Ydersbond, I. M., & Korsnes, M. S. (2016). What drives investment in wind energy? A comparative study of China and the European Union. *Energy Research & Social Science*, *12*(2), 50-61. https://dx.doi.org/10.1016/j.erss.2015.11.003

Yin, A., & Powers, N. (2010). Do state renewable portfolio standards promote in-state renewable generation? *Energy Policy*, *38*(2), 1140-1149. https://doi.org/10.1016/j.enpol.2009.10.067

Zwarteveen, J. W., Figueira, C., Zawwar, I., & Angus, A. (2021). Barriers and drivers of the global imbalance of wind energy diffusion: A meta-analysis from a wind power Original Equipment Manufacturer perspective. *Journal of Cleaner Production*, *290*, 125636. https://doi.org/10.1016/j.jclepro.2020.125636

Zwarteveen, J. W, Zawwar, I. & Angus, A. (2022). Market entry for wind energy: Strategic approaches for the original equipment manufacturer. *Business Strategy & Development*, *5*(3), 165-186. https://doi.org/10.1002/bsd2.188

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