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Technological investments and green energy production in Central and Eastern Europe

Marcin Salamaga

ABSTRACT

Objective: The article aims to examine the impact of technological investments on the development of wind energy and photovoltaics in Central and Eastern European countries (CEE) belonging to the EU.

Research Design & Methods: In the analysis of the impact of expenditure on technical investments, I used panel threshold analysis and bootstrap simulation tests. I built the models based on the basis of annual data on the renewable energy market from 2013-2023 from the 'Our World in Data' databases and Eurostat.

Findings: Research and development (R&D) expenditure stimulates the production of electricity from wind turbines to a greater extent than from PV panels. The strongest stimulation of electricity production simultaneously by a wind turbine and PV panels will occur when R&D expenditure ranges from 0.96% to 1.39% of GDP. If these expenses are in the range of 0.78% to 0.96% of GDP, solar energy will be stimulated the most, while if R&D expenditures are in the range of 1.39% to 1.61%, wind energy will be stimulated the most by these expenses. A simultaneous weakening of the development of wind and solar energy will occur when R&D expenditure is below 0.78% of GDP. Exceeding subsequent R&D expenditure thresholds weakens the effects of increasing energy production from renewable energy sources, which is caused by the intensification of the impact of various barriers inhibiting the development of renewable energy sources.

Implications & Recommendations: The obtained results may be helpful for decision-makers responsible for shaping energy policy in individual countries of Central and Eastern Europe. Stimulation of the renewable energy sector through R&D expenditure is limited due to the existing barriers to the development of renewable energy sources specific to various countries. Fully exploiting the potential of renewable energy requires a gradual overcoming of these limitations. Energy policy aimed at eliminating barriers to the development of renewable energy should consider the local conditions of individual countries in terms of their natural conditions, available resources, energy infrastructure, diversification of energy sources, etc.

Contribution & Value Added: The article presents an original analysis of the impact of expenditure on technological investments using panel threshold analysis and bootstrap simulation tests. The presented results bring added value to economic and policy research in the renewable energy sector.

Article type:	research article
Keywords:	renewable energy sources; wind energy; photovoltaics; panel threshold analysis; Central and Eastern Europe (CEE)
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INTRODUCTION

Climate change caused by excessive greenhouse gas emissions has far-reaching effects at the national and global levels. The costs that the economy incurs as a result of them are enormous and many sectors, industries, and entire societies experience them. Among others, they include material losses in the economy's infrastructure caused by devastating weather phenomena (floods, droughts, hurricanes), losses in agricultural crops and the growing threat to food security, costs resulting from disruptions in foreign trade and supply chains, and many others. Moreover, the limited supply of fossil fuels, their growing and unstable prices, and the desire to diversify energy sources force the governments of individual countries to conduct an energy transformation, the key element of which is replacing conventional energy sources with renewable energy sources (Xie *et al.*, 2020; Zhou *et al.*, 2019; Sun *et al.*, 2021). Photovoltaics and wind energy are very important in this respect, as they support sustainable development, combining economic benefits with environmental protection, and in the long term, improve the quality of life and help preserve natural resources for future generations. However, the development of this type of renewable energy requires continuous investments in new technologies. Thanks to them, it is possible to increase the efficiency of energy production through efficient solar panels and wind turbines and, in the longer term, reduce the costs of energy production (Matsuo, 2019; Zhou & Gu, 2019). Countries can achieve it through both innovative solutions and the modernization and expansion of the existing energy infrastructure, which in many countries of Central and Eastern Europe is very outdated (Mazurek-Czarnecka *et al.*, 2022; Szép *et al.*, 2023; Leal Filho *et al.*, 2021). In addition to improving photovoltaic panels and wind turbines to increase their efficiency, the key directions of technological investments in the area of renewable energy include the construction of energy storage facilities and smart energy networks integrated with traditional energy networks (Mengxuan *et al.*, 2024; Leal Filho *et al.*, 2021).

Of course, the effectiveness of the energy transformation is also conditioned by a number of other factors that will not be the subject of detailed considerations in this study, such as appropriate regulatory and political support (*e.g.*, a feed-in tariff system) or raising environmental awareness and appropriate education (Mengxuan *et al.*, 2024; Mazurek-Czarnecka *et al.*, 2022). Previous scientific research shows that the relationship between technological innovation and energy production from renewable energy sources is not necessarily linear and various factors such as technological infrastructure, the level of investment in modern technologies, or the state's energy policy may differentiate it. Thus, the efficiency of clean energy production and the rate of cost reduction of renewable energy technologies may depend on the level of countries' technological advancement, the level of expenditure on technological investments, and the number of patents related to renewable energy sources (Leal Filho *et al.*, 2021; Li *et al.*, 2023). Here, technological investments are financial outlays aimed at implementing new or improving existing technologies to increase productivity, efficiency or innovation.

In countries with a low level of innovation, these effects may be weaker, and among technological leaders – significant (Li *et al.*, 2023; Mengxuan *et al.*, 2024). Hence, it seems justified to look for appropriate threshold values of investments in technologies (measured by R&D expenditure or the number of patents), above which the effects of changes in the renewable energy sector are significant (and below which they are, for example, poorly visible). Indicating such thresholds is possible using econometric modelling conducted based on historical data including selected indicators of renewable energy development, R&D expenditure and other macroeconomic variables. A dedicated tool for estimating this type of threshold is panel threshold regression models and I will use these models in this article (Hansen, 1999). They allow us to capture the nature of relationships between variables that are not possible to observe in ordinary linear regression models.

In this research, such models will serve to isolate the range of values of the share of R&D expenditures in GDP, at which the strength and dynamics of stimulating wind energy and photovoltaics through investments in green technologies are the most intense, and the range of values of R&D expenditures, where they are weak. I aimed to comprehensively examine the impact of technological investments on the production of green energy in Central and Eastern European countries. The technological investments considered in this article concern projects involving the implementation of technologies related to renewable energy sources (construction of wind farms, photovoltaic farms, energy storage facilities or energy infrastructure), while the term green energy refers to electricity generated by wind turbines or photovoltaic panels. The choice of these countries resulted from the fact that researchers rarely analyze in a comprehensive way the impact of innovation and technological investments on the diffusion of renewable energy technologies and energy production from renewable energy sources in all these countries (Mengxuan *et al.*, 2024). Meanwhile, the energy transformation that these countries are going through requires overcoming numerous difficulties related to the strong dependence of their economies on fossil fuels, outdated energy infrastructure, lack of their own renewable energy technologies and the need to import them, insufficient funds for the modernization of energy systems requiring the withdrawal of conventional electricity sources and replacing them with renewable energy sources (Pakulska, 2021; Mazurek-Czarnecka *et al.*, 2022).

The problems that the economies of CEE countries face are often more serious than in Western European countries, which generally have their own base of advanced renewable energy technologies (Leal Filho *et al.*, 2021). Therefore, monitoring the progress in the energy transformation and identifying ways to overcome the barriers that slow down this transformation seems to be a necessity. By filling the research gap, this article will at least partially answer what actions to take to improve the effectiveness of renewable energy implementation in CEE countries and thus support the energy transformation process. The research conclusions can support decision-makers responsible for shaping energy policy at national and EU levels. This is even more important because EU countries, under various agreements, directives and general EU strategies, are obliged to replace conventional energy sources with renewable energy sources. Therefore, energy transformation is a necessity, and the countries of Central and Eastern Europe, due to their technological backwardness and the strong dependence of their economies on fossil fuels, require particularly intensive actions in this area. The main novelty of this article is the presentation of the impact of technological investments on the development of wind energy and photovoltaics in the countries of Central and Eastern Europe using the panel threshold regression model. This is the first application of this research method in the analysis of the production of these two types of green energy in the economies of Central and Eastern European countries. The main advantage of using panel threshold regression over the tools used by other researchers is the possibility of isolating nonlinear relationships between variables. Thanks to the applied approach, the research results allow for the formulation of specific recommendations for decision-makers responsible for economic policy. For example, the article answers the question of the level at which R&D expenditures should be set, and to which sectors they should be directed, to optimize the structure and level of green energy production.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Research on technological investments' impact on the development of renewable energy sources has been conducted for years. However, recently, the intensity of publications on this subject has significantly increased, which probably results from the intensification of activities aimed at energy transformation undertaken at the levels of individual countries and the entire EU. Based on the literature studies, we can conclude that researchers focus on various aspects of this issue, which allows us to distinguish certain directions of research on stimulating the development of renewable energy sources through technological investments, such as analysis of the efficiency and effectiveness of renewable energy sources, cost analysis, development of system innovations or research on the scalability of production of renewable energy infrastructure components. As part of the first of the above-mentioned research trends, I tried to check to what extent spending on research and development, together with other stimulants, increases the overall share of renewable energy sources in the energy mix of individual countries or regions, or examine how the efficiency and productivity of these energy sources change.

Using the autoregressive distributed lags model (ARDL), Chmielewski *et al.* (2023) showed that in EU countries there is a strong positive relationship between research and development expenditure and the increase in energy consumption from renewable sources, while their impact on reducing fossil fuel consumption and energy prices is less significant. Using a similar research methodology, Li *et al.* (2020) proved the positive impact of eco-innovation, as well as energy productivity, human capital, and energy prices on the development of renewable energy. In turn, Sun *et al.* (2021) examined the impact of R&D expenditure, and in particular, the impact of the international dissemination of knowledge related to the reduction of energy intensity on energy efficiency in EU countries. Using data from the OECD Triadic Patent Families database for 24 innovative countries from 1994-2013, they proved the existence of a positive relationship between these values, and among the most energy-efficient countries, they indicated Germany, France, Great Britain, the Netherlands and Switzerland. Churchill *et al.* (2021) analysed the impact of R&D expenditure on energy consumption per capita and using the local linear dummy variable estimation (LLDVE) method on the example of OECD countries, they showed positive effects in the area of renewable energy, although their occurrence depended on the period under study.

Geng and Ji (2016) demonstrated the existence of a long-term balance between technological innovation and other external drivers and renewable energy consumption. Moreover, they proved the existence of bidirectional causality between these categories. There are relatively many articles in which scholars examine the relationships in question for Asian markets. An example would be the article by He *et al.* (2018), in which the authors confirmed a positive relationship between the studied variables for the Chinese market. They obtained these results by examining 29 provinces in China using a dynamic panel approach. Kocsis and Kiss (2014) studied the relationships between the share of renewable energy consumption in gross energy consumption, GDP per capita and research and development expenditure in European Union countries. They confirmed a positive relationship between research and development expenditure and renewable energy consumption at various GDP levels.

Li *et al.* (2023) obtained interesting results from the study of the impact of technological investments on the diffusion of renewable energy technologies using panel threshold regression. Using the example of G10 countries, they showed that technological innovations have little impact on renewable energy when technological innovations are below a certain threshold of the share of R&D spending in GDP. Exceeding this threshold means that technological innovation has a strong positive impact on renewable energy. Xie *et al.* (2020) showed that the development of new technologies can stimulate the positive impact of renewable energy consumption on green economic development while reducing the dependence of gross domestic product (GDP) on fossil fuels improves the coordination of the relationship between these quantities. The second of the mentioned trends focuses on diagnosing factors that reduce the costs of renewable energy. Scholars who undertook cost analysis were, among others, Matsuo (2019), Zhou and Gu (2019), and Elia *et al.* (2021). They showed that research and development expenditure directed towards renewable energy sources contributes significantly to reducing unit production costs. These authors propose various forms of support for the renewable energy sector to increase its efficiency and reduce energy production costs.

For example, Esmaieli *et al.* (2018) suggest an approach based on supporting research and development activities to reduce the investment costs of wind units. It involves paying a fixed amount of money to wind units in proportion to their installed capacity, which then allocate the received funds for research and development activities. Appropriate simulations conducted by the authors confirmed the effectiveness of this type of support compared to other known incentives. Numerous works highlight the importance of both learning by doing and learning by searching (R&D spending) in driving technological progress that is expected to significantly accelerate cost reduction and market penetration of renewable energy (Hayamizu *et al.*, 2014; Zhou & Gu, 2019; Cory *et al.*, 1999). Moreover, researchers emphasize the need for institutional support and policy instruments to promote renewable energy adoption and cost reduction (Zhou & Gu, 2019).

Despite relatively numerous publications devoted to the impact of technological investments on the development of renewable energy in various countries, there is no in-depth analysis of such a relationship for the EU countries of Central and Eastern Europe. Meanwhile, most of these countries face greater challenges in implementing the energy transformation compared to Western European countries due to their strong dependence on their own fossil fuels (*e.g.*, Poland) or their import from abroad (Hungary), an outdated energy network requiring high expenditure, modernization, limited budget funds for costly transformation, the low energy efficiency of old buildings that dominate the housing structure, social and political resistance to the reduction of employment in the energy sector and mining. The few works that undertake a broader study of the impact of technological investments on energy efficiency in CEE countries include an article by Mengxuan *et al.* (2024). Using Grenger's panel causality analysis, the authors demonstrated the impact of various factors on energy efficiency and showed the existence of a feedback relationship. They showed, among others, that through various economic and political factors, technological investments significantly affect energy efficiency in the

Czech Republic, Latvia, Lithuania, Slovakia and Slovenia. They used panel threshold regression aggregate energy efficiency (calculated ratio of total energy generated to GDP), which makes it difficult to assess the contribution of renewable energy sources to the energy transformation of individual countries. For this reason, it seems necessary to fill the research gap and analyse the impact of technological investments separately on wind and solar energy in CEE countries, which will allow for assessing the effectiveness of tools stimulating the diffusion of energy based on renewable energy sources. To examine the relationship between technological investments and the development of wind and solar energy, I used a threshold panel regression model, which allowed me to capture the non-linear relationships that occurred between these variables (Mengxuan *et al.*, 2024; Li *et al.*, 2023). To achieve the main research objective, I decided to verify the following hypotheses:

H1: In CEE countries, there is at least one threshold point of R&D expenditure, exceeding which significantly changes the impact of technological investments on the amount of energy generated by wind turbines or photovoltaic panels.

H2: In CEE countries, the impact of technological investments on the production of energy from wind turbines is different than from photovoltaics.

Hypothesis H1 was inspired by literature studies, including empirical studies on various economies in the world, in which it was possible to identify threshold values for investment in innovations that differentiate the effects resulting from the production of green energy (Li *et al.*, 2023; Mengxuan *et al.*, 2024). Moreover, literature studies indicate that in CEE countries, the investment priorities of the governments of individual countries in the development of photovoltaics and wind energy are not the same, which is the result of, among others, specific natural conditions in these countries (*e.g.*, wind potential, solar radiation), social conditions (lower acceptance of wind energy) and economic conditions (differences in investment costs) (Mazurek-Czarnecka *et al.*, 2022; Leal Filho *et al.*, 2021). In turn, this shows the validity of hypothesis H2. The econometric model I used enabled the verification of both these hypotheses.

RESEARCH METHODOLOGY

Considering the differences in the levels of technological innovation measured by R&D expenditure in various EU countries, I expected that I would encounter thresholds affecting the production of electricity by wind farms and energy from photovoltaics. Determining threshold values for the level of technological innovation would allow for identifying the directions and strength of the impact of R&D on wind and solar energy in the surveyed countries. For this purpose, I used threshold panel regression (Hansen, 1999), which would eliminate the random effect of artificial grouping. I used this type of regression to study the relationship between energy efficiency and technological investments in Central and Eastern European countries, among others, Mengxuan *et al.* (2024).

However, they modelled the overall efficiency of electricity production, which does not allow for determining how R&D expenditure translates into an increase in energy production coming entirely from renewable energy sources or from individual types of renewable energy sources. This study overcame this limitation and built models separately for wind and solar energy (the amount of energy generated by these types of renewable energy sources was modelled), which facilitates the assessment of the ability of investment expenditure to stimulate energy transformation. This is also the unique contribution of this work: separating solar energy from wind energy in threshold panel regression models provides much greater possibilities for controlling the state's innovation policy in the field of RES. The study covered 11 Central and Eastern European countries that are EU members, namely, the Czech Republic, Croatia, Bulgaria, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia, and Slovenia. I built the models based on annual data on the renewable energy market from 2013-2023 from the 'Our World in Data' (2024) databases and Eurostat (2024).

The research included models with one threshold point for R&D spending and a model with two threshold points. The modelled endogenous variable is green energy production defined as energy generated by wind turbines or photovoltaic panels, which seems to be the right category to reflect the development of renewable energy sources (Mengxuan *et al.*, 2024). The proposed explanatory variables are substantively related to the development of renewable energy sources and the amount of energy produced by them. Obviously, GDP, R&D and the number of patents in renewable energy technologies influence the level of green energy production, because renewable energy sources require investment and innovation (Li *et al.*, 2023). Research and development expenditure includes expenses incurred on creating new technologies as well as improving existing solutions that support the efficiency, availability, and profitability of renewable energy. Electricity consumption also determines the demand for energy also from renewable energy sources (Geng & Ji, 2016). Thus, I also considered it. The model also includes the price of electricity as a determinant of green energy production, as it is expected that the rising prices of electricity from fossil fuels will encourage the search for cheaper energy sources (Elia *et al.*, 2021). Many studies also indicate a possible relationship (negative or positive) between CO2 emissions and renewable energy production (Mazurek-Czarnecka *et al.*, 2022). Thus, I also included this variable in the model. The equations of these models were as follows:

Single threshold model:

$$Y_{it} = \theta + \alpha_1 CO2_{it} + \alpha_2 TNP_{it} + \alpha_3 EP_{it} + \alpha_4 GDP_{it} + \alpha_5 EC_{it} + \alpha_6 RDE_{it} + \beta_1 RDE_{it} I(R\&D \leq \delta) + \beta_2 RDE_{it} I(R\&D > \delta) + \mu_i + \varepsilon_{it} \quad (1)$$

$$Y_{it} = \theta + \alpha_1 CO2_{it} + \alpha_2 TNP_{it} + \alpha_3 EP_{it} + \alpha_4 GDP_{it} + \alpha_5 EC_{it} + \alpha_6 RDE_{it} + \beta_1 RDE_{it} I(R\&D \leq \delta) + \beta_2 RDE_{it} I(R\&D > \delta) + \mu_i + \varepsilon_{it} \quad (2)$$

in which:

Y - energy generated by wind turbines or by photovoltaic panels (TWh);
CO2 - emissions per person (t);
TNP - total number of patents in renewable energy technologies;
EP - energy price (euro/MWh);
GDP - *GDP per capita* (USD);
EC - electricity consumption per capita (MWh);
RDE - research and development expenditure (% of GDP);
I - an indicator function, taking the value 1 when the condition is met and 0 otherwise;
R&D - threshold variable;
δ_1 - the single threshold value, δ_2 – the double threshold value;
μ - the individual fixed;
ε - random interference term.

I took the values of the following variables *Y*, *CO2*, *TNP* from the 'Our World in Data' database, and the remaining ones from the Eurostat database.

I estimated the parameters of equations (1) and (2) using the fixed effects (FE) estimator (Hansen, 1999). Prior to the estimation of the models, I tested the threshold effect, the aim of which is to demonstrate the existence of statistically significant non-linearity in the relationships between variables resulting from the presence of the threshold effect. This allowed me to confirm whether it is actually justified to distinguish separate subgroups depending on the value of the threshold variable. Moreover, it was also necessary to determine the appropriate number of thresholds for the considered relationship between the variables. As part of the examination of the existence of the threshold effect, I tested a set of statistical hypotheses: H_0 – the threshold effect does not occur in the linear model with the slope coefficient β ($\beta_1 = \beta_2$); H_1 – there is a threshold effect ($\beta_1 \neq \beta_2$). The test statistic then took the following formula:

$$F_1 = \frac{n(T-1)(S_0 - S_1(\hat{\delta}))}{S_1(\hat{\delta})} \quad (3)$$

in which:

S_0 - the sum of squared residuals in the model without threshold effect;
$S_1(\hat{\delta})$ - sum of squared residuals in model without threshold effect $(\hat{\delta})$;
n - number of observations;
T - number of time periods.

The F1 (3) test statistic when H_0 was true had a non-standard distribution without critical values, it was necessary to use bootstrap tools to generate quantiles of this distribution. Therefore, according to Hansen's (1999) procedure, I calculated the following test statistic:

$$LR_1(\delta) = \frac{n(T-1)(S_0(\delta)-S_1(\hat{\delta}))}{S_1(\hat{\delta})} \quad (4)$$

Statistics (4) serves to test the hypothesis H_0: $\delta = \delta_0$ and it has a non-standard distribution.

Moreover, it is proved that, assuming $n \to \infty$, $LR_1(\delta) \to \vartheta_d$, the random variable ϑ has the following distribution function:

$$P(\vartheta < x) = (1 - \exp(-0.5x))^2 \quad (5)$$

By transforming function (5), you can obtain a formula that serves to calculate critical values:

$$c(\alpha) = -2\ln\,(1 - \sqrt{1-\alpha}) \quad (6)$$

If $LR_1 > c(\tau)$, I rejected H_0: $\delta = \delta_0$ and confirmed the existence of a threshold point.

RESULTS AND DISCUSSION

This section will present the results of the panel threshold regression for wind energy and solar energy. Tables 1 and 2 present the results of bootstrap tests of the number of threshold points, which enabled the selection of the appropriate number of points used in the estimation of parameters of panel regression models built for energy production from wind turbines and photovoltaic panels.

Table 1. Results of testing the number of threshold points of panel regression for wind energy

Type of threshold	Threshold estimates	*F*	*p*
Single threshold	1.613	47.253	0.001
Second threshold	0.964 1.613	36.284	0.025
Triple threshold	0.536 0.964 1.613	5.72	0.642

Source: own study.

Based on the results of the F bootstrap and p-value bootstrap tests, I could conclude that the number of threshold points in the model describing wind energy production was two, and these were R&D shares of 0.964% and 1.613% of GDP, respectively (for triple threshold p-value>0.05).

Similarly to wind energy, I performed a test for the number of threshold points for photovoltaics (Table 2).

Table 2. Results of testing the number of threshold points of panel regression for photovoltaics

Type of threshold	Threshold estimates	*F*	*p*
Single threshold	1.392	41.796	0.002
Second threshold	0.779 1.392	28.389	0.031
Triple threshold	0.451 0.779 1.392	9.524	0.438

Source: own study.

The results of the F1, F2, and F3 statistics for single threshold, second threshold and triple threshold and bootstrap p-value proved that the number of threshold points in the model describing the production of electricity from PV was also two and these shares of R&D in GDP were equal to 0.779% and 1.392%, respectively. Tables 3 and 4 present the estimation results of the appropriate threshold panel regression models for wind energy and photovoltaics.

Table 3. Results of parameter estimation of panel threshold regression for wind energy

Parameter	*Coefficient*	*Standard error*	*t*	*p*
const	-4.3923	1.6576	-2.6498	0.0093
CO2	-0.3678	0.1309	-2.8101	0.0059
TNP	0.0056	0.0014	3.8978	0.0002
EP	0.0051	0.0019	2.7249	0.0075
GDP	0.8633	0.2429	3.5547	0.0006
EC	0.5528	0.2219	2.4915	0.0144
R&D ≤ 0.96 %	1.2915	0.5600	2.3064	0.0231
0.96% < R&D ≤ 1.61%	1.6812	0.7586	2.2161	0.0290
R&D >1.61%	1.5658	0.6159	2.5425	0.0125

Source: own study.

In both panel threshold regression models, there were two thresholds for research and development expenditure that differentiate the pace of development of wind and solar energy. Both models fit the empirical data quite well, as evidenced by the determination coefficient values of 0.7376 and 0.8699, respectively. Based on the results in Table 3, I could conclude that the strongest impact of technological investments on the volume of electricity production from wind farms occurred between the first and second thresholds of R&D expenditure, which amounted to 0.96% and 1.61% of GDP, respectively. If the share of R&D expenditure fell within this range, an increase in technological investments by 1‰ generated an increase in the production of electricity generated by wind turbines by an average of approximately 168 GWh, *ceteris paribus*. When R&D expenditure constituted less than 0.96% of GDP, their impact on wind energy was much weaker: an increase in technological investments by 1‰ results in an increase in electricity production by on average approx. 129 GWh, *ceteris paribus*. It seems obvious that with insufficient financing of scientific research and too little support for innovative activities, the development of renewable energy sources will obviously be slower and the amount of electricity they generate will be lower.

However, another effect may be surprising: with the level of R&D expenditure above 1.61% of GDP, the pace of wind energy development also slowed down: an increase in technological investments by 1‰ resulted in an increase in electricity production by an average of approx. 157 GWh *ceteris paribus*, *i.e.*, by approx. 11 GWh less than with the share of R&D expenditure ranging from 0.96% to 1.61% of GDP. This may result from various factors, such as redirecting part of R&D expenditure to support renewable energy sources other than wind energy, limited capacity of transmission networks in Central and Eastern European countries, lack of appropriate wind conditions for the effective use of wind technology, limited opportunities for the development of offshore farms due to lack of access to the sea (in the case of some countries), opposition of local communities to plans to build further wind farms (due to concerns about their undesirable impact on human health, landscape, etc.) Control variables such as GDP, electricity consumption, and the number of patents in the field of renewable energy have a stimulating effect on the development of wind energy, with GDP having the strongest impact on the development of this form of energy: its increase by 1 thousand USD per person implies an increase in energy production from wind turbines by an average of approximately 0.863 TWh. *ceteris paribus*. Other authors have confirmed the direction of the influence of control variables on renewable energy production (Zwarteveen *et al.*, 2021; Şener et al., 2018; Strantzali & Aravossis, 2016). The only control variable that destimulated wind energy turned out to be CO_2 emissions, which reduced the production of electricity from wind turbines. This may be surprising because the increase in CO_2 emissions is one of the reasons for moving away from traditional fossil fuels and replacing them with renewable energy sources. However, the ambiguous impact of CO_2 emissions on the production of energy from renewable energy sources is also confirmed by other scientific analyses (Saidi & Omri, 2020). The impact of energy prices on the development of wind energy was not statistically significant in the discussed model, while many research results confirm a significant relationship between these categories (Li *et al.*, 2020).

Table 4. Results of parameter estimation of panel threshold regression for photovoltaics

Parameter	*Coefficient*	*Standard error*	*t*	*p*
const	-0.4162	1.1389	-0.3654	0.7155
CO2	-0.1855	0.1809	-1.0259	0.3073
TNP	0.0096	0.0011	8.6390	0.0000
EP	0.0020	0.0027	0.7332	0.4651
GDP	0.9741	0.0321	3.0310	0.0031
EC	0.4912	0.1530	3.2108	0.0018
R&D ≤ 0.78%	0.3237	0.0817	3.9616	0.0001
0.78% < R&D ≤ 1.39%	0.9456	0.2418	3.9107	0.0002
R&D >1.39%	0.8552	0.2486	3.4398	0.0009

Source: own study.

The calculation results presented in Table 4 indicate that technological investments are a less effective tool for energy transformation related to photovoltaics than for wind energy. The increase in the production of electricity from PV due to the change in technological investments was lower than the increase in the production of electricity from wind turbines resulting from a similar increase in these investments. The strongest stimulation of electricity production from PV by R&D expenditure was visible when the share of these expenditures in GDP was in the range from 0.78% to 1.39%. Then, a 1-per-mille increase in technological investments results in an increase in electricity production from photovoltaics by an average of approximately 95 GWh, *ceteris paribus*. The same increase in technological investments implied an increase in electricity production from PV on average by approximately 32 GWh, if R&D expenditure constituted less than 0.78% of GDP, and caused an increase in energy production by approximately 86 GWh, *ceteris paribus*, if R&D expenditure constituted above 1.39% of GDP.

Therefore, too low a level of R&D expenditure (below the value of the first threshold of 0.78% of GDP) weakens the energy transformation in the field of photovoltaics, and this is not surprising: electricity production is then lower on average by approximately 63 GWh (compared to the situation when R&D expenditure is in the range from 0.78% to 1.39% of GDP). Similarly to the case of wind energy, exceeding the second threshold value of R&D expenditure also resulted in a reduction in the scale of electricity production from PV by approximately 9 GWh (compared to the scenario when R&D expenditure fell between the two thresholds). This situation may result from various barriers to the development of solar energy, such as the lack of attractive and guaranteed tariffs for settling the costs of selling and purchasing electricity by prosumers, limited capacity of transmission networks, lack of sufficient energy storage infrastructure, and insufficient level of sunlight, especially among the Baltic countries. In some countries of Central and Eastern Europe, the applicable settlement tariffs force prosumers to sell energy generated by PV at low prices when they have to pay a price for the purchased electricity that is many times higher. Moreover, frequent changes in tariffs and changes in regulations regarding renewable energy are not a factor conducive to the development of this sector (Mazurek-Czarnecka *et al.*, 2022). In turn, deficiencies in the energy infrastructure, and outdated solutions also constitute a serious technical barrier to the inclusion of further prosumers in the energy system, which is unable to absorb the overproduction of electricity.

The direction of influence of control variables on the development of photovoltaics turned out to be similar to that in the case of wind energy. The increase in energy production from PV is stimulated by GDP, per capita electricity consumption and the number of patents in the field of renewable energy. Among these variables, GDP has the strongest impact on the production of energy from PV: its increase by 1 thousand USD per person implies an increase in the production of energy generated by photovoltaics by an average of approximately 0.974 TWh, *ceteris paribus*. The obtained result stating a positive relationship between the number of patents filed in RES and green energy production is consistent with the results obtained by other researchers (Leal Filho *et al.*, 2021; Li *et al.*, 2023). CO_2 emissions did not have a significant impact on the development of photovoltaics in the analyzed model, which is confirmed, for example, by the results obtained by Saidi and Omri, 2020. Similarly to the study conducted for wind energy, here too electricity prices did not significantly stimulate energy production from PV, which is contrary to the results of other researchers (Li *et al.*, 2020). The above analysis regarding both types of renewable energy sources shows that the strongest stimulation of electricity production generated jointly by wind turbines and PV panels will occur when R&D expenditure ranges from 0.96% to 1.39%. If these expenses are in the range of 0.78% to 0.96% of GDP, solar energy will be most strongly stimulated by technological investments, while if R&D expenditures are in the range of 1.39% to 1.61%, only wind energy will be most strongly stimulated by these investments. A simultaneous weakening of the development of wind and solar energy will occur when R&D expenditure is below 0.78% of GDP. The results obtained in this work regarding the thresholds of R&D expenditures can be treated as specific guidelines for decision-makers in the countries of Central and Eastern Europe responsible for the investment and energy policy of the states. If the priority is the development of wind energy, then the state's expenditures on R&D should be correspondingly higher than in the case when the priority is the development of photovoltaics. If the country wants to develop both energy sources on a similar scale, then R&D expenditures at the level of about 1% of GDP are sufficient. Of course, the choice between investing in solar and wind energy should be decided individually for each country based on an assessment of natural conditions (sun exposure, wind potential), energy infrastructure, and social conditions (level of social acceptance for RES). In addition, decisions on setting priorities for the development of photovoltaics or wind energy must take into account the different impacts of technological investments on the development of wind and solar energy due to differences in the technological maturity of both types of green energy, its production costs and operating conditions. Wind energy is considered to be technologically more mature and more developed than photovoltaics, but requires larger initial investments (high costs of wind turbines). In turn, photovoltaics has a greater potential for breakthrough innovations, so marginal benefits from R&D expenditures may be greater compared to wind energy. The R&D expenditure thresholds given in this article are not excessive, and achieving/exceeding them will effectively stimulate the development of RES. However, it should be remembered that the given R&D expenditure thresholds are determined as averages for all the CEE countries considered, which results from the specificity of the econometric panel data models used. The natural conditions of these countries, their exposure to the sun, wind availability, and energy infrastructure may show some differences. This means that the implementation of a specific RES development policy in a specific country may require an appropriate correction of the estimated threshold values, so as to adapt them to the specificity of the natural and economic conditions occurring in that country. It is also necessary to note the potential limitations associated with the applied econometric model of threshold panel regression. They may concern, among others, possible problems with threshold identification, endogeneity of variables or specificity of panel data. In this study, appropriate control tests confirmed the correct specification of the model. The correctness of the number of threshold points and the correctness of their values was confirmed by the Hansen procedure (1999) based on strong results of bootstrap F and bootstrap p-value tests, while the lack of significant correlation between explanatory variables and the random component was confirmed by the Durbin-Wu-Hausman (DWH) test. Demonstrating the lack of endogeneity of explanatory variables indicates that the model did not contain significant measurement errors and that no significant variables were omitted. The added value of the presented results compared to the results in other works lies primarily in the fact that it was possible to create independent models for two types of green energy for the CEE countries, while other authors using similar research tools generally do not make such a separation of energy from RES (Mengxuan et al., 2024). Separating solar energy from wind energy provided much greater opportunities to assess the impact of technological innovations on the development of RES and made it possible to formulate much more detailed recommendations for decision-makers responsible for innovation policy than is the case in other scientific works. Moreover, by including two thresholds of R&D expenditure in the estimated models, the flexibility of the results increased significantly, which broadened the available decision-making options for those responsible for national renewable energy policies. Other works in the same area using similar research tools provide much less specific guidance for decision-makers and politicians in Central and Eastern European countries (Mengxuan *et al.*, 2024; Mazurek-Czarnecka *et al.*, 2022) or they are too general (Pakulska, 2021).

CONCLUSIONS

The countries of Central and Eastern Europe shape their energy transformation policy based on various factors resulting from their current structure of energy sources, the geographical location determining the optimal use of the renewable energy potential, the state of energy infrastructure, the possibility of diversification of energy sources, *etc*. However, all EU member states are obliged to achieve climate neutrality, which requires them to significantly increase the share of low-emission sources in their energy mix. This is not possible without appropriate technological investments that can be used to control the development of renewable energy sources. The mechanism of stimulating photovoltaics and wind energy can be modelled and I presented such an approach in this article.

The threshold regression tool I used provides valuable conclusions regarding the mechanism of the impact of variables on the development of wind and solar energy. This allowed me to formulate important recommendations regarding the thresholds of R&D expenditures depending on the priority set by the government in the energy mix. If this priority is the parallel development of wind energy and photovoltaics, the share of R&D expenditure should be between 0.96% and 1.39%. If the priority is the development of solar energy alone, these expenditures should not exceed the threshold of 0.96% of GDP, and if the governments of the countries focus on wind energy, the share of R&D expenditure in GDP should exceed 1.39%. Countries that currently fall short of their R&D spending targets should consider changing their budget plans to increase public funding for R&D. It may be necessary to implement budget programs that will allow for planning long-term investments in science and innovation, as well as increasing the intensity of applying for appropriate funds from EU programs. It should also be remembered that R&D expenditure includes not only funds from the state budget but also from the private sector. In the second area, decision-makers also have a lot to do: it is necessary to create a package of incentives for the private sector to participate in these expenditures to a greater extent. This can be achieved by, among others: a system of tax reliefs for private investors, credit guarantees, grants and financial subsidies, creating new research and development centres that connect companies, universities and research institutes to jointly solve technological problems and greater state involvement in public-private projects. To achieve the assumed thresholds of R&D expenditures, decision-makers must take actions that will lead to an increase in public expenditures on the one hand, and on the other hand, will mobilise the private sector.

The article positively verified two research hypotheses. I showed that in CEE countries, there was at least a threshold point of expenditure on R&D, (H1) and the strength of the impact of technological investments on the production of energy from renewable sources in the area of wind energy was significantly greater than in the area of photovoltaics (H2).

Noteworthy, the results allowed me to conclude that a continuous increase in the level of expenditure on research and development does not guarantee the achievement of maximum development effects of these energy sources and therefore does not guarantee the optimal pace of energy transformation. The results of this research have shown that no worse effects in this respect can be achieved when R&D expenditures are at a moderate level, because their further increase (after exceeding subsequent thresholds) weakens the effects of increasing energy production from renewable energy sources, which is caused by the intensification of the impact of various barriers. These include: insufficient pace of development of transmission and storage infrastructure in CEE countries (too slow modernization of technical infrastructure does not keep pace with investments in new technologies), priority treatment of sectors other than the RES sector (*e.g.*, digital technologies sector) when distributing funds allocated for R&D R, as well as the too slow pace of implementation of innovations in the area of renewable energy, which means that the increase in energy production from renewable energy sources is weaker than potentially possible (Pakulska, 2021; Mazurek-Czarnecka et al., 2022; Leal Filho et al., 2021).

Certainly, important barriers to fully benefiting from the increase in R&D in the area of renewable energy also include: low social awareness of renewable energy and residents' resistance to some renewable energy installations, lack of favourable and stable settlement tariffs with electricity prosumers, directing part of the investment into technologies ‘temporary’ related to non-renewable energy sources (*e.g.*, investments in LNG terminals), administrative and bureaucratic resistance creating problems for investors at the stage of obtaining permits for the construction of installations RES (especially wind farms), the insufficient share of private capital involved in often very expensive renewable energy infrastructure investments (Mengxuan *et al.,* 2024; Mazurek-Czarnecka *et al.*, 2022; Szép *et al.*, 2023; Leal Filho *et al.*, 2021). Undoubtedly, both photovoltaics and wind energy play a key role in the energy transformation of Central European countries belonging to the EU, but full use of their potential requires a gradual overcoming of the above-mentioned limitations. Otherwise, the constant increase in R&D spending will not translate into the development of the renewable energy sector as expected.

Based on the evaluation of the obtained threshold panel regression models, these models relatively well reflected the studied relationships, but we must remember that they have their limitations. In general, a methodological problem may be the determination of the number of thresholds, as well as the endogeneity of variables caused by, for example, the lack of taking into account important explanatory variables or measurement errors. If they occur, it may be necessary to change the specification of the entire model. The cognitive value of the model could certainly be expanded by considering further macroeconomic variables, thanks to which it would be possible to monitor the development of RES using other economic policy instruments. Noteworthy, the panel data model provides average results for the entire Central and Eastern Europe region, which may not be appropriate for the specific economy of a single country. Therefore, in the future, further detailed studies are necessary, conducted for each country. Thanks to this, recommendations regarding renewable energy policy will be more accurate, because they will be dedicated to individual economies.

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Author

Marcin Salamaga

Professor at the Department of Statistics at the Krakow University of Economics, Poland and a member of the Section of Classification and Data Analysis of the Polish Statistical Society. He holds a PhD in economics and the title of professor in the scientific discipline of economics and finance. He has published articles related to the application of statistical methods in economic research. His research interests include: foreign direct investment, foreign trade, and innovation.

Correspondence to: Prof. dr hab. Marcin Salamaga, Krakow University of Economics, Department of Statistics. ul. Rakowicka 27, 31-510 Krakow, Poland, e-mail: salamaga@uek.krakow.pl

ORCID https://orcid.org/0000-0003-0225-66511

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Use of Artificial Intelligence

I declare that I did not use AI/GAI tools when preparing this article.

Conflict of Interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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