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The Impact of Expenditure on Research and Development on Selected Energy Factors in the European Union

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Abstract: Due to the fact that the European Union is striving to achieve its sustainable development goals, in particular goal No. 7, which is to provide users with low-emission, and cheap access to, energy, this article's aim is to verify whether there is a relationship between R&D expenditure and key energy variables in the EU countries in 2010–2020. Data on R&D expenditures incurred by the EU Member States in the period 2010–2020 were used for the research and were tested using the Autoregressive Distributed Lags Model (ARDL). The study identified a strong positive relationship between total R&D expenditure and the increase in energy consumption from renewable energy sources, and a smaller impact of total R&D expenditure as well as enterprise R&D expenditure on the increase in fossil energy consumption. Also noted was a weak relationship between R&D expenditure and electricity and gas prices for both household and non-household customers. The obtained results prove that in the context of the level of implementation of SDG No. 7 in the EU countries, R&D expenditure results in greater access to low-emission energy from renewable sources, but the achievement of the aforementioned sustainable development goal in other aspects (reduction in energy consumption from fossil fuels and ensuring lower price energy) is not possible with the current level of R&D expenditure.

Keywords: sustainability; research and development; renewable energy; energy from fossil fuels; energy efficiency

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1. Introduction

Energy is recognized as the basic source of achieving economic goals in the form of the production of goods and services that lead to human well-being. Energy consumption remains an integral part of economic development [1,2].

On the one hand, the increase in the consumption of energy has a positive impact on the economy because it has a positive effect on real GDP and vice versa [3]; on the other hand, it is also the main cause of CO_2 and greenhouse gas emissions, which in turn affect climate change and global warming [4]. Due to the fact that the global consumption of energy from fossil fuels is as much as 84% [5], in order to maintain environmental balance, it is necessary to take action to reduce the overall consumption of energy from fossil fuels and CO_2 emissions [6].

Many economies have set goals for their energy sectors, emphasizing security, sustainable development, environmental friendliness, resource efficiency and actions to reduce emissions of harmful substances into the atmosphere [7]. The European Union is particularly active in this area, implementing a number of regulations and policies [8,9]. Sustainable energy policy instruments in the EU are intended to achieve the goals of a low-carbon economy, energy efficiency and renewable resources [10].

When introduced—there were eight Sustainable Development Goals developed by the UN for the years 2000–2015. After the signing of the Agenda for Sustainable Development 2030 (September 2015), the number increased to seventeen, among which the implementation of Goal 7 should enable access to affordable, reliable, sustainable and modern energy [11].

The research, conducted for the European Union Member States, confirms that the key element contributing to the reduction in CO_2 emissions into the atmosphere are R&D expenditures [12,13]. Taking into account that the research conducted for the European Union Member States confirms that the key element contributing to the reduction in harmful gas emissions (as CO_2) into the atmosphere is R&D expenditure and that the economic development is linked to energy consumption, it is reasonable to formulate a research goal to verify whether there is a relationship between expenditure on R&D and selected energy variables related to the content of the definition of Sustainable Development Goal No. 7 (SDG No. 7).

The explanation of the scientific problem formulated in this way would make it possible to fill the existing research gap as studies on the impact of the expenditure on research and development on implementing SDG No. 7 have not yet been conducted.

The explanation of the described relationship is important because according to the European Commission, the acceleration of the achievement of affordable, reliable, sustainable and modern energy should be achieved by offering the EU Member States facilitated access to research and technologies in the field of clean energy and promoting investments in resource and energy saving solutions and low-emission energy infrastructure.

In order to explain this research problem, the authors verified the null hypothesis that the total R&D expenditure incurred in the years 2010–2020 by the Member States of the European Union (excluding Great Britain) did not affect key factors of the energy area in the long term.

In addition, two auxiliary hypotheses were verified, namely that R&D expenditure of enterprises and R&D expenditures of the government did not affect key factors in the energy area in the long term.

The research limitation is the dualism of energy consumption in the European Union—there is both an increase in the consumption of energy from fossil fuels, which is a direct consequence of economic growth and, at the same time, an increase in the consumption of energy from renewable sources.

This article is structured as follows: Part 1 (Introduction) describes a research problem regarding the relationship between expenditure on research and development and specific effects in the area of energy in the European Union countries and identifies the research gap regarding the occurrence of indicated dependencies in the context of implementation in the European Union Member States of one of the objectives of sustainable development (SDG No. 7). Part 2 (Research method) describes the justification of the selected research model in the context of the shift in time of the effect of the selected independent variables on the selected dependent variables with an indication of the studies in which this type of approach was used. This section also presents the authors' reasoning in the selection of variables, which allowed for the verification of the relationship between R&D expenditure and representative factors in the field of energy, which are collected by the statistical services of Eurostat. Part 3 and Part 4 (Results and Discussion) contain the presentation of research results and the discussion with reference to the obtained research results against the background of the literature, and Part 5 (Conclusions), includes, among others, an analysis of effectiveness in the context of achieving the objectives related to SDG No. 7 along with a description of the possibilities of using the results obtained.

2. Research Method

Among many available data in the field of energy, those collected by Eurostat are helpful in explaining the research problem concerning the impact of the expenditure on research and development on selected variables in the field of energy. Considering what should be the effect related to the implementation of SDG No. 7, some Eurostat data may be used to monitor progress in its implementation.

For this purpose, the research defined as independent variables the data collected by Eurostat for the period 2010–2020 concerning three groups of expenditures on research and development, i.e., total expenditures on research and development, government expenditures on research and development and expenditures on research and development of enterprises, for which the measure is the percentage share in the Gross Domestic Product of the 27 European Union Member States. This group includes Belgium, Bulgaria, Czechia, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland and Sweden.

The group of dependent variables includes those factors from the energy area that may be important in the context of the implementation of SDG No. 7. Data on this subject for the period 2010–2020 come from Eurostat and their detailed summary is presented in Table 1 below.

Table 1. List of dependent variables used to describe the degree of implementation of SDG No. 7.

Lp.	Dependent Variable	Unit
1.	energy productivity	euro per kilogram of oil equivalent (KGOE)
2.	energy intensity	kilograms of oil equivalent (KGOE per thousand euro)
3.	energy efficiency	million tonnes of oil equivalent (MTOE)
4.	primary energy consumption	million tonnes of oil equivalent
5.	share of renewable energy consumption in gross final energy consumption	Percentage
6.	share of energy from fossil fuels in total energy consumption	Percentage
7.	electricity prices for non-household consumers	euro per Kwh
8.	electricity prices for household consumers	euro per Kwh
9.	gas prices for non-household consumers	euro per Kwh
10.	gas prices for household consumers	euro per Kwh

Source: own elaboration based on data collected by Eurostat.

Due to the shift in time of the effect of the expenditure on R&D, the panel was verified in terms of detecting long-term relationships between variables using the Westerlund and Pedroni cointegration tests [14,15]. Taking into account that the delay in the occurrence of the effects of the expenditure on research and development may result from various reasons—it may be related to the time of commercialization of patents used in the energy sector, the adoption of legal regulations enabling the introduction of a specific solution into economic circulation, the costs of technological adjustments in enterprises enabling the start of production of an innovative product. Such premises undoubtedly determine the consideration of the context of the deferred effect of the impact of incurring research and development costs on the relationship reflected in the value of the described variable.

In the literature, we can meet findings concerning, for example, some companies operating in the USA, indicating that R&D expenditure has an immediate positive impact on operating results [2,16,17]. Other studies indicate the existence of a delayed effect of R&D inputs [18,19] and have shown that this effect occurs after about one year in Japan and two years in China and in Taiwan for high-tech companies [20]. In connection with the approach described in the literature, the authors attempted to verify the relationship between the expenditure on research and development and selected variables in the area of energy immediately after they were incurred, taking into account the effect of shifting by one year and by two years.

The Pedroni test and the Westerlund test are used to test the stationarity of variables in the case of panel series. When used, the null hypothesis assumes no cointegration between the variables.

Ninety cointegration tests were performed for all pairs of variables, in which the independent variables were the expenditures on research and development in each of the three selected groups (total expenditures on research and development, the expenditures of enterprises on research and development, and government expenditures on research and development) was introduced in line with Table 1.

Methodologically, the authors assumed that the Error Correction Mechanism model (ECM model) would be applicable if the cointegration was confirmed for all pairs of explanatory and explanatory variables that were tested [21] Demonstrating cointegration, and thus rejecting the null hypothesis, between the indicated variables would mean the existence of a strong relationship between them that persists over time.

Due to the fact that the tests performed failed to confirm the above assumption of cointegration for all pairs of variables subjected to cointegration tests, the ARDL model using the Arellano–Bond estimator was used to take into account the possibility of a delay in the influence of the independent variable on the dependent variable. It should be noted that the ARDL model, through the lagged dependent variable, also takes into account previous periods of time. In other words—the use of the ARDL model allows us to consider not only the current value of the explanatory variable, but also its lagged values and the lagged values of the explained variable. Thanks to this approach, it is possible to identify and economically interpret both short-term and long-term parameters of the model.

Dynamic panel data models contain lagged levels of the dependent variable in the form of regressors. Including the lagged dependent variable as a regressor violates strict exogeneity because the lagged dependent variable is likely to be correlated with random effects and/or general errors.

In the case of the Arellano–Bond estimator used in the research, the Generalized Method of Moments (GMM) is used [22]. This method considers the first difference in the dependent variable of the regression equation to eliminate individual effects. Then, the deeper lags of the dependent variable are used as instruments for differentiated lags of the dependent variable. The Arellano–Bond estimator, due to the possibility of testing increments with its use, avoided the need to verify the non-stationarity of variables in the panels, because the variables in the study are the increments of the examined variables.

Taking into account the total number of lags for both the dependent variable and the independent variable, the model can be described by the following equation:

$$\Delta y_{i,t} = \alpha_0 + \sum_{w=1}^{w=q} \alpha_w \cdot \Delta y_{i,t-w} + \sum_{k=0}^{k=p} \beta_k \cdot \Delta x_{i,t-k} + \varepsilon_{i,t} \tag{1}$$

where

p—maximum delay-dependent variable;

w—maximum delay independent variable.

Random errors are assumed to have zero mean, no serial correlation, and constant residual variance (homoscedasticity).

In the calculations using the Arellano and Bond estimator, in the adopted short time series of 11 years, the fact of a possible shift of the impact effect by one or two years was taken into account in accordance with the following formula:

$$\Delta y_{i,t} = \propto_0 + \propto \Delta y_{i,t-1} + \Delta x_{i,t}\beta_0 + \Delta x_{i,t-1}\beta_1 + \Delta x_{i,t-2}\beta_2 + \varepsilon_{i,t} \tag{2}$$

The Arellano–Bond estimator is used to determine parameters for incremental variables, which avoids the need to study the stationarity of variables in panels.

The procedure refers to the two-stage GMM estimator. Alternatively, a one-step estimator can be used that takes into account the dynamic structure of the error term.

Due to the fact that a single change in the value of the variable in the next period causes a change in the lag value of the variable, both the size of the immediate response to the operation of the independent variable and the long-term effect of its operation were taken into account. The scope of impact was determined by calculating the long-term multiplier, which describes the response to a unit change in the independent variables in all periods considered (i.e., how a change in the independent variable in the current period will affect the change in the dependent variable in the long term). In the case of the variables taken into the study, the effect of immediate reaction in period t, as well as in period $t + 1$ and $t + 2$, was taken into account.

The long-run multiplier describes the magnitude of the expected change in the dependent variable as a result of a change in all past values of x by Δx, thus indicating the long-term impact of a permanent change in the independent variable on the expected value of the dependent variable. The introduction of lagged values of the dependent variable into the model allows the inertia of the examined economic phenomena to be captured.

The value of the long-term multiplier was calculated according to Formula (3)

$$\mathrm{LRM} = \Sigma\, \beta/(1 - \alpha) \tag{3}$$

where

β—coefficient value in period t, $t + 1$ or $t + 2$ with p-value ($p > |z|$) < 0.005;

α—the value of the independent variable in the period $t - 1$.

Assuming the short time series available in the study, the dependent variable lagged by 1 period ($t + 1$) is used to capture other time lags of the independent variables as in the standard Koyck linear model [23].

Due to its effectiveness in describing the relationships between variables over time, the ARDL model is very popular among researchers analyzing relationships involving variables from the energy sector. A summary of some studies in the energy sector in which the ARDL model was used is presented in Table 2.

Table 2. Selected research in the energy area using the ARDL model.

L.p.	Author	Research Topic	Research Findings	Year of Publication
1.	Apergis and Payne [24]	relationship between economic progress and renewable energy consumption in OECD countries	confirmation of the long-term relationship between real GDP and renewable energy consumption	2010
2.	Fei and Rasiah [25]	the short-term and long-term relationship between technological innovation, electricity consumption, energy prices and growth for Canada, Ecuador, Norway and South Africa from 1974 to 2010	in the long term, technological innovation does not affect the consumption of electricity powered by fossil fuels	2014
3.	Faisal et al. [26]	the relationship between energy consumption and GDP for Belgium in 1960–2012	GDP positively affects energy consumption in the long and short term	2017
4.	Farhani and Solarin [27]	the relationship between energy demand, financial development, economic growth, foreign direct investment, trade and capital in the United States from 1973 to 2014	financial development, economic growth and foreign direct investment lead to a decrease in energy demand, while trade and capital increase energy demand	2017
5.	Saudi et al. [28]	the role of technological innovations in energy intensity in Indonesia	confirmation that technological innovations help to improve energy efficiency in Indonesia	2019

Table 2. *Cont.*

L.p.	Author	Research Topic	Research Findings	Year of Publication
6.	Asongu et al. [29]	the impact of economic progress, urbanization, electricity consumption, fossil fuels and natural resources on pollutant emissions for 13 African countries	fossil fuels, urbanization and electricity consumption significantly increase pollution levels	2020
7.	Akadiri et al. [30]	the impact of economic, national security and trade policy uncertainty on renewable energy	political uncertainty, trade policy and national security have significant negative and positive impacts on renewable energy, respectively	2021

Source: own elaboration based on the results obtained using the STATA v. 12 software.

3. Results

The results of the research gave ambiguous results showing the relationship between some categories of R&D expenditure and six independent variables, i.e., consumption of energy from renewable sources (1), consumption of energy from fossil fuels (2), electricity prices for household (3) and non-household (4) consumers and gas prices for household (5) and non-household (6) consumers.

First of all, the very significant impact of total expenditure on research and development on the consumption of energy from renewable energy sources was confirmed. An increase in total expenditure on R&D in the current period by 1 unit means an increase in energy consumption from renewable energy sources in the long term by an average of 535.35 units, which confirms the effectiveness of research leading to an increase in energy consumption from these sources. A similar relationship could not be confirmed in the group of government R&D expenditure and corporate R&D expenditure.

The second important research finding is the confirmation of the relationship according to which an increase in total R&D expenditure and government R&D expenditure means an increase in the consumption of energy from fossil fuels. In the case of total R&D expenditure, an increase of 1 unit in the current period means an increase in long-term consumption of energy from fossil fuels by 27.57 units, while in the case of government spending on R&D, an increase of 1 unit in the current period means an increase in energy consumption from fossil fuels in the long term by 49.82 units.

It was also established that:

- Total research and development expenditure and government R&D expenditure have an impact on electricity prices for household customers; however, it is small in the long run (in the case of total research and development expenditure an increase of 1 unit in the current period means an increase in long-term on electricity prices for household customers by 0.15 units and, in case of government R&D expenditure, an increase of 1 unit in the current period means an increase in long-term on electricity prices for household customers by 0.65).
- Total research and development expenditure has an impact on energy prices for non-household customers, but, also in this case, it is small in the long run (in the case of total research and development expenditure, an increase of 1 unit in the current period means an increase in long-term on electricity prices for non-household customers by 0.13).
- R&D expenditures of enterprises have an impact on gas prices for household and non-household customers (separately for each customer group), but, also this time, it is small in the long run (an increase of 1 unit in the current period means an increase in long-term on gas prices for household customers by 0.48 units and an increase in long-term on gas prices for non-household customers by 0.28).
- No relationship was detected between R&D expenditure and energy intensity, energy productivity and primary energy consumption.

Descriptive statistics on the dependent variables showed the following characteristics:

- The average consumption of energy from renewable sources in the tested samples is 20,001. Typical renewable energy consumption differed from the average by 11.54 on average. The sample is characterized by significant variability at the level of 58%. At the same time, the consumption of energy from renewable sources is characterized by a strong positive right skewness and a stronger concentration around the average (kurtosis). A total of 50% of the observations of renewable energy consumption were no more than 17,082, 50% of the observations were above 17,082, and 50% of the observations of renewable energy consumption differed by 59,114.
- The average consumption of energy from fossil fuels in the tested samples is 2.29. Typical consumption of energy from fossil fuels differed from the average by 3.36. The sample is characterized by a very high variability of 147%. At the same time, the consumption of energy from fossil fuels is characterized by a strong positive skewness to the right and a stronger concentration around the mean (kurtosis). A total of 50% of the observations of the consumption of energy from fossil fuels were no greater than 1.24, 50% of the observations were above 1.24, and 50% of the observations of the consumption of energy from fossil fuels differed by 20:17.
- The average energy price for household customers in the surveyed samples is 0.122. The typical energy price for household customers differed from the average by 0.03 on average. The sample is characterized by low volatility at the level of 24%; at the same time, the price of energy for household customers is characterized by a strong positive right skewness and stronger concentration around the average (kurtosis). A total of 50% of the energy price observations for household customers were no greater than 0.118, 50% of the observations were above 0.118, and 50% of energy price observations for household customers differed by 0.169.
- The average energy price for non-household customers in the surveyed samples is 0.90. The typical energy price for non-household customers differed from the average by 0.25 on average. The sample is characterized by low volatility at the level of 28%; at the same time, the price of energy for non-household customers is characterized by a strong positive right skewness and stronger concentration around the average (kurtosis). A total of 50% of the energy price observations for non-household customers were no greater than 0.084, 50% of the observations were above 0.084, and 50% of energy price observations for non-household customers differed by 0.164 from each other.
- The average gas price for household customers in the surveyed samples is 0.45. The typical price of gas for household customers differed from the average by 0.12 on average. The sample is characterized by low volatility at the level of 28%. At the same time, the price of gas for household customers is characterized by a weak right skewness and a stronger concentration around the average (kurtosis). A total of 50% of the gas price observations for household customers were no greater than 0.044, 50% of the observations were above 0.044, and 50% of the gas price observations for household customers differed by 0.67 from each other.
- The average gas price for non-household customers in the surveyed samples is 0.03. The typical gas price for non-household customers differed from the average by 0.007. The sample is characterized by low volatility at the level of 22%; at the same time, the price of gas for non-household customers is characterized by a weak right skewness and a stronger concentration around the average (kurtosis). A total of 50% of gas price observations for non-household customers were no greater than 0.03, 50% of observations were above 0.03, and 50% of gas price observations for non-household customers differed by 0.38 from each other.

Detailed descriptive statistics on dependent variables are provided in Table 3 below.

Table 3. Descriptive statistics—dependent variables.

L.p.	Stats	Mean	sd	cv	Skewness	Kurtosis	Median	Range
1	Electricity prices household consumers	0.122	0.03	0.248	0.922	3.847	0.118	0.169
2	Electricity prices non-household consumers	0.09	0.025	0.282	1.956	8.092	0.084	0.164
3	Gas prices household consumers	0.045	0.012	0.277	0.113	2.95	0.044	0.07
4	Gas prices household consumers	0.031	0.007	0.22	0.447	3.085	0.03	0.038
5	Renewable energy in energy consumption	20.008	11.541	0.577	0.89	3.542	17.082	59.145
6	Solid fossil fuels in energy consumption	2.291	3.36	1.467	3.5	16.384	1.24	20.17
7	Energy primary energy consumption	50.678	71.67	1.415	2.231	7.252	23.1	314.5
8	Energy efficiency	50.670	71.699	1.415	2.231	7.253	23.06	314.44
9	Energy productivity	6.83	3.27	0.479	1.406	5.941	6.34	20.58
10	Energy intensity	180.27	85.728	0.4756	1.258	4.806	157.72	448.88

Source: own elaboration based on the results obtained using the STATA v. 12 software.

Descriptive statistics on the independent variables showed the following characteristics:

- The average R&D expenditure (total) in the tested samples is 1606. Typical R&D expenditure (total) differed from the average by 0.888 on average. The sample is characterized by 55% volatility. At the same time, R&D expenditure (total) is characterized by positive right skewness and stronger concentration around the mean (kurtosis). A total of 50% of gas price observations for non-household customers were no greater than 1.33, 50% of observations were above 1.33, and 50% of gas price observations for non-household customers differed by 3.33 from each other.
- The average government R&D expenditure in the surveyed samples is 0.191. A typical government R&D expenditure differed from the average by 0.095. The sample is characterized by a variability of 50% At the same time, the government R&D expenditure is characterized by positive right skewness and a stronger concentration around the mean (kurtosis). A total of 50% of gas price observations for non-household customers were no greater than 0.18, 50% of observations were above 0.18, and 50% of gas price observations for non-household customers differed by 0.45 from each other.
- The average enterprise R&D expenditure in the surveyed samples is 0.989. A typical enterprise R&D expenditure differed from the average by 0.684 on average. The sample is characterized by 69% volatility. At the same time, enterprise R&D expenditure is characterized by positive right skewness and stronger concentration around the mean (kurtosis). A total of 50% of the gas price observations for non-household customers were no greater than 0.75, 50% of the observations were above 0.75, and 50% of gas price observations for non-household customers differed by 2.51 from each other.

Detailed descriptive statistics on independent variables are provided in Table 4 below.

Table 4. Descriptive statistics—independent variables.

Tats	Total R&D Expenditure	Government R&D Expenditure	Enterprise R&D Expenditure
mean	1.606	0.191	0.989
sd	0.888	0.095	0.684
cv	0.553	0.499	0.691
skewness	0.587	0.325	0.608
kurtosis	2.103	2.789	2.097

Table 4. *Cont.*

Tats	Total R&D Expenditure	Government R&D Expenditure	Enterprise R&D Expenditure
median	1.33	0.18	0.75
range	3.33	0.45	2.51

Source: own elaboration based on the results obtained using the STATA v. 12 software.

Detailed results of research on statistically significant relationships between various categories of R&D expenditure and dependent variables in the energy area in the European Union are presented in Table 5.

Table 5. Relationships between different categories of expenditure on R&D and dependent variables in the energy sector in the European Union countries in the period 2010–2020.

L.p.	Independent Variable	Dependent Variable	Response Period of the Influence of the Independent Variable on the Dependent Variable (in Years)	Coeff	$p > \|z\|$	Long-Run Multiplier
1.	Expenditure on R&D (% GDP)	Electricity prices non-household consumers (EUR/Kwh)	0	−0.009	0.449	0.13
			1	0.655	0.004	
			2	−0.632	0.006	
		Expenditure on R&D (% GDP)	1	0.966	0.000	
		cons.	0	0.203	0.002	
2.	Expenditure on R&D (% GDP)	Electricity prices household consumers (EUR/Kwh)	0	−0.007	0.522	0.15
			1	0.057	0.038	
			2	−0.047	0.038	
		Expenditure on R&D (% GDP)	1	0.932	0.000	
		cons.	0	0.021	0.854	
3.	Expenditure on R&D (% GDP)	Solid fossil fuels in energy consumption (%)	0	−0.072	0.707	27.57
			1	−0.893	0.075	
			2	0.948	0.006	
		Expenditure on R&D (% GDP)	1	−0.966	0.000	
		cons.	0	0.024	0.890	
4.	Expenditure on R&D (% GDP)	Renewable energy in energy consumption (%)	0	1.638	0.251	535.35
			1	2.637	0.242	
			2	−4.863	0.04	
		Expenditure on R&D (% GDP)	1	1.009	0.000	
		cons.	0	1.463	0.166	
5.	Government R&D expenditure (% GDP)	Gas prices household consumers (EUR/Kwh)	0	0.023	0.004	−0.11
			1	−0.027	0.037	
			2	−0.01	0.451	
		Government R&D expenditure (% GDP)	1	0.971	0.000	
		cons.	0	0.003	0.0373	
6.	Government R&D expenditure (% GDP)	Electricity prices household consumers (EUR/Kwh)	0	0.035	0.038	0.65
			1	0.007	0.926	
			2	−0.049	0.609	
		Government R&D expenditure (% GDP)	1	0.947	0.000	
		cons.	0	0.008	0.437	

Table 5. *Cont.*

L.p.	Independent Variable	Dependent Variable	Response Period of the Influence of the Independent Variable on the Dependent Variable (in Years)	Coeff	$p > \|z\|$	Long-Run Multiplier
7.	Government R&D expenditure (% GDP)	Solid fossil fuels in energy consumption (%)	0	0.198	0.697	49.82
			1	−0.529	0.662	
			2	2.405	0.014	
		Government R&D expenditure (% GDP)	1	0.952	0.000	
		cons.	0	−0.39	0.079	
8.	Enterprise R&D expenditure (% GDP)	Gas prices non-household consumers (EUR/Kwh)	0	−0.031	0.146	0.28
			1	0.086	0.003	
			2	−0.055	0.013	
		Enterprise R&D expenditure (% GDP)	1	0.890	0.000	
		cons.	0	0.001	0.690	
9.	Enterprise R&D expenditure (%GDP)	Gas prices household consumers (EUR/Kwh)	0	−0.013	0.227	0.48
			1	−0.308	0.057	
			2	0.045	0.009	
		Enterprise R&D expenditure (%GDP)	1	0.906	0.000	
		cons.	0	0.002	0.657	

Source: own elaboration based on the results obtained using the STATA v. 12 software.

4. Discussion

Demonstrating the relationship between expenditure on R&D and the consumption of energy from renewable sources is, in principle, in line with research findings on this subject, having a positive impact on access to sustainable energy.

The growing role of renewable energy in the economy is confirmed by many studies. They concern, for example, the confirmation of the relationship between the consumption of energy from renewable sources and economic growth—this has been demonstrated, among others, in the studies on OECD countries [31–36]. Similar findings were found by Kose et al. [37] examining the role of renewable energy, non-renewable energy and research and development for sustainable growth in the European Union Member States. The results showed that all forms of energy and research and development contribute positively to the growth of European economies.

Another research aspect related to R&D and innovation is its impact on energy consumption. An additional conclusion from their research was that an additional aspect conducive to the use of renewable energy is the openness of trade. On the one hand, by stimulating innovation in energy saving, spending on R&D leads to a reduction in energy consumption [33]. The described effect results from technological progress based on innovations resulting from investments in research and development, which have a positive impact on production efficiency and energy consumption. In this sense, investments in research and development lead to a reduction in dependence on natural resources by enabling the use of more efficient technologies that reduce harmful emissions [38]. Murad and Alam [5] found that technological advances improve the use of renewable energy in OECD countries. This group also includes studies by Garbaccio et al. [39], who showed that in China between 1978 and 1995, technological changes in economic sectors accounted for most of the decline in the energy production ratio (compared to the decline in energy consumption).

On the other hand, there is no doubt that economic growth resulting from the development of trade is associated with an increase in energy consumption as a result of increased production. This is more common in economies where the marginal returns to innovation and R&D decrease over time. Due to the increasing time of knowledge accumulation, the return on research and development shows decreasing rates of return [40]. In this trend, the results of Chen et al. [41] and Wang and Wang [42] found that technological innovation positively affects energy efficiency, which means that the demand for energy increases with the increase in technological innovation.

The literature on renewable energy also addresses the issue of the impact of environmental regulations on the effectiveness of green innovations. The results of these studies are mixed—found positive [43–46], negative [47–49], or uncertain influence in this area [50–54].

From the perspective of the research results to date on the relationship between the expenditure on research and development and the consumption of energy from renewable sources, it appears that with the increase in innovation, an increase in the consumption of this type of energy should be expected. Findings of this kind confirm the possibility of implementing SDG No. 7 in terms of access to low-emission energy. Nevertheless, it should be noted that the benefits, for example, in the area of energy intensity, resulting from the increase in renewable energy consumption may be limited by the increase in energy intensity resulting from the overall increase in energy consumption related to the global increase in production.

It is a fact that in the European Union, we are dealing with a long-term increase in the consumption of energy from renewable sources, the share of which in gross final energy consumption has doubled since 2005, reaching 22.1%. The European Commission points out that several elements in the form of more efficient technologies, reduction in investment costs, streamlining of the supply chain and support schemes for renewable energy sources contributed to this result. Taking into account the indication of more efficient technologies among the reasons for the increase in energy consumption from renewable sources, the demonstrated relationship between the expenditure on research and development and the increase in renewable energy consumption seems justified.

The research finding that there is no relationship between the expenditure on research and development and energy intensity, energy efficiency and primary energy consumption coincides with one of the trends present in the literature.

In this area of research, the results are not so clear. A number of studies have confirmed the positive impact of innovation on energy efficiency and reduced energy intensity. Wen et al. [55] using panel data from 1995 to 2017 confirmed that renewable energy and energy efficiency have a beneficial effect on technological innovation. Vujanović et al. [56] documented that the use of advanced renewable technologies combined with the implementation of technologies can help save energy and improve the energy efficiency of buildings. Mavi and Mavi [57] examined the environmental and energy performance of OECD countries and showed that Ireland, Switzerland and the United States significantly improved their energy consumption and environmental and energy performance (which could be treated as energy efficiency) over the period under review. Saudi et al. [28] analyzing data on Indonesia confirmed that technological innovations help to improve energy efficiency in Indonesia.

In these types of results, there must be no contradictions, which may be influenced, for example, by the issues of various solutions adopted. An example can be the results of research by Verma et al. [58], who examined the importance of energy efficiency policy measures for Iceland, Norway and New Zealand, pointing to the possibility of developing a synchronized energy efficiency policy taking into account technological progress and innovation, but at the same time highlighting the different approaches to this problem depending on the country.

The study of the relationship between the expenditure on R&D and the increase in energy consumption from fossil sources is less frequent in the literature compared to the analysis of the relationship between the expenditure on research and development and the emission of CO_2 and other harmful substances into the atmosphere.

Research on the impact of R&D on energy consumption from fossil fuels mainly concerns the issue of pollution and very often this problem is approached from this perspective. There are studies in the literature on the impact of research and development on CO_2 emissions and other pollutants [33,59–63]. The results of these studies suggest that investments in research and development combined with improving the efficiency of existing technologies contribute to reducing CO_2 emissions.

In order to improve the negative impact of the energy sector on the natural environment, instruments are used in the form of funds for research and development, environmental protection and environmental taxes, prices of futures contracts for CO_2 emissions and the EU CO_2 emissions trading system [64,65].

The problem of the relationship between R&D and innovation activities and the consumption of energy from fossil fuels is less frequently studied. Research in this area was conducted, among others, by Fei and Rasiah [25], who showed that in the long run technological innovations do not affect the consumption of electricity powered by fossil fuels.

The least present in the literature is the issue of verifying the relationship between the expenditure on research and development and the price of energy, which is an aspect listed in SDG No. 7. Research by Parker and Liddle [66] on a sample of OECD countries in the manufacturing sector in the years 1980–2009 determined that rising energy prices improve energy efficiency.

The interpretation of the confirmation of the relationship according to which an increase in total R&D expenditure and government R&D expenditure means an increase in the consumption of energy from fossil fuels should be linked to the fact that the EU covers more than 50% of its demand for energy from imported fossil fuels. The magnitude of the phenomenon is shown, for example, by the import of fossil fuels to the EU and the gross energy indicator (GAE) used to describe it, which, measured by net imports (imports minus exports) in 2020, amounted to as much as 57% and corresponded more or less to the same value as in 2005. In this case, too, we have been dealing with a complex phenomenon for a long time, with opposing trends—on the one hand, the EU has been consuming energy and increasing the use of domestic energy sources, and on the other hand, it has seen a decline in primary energy production from indigenous fossil fuels due to depletion or lack of economic justification for using domestic sources, especially natural gas.

The structure of energy imports from fossil fuels, the main energy supplier to the EU in 2020, is as follows: Russia was the main import country for the EU countries, accounting for 53.7% of imports of solid fuels, 43.6% of gas and 28.9% of petroleum products. The second largest EU supplier of imports of solid fuels was the United States, which accounted for 18.8% of energy imports. In the case of imports to the EU other than solid fuels, Norway and the UK together account for 25.4% of gas and 16.5% of oil.

In the context of the scale of use of energy from fossil fuels in the EU in the period 2010–2020 described above, it may be justified to demonstrate the relationship that the expenditure on research and development is associated with an increase in energy consumption from fossil fuels.

Demonstrating the relationship between the expenditure on research and development and the increase in energy consumption from fossil fuels is a logical consequence of using energy from this source to finance the economic growth of the EU Member States in the analyzed period. At the same time, the finding remains contradictory to the assumptions of SDG 7 and does not coincide with some results present in the literature on the subject.

The issue of the vague relationship between R&D expenditure and electricity and gas prices may be related to cheap imports. Its very large scale for many years has not motivated research to be intensified, the effect of which would be a significant reduction in energy prices.

In the case of customers who are households, which account for 25% of energy consumption, the lack of a clear dependence on energy prices may also be related to the fact that the percentage of people in the EU who had problems with heating their homes is decreasing.

During the years 2012–2019, the percentage of people who could not afford to keep their flat at the right temperature was constantly decreasing, reaching 6.9% in 2019. It was only in 2020 that this indicator increased to 8.2%, which was caused by the scale of the

COVID-19 pandemic, with particular emphasis on the change in Germany and the change in the EU-SILC research methodology.

In the example of energy efficiency in the period 2010–2020, it can be seen how complex the interpretation of this phenomenon can be, which may be the reason for the lack of correlation between the expenditure on research and development and this variable. Over the period under review, the observed progress in energy efficiency was driven in many Member States by, among others, a structural transition towards less energy-intensive industries and improved end-use efficiency in the residential sector. In addition, the increase in energy consumption between 2014 and 2017 resulted, on the one hand, from the return to average demand for heating after the exceptionally warm 2014, and, on the other hand, from stronger economic growth in that period. At the same time, the recorded decrease in primary energy consumption and the stabilization of final energy consumption in 2018 and 2019 is associated with a general increase in energy efficiency, but the improvement was partially offset by higher consumption in the service sector, growing industrial production and an increase in the number of households.

The recorded very deep decrease in energy consumption in 2019–2020 by over 8% was mainly the result of measures taken to combat the COVID-19 pandemic and the related restrictions on public life and lower economic activity. In addition, long-term trends such as further increases in energy efficiency and the share of energy from renewable sources, as well as relatively mild weather in 2020, may have had an impact on reducing energy consumption.

It is possible that the force of the described events was so great that the positive effects of the expenditure on research and development were not statistically significant in relation to energy efficiency.

Notwithstanding the foregoing, it is common for energy consumption to increase with equipment efficiency increasing as more consumers use more energy-efficient equipment but consume more energy.

Research findings confirming the relationship between R&D expenditure and the share of energy from renewable sources in total energy consumption are in line with most studies, confirming the impact of energy from renewable sources on economic growth, which is "driven" by increasing energy consumption [25,31–35].

It should be emphasized that in the case of the research conducted by the authors, the indicated relationship applies only to total expenditure on research and development, which includes the expenditure on R&D incurred in the group of enterprises, government, higher education and the non-public sector. The lack of this relationship at the level of corporate and government spending may mean that, at the disaggregated level, the studied relationship is invisible in the period of impact covering two years from spending. In the article, the authors referred to research findings, according to which the relationships between R&D expenditure and selected dependent variables were non-linear (in the short term, R&D investment negatively impacts growth prospects in the EU countries, but in the long term, growth is dependent and associated with increased energy consumption [67].

Regardless of the above, the finding that in the long term, there is no relationship between the expenditure on research and development in the group of expenditures of enterprises and government expenditures of the EU Member States and energy variables does not have a positive impact on the implementation of SDG No. 7. The research and development activities of enterprises and governments in the analyzed period do not show any connection with the possibility of offering energy with the characteristics described in the definition of SDG No. 7.

The authors' demonstration that the expenditure on research and development in the EU countries increases the consumption of energy from fossil fuels is related to the dependence of the EU countries on fossil fuels to a greater or lesser extent in the period from 2010 to 2020 and is part of the research trend according to which technological innovation has a positive impact on energy efficiency, causing an increase in energy demand. The analyzed period, being a time of economic growth, was associated with the demand for very large amounts of energy, which could be met primarily by using fossil fuels. It is reasonable to assume that part of the expenditure on research and development was spent on developing solutions that would not so much enable independence from fossil fuels, but rather its more efficient use. In this context, the results of studies by Garbaccio et al. [39] regarding the decrease in the energy production rate as a result of introducing innovations in economic sectors, or the findings of Fei and Rasiah [25] that in the long run technological innovations do not affect the consumption of electricity powered by fossil fuels may be the subject of polemics.

Due to the lack of studies on the impact of research and development activity on electricity and gas prices, the authors' findings that total expenditure on R&D has a very moderate impact on the prices of energy carriers for both households and non-household consumers should be treated as an important supplement to the existing research in this area. Nevertheless, the results obtained in this area in terms of value cannot be classified as the achievement of SDG No. 7, which talks about access to affordable energy for consumers. The strength of dependence is far too weak.

The lack of a relationship between research and development activity in selected groups of R&D expenditures and increasing energy efficiency and reducing capital intensity in the long term is a new topic in research. Once again, it should be noted that the conducted research analyzed the possible impact of the expenditure on research and development, taking into account the two-year shift of effects. Taking into account the period of the commercialization of patents used in the energy sector, the adoption and implementation of legal solutions enabling the introduction of innovations to economic circulation, and the costs of adapting technologies in enterprises enabling the start of production of an innovative product, the effects of R&D expenditures should be expected at a later date.

It is also possible to interpret that the relationship between the expenditure on R&D in EU countries and key energy variables does not really exist in the long run. While there are studies confirming the relationship between the expenditure on R&D and the situation of the enterprises from the high-tech sector [63] or the biotechnology sector [68], such a relationship may not apply to the energy area.

5. Conclusions

The effects of R&D expenditure in the form of technological innovations have contributed to a significant increase in productivity, energy efficiency and improved environmental quality [69,70]. According to the Sustainable Development Goals (SDGs), technological and structural change and technological improvement are considered sources of energy supply, helping to achieve energy security and industrial goals [71].

The usage of efficient and renewable resources leads to lower costs, higher energy efficiency and a reduction in global greenhouse gas emissions. The development of renewable energy sources contributes to the reduction in energy consumption, which positively affects the aspect of sustainability of the economies of the European Union countries in the growth phase.

Global energy efficiency, measured as energy use per unit of GDP, decreased by a third between 1990 and 2015. Energy intensity has decreased in almost all regions of the world, with huge decreases in energy intensity in the richest OECD countries. However, the increase in per capita income has increased energy demand and energy efficiency. The increase in energy demand was also supported by financial developments supporting the financing of environmental technologies, which have played an important role in reducing energy consumption and improving (energy) efficiency in selected OECD economies.

Notwithstanding the above, economic growth, greater production and industrialization have resulted in an increase in the use of fossil fuels, causing many negative effects on the environment of countries, such as global warming, air pollution, and increased health risks.

Projections indicate that in the near future fossil fuels will still dominate the energy supply due to their higher calorific value, greater availability, lower cost of acquisition and longer time needed to implement energy innovations [25]. There is no denying that the described trend is not conducive to achieving the sustainable development goals in the broadly understood area of access to low-emission and cheap energy, which will accelerate and expand activities to promote new energy sources. Activities in this field will require investments in low-emission automation, renewable energy and energy infrastructure.

The research findings observed by the authors confirm the dualism associated with the positive relationship between the expenditure on research and development and the increase in energy consumption from renewable energy sources (which is a positive phenomenon and should be further supported) and the increase in energy consumption from fossil fuels (which is a negative phenomenon, the scale of which should be reduced).

The strength of the relationship that has been demonstrated in the case of the relationship between R&D expenditure and energy consumption from renewable energy sources should raise the level of understanding of factors that help to increase energy efficiency. There is little empirical evidence on the factors that contribute to energy efficiency; however, the authors' determination toward the role of the research and development expenditures in achieving this goal is an important research contribution.

At the same time, the demonstration of the relationship between the expenditure on research and development and the consumption of energy from fossil fuels should be the subject of further research. The need to deepen analysis in this area is related to the outbreak of the armed conflict between Russia and Ukraine, which is dramatically affecting the level of energy consumption from fossil fuels in European Union countries. The scale of changes in this area was very large already in 2022, but taking into account the inertia of the processes consisting in moving away from fossil fuels, a more precise picture of changes will be possible to assess in the coming years.

The results of the conducted research confirmed the complexity of the relationship between R&D expenditure and key energy variables in the EU Member States. Conducting an analysis on many levels of a complex research problem allows, however, conclusions to be drawn as to the direction to be taken in order to move closer to the implementation of SDG No. 7. At the moment, apart from the proven relationship between the expenditure on R&D and the increase in the consumption of high-power renewable energy, other findings for the period 2010–2020 concerning the relationship between the expenditure on R&D and the increase in the consumption of the energy from fossil sources, and the small relationship between the expenditure on R&D and the prices of energy and gas did not bring the Member States closer to the implementation of SDG No. 7.

This does not change the fact that the identified relationships provide a lot of information allowing the identification of the sources of problems and opportunities, which, if properly modeled, may bring the desired effects of planned activities related to research and development activities in the European Union. Further analyzes will have to take into account both the effects of the COVID-19 pandemic as well as the consequences of the conflict between Ukraine and Russia, both of which have brought huge changes in many aspects related to energy consumption in the EU countries.

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