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Energy Supplies in the Countries from the Visegrad Group

Edited by
Tomasz Rokicki

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Editor

Tomasz Rokicki

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Editor
Tomasz Rokicki
Department of Logistics
Warsaw University of Life
Sciences – SGGW
Warszawa
Poland

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

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About the Editor

Tomasz Rokicki

Professor at the Warsaw University of Life Sciences, in the Department of Logistics, Institute of Economics and Finance. Main area of research: regional development and conditions and functioning of energy markets and other products and services, theories of location of activity, conditions, functioning and organization of activities in the field of logistics in the agribusiness sector. Authored over 300 scientific and popular science publications, including several books. Manager of several national and international research projects. Participant of scientific internships in the Czech Republic, China, Austria and Hungary. Awarded many times by the Rector of the Warsaw University of Life Sciences for scientific and organizational activities.

https://orcid.org/0000-0003-3356-2643

https://www.scopus.com/authid/detail.uri?authorId=57193094616

https://www.researchgate.net/profile/Tomasz-Rokicki

Preface to "Energy Supplies in the Countries from the Visegrad Group"

The inspiration to accept the proposal to join the editorial process of this Special Edition was the cooperation of the Visegrad Group (V4) countries in many economic fields, including energy. The Visegrad Group is an association of four Central European countries—Poland, the Czech Republic, Slovakia and Hungary. The aim of the group was to deepen cooperation between these countries, and in the initial phase, in particular, in terms of accession to the structures of the European Union and NATO. The Visegrad Group was established in 1991 by three countries (Poland, Hungary and Czechoslovakia) forming the so-called Visegrad Triangle. Later, as a result of the dissolution of Czechoslovakia (January 1, 1993), the Czech Republic and Slovakia became members of the group. The V4 countries had similar goals for their foreign policies, but also similar possibilities for their implementation. These countries belonged to the former communist bloc, best prepared for a market economy. In addition, they represented a very similar level of socio-economic development. All these aspects mean that the V4 countries can be compared with each other in terms of energy policy, including energy production and consumption.

The purpose of this Special Issue was to collect research results and experiences on energy supply in the Visegrad Group countries. It considers both macroeconomic and microeconomic aspects. It was important to determine how the V4 countries deal with energy management, how they have undergone or are undergoing energy transformation and in what direction they are heading. The articles herein concern aspects of the energy balance in the V4 countries compared to the EU, including the production of renewable energy, as well as changes in its individual sectors (transport, food production). The energy efficiency of low-emission vehicles in public transport and goods deliveries are also discussed, as well as the energy efficiency of farms and energy storage facilities and the impact of the energy sector on the quality of the environment.

As Guest Editor for this Special Issue, I would like to extend my sincere thanks to MDPI and the *Energies* team for providing this extraordinary learning and development opportunity, and to the editorial team, especially Reka Kovacs, for their continued support and attention. I must admit that such interactions are excellent for scientific development, especially for young scientists. We hope readers will enjoy this research.

Tomasz Rokicki
Editor

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Article

Diversity and Changes in the Energy Balance in EU Countries

Tomasz Rokicki and Aleksandra Perkowska *

Institute of Economics and Finance, Warsaw University of Life Sciences, 02-787 Warsaw, Poland; tomasz_rokicki@sggw.edu.pl
* Correspondence: aleksandra_perkowska@sggw.edu.pl; Tel.: + 48-22-59-342-55

Abstract: The main purpose of the paper was to present the energy balance in the EU countries. The specific objectives were to show the concentration and directions of changes in the demand, production, import, and export of energy in the EU countries, to determine the degree of variability (or stability) of these energy balance parameters, and to establish the correlation between the energy balance parameters and economic parameters. All members of the European Union were determinedly selected for research on 31 December 2018 (28 countries). The research period embraced the years 2004–2018. The sources of materials were the literature on the topic and data from Eurostat. Descriptive, tabular, and graphical methods, Gini coefficient, Lorenz curve, coefficient of variation, Pearson's linear correlation coefficient, and constant-based dynamics indicators were used in the analysis and presentation of materials. It was determined that only the demand for energy and its import in EU countries were nearly related to the economic situation. In turn, exports and production were medium and weakly correlated. In these parameters, economic factors had a smaller impact than other factors, such as political development or the level of energy development in the country. It was also found that the EU countries' energy imports were characterized by lower volatility than its exports. As a rule, the most significant stabilization in the given parameters occurred in countries with a stable economy, the so-called developed economies, while the most significant volatility was in developing countries. Energy security is of great importance in all EU countries.

Keywords: energy supplies; energy security; energy market; EU countries

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1. Introduction

Energy is obtained from many sources, such as crude oil, fossil fuels (hard coal, lignite, peat), and natural gas. They are conventional energy sources. In turn, renewable sources include energy obtained from wind, sun, water, biomass and biofuels, or geothermal energy. There are differences in the structure of energy sources between countries [1–5]. There is a common energy policy in the EU which is gradually evolving, based on three pillars: competition, security of supply, and sustainable development. Energy security includes, among other aspects, availability of supply, affordability, and sustainability [6,7]. Energy security is understood in many dimensions and takes different specifics depending on the country (or continent), time frame, or energy source. It can also be stated that the concept of energy security is very broad and is constantly evolving. Primary energy supply security and geopolitics are essential. This approach will dominate the article [8–14]. In this context, a balanced supply and demand for energy resources are important, as well as their high availability and relative price stability [15]. It is the availability and affordability of energy that has the greatest impact on the overall energy security of the society. In turn, the promotion of renewable energy and diversification are important national energy security strategies [16–19]. Often, separate indicators for each energy source are used to measure energy security [20]. Overall, there are many indicators that measure energy security. As examples, indicators, more or less complex, developed by Scheepers et al. [21], Löschel et al. [22], Augutis et al. [23], Sovacool [24,25], Narula et al. [26–28], Erahman et al. [29], Ying and Liu [30], and Stavytskyy et al. [31] can be mentioned.

With the emergence of new technologies and the pursuit of policies favoring renewable energy sources, the energy system has transformed. As a result, some energy importers have become exporters, and countries long described as significant energy exporters have become centers of increasing demand. For each country, its technical, environmental, economic, and social conditions, i.e., country specificity, are essential. The right combination of policy and technology could support economic growth while ensuring safe and affordable energy [32–37].

The common electricity market in the EU has been established for almost 30 years. EU energy policy is based on three pillars: competition, the security of supply, and sustainable development. Objectives such as reducing greenhouse gas emissions, increasing the consumption of energy generated from renewable sources, and increasing energy efficiency and expanding electricity connections are also important [38–44]. On the one hand, energy policy focuses on the liberalization of the entire sector and, on the other hand, on development towards a smarter, more sustainable energy sector [45–49]. All goals were implemented gradually and evolved. The 2010 Strategy should be mentioned among the important documents concerning energy policy in recent years. It focuses on achieving energy efficiency targets and implementing low-carbon technologies [50]. In 2011, 2050 targets were set for a low-carbon economy [51]. Another document from 2015 is also concerned about supporting the previous goals in EU energy policy [52]. It is also necessary to mention the document from 2016 on renewable energy [53].

Different energy sources are used in EU countries. Despite this, there are energy crises, mainly related to interruptions in natural gas supplies from Russia. In such a case, it is crucial to diversify energy sources and suppliers [54–60]. The idea of the Energy Union is also gaining importance. The Energy Union strategy aims to provide Europe and its citizens with affordable, secure, competitive, and sustainable energy. Its key elements are the diversification of routes and sources of supply (the EU is heavily dependent on energy imports), regional cooperation, an integrated internal energy market, and energy infrastructure development [61–64].

The main purpose of the paper is to present the energy balance in EU countries. The specific objectives are to show the concentration and directions of changes in the demand, production, import, and export of energy in the EU countries, to determine the degree of variability (or stability) of these energy balance parameters, and to establish the correlation between the energy balance parameters and economic parameters. The research results make it possible to verify the correctness, based on current data. It is vital in the evolution of the situation of the European Union energy policy's objectives.

Two hypotheses are put forward in the study:

1. All the energy balance parameters in EU countries are closely related to a given country's economic situation.

Such parameters determined the economic situation as total and per capita GDP value, total and per capita household expenditure, the value of exports and imports, and added values of the economy's most critical energy-intensive sectors. T

2. Energy imports in EU countries were less volatile than energy exports.

Thus, there is stability in the volume of energy imports.

2. Materials and Methods

All members of the European Union were selected for research on December 31, 2018 (28 countries). The research period covers the years 2004–2018. In 2004, the EU enlarged considerably, with ten new countries joining. This also resulted in large differences in the EU energy balance. The last year in which there were complete data needed to carry out the research using the assumed research methods at the time of the research was 2018. The sources of materials were the literature on the subject and also data from Eurostat. The use of Eurostat data made it possible to compare all EU countries. The tested parameters were calculated based on the same methodology. Descriptive, tabular, and graphical methods, Gini coefficient, coefficient of variation, Lorenz curve, constant-based dynamics indicators, and Pearson's linear correlation coefficient method were used for the analysis and presentation of materials.

In the first stage of the research, the shaping of primary production, import, export, and total energy supply in the European Union was presented. Primary production of energy is any extraction of energy products in a usable form from natural sources. Imports of energy represent all entries into the national territory excluding transit quantities. Exports of energy represent all exits from the national territory excluding transit quantities. Total energy supply is the sum of production and imports subtracting exports and storage changes.

The aim is to show the changes in these parameters of the energy balance. In the second stage, the Gini concentration coefficient was calculated. It was used to determine the concentration level of primary production, import, export, and total energy supply in European Union countries. It is measured by the amount of energy produced, consumed, or traded in the EU. If these values were related to only one country, the coefficient would be 1. If they are spread over more countries, the coefficient becomes lower. The closer it is to 0, the more it proves that the volume of a given energy balance parameter is evenly distributed among the EU countries. The Lorenz curve is a graphical presentation of the level of volume concentration of a given parameter in the EU countries.

The Gini coefficient is a measure of the unevenness of a random variable's distribution. The coefficient can be represented by the formula below when the observations are sorted in ascending order [65]:

$$G(y) = \frac{\sum_{i=1}^{n}(2i - n - 1) \times y_i}{n^2 \times \bar{y}} \quad (1)$$

where:

n—number of observations;
y_i—value of the "i-th" observation;
$\bar{y}$—the average value of all observations, i.e., $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$

The degree of concentration of a one-dimensional random variable distribution determines the Lorenz curve [66]. With sorted observations y_i, which are non-negative values $0 \leq y_1 \leq y_2 \leq \ldots \leq y_n$, $\sum_{i=1}^{n} y_i > 0$, the Lorenz curve is a polyline which apexes (x_h, z_h), for h = 0,1, … , n, have the following coordinates:

$$x_0 = z_0 = 0, \quad x_h = \frac{h}{n}, \quad z_h = \frac{\sum_{i=1}^{h} y_i}{\sum_{i=1}^{n} y_i} \quad (2)$$

The Gini coefficient determines the Lorenz curve area and the diagonal of a unit square multiplied by 2.

The third stage of the research presents the structure of energy imports in the EU. The energy import structure in selected EU countries was presented—two with the highest imports, one with the middle of the rate, and one with the lowest imports. It made it possible to determine trends and differences in different countries regarding the volume of energy imports. Various country models are presented.

In the fourth stage, the dynamics indicators for the parameters of the energy balance were calculated. As a result, data on the directions and strength of primary production, import, export, and total energy supply in individual EU countries were obtained. The dynamics indicators with a constant base were used. The dynamics indicators with a fixed base are determined as follows [67]:

$$i = \frac{y_n}{y_0} \text{ or } i = \frac{y_n}{y_0} \cdot 100\% \quad (3)$$

where:

y_n—the level of the phenomenon in a certain period; y_0—the level of the phenomenon during the reference period.

In the fifth stage of the research, the coefficients of variation for the energy balance parameters in individual EU countries were calculated. Thanks to this, it was possible to determine whether the primary production, import, export, and total energy supply are stable or subject to very large-scale fluctuations.

The variation coefficient eliminates the unit of measurement from the standard deviation of a series of numbers. It is dividing them by the mean of series of numbers. Formally the coefficient of variation is computed as [68]:

$$C_v = \frac{S}{M} \tag{4}$$

where:

S—standard deviation from the sample;
M—arithmetic mean from the sample.

In the sixth stage, the relationship between the value of primary production, import, export, and total energy supply in the EU countries and the economy's parameters was examined. The parameters used for the analysis were selected on purpose and were selected based on a literature review. Parameters highlight the most important aspects related to the economy of the studied country. Thanks to this research, it was possible to determine which parameters are significant and the strength of their relationship with the energy balance parameters.

The strength of a straight-line relationship between two measurable features is a measure of Pearson's linear correlation coefficient, and it is expressed through the formula [69]:

$$r_{XY} = \frac{C(X,Y)}{\sqrt{{S_X}^2 \cdot {S_Y}^2}} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \cdot \sum_{i=1}^{n}(y_i - \overline{y})^2}} = \frac{C(X,Y)}{S_X \cdot S_Y} \tag{5}$$

where:

$C(X,Y)$—covariance between the X and Y;
${S_X}^2$—X feature variance;
S_X—X feature's standard deviation;
${S_Y}^2$—Y feature variance;
S_Y—Y feature's standard deviation.

The linear correlation coefficient is considered as the normalized covariance. The correlation takes values from the range $(-1, 1)$.

3. Results

3.1. Concentration and Directions of Changes in the Demand, Production, Import, and Export of Energy in EU Countries

The energy demand in the EU-28 countries was not covered by production (Figure 1). In 2004–2018, the energy deficit increased from 48% in 2004 to 53% in 2018. Therefore, it was necessary to import energy and energy resources. There was also export, which is the domain of the free market. However, the fact is that this market is not entirely free because high tariffs and non-tariff barriers partially limit it. Some countries produced more of a given type of energy and sold the surplus. In the years 2004–2018, energy production in the EU decreased by 19%, and its consumption by 10%. Nevertheless, the import of energy resources was still needed. In 2004–2018 it remained at a relatively similar level and increased slightly by 6%. On the other hand, exports of energy resources increased by 15%. Therefore, changes in the parameters of the energy balance in the entire EU were small. In individual EU countries, however, they could take place, mainly due to energy sources. In 2018, energy supply in the EU countries was mainly based on crude oil (29%), natural gas (22%), renewable energy sources (14%), solid fuels, and nuclear energy (12% each). The remaining energy sources were of little importance. In 2004–2018, the energy supply increased the most using renewable energy sources and non-renewable waste (109% each). The dynamics were slightly lower in the case of oil shale (increase by 43%). The supply of energy from solid fuels decreased the most (a decrease by 32%), followed by peat and peat products (by 21%), crude oil and nuclear energy (19% each), and natural gas (by 10%). The energy in the EU was produced from various sources. In 2018, renewable energy sources accounted for 31% of the total energy produced. It was followed by nuclear energy (28%), reliable fossil fuels (16%), natural gas (12%), and oil (10%). The production structure did not correspond to the consumption structure. Individual countries used their natural resources or opportunities to produce renewable energy. Trends in the dynamics of changes in internal energy production were quite similar to those in energy demand. However, much larger declines can be noticed in the case of energy production from natural gas (down 54%), crude oil (47%), and solid fuels (40%). In the case of exports, the dominant source of energy resources was crude oil. In 2018 it was accounted for 77% of all energy exports. Natural gas accounted for 12% and electricity 6% of exports. It should also be emphasized that energy trade often took place between individual EU countries located in close neighborhood.

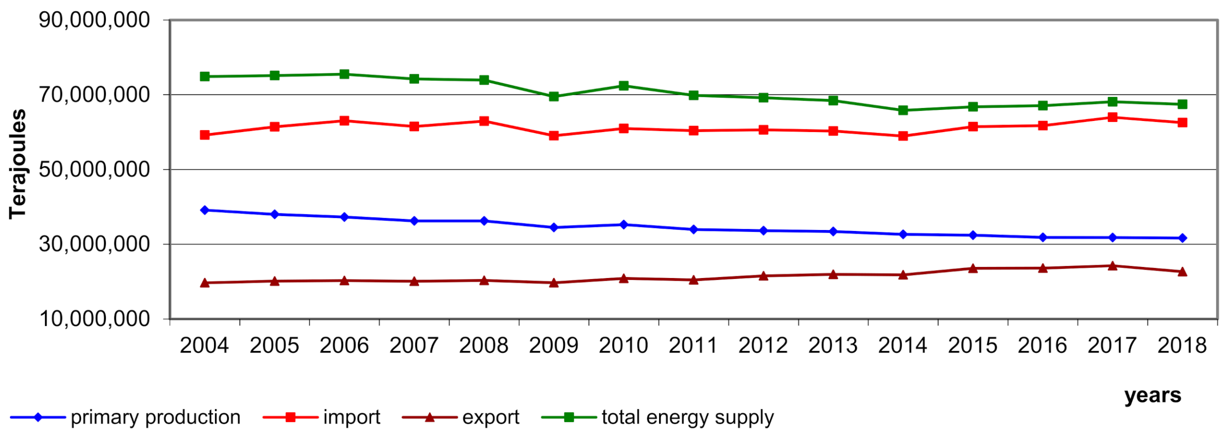
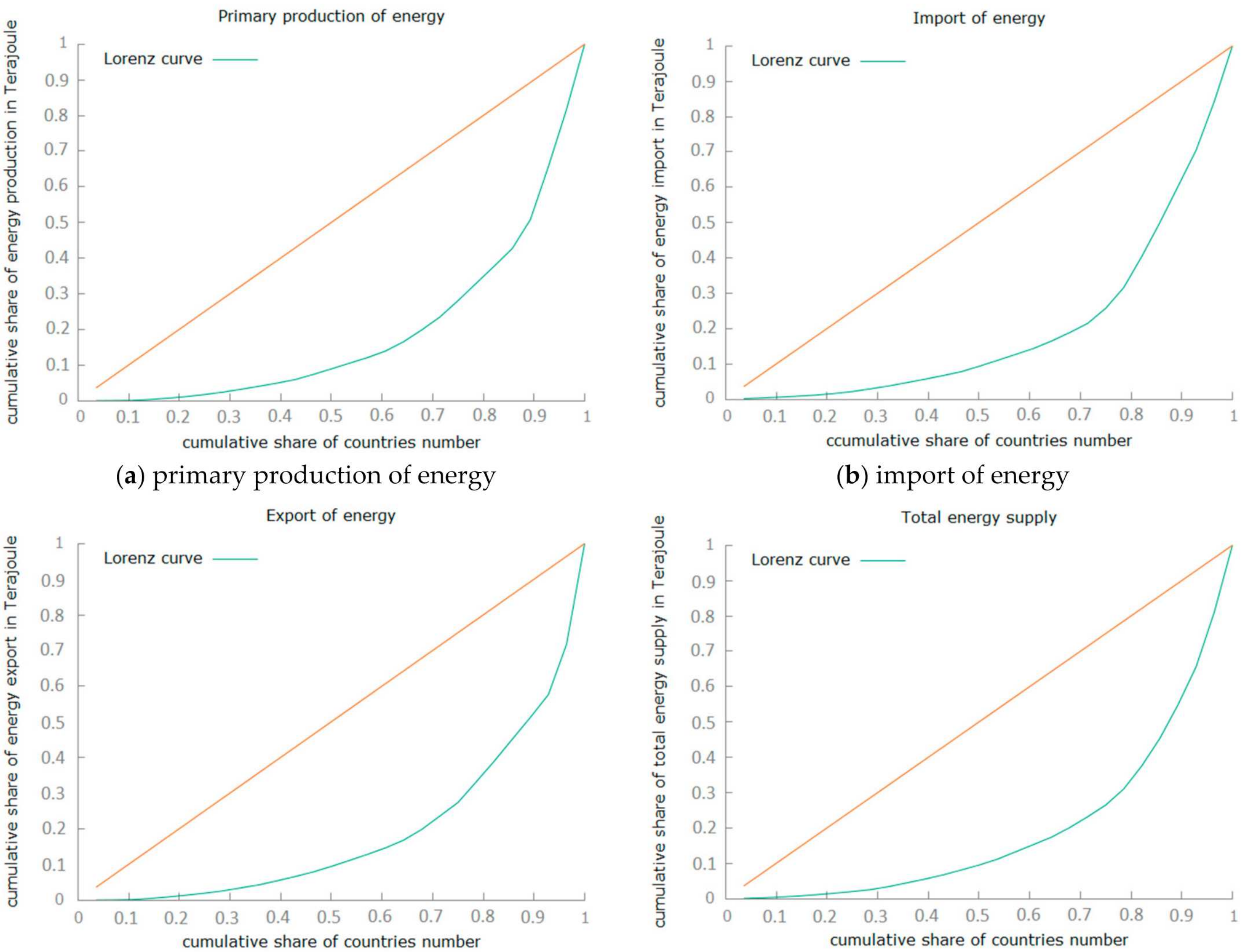


Figure 1. Primary production, import, export, and total energy supply in European Union in 2004–2018.

The Gini coefficient determined the concentration level of primary production, import, export, and total energy supply in the European Union. This coefficient is a commonly used measure of inequality, as it meets the postulated axioms in this respect [70]. It always takes values from 0 to 1. A result close to 1 means a very high concentration of one energy value, and a result close to 0 means a dispersion of these values. The data accepted for the study related to 2018 and covered all EU countries. The Gini coefficient calculated z for energy production in the EU was 0.62. The estimated coefficient for the population was 0.65. It suggests a high concentration of one or more countries in energy production. Gini coefficients were also calculated for the other energy parameters. Additionally, the differentiation was presented using the Lorenz concentration curve [71] (Figure 2). In 2018, there was a high concentration of energy imports in the EU countries (the sample coefficient was 0.60 and the estimated 0.63), as well as exports (from the sample 0.63, estimated 0.65) and energy consumption (respectively 0.62 and 0.64). Concentration coefficients were also calculated for 2004. There has been a significant reduction in energy production and exports in the EU from one or more sources towards diversification. The Gini coefficients for energy production in 2004 were 0.67 from the sample and 0.69 estimated. In the case of exports, it was 0.69 and 0.71, respectively. In the case of energy imports and consumption, there were virtually no changes. The concentration level did not change. For energy imports, the Gini coefficient from the sample was 0.62, and the estimated one was 0.64. For energy consumption, it was 0.62 and 0.65, respectively. Therefore, it can be concluded that there was a high concentration concerning individual elements of the energy balance in the EU. The changes did not occur at all or were very slow. The high concentration of production, import, export, and energy consumption in several countries is also due to several countries with high economic potential and large population populations. Additionally, there were many smaller countries in the EU reporting less energy demand. Changes in the future will not happen quickly. Different countries have access to quite similar technologies, so their energy efficiency differences are usually not very large. Therefore, it can be said with a high probability that the high level of concentration of production, trade, and energy consumption in the EU will be maintained for many years.



(**a**) primary production of energy

(**b**) import of energy

(**c**) export of energy

(**d**) total energy supply

Figure 2. Lorenz concentration curves for energy balance parameters in the EU countries in 2018. Source: Own study based on Eurostat.

Energy security depends to a large extent on access to energy resources. It is important to be slightly dependent on one or more suppliers. It is also advisable to diversify energy supply sources, improving energy security, and not using energy supplies as a political instrument. Import is a vital element of the energy balance of the EU countries. In 2018, mainly crude oil was imported (64% of all energy imports), but also natural gas (25%) and solid fuels (7%) (Figure 3). The share of other energy sources was 4%. Imports of other energy resources, such as those from non-renewable waste and renewable energy sources, grew the fastest. However, the scale of these imports was small. In the years 2004–2018, the import of natural gas (by 23%) and crude oil (by 2%) increased, while the import of solid fuels (by 26%) decreased. In the case of the energy balance parameters, slight changes in the energy volume can be noticed. However, there were changes in the structure concerning energy sources. Renewable energy sources were introduced. However, it was impossible to abandon crude oil, especially in transport, and natural gas, for use in households and industrial plants.

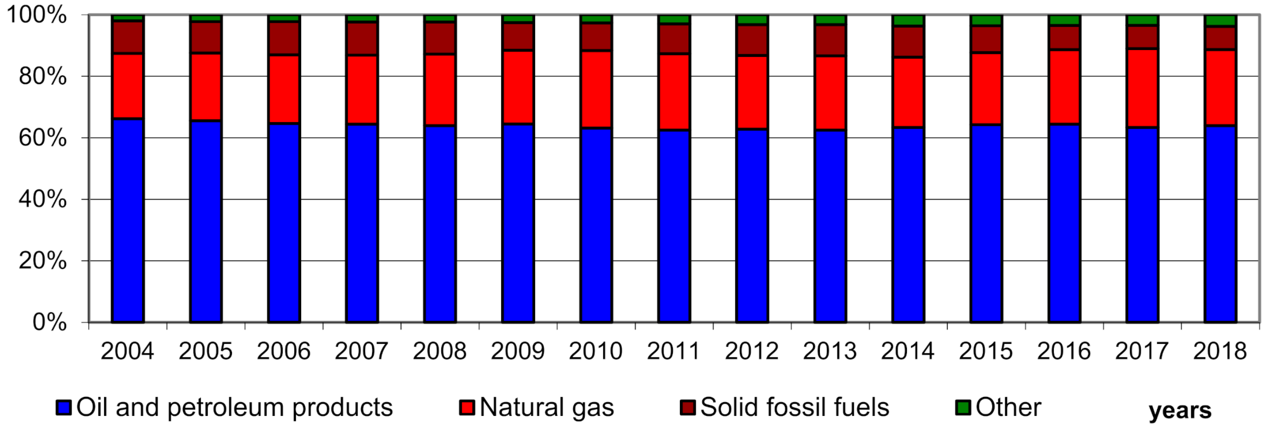


Figure 3. The structure of energy imports in the European Union according to the most important sources in 2004–2018.

3.2. Case Studies in the Field of Energy Balance in Selected EU Countries

The situation in individual countries in terms of energy balance was diversified. Malta, Luxembourg, and Cyprus were almost entirely dependent on external energy sources. Theoretically, energy production covered the reported demand only in Denmark in 2004–2012, Estonia in 2015 and 2017–2018, and Great Britain in 2004. However, there was practically no country that was self-sufficient in energy and did not need imports. The reason was the large variety of energy sources and the strict allocation of the raw materials to specific needs. For example, electricity used to power electric cars could be an alternative to crude oil in transport. However, the use of electric cars is low, so there is practically no alternative to oil. To select countries' representatives for a more detailed analysis compared investments received by individual countries regarding energy imports. Germany imported the most energy resources. Some justification may be the country's size and the degree of economic development, and the resulting needs. The country's energy self-sufficiency in 2018 was only 37%. The Netherlands took second place. It is also economically developed, but much smaller in terms of area and population. Energy self-sufficiency in 2018 amounted to 50%. Hungary (14th position) was in the middle to import energy resources in the EU. It was an economically developing country. The country's energy self-sufficiency in 2018 was 41%. Cyprus was last. However, it was a tiny country with little diversification of energy sources. Estonia was selected for the analysis. In terms of the volume of energy, imports was in the penultimate place. It was an economically developing country with an extensive diversification of energy sources. In 2018, this country was self-sufficient because production accounted for 106% of the energy supply. However, it must be taken into account that some energy sources have not been widely replaced, e.g., crude oil.

In the years 2004–2018 in Germany, the energy demand decreased (by 11%), its production (by 18%), export (by 11%), and import (by 9%). In the case of imports, crude oil dominated in the structure in 2018 (54% of total imports), while natural gas (30%) and solid fuels (13%) were of less importance. This structure did not change significantly (Figure 4). In the years 2004–2018, the fastest in relative terms was importing energy from renewable sources (an increase by 365%). Imports of solid fuels also increased slightly (by 9%). However, less crude oil (by 14%) and natural gas (by 7%).

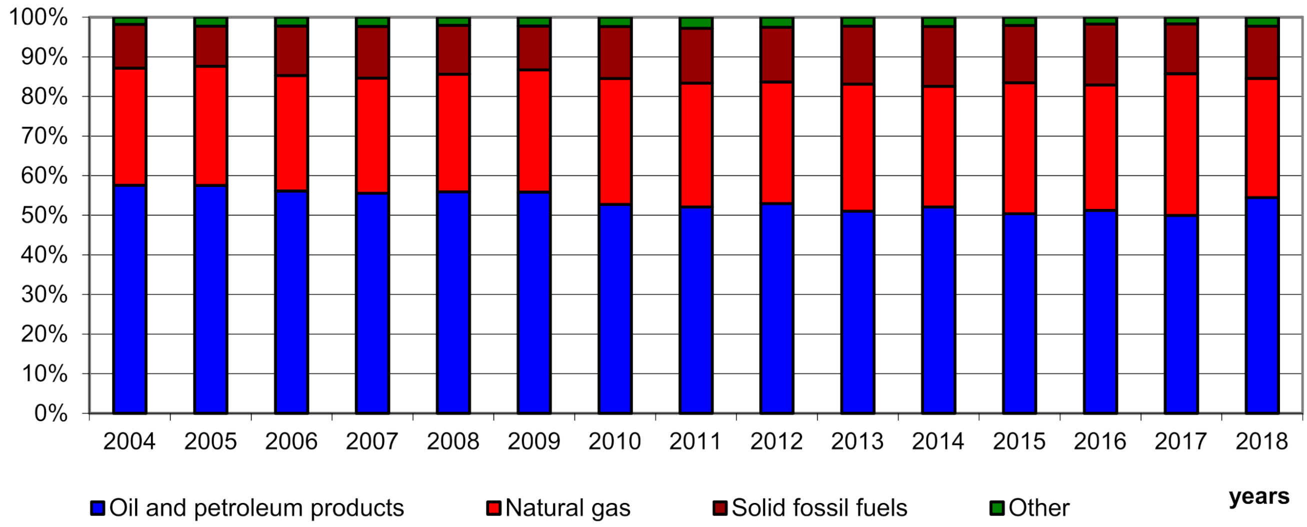


Figure 4. Share of energy import sources in Germany in 2004–2018.

In the Netherlands, between 2004 and 2018, energy demand decreased by 9% and its production by 46%. Interestingly, both exports (by 38%) and imports of energy resources (by 45%) increased during this period. The Netherlands is one of the countries that trade in energy resources. Some of the purchased raw materials were subject to foreign trade, making it possible to earn money on this type of activity. In 2018, crude oil dominated in energy imports (73%). Natural gas (21%) and solid fuels (4%) were of less importance (Figure 5). In the years 2004–2018, natural gas imports increased the fastest in relative terms (by 223%). Growth was also recorded in renewable energy (81%), electricity (25%), and oil (28%). Substantial fuel imports fell by 6%.

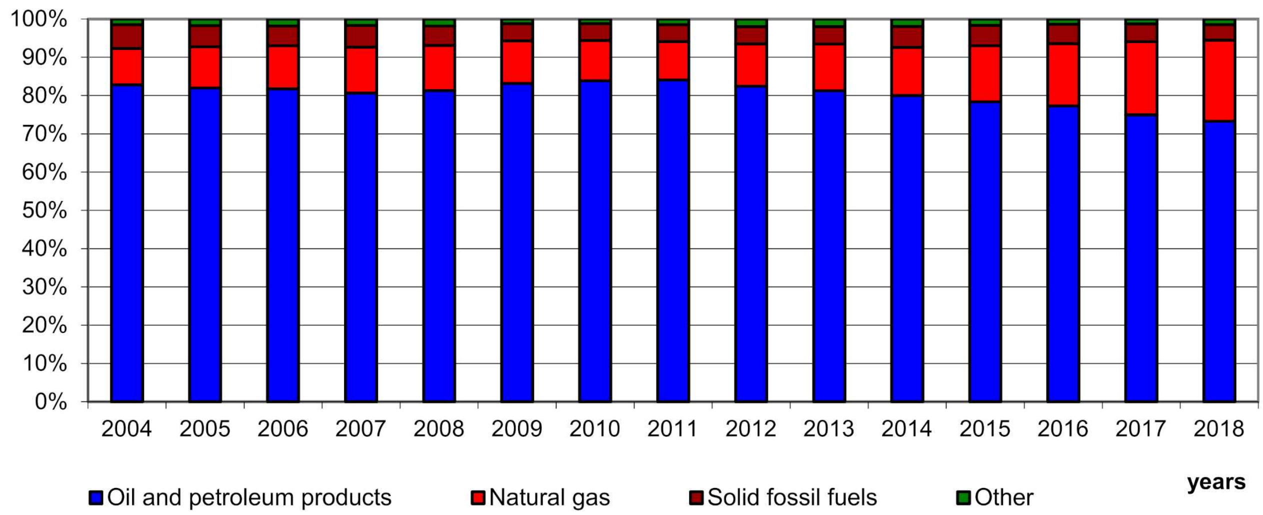


Figure 5. Share of energy import sources in Netherlands in 2004–2018.

Hungary was in the middle in terms of energy imports. In 2004–2018, the demand for energy in this country increased by 1%, and domestic production by 6%. Much more significant increases were recorded in energy imports (an increase by 28%) and its exports (by 194%). Two sources dominated the import structure in 2018, i.e., crude oil and natural gas (Figure 6). They accounted for 43% of imported energy each. The imports of electricity (7%) and solid fuels (5%) were much lower. In Hungary, in the analyzed period, the import of electricity (77%) and crude oil (38%) were increasing the fastest, and imports of natural gas (14%) and solid fuels (3%) the slowest. A separate category is an energy from renewable sources, which has been imported only since 2009. In 2009–2018, the growth dynamics for this type of energy was 435%. Still, the importance of renewable energy was low. Hungary is one of the economically developing countries with a high demand for imported energy.

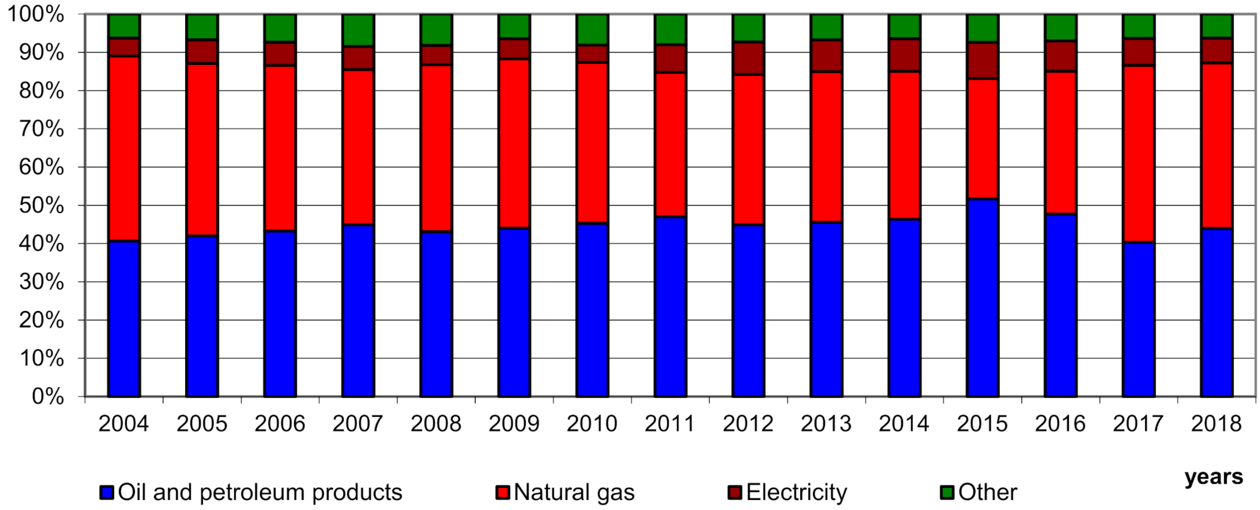


Figure 6. Share of energy import sources in Hungary in 2004–2018.

The lowest energy import was recorded in Estonia. In the years 2004–2018, all parameters of the energy balance in this country increased, i.e., energy demand (by 18%), its production (by 78%), export (by 399%), and imports (by 26%). The import structure was dominated by crude oil, as it accounted for as much as 73% of total energy imports in 2018. Natural gas (15%), electricity (9%), and renewable energy sources (1%) were of less importance (Figure 7). In the years 2004–2018, the imports of crude oil (an increase by 77%) and electricity (by 780%) increased, while the imports of solid fuels (by 19%) and natural gas (by 47%) decreased. In the case of other energy sources, the import of energy from renewable sources is growing rapidly. Such imports appeared only in 2009. In 2004, the import of bituminous shale was of great importance, but this source of energy was abandoned in the following years. The regularities in Estonia were quite similar to those in Hungary. It was different, among others structure of imported energy.

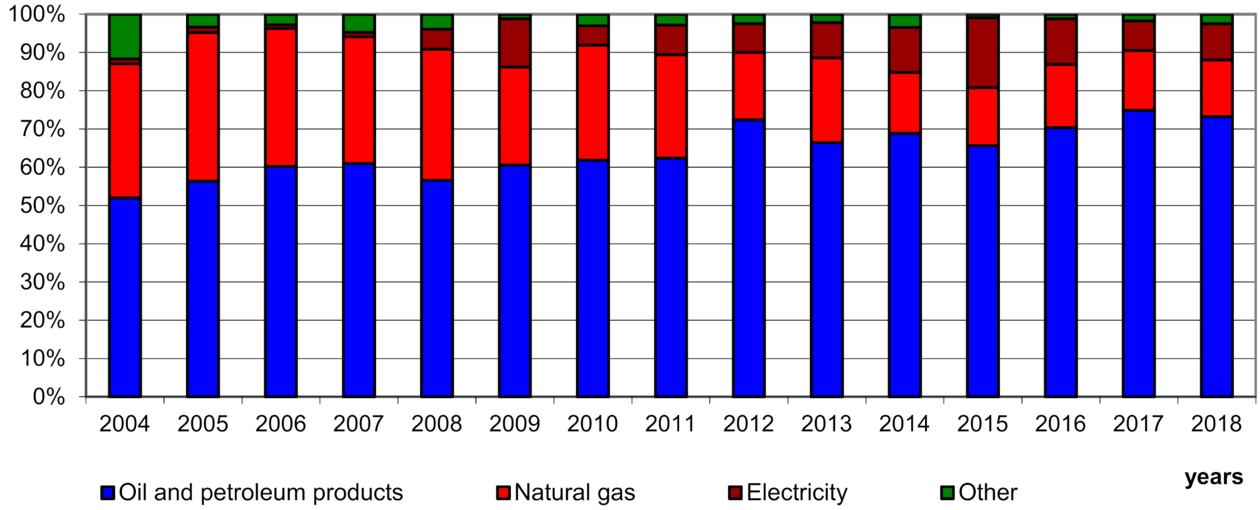


Figure 7. Share of energy import sources in Estonia in 2004–2018.

The presented examples of countries show some models concerning external energy sources and ensuring energy security. The countries differed in the size of imports, but also the degree of economic development. There have not been many changes in economically-developed countries, but, as a rule, energy production and consumption were reduced. Examples of such countries are Germany and the Netherlands, where many energy efficiency projects were implemented. In economically developing countries, all parameters of the energy balance tended to increase. This is due to the enormous economic needs of these countries and higher energy demand. Additionally, these countries, as a rule, used less efficient technologies in terms of energy efficiency. A common feature of all countries is the growing importance of renewable energies. Moreover, since 2009, this source of energy has become a relatively common subject of international trade. Renewable energy imports in all countries have grown tremendously. Of course, the scale of this energy import was still much smaller than conventional energy sources.

3.3. Degree of Variability (or Stability) of Energy Balance Parameters in EU Countries

In the next stage, the dynamics indices were calculated for the energy balance parameters, i.e., energy supply, production, export, and import. The level from 2004 was adopted as the basis (Table 1). The results were ordered in descending order due to the dynamics of energy imports. Energy imports have increased in most EU countries over the fourteen years. The decreases concerned nine countries, but they did not exceed 22%. The largest increase in energy imports was recorded in Poland. Imports almost doubled there. There were also high dynamics in Malta, the Netherlands, and Slovenia. Changes in imports may result from policies implemented at the country level. Due to the existing economic and social conditions, each country should be analyzed separately. In most EU countries, the energy demand has decreased. The changes were not significant. Much greater fluctuations occurred in the case of exports and energy production. Some countries increased energy sales several times, for example, Estonia, the Netherlands, Hungary, Denmark, the Czech Republic, and Germany. The explanation is that energy is increasingly being traded as a commodity. More and more energy is purchased to meet one's own energy needs and for speculative purposes. Additionally, a considerable diversification of energy sources and the inability to use a given source for all purposes causes the exchange to occur. Countries that specialize in producing given energy, or have considerable energy resources, sell energy to other countries. In turn, they buy energy and the necessary raw materials that are in shortage on their market. In energy production, one-half of the countries recorded declines, and the other half increases. The scale of the changes varied. In general, the largest increases in energy production occurred in small countries with low production. In larger countries, the scale of changes was not so significant.

Table 1. Dynamics indicators for energy parameters in EU countries in 2004–2018 (year 2004 = 100).

Countries	Dynamics Indicators for Energy Parameters in 2004–2018			
	Primary Production	Import	Export	Total Energy Supply
Poland	78.62	189.65	79.78	115.99
Malta	8387.14	173.98	-	82.11
Netherlands	53.63	144.62	138.33	90.79
Slovenia	98.73	143.26	349.46	95.12
Greece	72.67	128.19	344.95	76.48
Hungary	106.35	127.99	294.41	100.86
Estonia	178.02	125.93	498.82	117.62
United Kingdom	53.89	120.88	71.04	78.07
Czechia	81.65	116.54	86.53	94.41
Lithuania	37.43	116.47	105.81	81.06
Austria	121.86	112.87	222.17	101.45

Table 1. *Cont.*

Countries	Dynamics Indicators for Energy Parameters in 2004–2018			
	Primary Production	Import	Export	Total Energy Supply
Denmark	45.03	112.80	48.44	88.36
Latvia	154.84	109.60	294.55	104.55
Cyprus	392.20	109.53	-	104.82
Belgium	87.25	108.73	129.04	91.53
Sweden	108.14	107.93	159.63	95.75
Croatia	88.33	105.78	134.05	88.58
Spain	107.03	105.74	324.66	90.86
EU	80.87	105.58	115.19	90.10
Portugal	167.61	100.11	291.39	87.09
Bulgaria	116.48	95.22	157.81	99.55
Finland	124.11	92.15	147.40	91.42
Germany	81.78	91.30	78.80	89.35
Luxembourg	246.79	90.50	49.66	90.99
Slovakia	94.66	88.12	90.45	93.23
France	101.85	87.98	104.31	92.01
Romania	87.72	86.13	128.34	85.34
Italy	128.14	82.60	117.37	83.65
Ireland	268.05	78.26	139.04	95.45

Then, the coefficients of variation for the parameters related to the energy balance were calculated. The results refer to the years 2004–2018 and have been ordered in ascending order according to energy imports' variability (Table 2). The variation in energy demand was not very large, which means no sharp changes in energy consumption. The most significant fluctuations in energy demand occurred in Lithuania, Malta, and Greece. Austria and France were among the most stable countries in terms of energy demand. In the case of energy imports, the most significant variability was in Malta, Romania, Poland and Estonia. In turn, energy imports were the most stable in Belgium, Germany, and Austria. There was high variability in the production and export of energy. There was very high variability in energy production in Malta and Ireland, Lithuania, and Cyprus. Energy production was stable in France, Slovenia, and Slovakia. Energy exports were generally highly volatile, with the highest volatility in Cyprus, Malta, and Estonia. The smallest fluctuations in energy exports occurred in the Czech Republic, France and Slovakia. As a rule, in countries with a stable economy, the so-called economically-developed, there was better stability in energy consumption, production, and import. In turn, in developing countries, this variability was generally much higher. In addition to other economic development and applied government policies, there was also a different energy development level in individual EU countries.

Table 2. Coefficients of variation for energy parameters in EU countries in 2008–2019.

Countries	Coefficients of Variation for Energy Parameters			
	Primary Production	Import	Export	Total Energy Supply
EU	0.07	0.02	0.07	0.05
Belgium	0.10	0.04	0.09	0.04
Germany	0.07	0.04	0.15	0.04
Austria	0.08	0.05	0.26	0.02
Spain	0.06	0.05	0.42	0.07
Finland	0.06	0.05	0.18	0.05
Czechia	0.08	0.05	0.06	0.04
Sweden	0.06	0.06	0.20	0.04
Luxembourg	0.24	0.06	0.22	0.05

Table 2. *Cont.*

Countries	Coefficients of Variation for Energy Parameters			
	Primary Production	Import	Export	Total Energy Supply
France	0.02	0.06	0.07	0.03
Slovakia	0.03	0.06	0.07	0.05
Croatia	0.07	0.07	0.11	0.07
Portugal	0.18	0.07	0.45	0.07
Latvia	0.14	0.08	0.41	0.04
United Kingdom	0.25	0.08	0.14	0.09
Cyprus	0.38	0.09	2.59	0.08
Bulgaria	0.07	0.09	0.18	0.05
Lithuania	0.46	0.09	0.13	0.12
Greece	0.12	0.09	0.40	0.12
Ireland	0.52	0.09	0.19	0.05
Italy	0.08	0.10	0.10	0.08
Denmark	0.27	0.10	0.19	0.07
Netherlands	0.18	0.11	0.12	0.04
Slovenia	0.03	0.11	0.41	0.05
Hungary	0.04	0.12	0.31	0.05
Estonia	0.17	0.14	0.53	0.07
Poland	0.07	0.16	0.15	0.04
Romania	0.05	0.18	0.16	0.09
Malta	1.10	0.22	1.40	0.11

3.4. Correlation between the Energy Balance Parameters and Economic Parameters in EU Countries

To establish the relationship between the parameters related to the energy balance in the EU countries and economic parameters, Pearson's linear correlation coefficients were calculated (Table 3). $p = 0.05$ was adopted as the border value of the significance level. Irrelevant results are marked with red font color in the table. Correlation coefficients have been calculated for all EU countries for the entire 2004–2018 period. The study examined a correlation that does not indicate that a given factor affects another but indicates a strong or weak relationship. All parameters related to the energy balance were adopted for the research: primary production, import, export, and total energy supply [32]. It was essential to determine the relationship of these parameters with the relevant economic parameters. The research also used economic parameters that testify to the economic situation and situation. The parameters also referred to the results per capita, which indicated the country's economic development level. Parameters relating to individual sectors of the economy were also adopted. Virtually all departments are energy-dependent, so these departments' situations could be correlated with the energy balance parameters. Solid positive relationships were found between the demand for energy and its import and economy parameters. Only in the case of economic parameters related to per capita were these relationships were fragile. The expected results have been achieved as the economic situation has a strong influence on energy needs. When production increases, practically all sectors of the economy report a greater energy demand. Besides, energy consumption also results from consumption in households. In the case of energy exports, the relationships were also positive, but their strength was smaller. Similarly, per capita parameters showed less correlation with energy exports. One explanation for the observed regularities is the greater tendency to trade in energy. More and more countries are exporting energy or trading in energy resources. In the case of energy production, the dependencies with the economy were weak and negative. This means that the economic situation does not affect production decisions. European countries mainly produce energy from their resources, such as solid fuels, renewable sources, and gas. There is much pressure to abandon coal mining and replace this source with renewable energy. Hence, the achieved results are not surprising. In the absence of social and environmental pressure, the likely correlation would be high and positive. The general climate policy in contemporary realities more influences governments' decisions regarding the use of non-renewable energy sources than the economic situation.

Table 3. Pearson's linear correlation coefficients between energy parameters and the economic parameters.

Tested Parameters	Pearson's Linear Correlation Coefficients							
	Primary Production		Import		Export		Total Energy Supply	
	r	P-Value	r	P-Value	r	P-Value	r	P-Value
GDP value	−0.223	0.001	0.910	0.001	0.538	0.001	0.963	0.001
Final consumption expenditure of households	−0.216	0.001	0.891	0.001	0.528	0.001	0.950	0.001
Export of goods and services	−0.203	0.001	0.915	0.001	0.618	0.001	0.897	0.001
Import of good and services	−0.184	0.001	0.926	0.001	0.629	0.001	0.920	0.001
GDP per capita	−0.205	0.001	0.213	0.001	0.242	0.001	0.144	0.003
Final consumption expenditure of households per capita	−0.170	0.001	0.400	0.001	0.377	0.001	0.327	0.001
Value added of agriculture, forestry and fishing	−0.045	0.358	0.832	0.001	0.422	0.001	0.846	0.001
Value added of industry (except construction)	−0.187	0.001	0.890	0.001	0.466	0.001	0.941	0.001
Value added of manufacturing	−0.200	0.001	0.875	0.001	0.428	0.001	0.926	0.001
Value added of construction	−0.213	0.001	0.870	0.001	0.515	0.001	0.929	0.001

4. Discussion

In Matsumoto et al. [72] studies, it was found that the level of energy security improved in most EU countries between 1978 and 2014. The most remarkable improvement was recorded in Denmark and the Czech Republic. This was due to the increase in the diversification of primary energy sources and the diversification of imports, particularly the diversification of energy import sources. In the studies by Dudin et al. [73] it was found that, in a shorter period, in the years 1990–2018, the dependence on total energy imports increased. Such trends were observed for all energy sources. The given dependencies are consistent with the results obtained by the authors of this article. In studies by Augutis et al. [74], based on the example of the Baltic states, it was found that the level of energy security depended on their energy resources. Jonek-Kowalska [75] investigated the reasons for the transformation of energy balances in selected EU countries dominated by hard coal. It determined that these fuels are being replaced by other non-renewable energy sources or renewable energy sources, or nuclear energy. EU countries are most often compensated for the decreasing share of coal with the growing share of gas. The share of nuclear energy increased in France, the Czech Republic, and Great Britain. The research of other authors found that the share of renewable energy sources in the energy mix significantly depended on the economic condition of the EU countries. Countries without their fossil fuel sources invested in renewable energy to the greatest extent [76–79].

Bluszcz's [80] research showed similar results as authors of this article in terms of the dependence of the EU countries on imports. Dependence on oil, gas, and imported coal was highest in 2013 in Malta, Luxembourg, and Cyprus, and lowest in Estonia and Denmark. Many EU countries were utterly dependent on oil imports. Only Denmark and the United Kingdom had a positive balance sheet and were oil exporters. The member states were also highly dependent on imported natural gas. Only Denmark and the Netherlands had a positive balance sheet. In the case of hard coal, the dependence was smaller. Only Poland, the Czech Republic, and Estonia had a positive balance. Imports of energy in countries dependent on it and its export in the case of producers can significantly impact the country's balance of payments. Additionally, the costs of energy acquisition significantly affect the competitive position of the economy of the country [81–84].

Some studies show that energy consumption contributes to economic growth. Some studies show that energy consumption has little or no impact on economic growth that can be ignored. Many authors viewed energy as a critical resource used in all production phases and consumed as a product, increasing the welfare level [85–92]. This hypothesis is called the growth hypothesis in the literature. It assumes that energy is one of the critical indicators of economic growth. Opponents of this hypothesis argue that energy plays a minimal or neutral role in economic growth and proposes their assumption as the neutrality hypothesis. Many studies support the neutrality hypothesis [93–98]. In line with these assumptions, policies to reduce energy consumption do not affect economic growth. In their research, the article's authors confirmed the hypothesis about an enormous impact of energy on economic growth. However, it should be noted that this influence depended on a given parameter of the energy balance. The most significant dependence was found in the case of total energy supply, and a very weak one in the primary production of energy.

Many studies have found a positive relationship between economic growth and energy use. However, energy matters less at low levels of economic growth. The weak impact of economic growth on energy consumption also occurs in countries with the highest GDP. Economically developed countries have lower energy needs because they use more energy-saving technologies. In developing countries, there is a close link between energy consumption and economic growth [99–107]. Additionally, countries have to balance between economic growth and energy transformation. There are differences on this issue between economically developed and developing countries. However, all of them must strive to develop with the use of sustainable energy sources [108–110].

The increase in energy security and reducing the risk of dependence on imports can be influenced by using different tools. It is important to support the development of new technologies, renewable energy sources, and diversification of energy carriers. These elements are reflected in the provisions of the energy and climate package and the Energy Roadmap 2050 [111]. The increase in energy security is to be ensured by the Energy Union. However, there are differences between countries as regards the competences of the EU and individual countries in the field of energy policy [112,113]. The problems of energy balance and energy security are very important for the socio-economic development of EU countries. These problems cannot be solved quickly, they require an energy transformation of the country's economy. Such processes are spread over several decades.

5. Conclusions

Energy security is understood in many ways. In the simplest sense, it concerns the stability of supplies and the diversification of energy sources. Important parameters in the energy balance are production, import, export, and energy supply. In the EU, the demand for energy was not covered by production. The energy deficit was about 50% and did not change significantly from year to year. Energy has become a larger subject of trade, as evidenced by the growing share of exports. EU countries buy energy not only with their own supply in mind, but also with trade. Additionally, the surplus of energy generated from a given source is exported. This is especially the case with renewable energy.

In the EU, oil and natural gas were used as main energy sources. Subsequently, renewable energy, nuclear energy, and fossil energy were used. In the case of in-house production, the order was different, as energy generated from renewable sources and nuclear energy dominated. Other sources of energy were followed (solid fuels, natural gas, and crude oil each accounted for several percent of energy production in the EU). The production structure was different from the demand. The imports concerned mainly crude oil, which accounted for 64% of all energy imports in 2018. Natural gas accounted for 25%, and solid fuels for 7%. This structure is understandable. Crude oil is mainly consumed by transport, and European countries do not have large resources of this energy resource. Natural gas is increasingly imported in the EU. It should also be emphasized that in individual EU countries the situation in terms of the energy balance was varied. The largest energy imports were in Germany and the Netherlands. Germany was quite stable in terms of the volume of energy imports, which was also caused by the stabilization of the economy. This country has achieved a high level of economic development and introduced energy-efficient technologies. In the Netherlands, there were large increases in imports, mainly due to energy trade and its export. In both countries, the structure of imports was slightly different, but crude oil predominated, followed by natural gas and solid fuels. Hungary and Estonia are among the developing countries. Hungary found itself in the middle of the stakes in terms of energy imports, and Estonia at the bottom of it. In both countries, the demand for energy increased. More and more imports were necessary. The structure of imports was different. In Hungary, crude oil and natural gas had an equally high share, while oil was clearly dominant in Estonia. In all the countries analyzed in detail, renewable energy has become increasingly important in terms of production, trade and consumption. For example, in Estonia and Hungary, the import of renewable energy started in 2009 and was increasing very quickly.

In half of the EU countries, energy imports increased. These were developing countries like Poland, but also developed countries like the Netherlands. In Poland, the purchased energy was used for its own needs, while in the Netherlands it was traded. Each country had a separate energy policy. Overall, EU energy demand has fallen, but the changes have not been rapid. In the case of exports and production, these changes were very large. Energy has become a commodity subject to trade. There is also a diversification of energy sources. Energy production has declined in most countries, although there have also been some that have recorded increases. The presented regularities were also confirmed in regression models for individual parameters of the energy balance.

The volatility of energy demand and its import was insignificant. Much greater variability occurred in the case of energy exports and production. Thus, the second hypothesis was confirmed. As a rule, the greatest stabilization in the given parameters occurred in countries with a stable economy, the so-called economically developed, while the greatest variability was in developing countries. The energy policy and the level of energy development of each country had an impact on the achieved results. There was a very strong correlation between the demand for energy and its import, and the parameters of the economy. This result was expected. Only in the case of per capita parameters the strength of the relationship was small. In the case of energy exports, the strength of the relationship with the parameters was smaller, which also results from the increasingly common treatment of energy as an object of trade. The relationships between energy production and economic parameters were weak and negative, which results from the withdrawal of countries from, for example, hard coal mining and social pressure related to reducing the emission of pollutants into the environment. The first hypothesis was only partially confirmed with regard to energy demand and its import. For these parameters, there was a strong correlation with the parameters of the economy. The strength of the relationship was medium or weak for exports and energy production.

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Article

Analysis of Interrelationships between Markets of Fuels in the Visegrad Group Countries from 2016 to 2020

Anna Górska * and Monika Krawiec

Department of Econometrics and Statistics, Institute of Economics and Finance, Warsaw University of Life Sciences-SGGW, Nowoursynowska 166, 02-787 Warsaw, Poland; monika_krawiec@sggw.edu.pl

* Correspondence: anna_gorska@sggw.edu.pl

Abstract: A fuel market is an important sector of the economy and fuel prices influence the prices of numerous products and services. This paper focuses on the analysis of the interrelationships between markets of fuels in the Visegrad Group (V4) countries. The research is based on weekly prices of Pb95 gasoline and diesel in the Czech Republic, Hungary, Poland, and Slovakia observed from January 2016 through December 2020. After performing the preliminary statistical analysis, the long-term relationships between the prices of fuels are investigated through application of the cointegrated regression Durbin–Watson (CRDW) test. Next, Granger causality is tested to answer the question of whether changes in prices of fuels in separate V4 countries Granger-cause changes in prices of fuels in other V4 countries. The cointegration research uses logarithmic prices, whereas causality investigation is based on their first differences. The results reveal long-term relationships between the prices of Pb95 gasoline in the Czech Republic and prices in other V4 countries as well as Granger causality flowing from diesel price changes in Poland to diesel price changes in other V4 countries and bilateral causation between changes in the prices of Pb95 gasoline in Poland, Hungary and Slovakia.

Keywords: Visegrad Group countries; fuels; cointegration; Granger causality

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1. Introduction

The Visegrad Group, initially named the Visegrad Triangle, was established in 1991 by three Central European countries: Czechoslovakia, Hungary and Poland. In 1993, as a result of the breakup of Czechoslovakia into the Czech Republic and Slovakia, the Visegrad Triangle was transformed into the Visegrad V4 Group. At present, these four countries collaborate closely for the purposes of developing cultural, economic, energy and military cooperation. The current number of people living in the Visegrad Group accounts for 14.3% of the EU-27's population, making it the third-largest consumer market in the European Union. In 2019, the V4 countries' GDP reached EUR 996 billion (in current prices), which made them the sixth largest economic force in the EU. Poland is the country that makes the biggest contribution to V4's GDP (53.4%), then the Czech Republic with 22.5%, Hungary with 14.7% and Slovakia with 9.4%. In the period 1991–2019, an over 19-fold increase was observed in the value of V4 countries' exports and an over 16-fold increase in the value of V4 countries' imports of goods [1]. Although the main partner of the V4 in trade in goods is Germany, the trade among the V4 is also vital. For each of the V4 countries, the other three countries are among their top five trading partners [2,3].

A broadly understood cooperation in science, education, culture, regional development, and trade influences the economies of V4 countries. One of the most important sectors of each economy (also of V4 countries) is a fuel market. Fuels are major internationally traded products and, for many countries, especially crude oil exporters, they are significant items in terms of current accounts and budget revenues. The prices of fuels that influence the prices of numerous products and services are determined by market principles and depend on many economic and political factors, such as the price of crude oil in world markets or the exchange rate of the domestic currency to the US dollar. Other factors include, for example, the producer's margin, the amount of excise duty, VAT and the fuel surcharge.

Crude oil is a natural industrial and energy resource which, apart from natural gas and coal, is one of the primary commodities exploited in the world. It is mainly used to produce liquid fuels that are utilised in transport, such as gasoline and diesel oil. There are many studies and analyses focusing on the relationships between the prices of crude oil (spot or futures) and the prices of various products (refined products, fuels, agricultural commodities, precious metals), the exchange rates, stock market indexes, and inflation rates (see Section 2). However, a certain research gap can be found in the investigation of relationships and dependencies between fuel prices in international terms, especially in Central European countries, where petroleum products (gasoline Pb95 and diesel oil) are traded (taking the commodity structure of Visegrad Group foreign trade into account, the share of product group "Mineral fuels, lubricants and related materials" is close to 10% in each of V4 countries [2]). The purpose of this paper is to fill this gap after thoroughly reviewing the existing studies.

Our research contributes to the extant literature by examining the interrelationships between markets of fuels in the Visegrad Group (V4) countries: the Czech Republic, Hungary, Poland and Slovakia. After performing a preliminary statistical analysis, we investigate the long-term relationships between the fuel prices through application of the cointegrated regression Durbin–Watson (CRDW) test. Next, we tested Granger causality to answer the question of whether changes in prices of fuels in separate V4 countries Granger-cause changes in fuel prices in other V4 countries. The development of fuel trade and the integration of the countries may result, among others, in price transmission between countries, cointegration and causal relationships. To the best of our knowledge, this is probably the first study of the cointegrating and causal relationships between the Visegrad Group fuel markets. Our results provided new insight revealing long-term relationships between the prices of Pb95 gasoline in the Czech Republic and prices in other V4 countries, as well as Granger causality flowing from diesel price changes in Poland to diesel price changes in other V4 countries and bilateral causation between changes in the prices of Pb95 gasoline in Poland, Hungary and Slovakia.

The paper is organised as follows. Section 2 offers a literature review, Section 3 describes the data and methodology, Section 4 presents the detailed results, and Section 5 provides concluding remarks.

2. Literature Review

The analyses presented in numerous papers usually concern the relationships between crude oil prices and different variables, for example, refined products and other fuels prices (Asche et al. [4], Papież and Śmiech [5], Kristoufek et al. [6] or Waściński et al. [7]. Asche et al. [4] investigated the relationships between crude oil (Brent) and four major refined products prices from the Rotterdam market, i.e., prices of gas oil, heavy fuel oil, naphtha and kerosene in the period from January 1992 to November 2000 and showed a long-term relationship between the crude oil price and the gas oil, kerosene and naphtha prices. These findings implied market integration for these products. Papież and Śmiech [5] studied the mutual relationship between the prices of the major important primary fuels (crude oil, natural gas and steam coal) on the European market in the period October 2001–May 2011 and revealed a long-term price equilibrium. Moreover, oil prices appeared to be a major factor in changes in the prices of non-renewable energy resources. Kristoufek et al. [6] analysed the link between the weekly and monthly prices of crude oil (Brent), biodiesel, ethanol and related fuels (German diesel and gasoline, the US diesel and gasoline) in the period from 24 November 2003 to 28 February 2011. Their analysis showed a very weak connection between the prices of biofuels and ethanol. However, in the medium-term, prices of biodiesel were connected with fuel prices. Waściński et al. [7] demonstrated a strong impact of the wholesale fuel prices of the Polish oil-processing companies (Orlen and Lotos) on retail prices in Poland from 2004 to 2008.

Another group of papers refer to the relationships between crude oil and precious metal prices (Zhang and Wei [8], Jain and Ghosh [9]) or between crude oil and agricultural items prices (Kristoufek et al. [6], Eissa and Al Refai [10], Sarwar et al. [11]). Zhang and Wei [8] analysed cointegration and causality among the gold market and the crude oil market and observed consistent trends with a significant positive correlation between the price of crude oil and the gold price from January 2000 to March 2008. Moreover, there was a long-term equilibrium between these markets, and the price of oil Granger-caused the volatility in the price of gold. Jain and Ghosh [9] examined the long-term equilibrium relationship, cointegration and Granger causality between prices of oil, precious metals (gold, platinum, silver) and Indian Rupee–US Dollar exchange rate. They used daily data from 2009 to 2011 and discovered that fluctuations in international oil and precious metal prices were transmitted to the Indian economy, which was visible in the changes in the exchange rates. Kristoufek et al. [6] analysed the relationships between the weekly and monthly prices of crude oil (Brent), biodiesel, ethanol and prices of agricultural items (corn, soybeans, sugar beets, sugar cane, wheat) in the period from 24 November 2003 to 28 February 2011. In the medium-term, they showed that ethanol prices were connected to the food prices. Eissa and Al Refai [10] investigated the dynamic linkage among crude oil (WTI, Brent, Dubai Fateh) prices and agricultural products (corn, barley, rapeseed oil) prices from January 1990 to December 2018. Their findings, based on results from linear models, showed that the prices of these agricultural items did not co-move with oil prices in the long term. However, the nonlinear ARDL model provided the opposite conclusion, that barley, corn and rapeseed oil co-moved with oil prices in the long-term. Sarwar et al. [11] examined the pass-through effect of crude oil prices on food and non-food prices in Pakistan in the period 1990–2019. The results revealed that oil prices affected food and also non-food inflation, but the impact was more pronounced in the case of non-food inflation.

There are also papers related to the linkages between crude oil and stock markets (Singhal et al. [12], Çatık et al. [13], Zaighum et al. [14]). Singhal et al. [12] studied the dynamic relationship between international oil prices (WTI), gold prices, Mexican stock market index (BMV IPC) and Mexican peso–US Dollar exchange rate in the period from January 2006 to April 2018. Their findings discovered that the gold prices positively affected index of Mexican Stock Exchange and negatively affected oil prices. Çatık et al. [13] analysed the influence of oil price changes on the sectoral Turkey stock market returns in the period 3 January 1997–9 August 2018. They used daily returns data for 12 sectors. The results showed that the impact of oil price returns differed clearly over time and often had a smaller effect on sectoral returns compared with Turkish lira—US Dollar exchange rate returns. Zaighum et al. [14] analysed nonlinear relationship between the Dow Jones Islamic Market Index (DJIMI) and the prices of WTI crude oil, gasoline, natural gas, and heating oil. In the long- and short-term, they observed a strong positive reaction of crude oil and gasoline to the DJIMI, whereas heating oil prices responded inversely to the DJIMI. Furthermore, they discovered the asymmetric and non-linear transmission of energy prices to the Islamic stock market, and a feedback effect between energy sources and DJIMI. Their findings also recognised crude oil and gasoline as two principal economic drivers explaining the short- and long-term Islamic stock market dynamics.

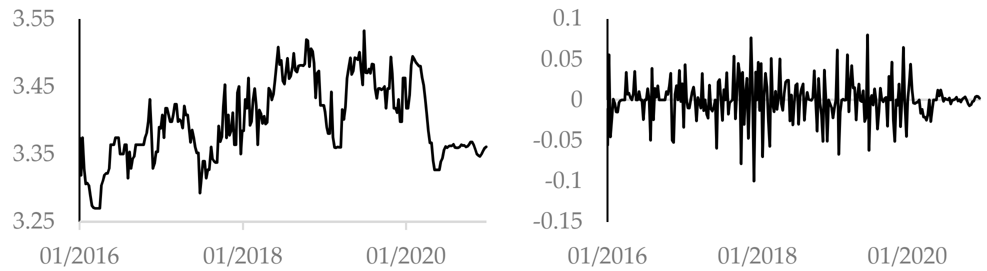
Examples of studies examining the relationships between crude oil prices and different macroeconomic factors are papers by Kırca et al. [15], Aye and Odhiambo [16] or Zakaria et al. [17]. Kırca et al. [15] investigated the relationship between the oil–gas prices index and economic growth in Turkey in the period 1998–2019. The results, based on Granger and the Frequency Domain Causality tests, demonstrated an insignificant causality relationship between the variables, whereas the Toda–Yamamoto causality test with a structural break exhibited a causal relation running from oil–gas to economic growth. Aye and Odhiambo [16] used quarterly data from 1980 to 2020 and showed that, beyond the identified threshold values, the WTI and Brent crude oil prices would have significant negative effects on agricultural growth in South Africa. Zakaria et al. [17] tried to estimate the impact of oil prices on inflation rates in South Asian countries (Bangladesh, India, Pakistan, Sri Lanka) in the period from 1980 to 2018. They identified a cointegration of oil prices and inflation, and also noticed that the oil price caused inflation. Moreover, the global oil price shock had a positive impact on inflation, and this positive effect was permanent.

Wang et al. [18] examined the relationships between the Singapore fuel oil spot market and China fuel oil markets (Shanghai oil future price, Huangpu oil spot price) over the 25 August 2004–30 June 2006 period. The analysis revealed a very strong correlation between these oil prices, the long-term relation and cointegration among oil prices in Singapore, Shanghai and Huangpu.

The aim of our paper is to investigate the interrelationships between markets of fuels in the Visegrad Group (V4) countries: the Czech Republic, Hungary, Poland and Slovakia.

3. Materials and Methods

The dataset used for the purpose of the research covers weekly prices (260 observations) of basic fuels: gasoline Pb95 and diesel in the Czech Republic, Hungary, Poland and Slovakia from January 2016 through December 2020. The prices are expressed in domestic currencies per 1 litre. The data are provided by e-petrol.pl (www.e-petrol.pl (accessed on 21 June 2021)) and published every Wednesday at 3 pm. The quantitative analysis is based on logarithmic transformations of prices (log-prices) and their first differences (log-returns). They are displayed in Figures 1 and 2.



(a)

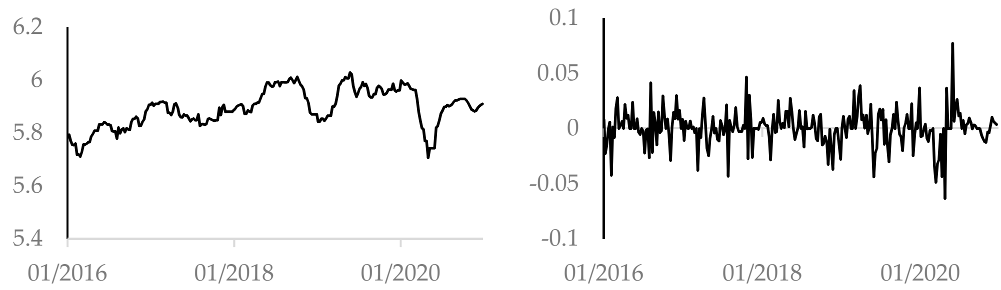


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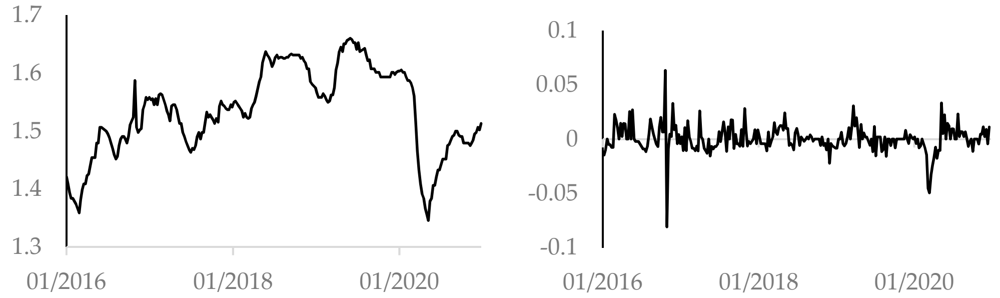
Figure 1. *Cont.*



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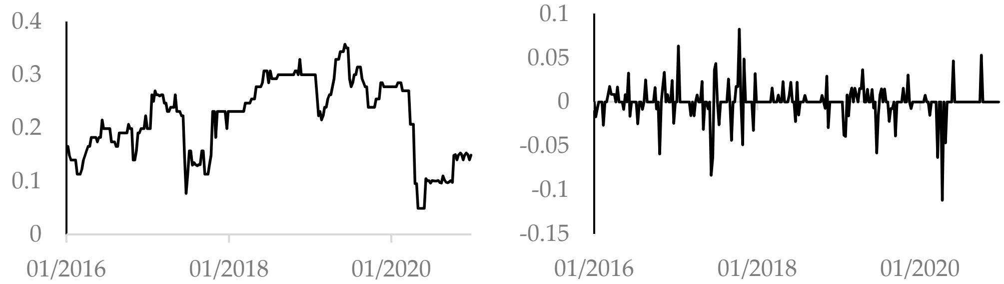
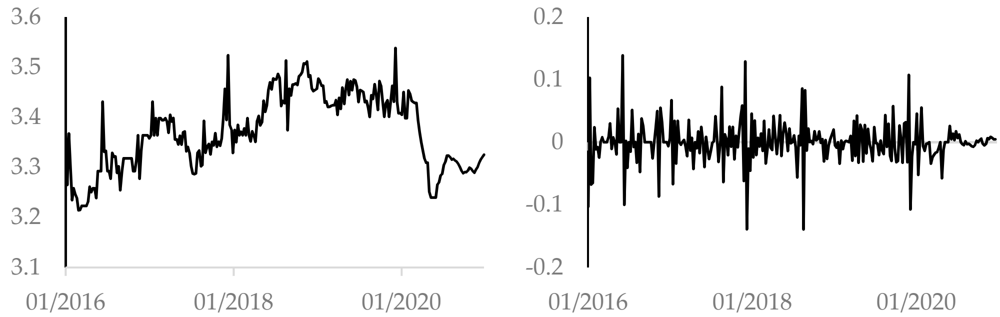


(d)

Figure 1. Pb95 gasoline logarithmic weekly prices (left panel) and returns (right panel) in the Czech Republic (**a**), Hungary (**b**), Poland (**c**) and Slovakia (**d**) from January 2016 through December 2020. Source: own elaboration.



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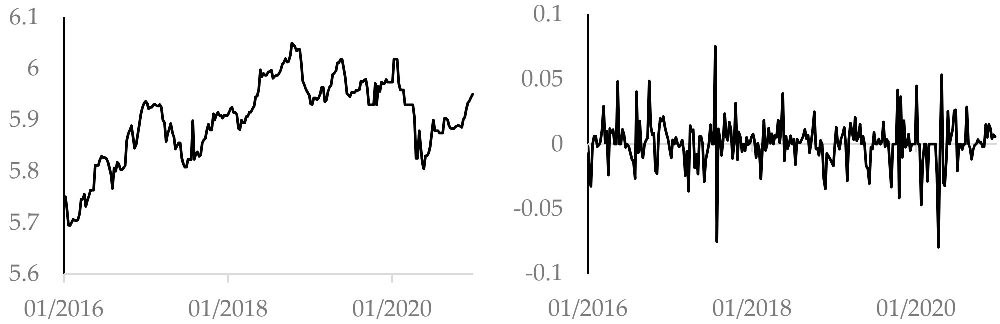
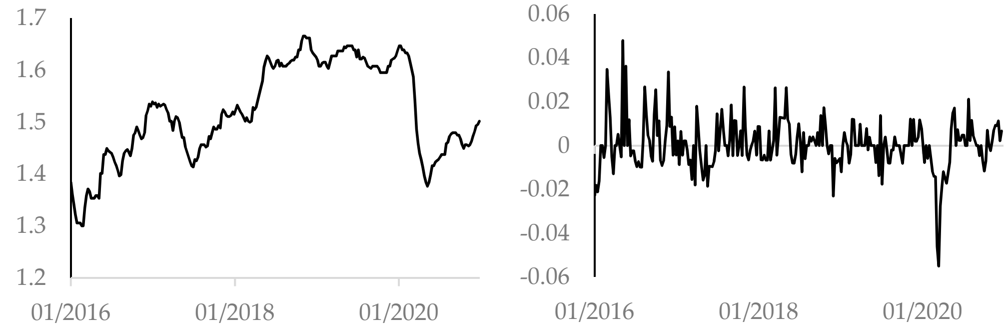


(b)

Figure 2. *Cont*.



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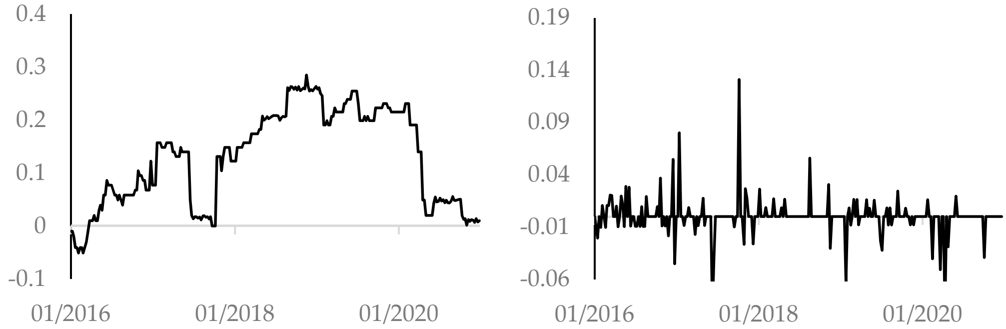

(d)

Figure 2. Diesel logarithmic weekly prices (left panel) and returns (right panel) in the Czech Republic (**a**), Hungary (**b**), Poland (**c**) and Slovakia (**d**) from January 2016 through December 2020. Source: own elaboration.

3.1. Testing for Stationarity

According to the theory, the stationary properties of time series should be examined before testing the cointegration. Additionally, the verification of causality should be preceded by an analysis of variables stationarity. A stochastic process (a random or stochastic process can be defined as a collection of random variables ordered in time) is called stationary if its mean and variance are constant and independent of time, and the covariance between a number of equally spaced elements depends only on the distance of these elements—not on a point on the timeline. In the econometric literature, such a process is called weakly stationary, or covariance stationary. Time series that are stationary tend to return to the mean (mean reversion) and fluctuations around this mean (measured by its variance) will have a broadly constant amplitude. However, a nonstationary process or unit root process has a time-varying mean or a time-varying variance or both and belongs to a more general class of stochastic processes known as integrated processes. Order of integration of a series is the minimum number of times the series need to be first differenced to yield a stationary series [9]. There are several stationarity tests. One of the most popular methods of examining stationarity is the augmented Dickey–Fuller test (the ADF-test). The first step of the procedure is to estimate one of the following equations:

$$\Delta Y_t = \alpha_1 Y_{t-1} + \sum_{i=1}^{p} c_i \Delta Y_{t-1} + \varepsilon_t, \quad (1)$$

$$\Delta Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \sum_{i=1}^{p} c_i \Delta Y_{t-i} + \varepsilon_t, \quad (2)$$

$$\Delta Y_t = \alpha_0 + \lambda_1 t + \alpha_1 Y_{t-1} + \sum_{i=1}^{p} c_i \Delta Y_{t-i} + \varepsilon_t. \quad (3)$$

The null hypothesis is

H_0: $\alpha_1 = 0$,

that is, there is a unit root—the time series is nonstationary.

The test statistic (τ) is given by:

$$\tau = \frac{\hat{\alpha}_1}{S(\hat{\alpha}_1)}. \quad (4)$$

where: $\hat{\alpha}_1$OLS estimate of α_1 in any of Equations (1)–(3), $S(\hat{\alpha}_1)$—standard error of α_1 estimate.

When the value of τ is lower than the critical value, we should reject the null hypothesis. Dickey and Fuller [19] computed the critical values on the basis of Monte Carlo simulations. Later, MacKinnon [20] presented more extensive tables [21].

3.2. Testing for Cointegration

The idea of cointegration was proposed by Granger and Engle [22,23]. Cointegration is defined as systemic co-movement among variables over the long term. If there is a long-term relationship between two (or more) nonstationary variables, then the deviations from the long-term path are stationary. This means that a long-term equilibrium path between two economic processes that is independent of time can be determined, and the values located elsewhere are short-term deviations from the equilibrium, which depend on time. Thus, cointegrated processes are characterised by a common long-term growth path and the difference between them has an almost constant level over time. On the other hand, non-cointegrated processes diverge in the long term, and the difference between them changes over time. In brief, two variables are cointegrated if there is a long-term, or equilibrium, relationship between them.

One of the methods for finding cointegration is the cointegrated regression Durbin–Watson (CRDW) test. The procedure for this is first to estimate the following equation, called the cointegrating regression:

$$Y_t = \alpha_0 + \alpha_1 X_t + \varepsilon_t. \quad (5)$$

The Durbin–Watson statistic is given by:

$$d = \frac{\sum_{t=2}^{T}(e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t^2}, \quad (6)$$

where e_t—residuals obtained from Equation (5).

One way of testing for a lack of cointegration is to see if d is close to zero, so the null hypothesis is

H_0: $d = 0$.

This is because one would generally expect ε to be I(1) if X and Y are I(1). If this were so, the d statistic would be about zero, and the two series would not be cointegrated. If d is significantly positive, then we would suspect that the two series are cointegrated. The standard tables for the Durbin–Watson test are not applicable here because there the null hypothesis is that $d = 2$ for an AR(1) process, rather than that $d = 0$. However, Engle and Granger carried out a simulation study and obtained the critical values [24].

3.3. Testing for Granger Causality

Granger causality test is a useful approach to detect a causal relationship between variables (two or more). According to Greene [25], causality, in the sense proposed by Granger [26], is inferred when the lagged values of one variable (X) have explanatory power in a regression of another variable (Y) on lagged values of Y and X. Alternatively, when one identifies one variable as the dependent variable (Y) and another as the independent variable (X), one makes an implicit assumption that changes in the independent variable induce changes in the dependent variable. Consequently, including past or lagged values of X in a regression of Y on other variables (including its own past values) significantly improves the prediction. An analogous definition applies if Y Granger-causes X. Finally, if

X Granger-causes Y and Y Granger-causes X, the two variables are jointly determined and there is a bilateral causation.

Granger devised some tests of causality, which proceed as follows. If there are two time series, Y_t and X_t, the time series X_t fails to Granger-cause Y_t in an unrestricted regression of Y_t on lagged Ys and lagged Xs:

$$Y_t = \sum_{i=1}^{p} \alpha_i Y_{t-i} + \sum_{j=1}^{q} \beta_j X_{t-j} + u_t, \tag{7}$$

the coefficients of the latter are zero ($\beta_j = 0$ for $j = 1, 2, \ldots, q$).

Next, we consider the restricted model:

$$Y_t = \sum_{i=1}^{p} \alpha_i Y_{t-1} + v_t. \tag{8}$$

The test statistic is:

$$F = \frac{(ESSR - ESSU)/q}{ESSSU/(n-p-q)}, \tag{9}$$

where n denotes the number of observations used in Equation (7), $ESSU$ is the error sum of squares for Equation (7), and $ESSR$ is the error sum of squares for the restricted model (8). Under the null hypothesis of X not Granger-causing Y, F follows the F-distribution with q degrees of freedom for the numerator and $n - p - q$ degrees of freedom for the denominator. Lag lengths p and q are, to some extent, arbitrary [27].

4. Results and Discussion

4.1. Preliminary Statistical Analysis

In the first stage of the research, we performed a preliminary statistical analysis. In Tables 1 and 2, we provide the estimates of basic distributional characteristics (mean, standard deviation, coefficient of variation, asymmetry, kurtosis) and the results of the Jarque–Bera normality test for Pb95 gasoline and diesel log-returns. In Table 3, we report the values of Pearson correlation coefficients between these log-returns series.

Table 1. Summary statistics for Pb95 gasoline weekly log-returns.

Country	Measure					
	Mean	**Std. Dev.**	**Coeff. of Var.**	**Assymetry**	**Kurtosis**	**JB**
Czech Rep.	−0.000519	0.025200	485.400	−0.23499	1.8572	39.607 *
Hungary	0.000479	0.016328	34.063	−0.11461	3.0632	101.827 *
Poland	0.000351	0.012432	34.912	−0.67453	10.0450	1108.560 *
Slovakia	−0.000066	0.018784	284.600	−1.07920	8.9212	909.171 *

* rejection of the null hypothesis of normality at 0.05 level. Source: own calculation and elaboration.

Table 2. Summary statistics for diesel weekly log-returns.

Country	Measure					
	Mean	**Std. Dev.**	**Coeff. of Var.**	**Assymetry**	**Kurtosis**	**JB**
Czech Rep.	−0.000163	0.033940	208.010	−0.04877	4.3024	99.859 *
Hungary	0.000763	0.016874	22.117	−0.30817	5.0614	280.562 *
Poland	0.000456	0.011298	24.785	−0.03537	4.2141	191.700 *
Slovakia	0.000039	0.017487	450.640	0.72764	1.3670	4070.42 *

* rejection of the null hypothesis of normality at 0.05 level. Source: own calculation and elaboration.

Table 3. Matrix of correlation coefficients between fuel log-returns.

Variable		**Pb95**				**Diesel**			
		Czech Rep.	**Hungary**	**Poland**	**Slovakia**	**Czech Rep.**	**Hungary**	**Poland**	**Slovakia**
Pb95	**Czech Rep.**	1							
	Hungary	0.159 *	1						
	Poland	0.021	0.354 *	1					
	Slovakia	0.134 *	0.256 *	0.066	1				
Diesel	**Czech Rep.**	0.137 *	0.060	0.069	0.007	1			
	Hungary	0.074	0.358 *	0.262 *	0.189 *	0.006	1		
	Poland	0.052	0.358 *	0.724 *	0.168 *	0.135 *	0.281 *	1	
	Slovakia	0.159 *	0.216 *	0.112 *	0.506 *	0.034	0.109 *	0.125 *	1

* statistical significance at 0.05 level. Source: own calculation and elaboration.

The results displayed in Tables 1–3 report important findings. First, Pb95 gasoline and diesel exhibit positive mean returns (except for Pb95 returns in the Czech Republic and Slovakia, and diesel returns in the Czech Republic). The volatilities observed for the Czech Republic and Slovakia differ remarkably from those obtained for Hungary and Poland (which are much higher). The returns are also described by negative skewness (except for diesel in Slovakia) and a kurtosis greater than 3 (except for Pb95 in the Czech Republic and diesel in Slovakia). The Jarque–Bera (JB) statistics of normality suggest a rejection of the null hypothesis for all returns series at the 0.05 significance level, so they do not follow normal distribution. They are also characterised by a positive linear correlation. The strongest relationship is observed for Pb95 gasoline and diesel in Poland (0.724). When considering intercountry relationships, the strongest positive correlation is between Pb95 gasoline in Hungary and diesel in Poland (0.358).

4.2. The ADF Test Results

In the second stage of the research, we examined the stationarity of the time series under consideration. In Tables 4 and 5, the results of the ADF test performed on the natural logarithms of price levels (log-prices) and the first differences (log-returns), respectively, are reported.

Table 4. The ADF test results for fuel log-prices.

Country and Fuel Type	**Tau (*p*-Value)**		
	without Constant	**with Constant**	**with Constant and Trend**
Czech Rep. Pb95	0.058 (0.701)	−2.284 (0.172)	−2.260 (0.455)
Hungary Pb95	0.4213 (0.804)	−3.177 (0.021)	−3.309 (0.064)
Poland Pb95	0.319 (0.778)	−3.152 (0.023)	−3.000 (0.321)
Slovakia Pb95	−0.697 (0.414)	−2.036 (0.271)	−1.989 (0.604)
Czech Rep. diesel	0.032 (0.693)	−2.295 (0.173)	−2.195 (0.491)
Hungary diesel	0.698 (0.865)	−2.226 (0.198)	−2.246 (0.461)
Poland diesel	0.414 (0.802)	−2.617 (0.089)	−2.366 (0.397)
Slovakia diesel	−0.902 (0.324)	−1.602 (0.479)	−1.155 (0.916)

Source: own calculation and elaboration.

Table 5. The ADF test results for fuel log-returns.

Country and Fuel Type	Tau (*p*-Value)		
	without Constant	with Constant	with Constant and Trend
Czech Rep. Pb95	−12.116 (3.874×10^{-25})	−12.092 (5.23×10^{-26})	−12.105 (6.762×10^{-29})
Hungary Pb95	−7.161 (6.935×10^{-12})	−7.163 (1.189×10^{-10})	−7.179 (7.413×10^{-10})
Poland Pb95	−6.502 (2.975×10^{-10})	−6.506 (6.621×10^{-9})	−7.950 (2.849×10^{-12})
Slovakia Pb95	−15.478 (4.952×10^{-31})	−15.447 (3.11×10^{-27})	−15.445 (3.7×10^{-28})
Czech Rep. diesel	−27.324 (6.879×10^{-34})	−27.270 (1.259×10^{-18})	−27.245 (2.85×10^{-23})
Hungary diesel	−16.180 (2.847×10^{-32})	−16.182 (4.684×10^{-28})	−16.179 (2.921×10^{-29})
Poland diesel	−6.907 (3.021×10^{-11})	−6.917 (5.515×10^{-10})	−7.002 (2.445×10^{-9})
Slovakia diesel	−16.080 (4.21×10^{-32})	−16.045 (6.419×10^{-28})	−16.185 (2.864×10^{-29})

Source: own calculation and elaboration.

The results presented in Tables 4 and 5 show that, in the case of logarithmic prices, we cannot reject the null hypothesis of the presence of a unit root at a 0.05 level of significance. For the first differences (log-returns), we reject the null hypothesis. Therefore, the results of the ADF test indicate that all series are I(1) in nature. This means that the log-prices of Pb95 gasoline and diesel are not stationary, but their first differences (log-returns) are stationary.

4.3. The CRDW Test Results

In the third stage of the research, we examined the cointegration between prices of Pb95 gasoline and between prices of diesel in V4 countries (inter-country relationships). The test was performed on the logarithmic transformations of the prices. The results (values of *d* statistics) are reported in Table 6.

Table 6. The CRDW test results for Pb95 gasoline and diesel prices.

Independent Variable	Dependent Variable	*d*	Independent Variable	Dependent Variable	*d*
Czech Rep. Pb95	Hungary Pb95 Poland Pb95 Slovakia Pb95	0.457 * 0.523 * 0.455 *	Czech Rep. diesel	Hungary diesel Poland diesel Slovakia diesel	0.608 * 0.930 * 0.919 *
Hungary Pb95	Czech Rep. Pb95 Poland Pb95 Slovakia Pb95	0.591 * 0.207 0.140	Hungary diesel	Czech Rep. diesel Poland diesel Slovakia diesel	0.770 * 0.325 0.197
Poland Pb95	Czech Rep. Pb95 Hungary Pb95 Slovakia Pb 95	0.681 * 0.231 0.315	Poland diesel	Czech Rep. diesel Hungary diesel Slovakia diesel	1.125 * 0.357 0.259
Slovakia Pb95	Czech Rep. Pb95 Hungary Pb95 Poland Pb95	0.576 * 0.126 0.277	Slovakia diesel	Czech Rep. diesel Hungary diesel Poland diesel	1.092 * 0.207 0.237

* cointegration significant at 0.05 level. Source: own calculation and elaboration.

The results given in Table 6 reveal a significant cointegration between prices of Pb95 gasoline in the Czech Republic and prices in other V4 countries (if the computed d value is smaller than 0.386, we reject the null hypothesis of cointegration at the 0.05 level), and also between diesel prices in the Czech Republic and prices in other V4 countries, so there are significant long-term relationships between them.

4.4. Granger Causality Test Results

In the last stage of the research, to answer the question of whether changes in prices of fuels in separate V4 countries Granger-cause changes in the price of fuels in other V4 countries, a Granger causality test was run. The results (F-statistic values) are reported in Tables 7 and 8, where arrows point to the direction of causality.

Table 7. Granger causality test results for Pb95 gasoline.

Relationship	Lag Length			Relationship	Lag Length		
	1	2	3		1	2	3
Czech Rep.→Hungary	0.428	2.851	1.697	Poland→Czech Rep.	13.076 *	21.379 *	20.857 *
Czech Rep.→Poland	5.233 *	1.571	1.249	Poland→Hungary	60.774 *	26.253 *	16.528 *
Czech Rep.→Slovakia	0.192	3.810 *	2.994 *	Poland→Slovakia	8.512 *	6.068 *	6.578 *
Hungary→Czech Rep.	2.682	10.513 *	11.522 *	Slovakia→Czech Rep.	2.962	2.063	1.746
Hungary→Poland	29.507 *	9.418 *	5.963 *	Slovakia→Hungary	0.610	0.279	0.207
Hungary→Slovakia	0.487	7.301 *	5.338 *	Slovakia→Poland	10.706 *	4.522 *	3.355 *

* rejection of the null hypothesis at 0.05 level. Source: own calculation and elaboration.

Table 8. Granger causality test results for diesel.

Relationship	Lag Length			Relationship	Lag Length		
	1	2	3		1	2	3
Czech Rep.→Hungary	0.045	1.402	1.468	Poland→Czech Rep.	12.752 *	11.487 *	8.298 *
Czech Rep.→Poland	0.116	0.524	0.220	Poland→Hungary	22.814 *	13.692 *	9797 *
Czech Rep.→Slovakia	1.106	3.258 *	2.624	Poland→Slovakia	12.220 *	10.638 *	10.070 *
Hungary→Czech Rep.	4.063 *	3.022	4.834 *	Slovakia→Czech Rep.	2.243	4.264 *	3.743 *
Hungary→Poland	2.696	1.322	1.216	Slovakia→Hungary	0.518	0.273	0.477
Hungary→Slovakia	3.042	3.420 *	4.056 *	Slovakia→Poland	1.650	0.477	0.970

* rejection of the null hypothesis at 0.05 level. Source: own calculation and elaboration.

The results presented in Tables 7 and 8 show that, in most cases, the number of lags does not influence the test results. Thus, regardless of lag length, there is a causality running from Pb95 gasoline prices in Poland to Pb95 gasoline prices in the Czech Republic. There are also bilateral causalities between Pb95 gasoline prices in Poland and in Hungary, as well as between Pb95 gasoline prices in Poland and in Slovakia. At a lag length equal to 2 and 3, Granger causality flows from Pb95 prices in the Czech Republic to Pb95 gasoline prices in Slovakia, and from Pb95 gasoline prices in Hungary to Pb95 gasoline prices in the Czech Republic and in Slovakia. Regardless of the number of lags, there is a causality running from diesel prices in Poland to diesel prices in the Czech Republic, Hungary and Slovakia. At a lag length equal to 2 and 3, there is a Granger causality flowing from diesel prices in Hungary to diesel prices in Slovakia and from diesel prices in Slovakia to diesel prices in the Czech Republic. Finally, at lag lengths 1 and 3, there is causality running from diesel prices in Hungary to diesel prices in the Czech Republic.

5. Concluding Remarks and Future Work

This paper aimed to investigate the interrelationships between fuel markets in the Visegrad Group countries. The research was based on weekly prices of Pb95 gasoline and diesel in the Czech Republic, Hungary, Poland and Slovakia, observed from January 2016 through December 2020. The preliminary statistical analysis discovered positive linear correlation between them. Next, results of the cointegration test detected long-term relationships between prices of Pb95 gasoline and diesel in the Czech Republic and the prices in Hungary, Poland and Slovakia. As cointegration does not indicate the direction of the relationships, the Granger causality test was used to examine this. Regardless of lag length the results revealed that changes in the prices of Pb95 gasoline in Poland Granger-caused changes in prices of this fuel in other V4 countries. At the same time, changes in the prices of Pb95 gasoline in Hungary and in Slovakia Granger-caused changes in the prices of this fuel in Poland, so there is bilateral causation between these markets. Regardless of the number of lags, changes in the prices of diesel in Poland Granger-caused changes in the prices of diesel in other V4 countries. It seems that the dominant direction of information flow is price transmission from Poland to the rest of the Visegrad Group. Consequently, we can better predict the prices of fuels in separate V4 countries by considering the lagged values of prices observed in Poland.

The results are closely related to the structure of the Visegrad Group fuel market, in which Poland plays an important role. PKN Orlen, the leading Polish oil-processing company, competes with Hungarian MOL and tries to dominate the Czech and Slovak markets, for example through the acquisition of Unipetrol, the biggest oil-processing enterprise in the Czech Republic, or through increasing its share in the Slovak retail market under the 'Orlen Unipetrol Slovakia' label. However, Slovakia and the Czech Republic are among the three main countries from which Poland imports petrol (the third one is Germany). In 2020, the import of gasoline from Slovakia to Poland reached 34% of total imports, and imports from the Czech Republic formed 9% of total imports. Furthermore, Slovakia, the Czech Republic and Hungary are among the eight main countries from which Poland imports diesel. In 2020, imports of this fuel from Slovakia accounted for 4.7% of the total imports, while imports from the Czech Republic account for 1.2% and imports from Hungary accounted for only 0.5% of total imports to Poland. On the other hand, the V4 countries are not the main destinations for Polish exports of liquid fuels. In 2020, exports to the Czech Republic were the only significant amounts, as 39% of diesel and 15% of JET fuel from Poland were delivered to this country [28].

This paper provides new insight regarding the interrelationships between fuel markets in the Visegrad Group countries from 2016 to 2020. The results of the analysis revealed that, in this period, the prices of Pb95 gasoline and diesel in the Czech Republic and their prices in Hungary, Poland and Slovakia were in a long-term equilibrium. Market mechanisms and fundamental factors such as changing economic situation made the prices move (increase and decrease) together in the long-term. This prevents arbitrage opportunities. Moreover, bidirectional causal linkages between the prices of Pb95 gasoline in Poland, Hungary and Slovakia imply that these markets react to new information simultaneously, and there are feedback relationships between them, which may lead to reduced price competition.

As fuels are important energy sources for development in emerging economies (including V4 countries), our findings may be important to the main actors in the Visegrad Group fuel market, such as policymakers, producers, retail traders and consumers. However, when accounting for the complexity of the relationships between fuel markets in the V4 countries, in future work, the nonlinear Granger causality approach could be employed to investigate their nonlinear interactions. This concept, proposed by Baek and Brock [29] and Hiemstra and Jones [30], is based on the residuals obtained from linear VAR models such as Equation (7). A detailed description of the methodology can be found in Zhang and Wei [8].

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Use of Renewable Energy Sources in the European Union and the Visegrad Group Countries—Results of Cluster Analysis

Elżbieta Kacperska [1], Katarzyna Łukasiewicz [2] and Piotr Pietrzak [2,*]

[1] Institute of Economics and Finance, Warsaw University of Life Sciences, 02-787 Warsaw, Poland; elzbieta_kacperska@sggw.edu.pl
[2] Management Institute, Warsaw University of Life Sciences, 02-787 Warsaw, Poland; katarzyna_lukasiewicz@sggw.edu.pl
* Correspondence: piotr_pietrzak1@sggw.edu.pl

Abstract: Increasing the use of renewable energy sources is one of the strategic objectives of the European Union. In this regard, it seems necessary to answer the question: which of the member countries are the most effective in its implementation? Therefore, the main goal was to distinguish groups of European Union countries, including the Visegrad Group, differing in the use of renewable energy sources in transport, electricity, heating and cooling (based on cluster analysis). All members of the EU were determinedly selected for research on 1 February 2020 (27 countries). The research period embraced the years 2009–2019. The sources of materials were the literature on the topic and data from Eurostat. Descriptive, tabular, graphical methods and cluster analysis were used in the presentation and analysis of materials. In 2019 wind and hydro power accounted for two-thirds of the total electricity generated from renewable sources. In 2019, renewable energy sources made up 34% of gross electricity consumption in the EU-27. Wind and hydro power accounted for two-thirds of the total electricity generated from renewable sources (35% each). Moreover, it was determined that there were 5 clusters that differed in their use of renewable energy sources. The highest average renewable energy consumption in transport, heating and cooling in 2019 was characterized by a cluster consisting of Sweden and Finland. In contrast, the highest average renewable energy consumption in electricity was characterized by a cluster consisting of countries such as: Austria, Croatia, Denmark, Latvia and Portugal. Finally, in a group that included countries such as Belgium, France, Luxembourg, Malta, the Netherlands and the entire VG (Hungary, Czechia, Slovakia and Poland), renewable energy consumption rates (in transport, electricity, heating and cooling) were lower than the EU average (27 countries).

Keywords: sustainability; renewable energy sources; European Union; Visegrad Group; cluster analysis

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1. Introduction

During the last three decades, the fashionable concept in environmental discourse has been "sustainable development" (SD). "It has spawned a vast literature and has strengthened the arm of empire builders in many research institutes, Universities, national and international bureaucracies and statistical offices" [1] (p. 191). SD is also a fundamental and overarching objective of the European Union (EU), enshrined in Article 3 of the Treaty on EU. Since 2005 Eurostat has regularly produced biennial monitoring reports of the EU Sustainable Development Strategy (EU SDS), based on the EU set of Sustainable Development Indicators (SDIs).

The concept of SD has also been constantly criticized, mostly due to the inconsistency of mixing economic expansion and natural system preservation in one concept [2]. It was also mentioned that "there is no agreement on a comprehensive sustainable development theory, there are different contested theoretical approaches and definitions" [3] (p. 468). Nonetheless, the scientific community has agreed that SD is governed by a dynamic balance between the three pillars of civilization's progress: (1) economic, (2) social, and (3) environmental [4].

Nowadays, there is a growing emphasis on the importance of applying the concept of SD to the energy sector [5]. Therefore, the term sustainable energy development (SED) is increasingly used in the literature [6]. SED is defined by the International Atomic Energy Agency (IAEA) as "the provision of adequate energy services at affordable cost in a secure and environmentally benign manner, in conformity with social and economic development needs" [7]. Figure 1 depicts the relationship between the three dimensions SD and energy as illustrated by the IEA/IAEA [7].

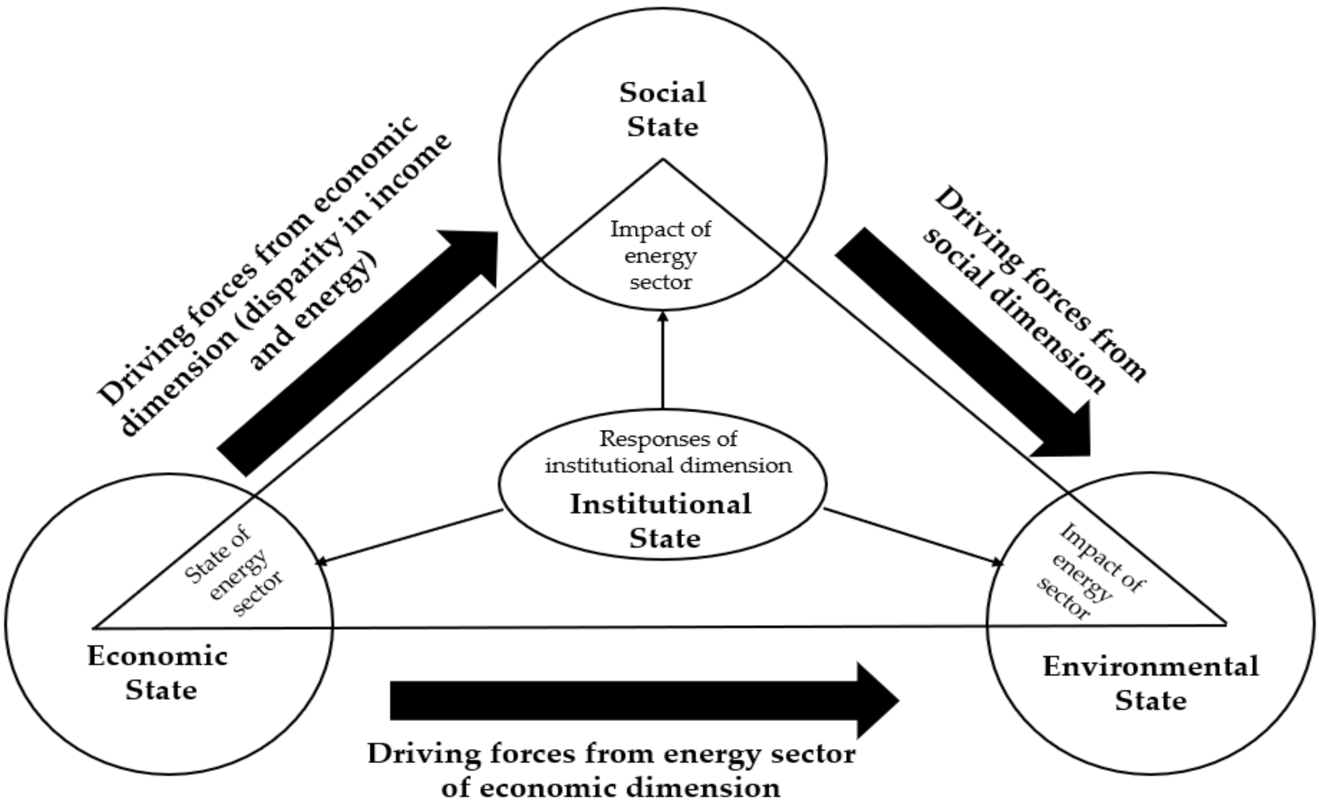

Figure 1. Interrelationship among sustainability dimensions of the energy sector.

SED is also one of the priorities of the EU. One of the most important initiatives in this area is the "Clean Energy for All Europeans" [8]. In May 2019, the EU completed the final legislative acts of this package, thus reaching an important stage towards the completion of the Energy Union. The package includes "documents on energy efficiency (. . .) new energy and climate laws, consumer rights, energy security, electricity market efficiency, and cooperation between the EU and Member States to achieve the ambitious energy and climate goals" [9].

According to the package, the EU is to become a world leader in the use of renewable energy sources (e.g., biomass energy, hydropower, geothermal power, wind energy, and solar energy). Thus, it seems necessary to answer the question of which member countries are the most efficient in the use of renewable energy sources? That is why the main goal of this article is to distinguish groups of EU countries, including the VG, differing in the use of renewable energy sources in transport, electricity, heating and cooling based on cluster analyses. Through its implementation, it will be possible to identify the countries that are most committed to the use of renewable energy sources and, thus, the countries that most effectively implement the concept of SED. The following set of research tasks was adopted for its implementation: conduct a critical review of the literature on SD; show the changes in the use of renewable energy in transport, electricity heating and cooling in EU member states (including VG countries) from 2009 to 2019; show the structure of utilization of renewable energy sources in EU member states; identify leaders among EU member states in the development of the renewable energy sector.

The remainder of the article is structured as follows. The next section provides a brief description of the methodological approach and is followed by the literature review. The article ends with discussion and some concluding remarks.

2. Materials and Methods

All members of the EU were selected for research on 1 February 2020 (27 countries). The research period covers the years 2009–2019. In 2009, the European Parliament adopted the Directive 2009/28/EC [10]. It established a common framework for the use of energy from renewable sources in order to limit greenhouse gas emissions and to promote cleaner transport. The last year in which there were complete data needed to carry out the research using the assumed research methods at the time of the research was 2019. The sources of materials were the literature on the subject and also data from Eurostat (share of renewable energy in transport, share of renewable energy sources in electricity, share of renewable energy sources in heating and cooling). The use of Eurostat data made it possible to compare all EU countries.

Descriptive, tabular and graphical methods and cluster analysis were used for the presentation and analysis of materials.

In the first stage of the research, the changes in the use of renewable energy sources in the EU and VG countries were presented. The analysis includes the shares of renewable energy in transport, electricity, heating and cooling.

In the second stage, based on 2019 data, the cluster analysis was conducted. The term "cluster analysis" was coined by Tryon [11] and then further developed by Cattell [12], and the use of cluster methods has increased significantly over the past 30 years [13]. Cluster analysis is the set of multivariate techniques whose main aim is to aggregate items, objects or individuals (here: EU and VG countries) based on their characteristics [14]. The basic criteria used to group objects is their similarities. In this manner, objects belonging to the same cluster are similar to each other concerning the variables that were measured in them, and the elements of distinct clusters are dissimilar for these same variables [15].

Clustering techniques are classified into two types: agglomerative and divisive. In this research the authors used Ward's method, which is one of the most frequently employed agglomerative clustering method. The characteristic feature of this method is the use of a variance analysis for the purpose of determining the distance between clusters. The distance between one cluster composed of objects and another one cannot be directly expressed by way of the distance between the objects belonging to these clusters [16]. Hence, "the method aims to minimize the sum of squared deviations of any two clusters which can be formed at any stage" [17] (p. 54). Therefore, clusters that "ensure the minimum sum of squared distances from the centre of mass of a new cluster, which they create" are merged [18] (p. 74). The literature points out that this kind of agglomerative method is cognitively effective; however, it yields small and yet most natural clusters. In this paper, the measure of similarity used was the squared Euclidean distance.

3. Literature Review

3.1. The Concept of Sustainable Development

The concept of SD has been developed in response to serious concerns over the potential of the Earth's global ecosystem to sustain the impact of anthropo-pressure. It has been aimed at the preventive elimination or at least reduction of the imbalance between economic growth and social development as well as socio-economic development and the natural environment [19]. The concept of SD was introduced to the globally used terminology by the United Nations (UN) agencies [20,21]. This term was used extensively for the first time at the UN Conference on the Human Environment in 1972. It stemmed from the original concept of sustainable management of natural resources. It was defined as a strategy aiming at development based on the rational utilization of local resources and knowledge gained by farmers to satisfy the needs of remote rural areas in Third World countries [22].

The concept of SD is defined as an interdisciplinary approach, which covers in its scope the environmental (the natural capital), social (social capital) and economic spheres (the economic capital). It is an idea and at the same time a concept of actions leading to changes in the life of the human population in the 21st century to ensure adequate living conditions for the present and future generations, as well as the potential to satisfy their needs [23].

It may be assumed that the idea of SD is a certain compromise between the concepts for several component capitals of the natural, social and economic development. It needs to be indicated here that the term SD in terms of economic sciences stems from the development economics, which comprises both neoclassical theories (theories based on the linear model of economic growth, based on the two-sector and bipolar character of global economy) and theories which stress the problem of responsibility in the context of planned and realized economic development [24,25]

The concept of SD is mainly considered within the framework of three approaches [26]: (1) the socio-philosophical concept (assuming the need for changes in the system of human values), (2) a modern direction of economic development (assuming new economic organization and management methods), (3) a newly developed discipline of science.

Such studies as those by Górka [27,28] have attempted to standardize the terminology related to the discussed concept. It should be noted that sometimes, wrongly, the term sustainable is replaced by balanced. However, the state of lasting balance is not consistent with the essence of this concept. This may lead to economic stabilization or even retrogression [27].

Pirages [29] was of an opinion that SD refers to economic growth, which is sustained by the natural and social environment. In turn, Goodland and Ledec [30] stressed that SD is a process of economic transformation consisting in the optimization of current economic and social benefits without jeopardizing the potential to attain these benefits in the future. Turner [31] presented an opinion that SD requires maximization of net benefits of economic growth in order to maintain accessibility of environmental services and the quality of natural resources over time.

It should be noted that Pearce et al. [32] were of an opinion that SD includes the formation of the socio-economic system, which sustains the following objectives: growth of real income, improvement of educational standards, health and the quality of life. In turn, Górka et al. [33] defined SD as such a course of economic development, which does not significantly or irreversibly disturb the living environment for humans, while respecting the laws of nature and economics.

In the opinion of Runowski [34] SD consists in efforts to attain balance between various goals of socio-economic development, without which sustainability of the system may be difficult to attain. The primary aim is to ensure lasting development in terms of its stability and continuity. SD provides guidelines for sustainability as a goal to be reached. In turn, Giovannini and Linster [35] stated that the concept of SD refers both to the quality and volume of economic growth and combines three dimensions of welfare: economic, social and natural. Borys [36] defined SD as an integrated order, i.e., a certain game of limitations in the use of all capitals.

Holger [37] was of an opinion that SD strives to define such management conditions which might guarantee sufficiently high ecological, economic and socio-cultural standards to the entire presently living human population and to the future generations while observing tolerance of nature and realizing inter- and intragenerational justice. In turn, Stanny and Czarnecki [38] expressed an opinion that SD is a compromise between environmental, social and economic goals determining the welfare of future generations. The economic aspect refers not only to the satisfaction of the present-day needs, but also preservation of resources required to meet the needs of future generations. The social aspect is connected with education and the potential to attain the capacity to solve major social problems and to participate in development process of the entire system. Finally, the ecological aspect refers to the identification of absolute limits to human activity.

SD is a concept fully referring to the entire scope of human activity and the resulting interactions with the environment. It may be considered to be a certain type of socio-economic development, which in view of the changes occurring on Earth needs to be constantly monitored and analyzed.

One of the main principles of SD is the use of renewable energy sources. Therefore, it is to them that the next part of the article will be devoted.

3.2. The Development of Renewable Energy Sources in the Entire EU and the VG Countries

Energy generated from renewable sources constitutes an important element in the strategy for SD of the EU member countries, including the VG. Public authorities in the EU have adopted the assumptions of SD for the power industry sector, defining them as an efficient use of energy, human, economic and natural resources [39]. This results from the rapid economic development, a continuous increase in energy demand as well as the awareness that global traditional energy resources are limited [40–42]. The concept of SD emphasizes the importance of environmental protection and repletion of renewable resources, which is particularly essential under new conditions observed globally [43]. In view of the above, SD is such an activity, which sustains the natural environment and may not be conducted at the expense of future generations [44,45]. The concept of SD is based on humans as subjects having an impact on the environment, our planet as an area (object) of human impact and partnership as a method of integrated activity [8]. The global actions towards SD need to ensure welfare and peace worldwide. Such foundations were also presented in the UN Resolution “Transforming our world: the 2030 Agenda for Sustainable Development”, adopted in September 2015 [46]. The global initiative for SD points to climate change and problems of renewable energy [47]. The 17 global sustainable development goals (SDGs) include energy issues, e.g., SDG7 indicates access to cheap, clean, reliable, technologically advanced and sustainable energy for all people by 2030 [8,48]. This is to be attained by [46]:

- Providing common access to cheap, reliable and technologically advanced power supply services;
- Considerably increasing the share of renewable energy in the total energy balance,
- Doubling the global energy efficiency index;
- Strengthening international cooperation in order to facilitate access to clean energy and technology, including renewable energy sources, ensuring greater energy efficiency and state-of-the-art clean fossil fuel technologies as well as supporting investments in the power engineering infrastructure and clean energy generation technologies;
- Development of the infrastructure and modernization of technologies supplying advanced and sustainable energy services in all developing countries, particularly the least economically developed countries.

The EU has also played a significant role in the development of the 2030 Agenda, which is fully consistent with the European vision and constitutes a global program for actions for SD on the global scale, based on the SDGs. For many years, the EU has been undertaking actions for SD in the power sector. Since the beginning, the energy sector has been the most important aspect of the integration processes in Europe. The establishment of the European Coal and Steel Community (CSC) and the European Atomic Energy Community (EAEC) aimed at controlling this sector and ensure the energy security for the member countries [49,50].

In 1987 the “Single European Act” introduced the environmental protection policy and a year later the “European Commission Working Document on Internal Energy Market” presented goals in the energy policy. Since 1992 the EU has been working on the establishment of the single energy market, which comprises three stages. The next step in the development of cooperation in the energy sector was connected with the adoption in 2010

"A strategy for competitive, sustainable and secure energy", specifying priorities of the EU in the energy policy by 2020. The EU identified these priorities as ensuring competitiveness of prices and energy supply security as well as enhancing the technological advantage in this sector [51]. The assumptions of the "Europe 2020" strategy assumed and increase in energy efficiency by 20%, an increase in the share of energy from renewable energy sources to 20% total energy consumption, reduction of greenhouse gas emissions to the level of 20% in 1990 [8,51]. In the next "2030 Energy Strategy" the EU defined the goals for climate and energy, within which the member countries declared by 2030 to reduce by min. 40% their greenhouse gas emissions compared to the levels of 1990, to increase the share of renewable energy sources to 32% energy consumed in the entire EU, to improve energy efficiency by 30% and to ensure potential transfer of 15% electricity generated in the EU to other EU countries within the framework of interconnection systems [8,51]. Reduction of greenhouse gas emissions by 80–90% compared to that in 1990 is another strategic goal of the EU specified in the "2050 Energy Roadmap" of 2011 [52].

The next step was connected with the adoption of the European Council in 2014 of the "European Energy Security Strategy", assuming short-term actions in case of gas supply stoppages or disruptions in its imports to the EU. The framework for the energy policy for the years 2020–2030 was updated by the European Commission in 2016 in the "Clean Energy for all Europeans" package, which indicated the ambitious goal of energy efficiency increased by 32% [9].

In accordance with the climate strategy assumptions referred to as the European Green Deal [53], presented at the 2019 Climate Summit in Spain, the EU declared to reduce greenhouse gas emissions. Initially, it was assumed to reduce it by 80–95% by 2050 compared to the levels of 1990; finally, it was decided that the EU countries are to become zero-emitters (climate neutral) by 2050. In turn, during the European Council summit on 10–11 December 2020, the UE-27 leaders agreed to increase the CO_2 reduction goal to 55% by 2030 [54].

All the actions undertaken by the EU, including the VG, related to energy and climate are consistent with the "2030 Agenda" assumptions [46]. These ambitious EU goals to attain new climate and energy goals focus primarily on the SD of the energy sector. These actions concentrate, e.g., on increased use of alternative energy sources, including renewable sources, in the energy balance [55]. A growing body of evidence on the negative effect of fossil fuels used to produce energy on the natural environment, human life and health are primary reasons for the growing interest in renewable energy sources [42]. The main goal of the sustainable energy policy is to limit the consequences of the negative impact of the energy sector on the atmosphere [56]. Governments worldwide are promoting the use of renewable energy sources [57,58].

Energy should be produced and consumed solely when generated from clean energy sources, i.e., mainly renewable energy [59–62]. Renewable energy sources include biomass energy, solar energy, hydropower, tidal power, wind and geothermal power [63–65]. In view of the above, SED in individual countries is required for the further existence of the energy sector, and it is key for the development not only of renewable energy sources, but also the economy, the environment and society [66]. "Increased importance of renewable energy in the global fuel and energy balance may contribute to savings in the consumption of energy raw materials and improve the condition of the natural environment thanks to reduced air and water pollution levels and decreased amounts of generated waste. For this reason support for the development of renewable energy sources is rapidly becoming a major direction in politics, which has to be considered when planning the energy policies of many countries worldwide" [42].

The use of renewable energy sources has been investigated in many studies and scientific analyses. They concern mainly the development of renewable energy in the context of SD [67], the potential to use solar energy from photovoltaic systems, their efficiency and environmental impact [68,69], potential to use wind energy [70,71], hydropower [72], tidal energy [73], geothermal energy [74] and biomass energy [75]. Many publications are devoted to the economic efficiency of investments in renewable energy sources in the EU [5,76–78], and the VG [79–81].

The primary indications for the growth and development of the renewable energy sector include the fact that these sources emit considerable lower amounts of greenhouse gases and other pollutants [82] and contribute to reduced greenhouse gas emissions [83]; renewable energy has a minimal environmental impact [84]; it does not require a specialized infrastructure and may contribute to an increase in employment rates [60] and provide economic benefits, particularly in rural areas, while its production is cheaper compared to conventional sources [61].

However, there are some barriers hindering rapid implementation of renewable energy sources. The main barrier is connected with the high initial cost of renewable technologies (e.g., photovoltaic panels or wind turbines), lack of data and information on resources, lack of storage facilities, insufficient capacity to construct the systems and monitor efficiency of renewable energy sources, challenges related to the integration of conventional and renewable energy technologies, the effect on agricultural land use, lack of potential for the enforcement of respective policies or design and implementation of renewable energy programs [85].

Dependencies between sustainable development and renewable energy indicated in literature on the subject include the role of renewable energy in economic development. Humanity since the very beginning was based on renewable energy. Biomass, water energy or solar energy were the only available energy sources. However, in the course of development, industrial countries started to exploit new energy sources, including also nuclear energy. At present, in many countries, energy is perceived as a right and governments are expected to meet this need. Consumers of energy services mainly want them to be abundant, reliable and accessible. However, many renewable energy sources are dependent on the nature forces and the environment, as is the case with, e.g., wind or solar energy. Thus, abundance or reliability of many energy sources varies depending on the region. Shortages or disruption in energy supply may also be experienced. For small settlements or remote communities, energy may be sufficient, but when considering large agglomerations or industrial areas with high energy demand, the use of renewable energy sources has to be adequately designed. Costs of renewable energy are also crucial. In many cases, the use of renewable energy is being promoted based on the prospective reduction in its cost. The EU policy concentrated on the support for policies and enterprises of its member states to use environmentally friendly energy from renewable sources [56,67].

At present, in the EU, including the VG, it is promoted to use solar energy in households thanks to subsidies for the purchase of photovoltaic panels, replacement of coal-fired furnaces and thermal retrofitting of family housing. Incentives are also introduced for the purchase of electric cars.

An essential aspect discussed in literature is also connected with the energy security as an aspect of sustainable development [85]. This concerns the reliability and availability of energy services, particularly in industrialized countries, where energy supply disruptions generate costs. In turn, the threat of fluctuations in energy prices may influence the economy and in extreme cases lead to an economic crisis. An important role in this respect is played by the state and its energy security policy. The EU, to promote energy security, has formed the single energy market, where a diversification of energy sources is being implemented. The EU is trying to become independent of external energy supplies; thus, diversification is observed in the forms of energy generation aiming at the increased use of renewable energy [9].

In terms of the EU energy policy, including that of the VG, a priority is to maintain a balance between security, satisfaction of social needs, economic competitiveness and environmental protection [67]. The strategy to develop the renewable energy sector indicates rational use of renewable energy sources, which will contribute to improved efficiency in the use and conservation of energy material resources and improve the condition of the natural environment [67].

Within the last 30 years the EU countries have recorded a considerable increase in the production and consumption of energy generated from renewable sources. In the years 1990–2019 greenhouse gas emissions decreased by 24%, while GDP increased by 60% [8].

The EU is the largest world source of public funds allocated to countering climate change. In 2019 they amounted to 21.9 billion euro. The EU finances sustainable transformation to meet the assumption of the European Green Deal. The countries of the VG diversified energy supplies, but in each of these countries, the structure of energy sources was different. Renewable energy sources were also introduced gradually and systematically. Their level is still low, but an upward trend was visible [79].

One of its goals is to co-finance renewable energy production. Although renewable energy in the electricity generation sector has been developing rapidly, an accelerated progress is also needed in transport, heating and cooling [86]. Within the last few years, globally, access to electricity has increased greatly; the use of renewable energy in the power engineering sector has increased, and energy efficiently has improved. However, due to the COVID-19 pandemic, millions of people are losing access to electricity [87]. Progress in the realization of the "2030 Agenda" SDG 7 seems to be too slow to promise the global energy goals are reached by 2030, with the pandemic additionally slowing it down or even reversing the progress [86,87].

4. Results and Discussion

Tables 1–3 show the changes in renewable energy consumption in transport, electricity, heating and cooling from 2009 to 2019. It is easy to see the increase in the use of renewable energy EU countries. In 2019, countries such as Sweden, Finland and the Netherlands had the largest share of renewable energy use in transport (30.31%, 21.29%, and 12.51%, respectively). For renewable energy use in electricity, countries such as Austria, Sweden and Denmark led the way. When it comes to renewable energy use in heating and cooling, countries such as Sweden, Latvia and Finland were the leaders: 66.12%, 57.76%, and 57.49%.

In contrast, the lowest renewable energy consumption occurred in countries such as:

- In transport—Cyprus, Lithuania and Greece.
- In electricity—Malta, Cyprus and Hungary.
- In heating and cooling—Ireland, the Netherlands and Belgium.

During the period under review, the biggest changes in renewable energy consumption took place in countries such as: Malta (in 2009, the shares of renewable energy consumption especially in transport, electricity were 0.00, while in 2019, they were already close to the EU average), Estonia (the share of renewable energy consumption in transport has increased more than tenfold), Cyprus (the share of renewable energy consumption in electricity has increased more than 16-fold), and Slovakia (the share of renewable energy consumption in heating and cooling has more than doubled). However, as noted earlier, despite the significant increase in renewable energy consumption, most of the countries mentioned are still characterized by the lowest percentage of renewable energy use.

It should be mentioned that in 2019, renewable energy sources made up 34% of gross electricity consumption in the EU-27, slightly up from 32% in 2018. Wind and hydro power accounted for two-thirds of the total electricity generated from renewable sources (35% each). The remaining one-third of electricity generated was from solar power (13%), solid biofuels (8%) and other renewable sources (9%).

In 2019, hydro power use dominated the renewable energy mix in countries such as: Austria (76%), Bulgaria (48%), Croatia (74%), Finland (43%), France (53%), Italy (41%), Latvia (73%), Romania (65%), Slovakia (65%) and Sweden (66%)—Figure 2. Wind energy, on the other hand, dominated the structure of renewable energy sources in countries such as: Belgium (48%), Cyprus (45%), Denmark (69%), Germany (50%), Greece (42%), Ireland (86%), Lithuania (55%), Netherlands (49%), Poland (57%), Portugal (43%) and Spain (52%)—Figure 2.

Table 1. Share of renewable energy in transport in years 2009–2019 (Note: countries were ordered by 2019 index value, from highest to lowest).

EU Country	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2009 = 100
Sweden	9.36	9.63	11.94	13.78	15.32	18.83	21.49	26.56	26.84	29.70	30.31	323.95
Finland	4.56	4.41	1.02	1.07	10.68	24.54	24.78	8.89	18.81	17.68	21.29	467.32
Netherlands	4.57	3.40	5.07	5.22	5.34	6.56	5.50	4.92	6.02	9.62	12.51	273.70
Austria	11.18	10.71	10.08	10.04	9.70	10.99	11.41	10.59	9.71	9.95	9.77	87.39
France	6.65	6.58	0.99	7.42	7.60	8.25	8.37	8.41	8.76	8.96	9.25	139.09
Portugal	3.89	5.55	0.70	0.81	0.93	3.67	7.43	7.65	7.91	9.04	9.09	233.95
Italy	4.00	4.92	5.06	6.16	5.41	5.02	6.51	7.41	6.48	7.66	9.05	226.23
Ireland	1.96	2.49	3.84	4.04	4.89	5.20	5.94	5.16	7.44	7.17	8.93	455.25
Malta	0.00	0.00	2.02	3.22	3.48	4.67	4.68	5.27	6.83	8.02	8.69	86.900
Slovakia	5.36	5.29	5.73	5.60	6.21	7.95	8.63	7.77	6.95	6.99	8.31	154.88
Hungary	5.89	6.16	6.17	6.00	6.34	7.00	7.17	7.77	7.73	7.75	8.03	136.44
Slovenia	2.25	3.12	2.48	3.25	3.77	2.88	2.24	1.60	2.57	5.48	7.98	354.64
Bulgaria	1.09	1.50	0.90	0.65	5.89	5.74	6.49	7.20	7.27	8.08	7.89	722.80
Romania	1.30	1.37	2.85	4.96	5.45	4.68	5.49	6.17	6.56	6.34	7.85	604.93
Czechia	4.31	5.22	1.29	6.25	6.45	7.00	6.54	6.50	6.62	6.56	7.83	181.63
Germany	5.88	6.41	6.46	7.32	7.30	6.90	6.57	7.01	7.03	7.92	7.68	130.68
Luxembourg	2.23	2.09	2.36	2.83	4.07	5.55	6.70	5.96	6.47	6.57	7.66	342.81
Spain	3.71	5.02	0.77	0.87	0.95	1.03	1.11	5.19	5.80	6.93	7.61	205.01
Denmark	0.69	1.15	3.61	6.28	6.46	6.56	6.43	6.73	6.94	6.92	7.17	1034.49
Belgium	2.20	4.80	4.79	4.91	5.08	5.84	3.91	6.02	6.62	6.69	6.81	309.88
Poland	5.41	6.64	6.92	6.53	6.67	6.32	5.69	3.97	4.23	5.65	6.12	113.15
Croatia	1.29	1.12	1.03	1.05	2.72	2.65	2.36	1.22	1.17	2.58	5.86	453.52
Estonia	0.44	0.43	0.45	0.45	0.45	0.42	0.41	0.43	0.42	3.30	5.15	1175.34
Latvia	1.89	3.98	4.09	4.00	4.03	4.08	3.64	2.45	2.27	4.73	5.11	270.87
Greece	1.10	1.92	0.60	0.90	0.98	1.33	1.10	1.62	4.00	4.11	4.05	367.42
Lithuania	4.48	3.79	3.83	4.97	4.84	4.36	4.58	3.65	4.30	4.33	4.05	90.36
Cyprus	2.04	1.99	0.00	0.00	1.13	2.68	2.52	2.67	2.56	2.66	3.32	162.87
Minimum	0.00	0.00	0.00	0.00	0.45	0.42	0.41	0.43	0.42	2.58	3.32	33.200
Average	3.62	4.06	3.52	4.39	5.26	6.32	6.58	6.25	6.97	7.83	8.79	242.90
Maximum	11.18	10.71	11.94	13.78	15.32	24.54	24.78	26.56	26.84	29.70	30.31	271.12

Table 2. Share of renewable energy in electricity in years 2009–2019 (Note: countries were ordered by 2019 index value, from highest to lowest).

EU Country	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2009 = 100
Austria	68.62	66.36	66.78	67.44	68.91	71.06	71.49	72.52	71.63	74.21	75.14	109.50
Sweden	58.25	55.77	59.62	59.78	61.74	63.21	65.73	64.87	65.91	66.23	71.19	122.21
Denmark	28.26	32.74	35.87	38.72	43.08	48.49	51.29	53.72	59.94	62.40	65.35	231.27
Portugal	37.56	40.61	45.78	47.51	49.10	52.05	52.62	53.99	54.17	52.19	53.77	143.16
Latvia	41.94	42.05	44.69	44.88	48.69	51.04	52.21	51.25	54.35	53.50	53.42	127.37
Croatia	35.88	37.52	37.59	38.76	42.08	45.24	45.41	46.67	46.44	48.14	49.78	138.76
Romania	30.89	30.38	31.13	33.57	37.52	41.68	43.16	42.71	41.97	41.79	41.71	135.01
Germany	17.52	18.24	20.93	23.59	25.28	28.17	30.88	32.27	34.61	37.85	40.82	232.95
Finland	27.35	27.66	29.39	29.50	30.88	31.42	32.47	32.93	35.22	36.77	38.07	139.21
Spain	27.84	29.78	31.56	33.47	36.73	37.78	36.95	36.49	36.29	35.06	36.93	132.67
Ireland	14.06	15.64	18.25	19.84	21.25	23.51	25.53	26.84	30.10	33.26	36.49	259.53
Italy	18.81	20.09	23.55	27.42	31.30	33.42	33.46	34.01	34.10	33.93	34.77	184.87
Slovenia	33.76	32.20	31.05	31.63	33.09	33.94	32.73	32.06	32.43	32.31	32.63	96.67
Greece	11.02	12.31	13.81	16.36	21.24	21.92	22.09	22.66	24.47	26.00	31.30	284.09
Bulgaria	10.91	12.36	12.62	15.82	18.68	18.69	18.98	19.15	19.02	22.36	23.51	215.56
France	15.09	14.82	16.18	16.55	16.97	18.46	18.82	19.21	19.93	21.13	22.38	148.36
Estonia	5.97	10.29	12.20	15.67	12.95	14.02	15.62	15.56	17.03	19.69	22.00	368.72
Slovakia	17.77	17.77	19.31	20.05	20.80	22.87	22.66	22.51	21.34	21.50	21.95	123.53
Belgium	6.17	7.23	9.01	11.34	12.55	13.45	15.61	15.90	17.26	18.90	20.83	337.46
Lithuania	5.87	7.40	9.02	10.88	13.15	13.71	15.54	16.87	18.26	18.41	18.79	320.16
Netherlands	9.07	9.60	9.74	10.35	9.91	9.92	11.04	12.55	13.81	15.19	18.22	200.89
Poland	5.83	6.65	8.16	10.68	10.73	12.40	13.43	13.36	13.09	13.03	14.36	246.18
Czechia	6.38	7.52	10.61	11.67	12.78	13.89	14.07	13.62	13.65	13.71	14.05	220.24
Luxembourg	4.11	3.79	4.08	4.66	5.33	5.96	6.20	6.67	8.06	9.13	10.86	264.48
Hungary	6.96	7.10	6.38	6.06	6.60	7.31	7.34	7.29	7.52	8.31	9.99	143.60
Cyprus	0.59	1.39	3.45	4.93	6.65	7.40	8.45	8.59	8.91	9.36	9.76	1656.37
Malta	0.00	0.03	0.45	1.12	1.57	3.33	4.31	5.71	6.85	7.66	8.04	80.400
Minimum	0.00	0.03	0.45	1.12	1.57	3.33	4.31	5.71	6.85	7.66	8.04	80.400
Average	20.24	21.01	22.64	24.16	25.91	27.57	28.45	28.89	29.86	30.82	32.45	160.32
Maximum	68.62	66.36	66.78	67.44	68.91	71.06	71.49	72.52	71.63	74.21	75.14	109.50

Table 3. Share of renewable energy in heating and cooling in years 2009–2019 (Note: countries were ordered by 2019 index value, from highest to lowest).

EU Country	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2009 = 100
Sweden	60.57	58.48	59.95	62.39	63.53	64.46	65.28	65.45	65.77	65.34	66.12	109.16
Latvia	47.89	40.75	44.71	47.27	49.65	52.15	51.74	51.81	54.60	55.43	57.76	120.63
Finland	42.89	43.97	45.76	48.25	50.77	51.95	52.62	53.70	54.59	54.64	57.49	134.04
Estonia	41.78	43.25	43.97	42.99	42.99	44.97	49.33	50.95	51.70	53.68	52.28	125.11
Denmark	29.51	30.45	32.05	33.28	34.80	38.17	40.23	41.59	44.64	45.55	48.02	162.74
Lithuania	33.72	32.54	32.79	34.54	36.88	40.63	46.09	46.57	46.50	46.02	47.36	140.45
Portugal	37.95	33.83	35.20	33.16	34.64	40.46	40.11	41.63	41.03	40.93	41.65	109.74
Croatia	31.30	32.88	33.82	36.55	37.31	36.22	38.62	37.64	36.63	36.65	36.79	117.56
Bulgaria	21.64	24.33	24.77	27.24	29.23	28.52	28.90	29.99	29.88	33.30	35.51	164.09
Cyprus	17.32	18.84	20.02	21.84	22.62	22.26	24.13	24.76	26.48	37.23	35.10	202.69
Austria	29.63	30.96	31.52	33.08	33.22	33.38	33.23	33.48	33.67	34.19	33.80	114.08
Slovenia	28.87	29.54	31.78	33.14	35.11	34.64	36.15	35.56	34.64	32.34	32.16	111.39
Greece	17.25	18.66	20.11	24.12	27.42	27.87	26.56	25.42	28.25	30.29	30.19	175.05
Romania	26.43	27.23	24.31	25.75	26.20	26.74	25.89	26.87	26.58	25.43	25.74	97.37
Malta	2.01	7.28	12.03	13.40	15.40	15.03	14.64	16.86	19.31	23.35	25.70	1277.72
Czechia	14.26	14.10	15.39	16.25	17.70	19.52	19.78	19.87	19.72	20.63	22.65	158.81
France	15.04	16.16	15.37	16.67	17.67	18.19	19.02	20.24	20.73	21.36	22.46	149.36
Slovakia	8.18	7.90	9.26	8.80	7.88	8.87	10.79	9.88	9.84	10.60	19.70	240.84
Italy	16.43	15.64	13.82	16.98	18.09	18.91	19.25	18.88	20.08	19.23	19.67	119.74
Spain	13.32	12.62	13.66	14.16	14.15	15.82	16.98	17.30	17.70	17.57	18.87	141.66
Hungary	17.02	18.08	20.04	23.31	23.70	21.28	21.34	21.03	19.87	18.17	18.12	106.47
Poland	11.61	11.81	13.24	13.50	14.27	14.24	14.80	14.92	14.88	15.14	15.98	137.69
Germany	11.16	12.06	12.57	13.42	13.41	13.42	13.44	13.04	13.38	14.12	14.55	130.47
Luxembourg	4.63	4.70	4.74	4.94	5.35	7.06	6.86	7.05	7.47	8.48	8.71	188.12
Belgium	5.94	6.70	6.65	7.09	7.58	7.74	7.86	8.23	8.14	8.31	8.31	139.88
Netherlands	3.37	3.10	3.69	3.77	4.00	4.93	5.20	5.12	5.67	6.07	7.08	210.12
Ireland	4.19	4.32	4.60	4.81	5.19	6.29	6.19	6.27	6.62	6.35	6.32	150.91
Minimum	2.01	3.10	3.69	3.77	4.00	4.93	5.20	5.12	5.67	6.07	6.32	314.12
Average	22.00	22.23	23.18	24.47	25.51	26.43	27.22	27.56	28.09	28.90	29.93	136.07
Maximum	60.57	58.48	59.95	62.39	63.53	64.46	65.28	65.45	65.77	65.34	66.12	109.16

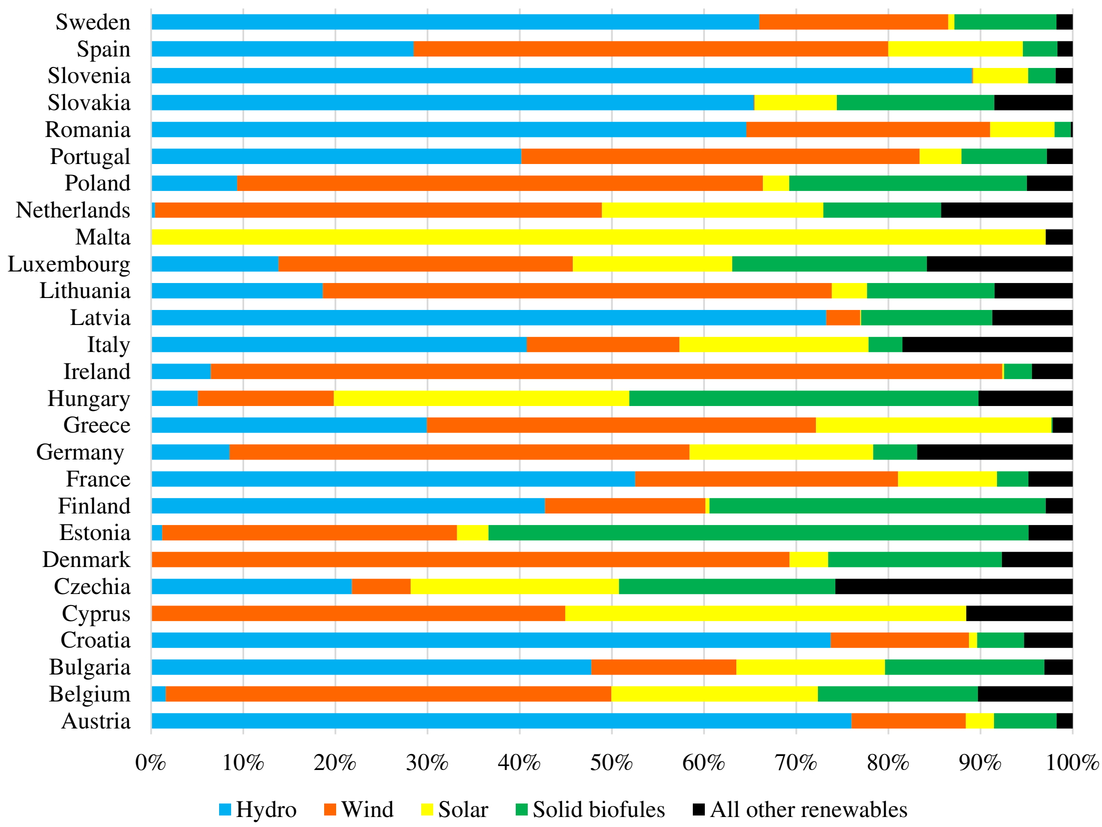

Figure 2. Structure of renewable energy use in EU countries in 2019.

In the next step, a cluster analysis was carried out, but before starting the cluster analysis, we standardized all three variables. As a first step in the cluster analysis, we analyzed correlations among the clustering variables (x_1: share of renewable energy in transport in 2019, x_2: share of renewable energy sources in electricity in 2019, x_3: share of renewable energy sources in heating and cooling in 2019): strong correlation leads to an overrepresentation of the variables in the final clustering solution [88]. All bivariate correlations fell well below the 0.9 threshold, indicating no potential collinearity issues.

The clustering was performed based on the method of Ward. The results are given in Figures 3 and 4. The tree diagram (Figure 3) is the first and the simplest result of the cluster analysis, and it is closely related to the second result, the graph of amalgamation schedule (Figure 4). The algorithm first calculates all the Euclidean distances between the countries (and puts them in the tree diagram), and only after arranging the distances in an ascending scale, it shows the amalgamation schedule.

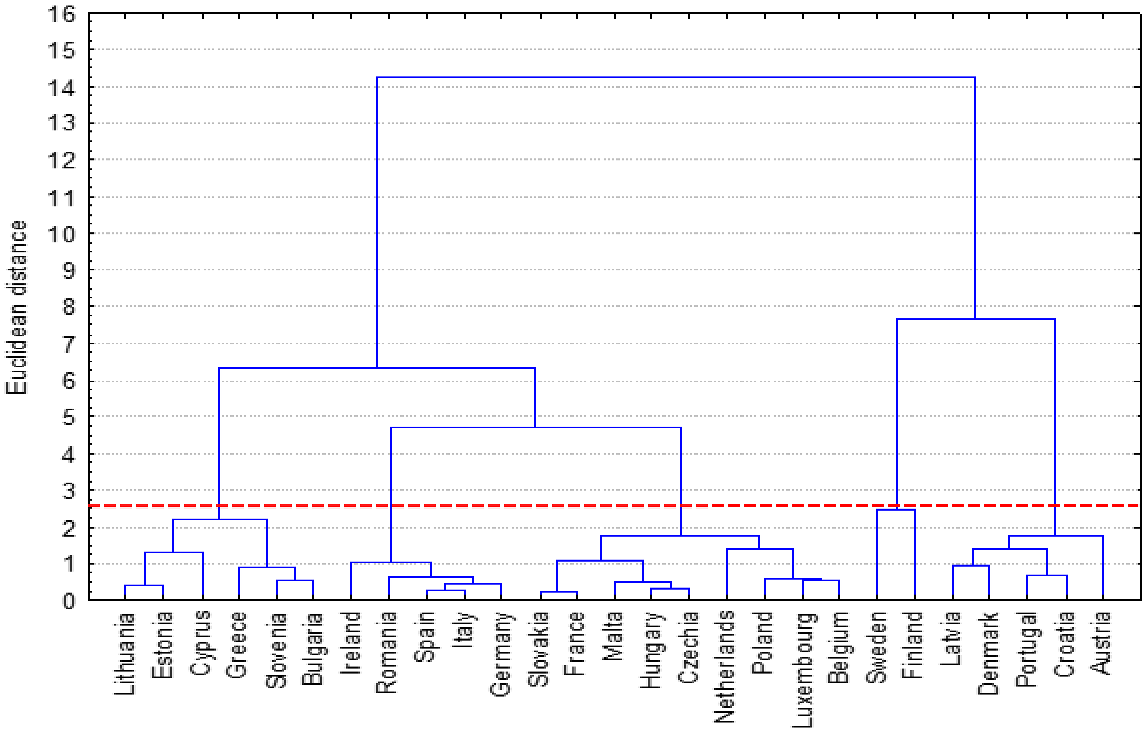

Figure 3. Tree diagram: hierarchical cluster analysis of renewable energy consumption in European countries in 2019.

The key to interpreting a hierarchical cluster analysis is to look at the point at which any given pair of countries "join together" in the tree diagram. Countries that join together sooner are more similar to each other than those that join together later. For example, the pair of countries with the lowest (shortest) distance (Spain and Italy; Slovakia and France, distance = 0.45) join together first in the tree diagram.

To find the optimal number of clusters, use the graph of amalgamation schedule. One could observe that at 23rd step, Euclidean distance rises sharply at value 3.9 (indicated by red line). Determining 2.5 as a cutoff point (as suggested by the amalgamation schedule in Figure 4) results in five distinct clusters of EU countries (Figure 3).

Based on the cluster analysis results, it is perceived that the first cluster includes: Lithuania, Estonia, Cyprus, Greece, Slovenia, and Bulgaria. This is the group of countries that is characterized by the lowest share of renewable energy use in transport compared to other clusters. The average for these countries is 5.41% (in 2019).

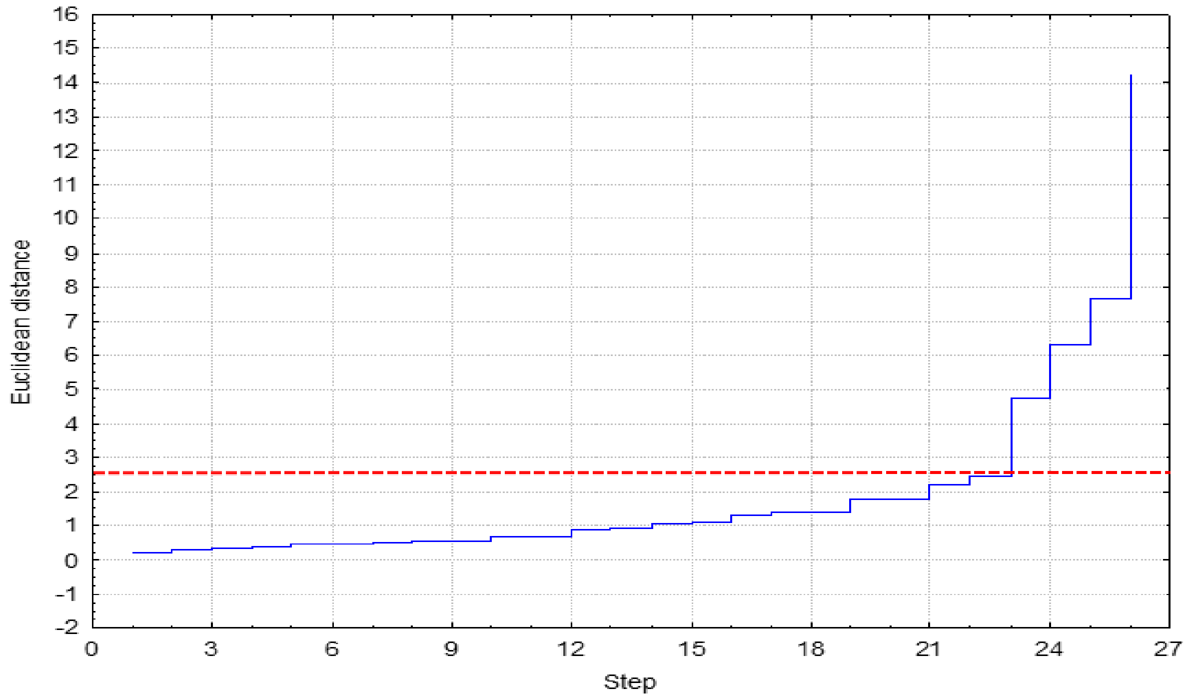

Figure 4. Graph of amalgamation schedule.

The next, third cluster includes nine EU countries: Slovakia, France, Malta, Hungary, Czechia, the Netherlands, Poland, Luxembourg and Belgium. Thus, it is the most diverse cluster. This group includes for example the entire VG (Poland, Slovakia, Czechia and Hungary). This is the cluster with the lowest share of renewable energy in electricity, heating and cooling. In 2019, on average, these shares were: 15.63%, and 16.52%. It is worth noting that in this group all the indicators used in the analysis were below the average for the whole European Union (27 countries).

The fourth cluster includes only two EU countries: Sweden and Finland. In 2019, in these Nordic countries, electricity production was in one half renewable (in average 54.62%). Within it, the largest share was hydro power followed by biomass (from forestry) and wind power (like it was mentioned before). Importantly, in 2017, Finland adopted a "National Energy and Climate Strategy" [89]. A specific target for overall renewable energy share was not defined in this policy, but it had exceeded already in 2014 the 67.5% target set for 2020 in the NREAP (National Renewable Energy Action Plan) [90]. In turn, Sweden had an energy commission in place, which submitted its final report in January 2017 [90]. The commission proposed a 100% renewable energy target for 2040.

The last, fifth, cluster includes five countries: Latvia, Denmark, Portugal, Croatia, and Austria. It is worth noting that this is the group of countries with the largest share of renewable energy consumption in electricity. In 2019, the average for countries was 59.50%. For example, Denmark has the highest share of wind power in the world.

Using the hierarchical cluster analysis method, we can group the EU Countries according to the characteristics of the analyzed three variables, revealing the existing structures as well as the way in which the analyzed countries are linked in hierarchical structures. Thus, by tackling these clusters as a whole, it is possible to improve efficiency and more effectively focus public policies and financial support instruments for renewable energy sources, resulting in effects in the countries that are part of the same cluster.

According to the results of the study, there is a serious gap in 2019 regarding the differences in the use of renewable energy sources in EU countries. In the case of transport, the gap recorded between the lowest share (Cyprus, 3.32%), and the highest (Sweden, 30.31%) was about 9.2 times larger. In the case of electricity, the gap recorded between the lowest share (Malta, 8.04%) and the highest (Austria, 75.14%) was about 9.3 times larger. Finally, in the case of heating and cooling, the gap recorded between the lowest share (Ireland, 6.32%) and the highest (Sweden, 66.12%) was about 10.5 times larger. These unfavorable differences in the use of renewable energy sources will obviously have an impact in the medium to long term on the ability of individual countries to achieve their sustainable development goals.

The results obtained are consistent with those obtained by Włodarczyk et al. [91]. The cluster analysis conducted by the researchers made it possible to distinguish 5 groups of EU countries differing in their effectiveness in achieving sustainable development goals. The group of countries that were characterized by "highest average value of share of renewable energy in transport (15.97%, exceeding the EU average with 81.7%), highest average value of share of renewable energy in electricity (57.01%, representing an increase of 75.7% compared to the EU average), highest average value of share of renewable energy in heating and cooling (57.35%, exceeding the EU average with a remarkable 91.6%), next to the lowest average value of greenhouse gas emissions intensity (71.77%, representing a decrease of 13.4% compared to the EU average)" [91] (p. 10) included: Denmark, Finland, Latvia and Sweden. In contrast, the group of countries that do not perform as well in these areas included: Belgium, Cyprus, Lithuania, Luxembourg and Malta [91].

Finally, we want to emphasize that the importance of renewable energy in the energy mix is increasingly reflected in specific activities and regulations at the international level. In practice, the environmental benefits of adopting renewable energy sources are undeniable today, and they are increasingly explored and analyzed in the literature. Research in this area has been carried out not only at the European Union level [91,92] but also at the level of individual countries, e.g., Germany [93,94], Hungary [95,96], France [97], Greece [98] or Spain [99].

5. Conclusions

The use of renewable energy sources is becoming one of the priorities of the EU. This is a consequence of the growing importance of the concept of SD and SED. Thus, more and more often biomass energy, solar energy, hydropower, tidal power, wind and geothermal power are used in cooling, heating, electricity and transport.

Our paper makes several contributions. Firstly, our study contributes to the SD and SED literature by offering a comprehensive grasp of its underpinnings in light of recent advances. Secondly, on the basis of the conducted research, the following can be noted: (1) In 2019, renewable energy sources made up 34% of gross electricity consumption in the EU-27; wind and hydro power accounted for two-thirds of the total electricity generated from renewable sources. (2) Between 2009 and 2019 there was an increase in the use of renewable energy sources in transport, electricity, cooling and heating (the biggest changes in renewable energy consumption took place in countries such as Malta, Estonia, Cyprus and Slovakia). (3) Five groups of EU member states have been identified, which differ in terms of renewable energy consumption. (4) The undisputed leader in the European Union in terms of the development of the renewable energy sector is Sweden, which had the largest share of renewable energy consumption in transport, heating and cooling during the period under review. (5) The entire VG (and also France, Malta, the Netherlands, Luxembourg and Belgium) in comparison with other EU countries is characterized by the lowest share of renewable energy in electricity, heating and cooling.

Despite these contributions, our study is not without limitations. Firstly, the literature review section does not include all possible studies on the discussed concepts. In the selection of literature, the authors were guided by its diversity, availability and timeliness. Secondly, cluster analysis was performed on three indicators only. Such indicators were omitted, e.g., greenhouse gas emissions intensity of energy consumption or final energy consumption in households per capita. Thirdly, the use of Ward's method resulted in low abundance clusters (e.g., one of the clusters includes only two EU countries: Sweden and Finland).

The results provide an interesting starting point for future research. The methodology used in this article can be reproduced with other indicators both quantitative and qualitative. Another suggestion would be to perform a cluster analysis based on indicators showing changes in consumption of renewable energy sources over several years (dynamic approach). Finally, in cluster analysis, other methods could be used in addition to Ward's Method (possibility of comparing results).

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Article

Diversity and Changes in Energy Consumption by Transport in EU Countries

Tomasz Rokicki [1], Grzegorz Koszela [1], Luiza Ochnio [1,*], Kamil Wojtczuk [1], Marcin Ratajczak [2], Hubert Szczepaniuk [2], Konrad Michalski [2], Piotr Bórawski [3] and Aneta Bełdycka-Bórawska [3]

[1] Institute of Economics and Finance, Warsaw University of Life Sciences, 02-787 Warsaw, Poland; tomasz_rokicki@sggw.edu.pl (T.R.); grzegorz_koszela@sggw.edu.pl (G.K.); wojtczukkamil@gmail.com (K.W.)

[2] Management Institute, Warsaw University of Life Science, ul. Nowoursynowska 166, 02-787 Warszawa, Poland; marcin_ratajczak@sggw.edu.pl (M.R.); hubert_szczepaniuk@sggw.edu.pl (H.S.); konrad_michalski@sggw.edu.pl (K.M.)

[3] Department of Agrotechnology and Agribusiness, Faculty of Agriculture and Forestry, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 2, 10-719 Olsztyn, Poland; pboraw@uwm.edu.pl (P.B.); aneta.beldycka-borawska@uwm.edu.pl (A.B.-B.)

* Correspondence: luiza_ochnio@sggw.edu.pl

Abstract: The main purpose of this paper is to present the differences in the volume of energy consumption in transport in the EU (European Union) countries. The specific objectives aim to determine the directions of changes and the degree of concentration in the volume of energy utilized by the transport sector in EU states, showing various models in this area, to establish the association between energy absorption and the parameters of the economy and in the field of transport. All EU countries were selected for research by the use of the purposeful selection method as of 31 December 2018. The analyzed period covered the years 2004–2018. For the examination of data, grading data analysis was used as one of the methods of multivariate data analysis. Descriptive, tabular and graphic methods were used to present the results. Findings reveal that there is a general tendency to reduce total energy consumption in the EU countries. The same is the case of energy in transport. Only in 2016–2018 was there an increase in energy absorption in transport. The reason was the better economic situation in this period. Road conveyance is the most important factor in energy utilization (over 90%). The share of other modes of transport was very small. Economically developing countries were the fastest in increasing energy absorption in transport per capita. In turn, highly developed states recorded slight growth and were stable in this aspect. There was a close relationship between energy utilization in transport per capita and GDP per capita. The reduction of energy consumption in transport depends on changes in road haulage, e.g., the pace of introducing innovative energy-saving technologies in automotive transport.

Keywords: energy in transport; energetic efficiency; energy sources; economic growth; developing and developed countries

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1. Introduction

1.1. The Importance of Transport in Energy Consumption

The transport sector is one of the industries with the highest energy absorption in the world. In 2018, this form of business accounted for about 64% of global oil consumption and around 29% of total final energy absorption [1]. Both passenger and freight conveying exploit energy. As a rule, it is not possible to split energy consumption solely into any of these modes of transport [2]. Dingil et al. [3] found that a significant increase in transport energy intensity occurs in cities with a low population density. The main reason for the high energy absorption of transport in such municipalities was the high share of private means of transportation. Brownstone and Golob [4] achieved similar results. More fuel was used in sparsely populated areas. Schippl and Arnold [5] demonstrated that political measures that limit automotive car mobility would also be needed to achieve a full-scale transition towards multimodal urban mobility. Newman and Kenworthy [6] argued for an energy compromise in transport. In downtowns, energy efficiency was lower than in suburban areas. However, the total fuel depletion is smaller in these areas. The conclusions from the presented research are similar. Urbanization and patterns of settlement used in a given country have a significant impact on the energy efficiency of passenger conveyance.

Thus, the energy consumption of transport may be related to the economic situation and the mobility of the society. Enhanced energy absorption in transport is associated with increased total energy utilization in the economy [7–11]. Such relationships were found in the Banister and Stead studies. They showed that the strong relationship between economic activity and transport demand significantly increases energy consumption and, consequently, carbon dioxide emissions [12]. Thus, higher economic growth leads to increased energy utilization. Conversely, the use of large volumes of energy reflects high levels of economic growth. There is a great number of research confirming such relationships [13–25]. Ozturk and Acaravci [26] presented the feedback between energy absorption and economic growth in Hungary. Belloumi conducted similar research in Tunisia [27].

The increase in transport output causes an enhancement in energy consumption. Innovations are needed to reduce transport energy absorption and to reduce air pollution. For example, advances in vehicle technology can decrease the energy intensity of the transport sector and improve the energy efficiency of haulage activities. As a result, the positive importance of transport in global economic activity will increase. Solutions such as electric drive, hybrid plug-ins, and hydrogen are implemented to reduce energy consumption. Cars also use other innovative technologies that facilitate driving and reduce energy consumption [28–34]. Another way is to maximize the use of the load capacity of the means of transport for the movement of goods and the number of seats for the conveyance of people [35]. When transporting people in cities, no car traffic zones are introduced to force urbanites to use public transport [36–40].

Change in transport is heading towards ecological and economic balancing (sustainability) [41]. Thus, various forms of transportation are used. In general, there is a tendency towards intermodal transport to utilize the best properties of individual means of transport. Scientific research has focused mainly on energy efficiency in road transport [42–44]. Many studies also refer to the efficiency of urban transport, which uses various types of transport [45–47].

1.2. Selected Ways to Improve Energy Efficiency

Technological progress allows for benefits in terms of productivity and technology of energy utilization, which contribute to the reduction of greenhouse gas emissions. A move towards renewable energy production by emphasizing cleaner energy carriers (such as electricity and hydrogen) would improve urban air quality [48,49]. Efficient use of energy is a very attractive way of reducing the impact of energy on the environment and health. Achieving the same outcomes with less energy should theoretically reduce costs and emissions of local pollutants and greenhouse gases [50–52].

The improvement of global energy efficiency is indicated by the ratio of energy consumption to gross national income (GNI). Historically, total energy absorption per person has steadily increased. This was because the surged energy efficiency coexisted with economic growth, rising expectations, social changes and population growth. Therefore, people must reduce energy-related emissions of greenhouse gases and other pollutants [48,53–55].

1.3. Relationship between Sustainable Transport Development and Economic Growth

Many studies emphasize the two-way symbiosis between transport and economic growth, which influence each other through feedback. Transport is important to the development of a sustainable economy that aims to provide new services. Transport should enable the movement of goods and people, and at the same time, contribute to environmental protection and ensure safety [56–60]. Sustainable development requires an efficient and safe transport system powered by clean, low-emission, secure and inexpensive energy. Energy used in transport enables social and economic development. Therefore, energy policy in transport should result from the program of sustainable development of the economy [61–63].

The relationship between energy consumption by transport and pollutant emissions (mainly CO_2 and other harmful compounds) is known. The environmental Kuznets curve is empirically tested in many countries and regions using various indicators of environmental degradation and many econometric techniques of cross-sectional and panel data. The Kuznets curve shows the relationship between GDP per capita and inverted U-measures of environmental degradation [64]. Industrialization increases the negative environmental influence of economic activity up to a point where the impact decreases with continued economic growth. Individual EU states differ in terms of economic development, which means that they may be at different stages of evolution. The environmental impact of these countries may also vary. Obtained results and relationships can be related to transport, which absorbs a lot of energy and emits many pollutants at the same time. Energy consumption was used as a variable in many studies [65–76]. Some researchers also negate the assumptions of the existence of the Kuznets curve. It all depends on the type of contamination [77–80]. As a result, in each state or group of countries, it is possible to obtain different outcomes confirming or negating the existence of the Kuznets curve. The results received will largely depend on the level of energy efficiency of the country and region. In general, in states with high GDP, the Kuznets curve was most often used. Examples are France [81,82], Canada [83], Spain [84] and the United States of America [85]. Patterns are also confirmed in countries with average GDP levels, such as Malaysia [86], China [87], Turkey [74], Romania [88], Tunisia [89] and Latin America and the Caribbean [90]. Many studies have confirmed that the use of fossil fuel energy increases air pollution. An example is the use of crude oil to power internal combustion engines [91–93].

It should also be mentioned that there is an interaction between economic growth, energy consumption and environmental quality. These relationships are the subject of energy economics research [94–96]. Environmental quality can generate positive or negative externalities. Consequently, it stimulates economic growth by focusing on human health, which is potentially affected by emissions. The link between energy variables, progress and environmental quality has been the subject of conflicting and paradoxical goals set by policymakers. This relationship is the basis for creating a sound economic policy consistent with its environmental and energy policy objectives. Empirical work on the tripartite causality link between energy, economic growth and the environment can be broken down into three lines of research. The first concerns the relationship between energy variables and economic growth. According to the assumptions, very good economic results require a high level of energy absorption, and effective energy utilization requires large economic growth [97–104].

The sustainable development of the transport sector can be divided into three main sections: society, economy and environment. The evolution of transport requires sustainability to achieve the minimum expectations in these three sectors. Increasing the role of transport in sustainable development is realized by promoting public transport, demand management, improved road management, pricing policy, improved vehicle technology, using clean fuels and transport planning [105,106]. From their current structure to one that is compatible with sustainable development, transforming global transport systems is likely to be a long-term process involving continuous changes in several physical, technological and institutional systems [107].

1.4. Justification, Aims and Structure of the Article

The subject matter of the article is important and up-to-date. Transport is a significant energy consumer. Many research papers are describing the relationship between energy absorption in transport and the parameters of the economy. A novelty is the application of multidimensional analysis using the Gradestat software. As a result, it was possible to investigate the situation in individual countries regarding energy consumption in transport and GDP (Gross domestic product). Data per capita were also calculated in the research, which enabled an accurate comparison of countries with different levels of economic development.

There is a research gap that this article can fill. The literature review shows no previous studies on the relationship between energy consumption and economic development. For instance, we found only one publication that reported the relationship between energy absorption in transport per capita and GDP per capita. In addition, our research will cover the area of the EU, which is still quite diverse. In addition, the quite rare method, the GCA algorithm (grid-based clustering algorithm), was used in the study. The above aspects make the research necessary and original.

The main goal of the article is to present the differences and changes in the volume of energy utilization by transport in the EU states. The specific objectives are:

- Identifying the directions of changes and the degree of concentration in the volume of energy consumption in transport in EU countries;
- Showing various models in the area of energy absorption in transport;
- Determining the relationship between energy consumption by transport and the parameters of the economy and in the field of transport.

One research hypothesis was formulated in the paper:

Hypotheses: the rate of changes in energy absorption in transport per capita is closely related to the level of economic development of the country.

The organization of this paper is as follows: Section 1 provides an introduction to the subject. The importance of transport in energy consumption, ways of improving energy efficiency, the tripartite relationship between transport energy use, environmental pollution and economic growth are presented. This section also contains the justification and aims of the article. Section 2 proposes methods to identify differences and changes in the volume of energy absorbed by transport in the EU states. In Section 3, the research findings are presented. In Section 4, the reference is made to other research results that dealt with the relationships tested. Finally, Section 5 concludes this paper.

2. Materials and Methods

2.1. Data Collection, Processing and Limitations

All EU countries were selected for this research using the purposeful selection method as of 31 December 2018. In total, 28 EU states were examined. When presenting the results in tables and graphs, the abbreviations of country names were used. Acronyms of the country name were used in work in accordance with ISO 3166-1 alfa-2. They are as follows: Austria (AT), Belgium (BE), Bulgaria (BG), Cyprus (CY), Czechia (CZ), Germany (DE), Great Britain (GB), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Greece (GR), Croatia (HR), Hungary (HU), Ireland (IE), Italy (IT), Lithuania (LT), Luxembourg (LU), Latvia (LV), Malta (MT), Netherlands (NL), Poland (PO), Portugal (PT), Romania (RO), Sweden (SE), Slovenia (SI), Slovakia (SK).

The research period covered the years 2004–2018. This is because 2004 saw a significant expansion of the EU with 10 new states, and 2018 was the last year when complete research data were available.

The data used in the study come from Eurostat for the 15 years 2004–2018. To ensure the stability and transparency of the obtained results, this period was most often divided into 3-year sub-periods. Data collection is limited by the lack of detailed and timely information on energy in transport. Additionally, these data are aggregated at the country level, so there is a problem with performing analyses at the regional level.

Energy absorption was measured in the toe. The ton of oil equivalent (toe) is a unit of energy defined as the amount of energy released by burning 1 ton of crude oil. It is approximately 42 gigajoules or 11.630 megawatt-hours, although as different crude oils have different calorific values, the exact value is defined by convention [1].

The study is a result of the authors' previous research on transport. Quite recently, the field of the writers' interest has been power engineering. These two areas are closely connected because without energy, transport is impossible. The vast majority of authors are economists. Therefore, the aspect related to economics was raised. Additionally, it was noted that there are no current academic studies on the relationship between energy consumption in transport and economic development.

2.2. Applied Methods

The research was divided into stages. Figure 1 shows a diagram of the conducted research.

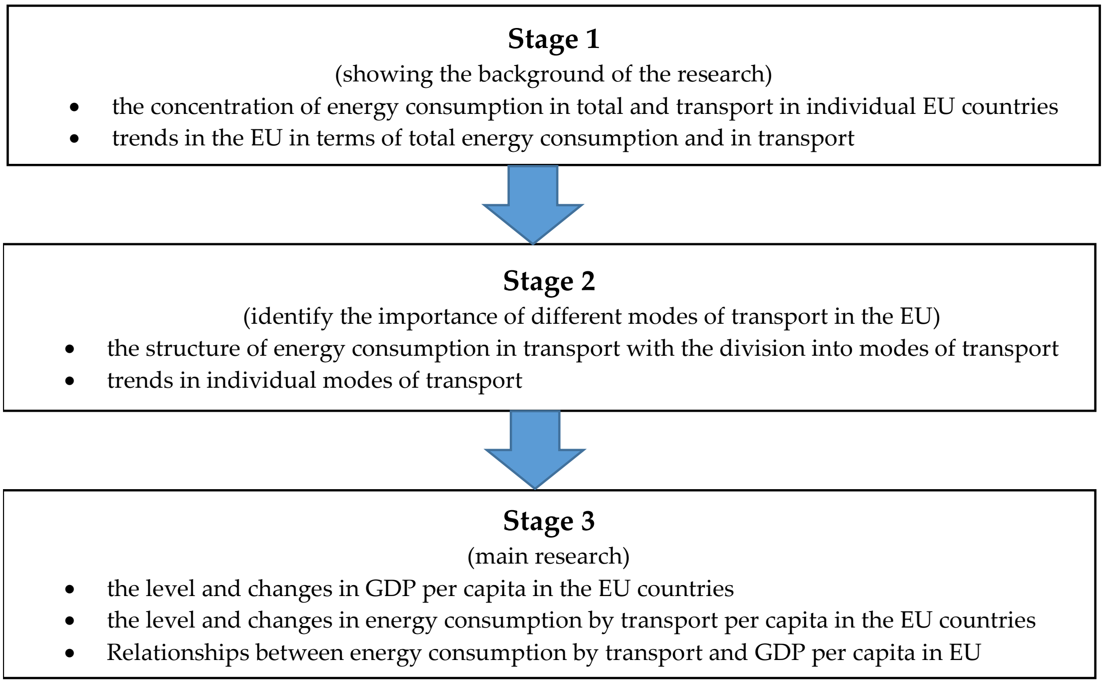

Figure 1. Diagram of the conducted research.

The first stage of the research shows the concentration of energy consumption in total and transport in individual EU states. The data concern 2018, the last year of the analyzed period. As a result, it was possible to compare the degree of concentration of energy absorption in total with energy intended for transport. All EU countries were examined. Furthermore, all 3-year periods in 2004–2018 were investigated. As a result, it was possible to notice the current trends in the EU in terms of total energy utilization and in transport.

In the second stage of the research, the structure of energy consumption in transport with the division into modes of transport was shown. The purpose of this section was to identify the importance of different modes of transport in the EU. Additionally, trends in individual modes of transport were presented.

The third stage of the research presents changes in GDP per capita in individual EU states. For data examination, the grading data analysis method was implemented as one of the multivariate data analysis techniques that can be used to graphically present the dynamics of phenomena or differences between objects in the form of overrepresentation maps.

The GCA algorithm (grid-based clustering algorithm) also allows creating groups, but it generates them in a way that allows creating, in this case, 3 objects that are characterized by the greatest possible differentiation among themselves. These clusters are formed as a result of combining objects that ensure such differentiation, and for this purpose, a certain independence index, Ro or Tau, is optimized [108].

There are many proposals in the literature for the construction of structure dissimilarity indicators. Distances are often used for this purpose, e.g., Minkowski metric [109].

$$d(x,y) = \left(\sum_{i=1}^{n} |x_i - y_i|^p) \right)^{\frac{1}{p}} \tag{1}$$

If we have two structures: x and y, where:

$$x_i \geq 0 \qquad \sum_{i=1}^{n} x_i = 1 \qquad y_i \geq 0 \qquad \sum_{i=1}^{n} y_i = 1 \tag{2}$$

this measure certainly meets two conditions:

1. The distance between objects with the same structure is equal to "0", that is: $d(x,x) = 0$.
2. The distance between the Y object and the X object is the same as between X and Y and is not less than "0", that is: $d(x,y) \geq 0$.

$$\Lambda_{n \geq k > j > i \geq 1} d\left(x, x_{ij,\varepsilon}\right) \leq d\left(x, x_{ik,\varepsilon}\right) \tag{3}$$

However, one can have some doubts as to the correctness of the fulfillment of the third condition by the dissimilarity index:

3. The distance measure changes according to the "transfer sensitivity" adopted in the concentration indices. The increase in the value of the dissimilarity index at a constant transfer value is the greater the "richness" of the object to which the transfer was made.

$$x = (x_1, \ldots, x_i, \ldots, x_j, \ldots, x_k, \ldots, x_n) \tag{4}$$

$$x_{ij,\varepsilon} = (x_1, \ldots, x_i - \varepsilon, \ldots, x_j + \varepsilon, \ldots, x_k, \ldots, x_n) \tag{5}$$

$$x_{ik,\varepsilon} = (x_1, \ldots, x_i - \varepsilon, \ldots, x_j, \ldots, x_k + \varepsilon, \ldots, x_n) \tag{6}$$

In the case of this study of energy consumption from transport, it is about shifting the value of energy absorption between years (the more years shifted, the greater the value of the dissimilarity index should be) because we are interested in which countries have experienced faster growth in energy consumption. The construction of the dissimilarity index of structures meeting condition three can then be based on the concentration index (Gini coefficient) and the Lorentz curve.

By analogy with the Lorentz curve, the dissimilarity of the Y structure to the X structure can be presented as a broken line connecting certain points, the coordinates of which in this case are successive cumulative structures, and the measure of the dissimilarity of the Y structure to the X structure also by analogy—this time with the Gini coefficient—is the measure "*ar*".

$$ar(y:x) = ar\left(C_{[y:x]}\right) = 1 - 2\int_{0}^{1} C_{[y:x]}(t)dt \tag{7}$$

where $C_{[y:x]} : [0,1] \to [0,1]$ belongs to the group of continuous functions.

By measuring the distances between structures (in the case of our study, e.g., dynamics of changes in the GDP per capita of the European Union countries) using the ar measure, we can spot subtleties to which Minkowski's metric is insensitive. Visualization of the structures was made with the use of overrepresentation maps. Overrepresentation, in this case, is the ratio of the component structures (in this case, the structures for individual countries in periods) to the average value. Thus, as an average, we understand the ratio of the sum of the quantities, e.g., energy consumption in individual periods, to energy consumption in the entire period under examination for the entire EU.

After determining the average values, we can calculate the so-called "overrepresentation indicators". The overrepresentation indicator shows how far the observed value differs from that which would be expected given the ideal proportionality of the distribution. For an ideal representation, the indicator will take the value 1. Those determined overrepresentation coefficients allow drawing the "map of overrepresentation" where, with appropriate values of the indicators, different shades of gray are encoded (the overrepresentation map for the proportional distribution would be uniformly gray without any shades). The map of overrepresentation is a square with sides equal to 1, wherein in this case, the rows are EU countries, and the columns are energy consumption in particular periods. Colors show overrepresentation (extreme black) or underrepresentation (extreme white). The map has rows and columns of varying heights and widths:

- Height is determined by the percentage share of energy consumption value for each period to the amount of energy consumption for the entire period.
- Width of the columns is the average energy consumption structures by EU countries in the interested period.

The concepts discussed: the concentration curve, the ar index and the overrepresentation map are closely related to the Grade Data Analysis (GDA). As part of the Grade Data Analysis, some quite complex operations are performed. The main issue in GDA is studying the diversity of rows and columns and striving to arrange them in the data matrix in such a way as to achieve the maximum contrast between the outermost rows and columns. This goal is implemented by the GCA (Grade Correspondence Analysis) algorithm. It rearranges the rows and columns of the data matrix to maximize a certain dependency ratio. In this case, only the rows are rearranged as the columns are in chronological order. This dependency index is the rho-Spearman or Kendall's tau correlation coefficient and depends mainly on the dissimilarity index ar. Based on these indicators, clusters are built in such a way as to maximize the differentiation between them. In contrast, the differentiation between two clusters is understood as the differentiation between two objects formed from these groups as the sum of the objects included in them.

The number of clusters, in this case, depends on the number of observations (there are only 28). Therefore, it is a subjective choice of the authors.

The third stage of the research also shows the relationship between energy consumption and GDP in individual EU countries. The aim was to determine whether such a correlation exists and whether it concerns all EU states or a group of countries. Looking for a linear relationship between two rankings, it was decided to perform a procedure that allowed to reconcile the classic approach of the Spearman rank correlation coefficient r_s with Pearson's linear correlation coefficient r [110,111].

Descriptive, tabular and graphic methods were also used to present some of the findings.

3. Results

3.1. Energy Consumption in the EU Countries

As an introduction to the study, it seems reasonable to define energy consumption in EU countries compared to the entire EU. For this purpose 2018, was taken into account. It should come as no surprise that the EU states in terms of energy absorption in the analyzed period were dominated by the countries with the largest population, i.e., Germany, France, Great Britain and Italy, which together consumed more than 50% of energy for the entire EU (Figure 2a). Figure 2a shows the share of individual countries in energy consumption compared to the EU as a whole for 2018.

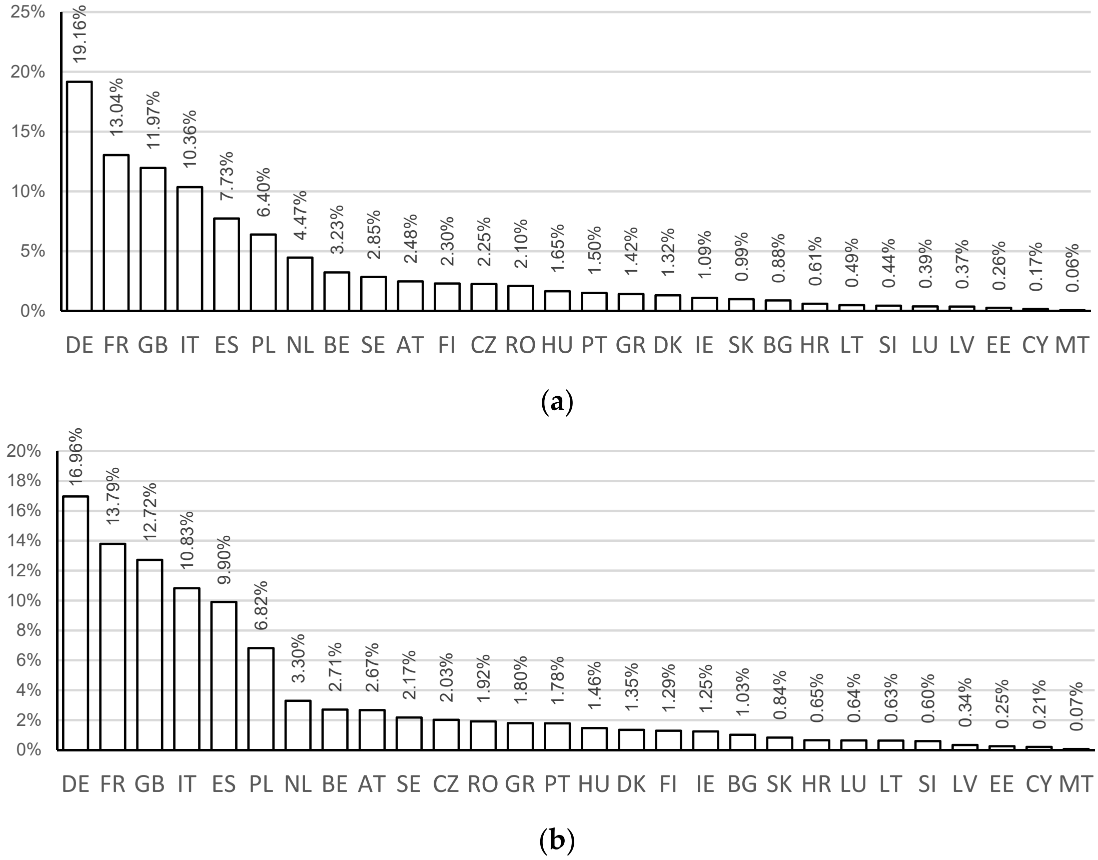

Figure 2. Final energy consumption in EU in 2018. (**a**) Total energy consumption. (**b**) Transport energy consumption.

Bearing in mind that in the scale of the entire EU, approx. 30% of energy consumption resulted from transport, Figure 2b, which, in this case, is a certain supplement to the list in Figure 2a. On the EU scale, in terms of energy absorption for transport, countries with the highest energy utilization are very similar. A total of 30% of the share of transport in energy consumption applies to the entire EU. However, the share of energy used in transport varied across states. Figure 3 shows the countries (where 2018 was included for the sake of comparability with Figure 2a), where the absorption of energy from transport to the total energy consumption was relatively the highest.

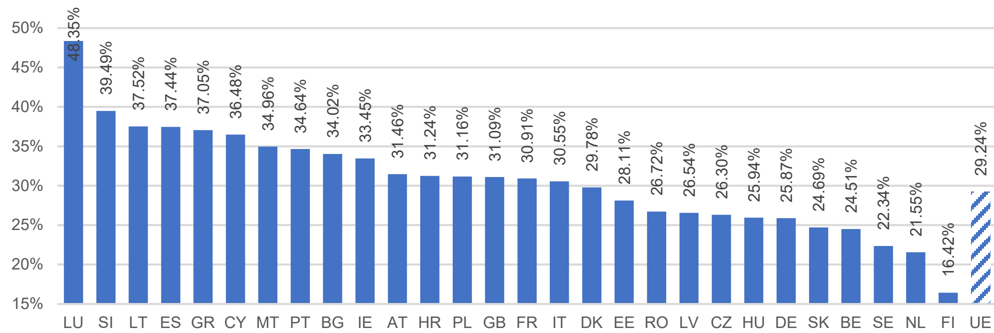

Figure 3. Transport sector energy use in UE in 2018.

With this approach to the problem, among the states from Figure 3, there is no leader in the ranking with the highest energy consumption in the EU. For example, Germany had a lower share of energy utilization in transport than the total EU average. Only Spain was included in the list of large countries. On the other hand, the energy absorption due to transport was significantly higher in Luxemburg and Slovenia than in the EU. For the sake of completeness, it can be added (which is not shown in Figure 3) that for 2018 the lowest percentage share in energy utilization from transport was in Sweden, the Netherlands and Finland.

Energy consumption in the EU in 2004–2018 was characterized by a rather downward trend (Figure 4a). Considering the 3-year periods, the lowest level of energy absorption in the EU states occurred in 2013–2015. This significant decrease was due to the improvement in energy efficiency. Only in the years 2016–2018 was there an increase in energy utilization by 2.53% compared to the previous 3 annums. In 2016–2018, the economic situation was exceptionally favorable. However, this consumption was still 6.24% lower than in the years 2004–2006. Transport energy absorption has undergone slightly different changes to total energy consumption. The transport sector had made little use of renewable energy sources. It was also less prone to efficiency gains. The transport sector was also closely related to the economic situation in the country. Therefore, these changes were quickly visible in the trend of demand for transport and, consequently, in demand for energy in transport.

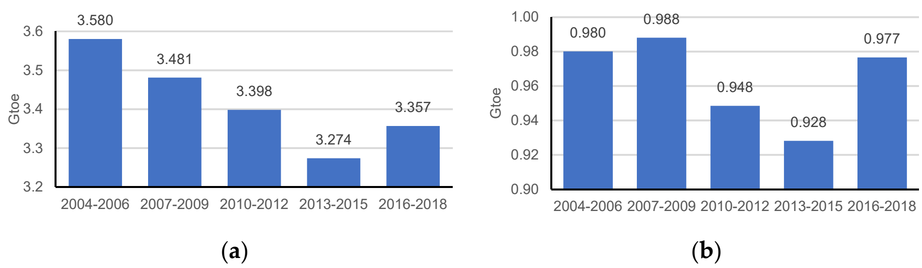

Figure 4. Final energy consumption in UE 2004–2018 in gigatons of oil equivalent (Gtoe). (**a**) Energy total. (**b**) Transport sector.

3.2. Structure and Trends of Energy Consumption in Transport in the EU Countries

The next stage presents the results concerning the structure and trends of energy consumption in transport. There was no relatively regular direction in the energy absorption of transportation in the EU countries. Considering the Eurostat nomenclature, the following sectors are distinguished within the energy consumption in the transport sector: rail transport, road transport, domestic aviation, domestic navigation, pipeline shipping and not elsewhere specified. In the EU states, different modes of transport have varying levels of energy intensity. Sometimes these differences were significant.

The largest share in energy consumption due to transport was recorded in road transport, which accounted for over 90% of the total energy utilization in the whole transport sector (Figure 5). For example, the list of individual components in the transport sector 2018 is presented. The results were similar in previous years. This means that the structure of energy absorption in transport within the EU is stabilized. Obviously, from the point of view of sustainable transport development, a large share of energy consumption in road transport is disadvantageous.

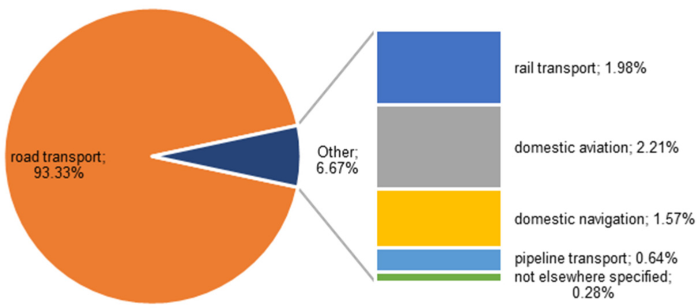

Figure 5. Energy consumption in different transport in various branches of transport by EU countries in 2018.

To find the relationship between the dynamics of changes related to energy absorption due to transport and the dynamics of changes in economic indicators, it was first decided to compare trends in the value of gross added value in current prices in one million euro gross for individual modes of transport and gross domestic product current prices, euro per capita in 2004–2018 (Figure 6).

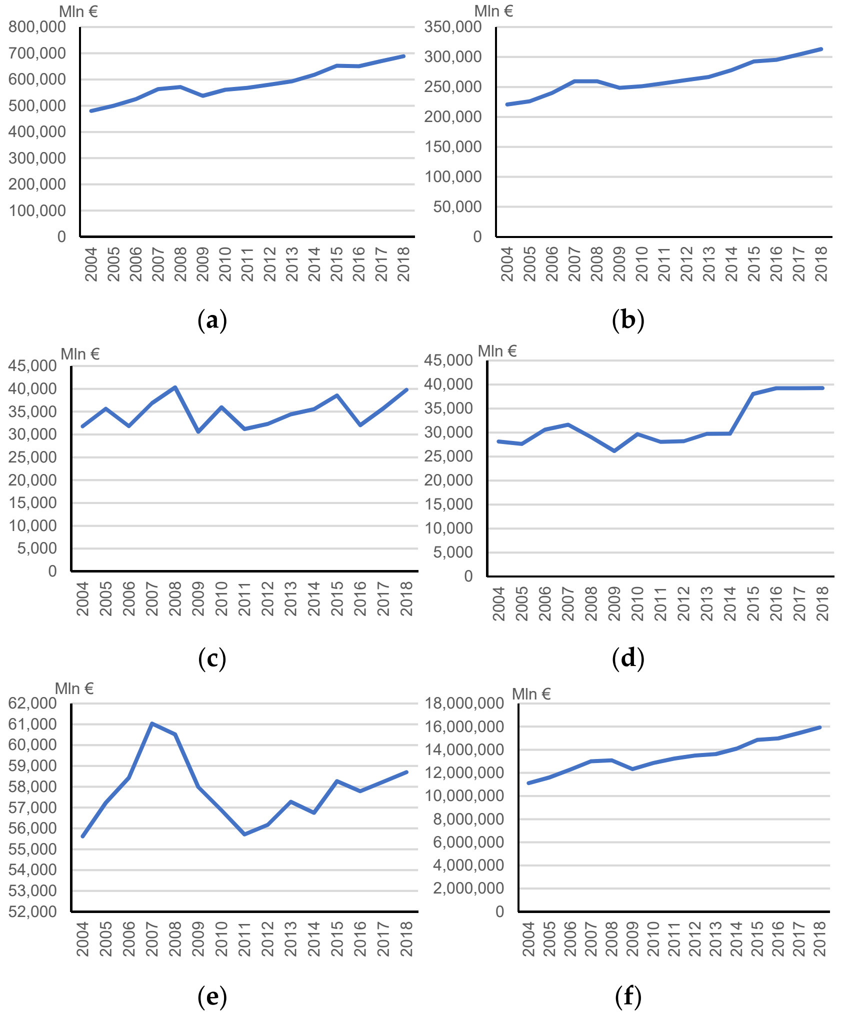

Figure 6. Trends in changes in gross value added in transport and the trend of gross domestic product in 2004–2018 (current prices, million euro). (**a**) Transportation and storage. (**b**) Land transport and transport via pipelines. (**c**) Water transport. (**d**) Air transport. (**e**) Postal and courier activities. (**f**) Gross domestic product at market prices.

It is easy to notice that the trends of changes in transportation and storage, land conveyance and pipelines shipping and GDP are practically identical. Due to this and the fact that energy consumption in road transport accounted for more than 90% of the total energy utilization in the transport sector, it can be concluded that the other industries are of minor importance in the total energy consumption in transport.

3.3. The Level and Changes in GDP per Capita in the EU Countries

The next stage presents the differentiation between EU countries in terms of GDP per capita. Comparing the direction of changes in energy consumption due to transport with the dynamics of alterations in GDP per capita, it is worth noting that GDP per capita shows large differences depending on the EU country, as shown in Figure 7, which compares GDP with the average for the EU in general. All the disproportions in this comparison are too visible. Luxembourg is particularly distinct from the EU average, exceeding it more than twice. Most countries had a lower level of GDP per capita than the EU average. This group included all Central and Eastern European countries that joined the EU in 2004 and in subsequent years. Thus, there were large disparities between the EU countries. It is a background to define the dynamics of his trend.

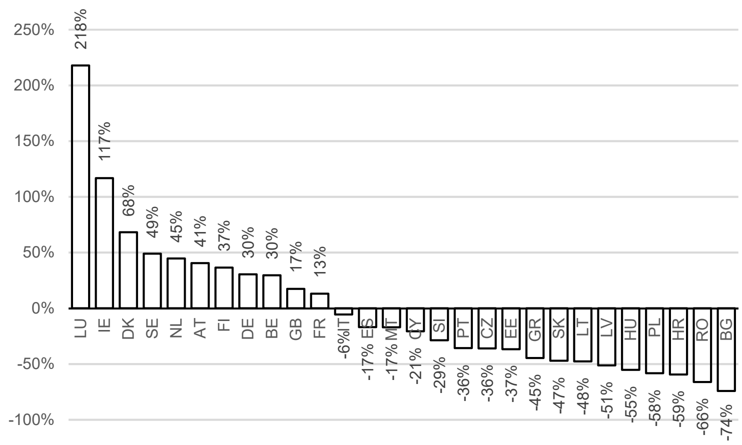

Figure 7. GDP per capita in UE countries in 2018 in comparison to the average in UE.

The dynamics of GDP per capita changes against the background of the entire EU can be presented using the so-called overrepresentation maps. Figure 8a shows the dynamics of GDP per capita in an orderly manner. The countries were divided into three groups. First, declining dynamics were found in highly developed countries, such as Spain, Italy, Great Britain and France. Then, in turn, the third group includes the fastest developing countries. First of all, these are the countries of Central and Eastern Europe that develop rapidly because they want to move closer to the level of development of Western European states.

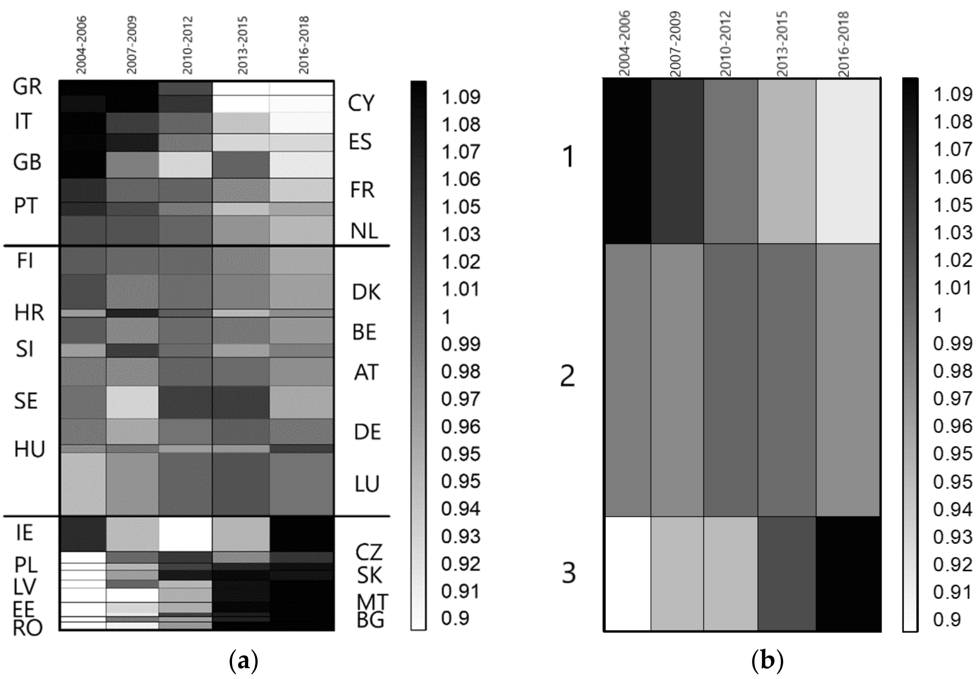

Figure 8. Dynamics of the pace of changes in the GDP per capita of the European Union countries in 2004–2018. (**a**) Dynamics in countries. (**b**) Dynamics in group of countries.

Based on scores, it is possible to rank states depending on the strength of the growth dynamics, in this case—GDP per capita compared to the EU. The countries with the corresponding scores and their group members are presented in Table 1. The economically developed states of Western Europe were in the cluster with the lowest GDP growth per capita. The group with the average dynamics included both economically developed and developing countries. This group included Germany, but also Hungary and Slovenia. The bunch of countries with the highest growth of GDP per capita mainly included Central and Eastern European states that joined the EU in 2004 and later. The only exceptions were Malta and Ireland. Such a division into clusters is not surprising. Economically developing countries need to catch up with the differences that separate them from highly developed countries. Such a situation is beneficial for the entire EU, as it leads to more minor differences in the economic development of individual countries. As a result, the area of the EU may be more cohesive in the coming years.

Table 1. Ranking of countries by the strength of GDP per capita growth in accordance with the GCA algorithm.

Group 1		Group 2		Group 3	
Country	**Score**	**Country**	**Score**	**Country**	**Score**
GR	0.01	FI	0.33	IE	0.82
CY	0.04	DK	0.38	CZ	0.87
IT	0.08	HR	0.42	PL	0.88
ES	0.11	BE	0.45	SK	0.90
GB	0.15	SI	0.49	LV	0.92
FR	0.20	AT	0.53	MT	0.94
PT	0.23	SE	0.58	EE	0.96
NL	0.27	DE	0.64	BG	0.97
		HU	0.67	RO	0.98
		LU	0.73	LT	0.99

3.4. The Level and Changes in Energy Consumption by Transport per Capita in the EU Countries

The same operation on the overrepresentation maps as in the case of GDP per capita was repeated for the data on energy consumption in transport. Additionally, to ensure the comparability of the results with GDP per capita, the data on energy absorption from transport in kToe were converted per capita. In this approach, we remove the number of people in countries on energy consumption.

The map clearly shows the width of the row for Luxemburg, which means the highest energy utilization from transport per capita in this country (Figure 9a), and this result is greater than for the other states. The dynamics of changes for this country are not homogenous, but the trend is decreasing compared to the rest of the European states. On the opposite side is Romania, which belongs to the countries with the lowest energy absorption from transport per capita, and its direction of the trend is increasing. The majority of EU states have a moderate value of energy consumption from this industry per capita.

The first group, broken down by the GCA algorithm, consists of countries with lower energy absorption in transport than the average value of consumption in the EU countries. There are countries with stronger dynamics of changes in the third group than the average rate for the EU (Table 2). Developing states such as Romania, Slovakia and Poland are among the countries where more energy is utilized due to transport than the EU average.

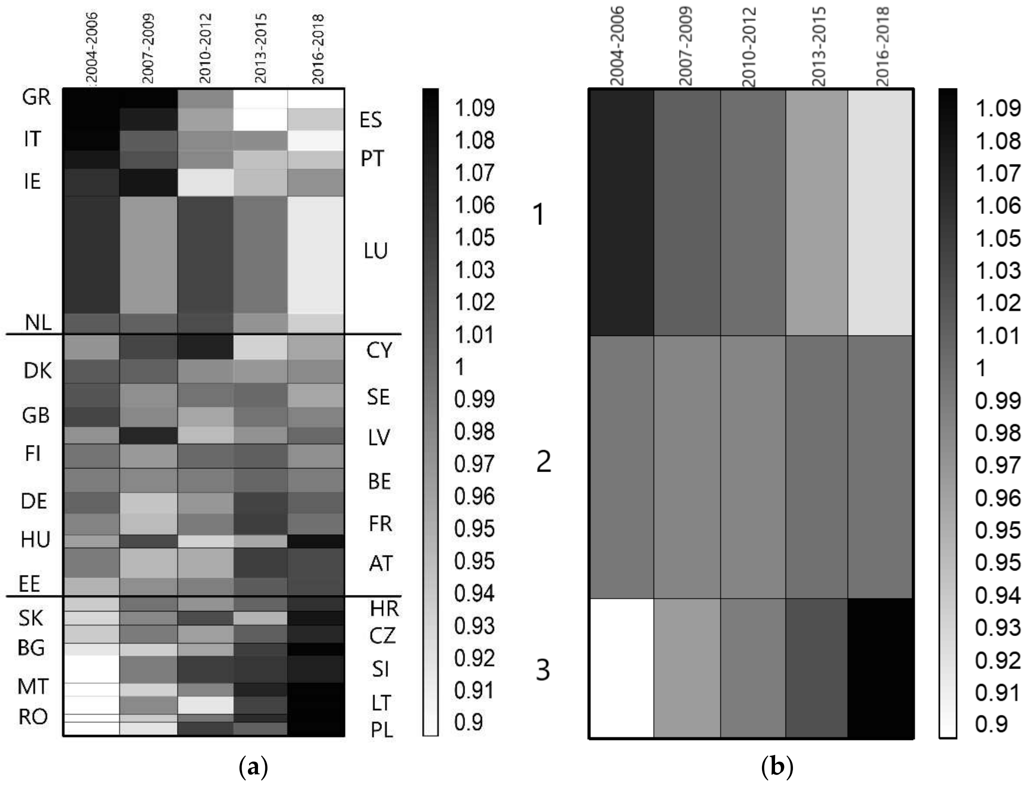

Figure 9. Overrepresentation maps of energy consumption by transport per capita in European Union countries in 2004–2018. (**a**) Dynamics in countries. (**b**) Dynamics in group of countries.

Table 2. Ranking of countries according to the dynamics of energy absorption in transport per capita according to GCA algorithm.

Group 1		Group 2		Group 3	
Country	**Score**	**Country**	**Score**	**Country**	**Score**
GR	0.02	CY	0.4	HR	0.8
ES	0.05	DK	0.44	SK	0.82
IT	0.08	SE	0.47	CZ	0.84
PT	0.11	GB	0.51	BG	0.87
IE	0.15	LV	0.54	SI	0.9
LU	0.26	FI	0.57	MT	0.93
NL	0.36	BE	0.61	LT	0.95
		DE	0.64	RO	0.97
		FR	0.67	PL	0.99
		HU	0.7		
		AT	0.73		
		EE	0.77		

The split carried out is mainly similar to that made in the case of GDP per capita. Highly developed states introduce technological innovations in transport to a greater extent. Of course, the energy efficiency of means of transport changes relatively slowly. Nevertheless, there is a clear advantage of these states over economically developing countries. On the other hand, in developing economies, higher energy consumption in transport is due to greater economic growth. Growing production and absorption in these societies must be handled by transport. These economies do not introduce technological innovations in transport on a large scale. An additional factor may be the expansion of the road network in economically developing countries. Huge funds from the EU have been allocated for this purpose. Another reason could be the rapid increase in the number of vehicles in Eastern European states. The increased wealth of the society and better roads resulted in greater availability of private cars. Transport companies from Eastern EU successfully competed with enterprises from Western Europe. An example is Poland, which dominated this market. Polish organizations performed about 30% of international road transport.

3.5. Relationships between Energy Consumption by Transport and GDP per Capita in EU Countries

The next stage presents the relationship between energy consumption by transport and economic growth. Based on two rankings of dynamics of changes in GDP and energy absorption in transport, the rank correlation coefficient was calculated (r_s = 0.7219). The high dependence can be easily observed in Figure 10.

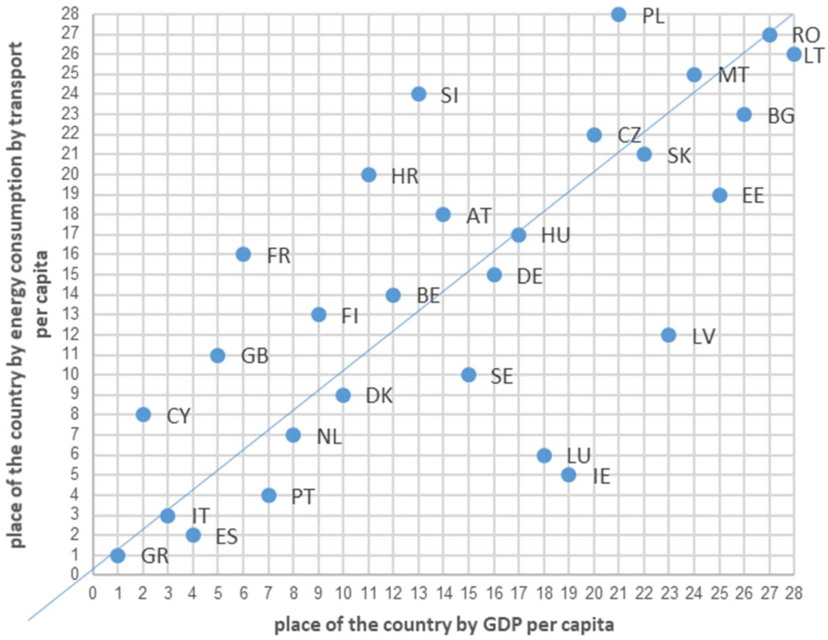

Figure 10. Countries' positions in the rankings of changes in energy consumption by transport per capita and GDP per capita.

On the vertical axis, positions from the ranking of alterations in energy consumption from transport per capita are marked (by the maps in Figure 9a). On the horizontal axis, positions are taken in the ranking of changes in GDP per capita. Most of the points representing the positions for States are located close to the diagonal of the square, which reflects the perfect agreement of both rankings. Nevertheless, there are quite significant and clear exceptions to this rule. This applies to Luxembourg, which, despite the GDP per capita growth in line with the pace of changes in the EU, clearly shows a slower pace of changes in energy absorption in transport per capita than the EU average. The situation is similar in Ireland (IE) and less clear but visible in Latvia (LV). It can be considered that these are cases of positive actions compared to the entire EU. Countries for which the points in Figure 9 are above the diagonal of the square and are significantly distant from it are the opposite. These include Slovenia (SI), France (FR) and Croatia (HR). Here, the increase in energy consumption from transport per capita to the GDP per capita growth rate is disproportionately higher than in the EU states. Immediately after these countries is Poland (PL), which also turned out to be the state with the highest growth rate of energy absorption in this sector in the entire EU.

Despite these cases, which can be considered outliers, attention should be paid to the very high value of Spearman's rank correlation coefficient. If the data for the countries with the greatest discrepancies in terms of places in both rankings, i.e., Luxemburg (LU) and Ireland (IE), were removed, the value of this coefficient would increase to the level of r_s = 0.8114. The results confirm a high correlation in most countries between GDP per capita growth rate and the rate of energy consumption in transport per capita.

4. Discussion

According to Ibrahiem [112], energy consumption by road transport determines economic growth both in the short and long term. In contrast, economic growth causes energy absorption of road conveyance in the short term. Thus, there are feedbacks. Ibrahiem conducted his research on the example of Egypt in the years 1980–2011. Nasreen et al. [28] examined the relationship between economic growth, freight shipping and energy consumption for 63 developing countries for 1990–2016. Country panel analysis was used. Countries were divided into three sub-panels, namely middle–low income countries, medium–high-income countries and high-income states. The findings showed a two-way causal relationship between economic growth and freight transport for all selected panels and between economic growth and energy absorption for high-income and medium-high income panels. For the lower–middle-income panel, causation was one way, from energy consumption to economic growth. Additionally, the results indicate that the relationship between freight conveyance and energy consumption was bidirectional for high-income countries and one-way from freight to energy consumption for higher-middle-income and lower-middle-income countries. We obtained similar findings in our research. Economically developing states in the EU tended to proportionally absorb more energy (see Figure 10).

Liddle and Lung [113] conducted panel studies on 107 countries covering the years 1971–2009. They found that transport has been an important energy aggregation as transport energy consumption has increased in highly developed and developing countries. They distinguished between three balanced income-based panels, i.e., 40 high-income countries, 39 middle-income states and 28 low-income countries. Energy absorption in transport per capita was the dependent variable, and GDP per capita was an independent variable. The share of countries with significant positive correlations ranged from three-quarters (for high- and low-income panels) to two-thirds (for middle-income panels). However, there was no unanimity. Our research also showed a high correlation between GDP per capita growth rate and the trend of energy consumption in transport per capita. After removing a few outliers, the r_s correlation coefficient was 0.8114.

Achour and Belloumi [114] explored the causal relationships between transport infrastructure (rail and road), transport value added, gross accumulation and energy intensity of transport in Tunisia in 1971–2012. A one-way relationship between energy consumption in transport and economic growth was found. Infrastructure and population density had a significant impact on the energy consumption of transport. Achour and Belloumi [115] conducted another study on Tunisia's example in 1985–2014. They found that energy intensity played the dominant role in decreasing energy absorption during the study period. Improving the transport intensity exerts a significant effect on saving energy. These studies are interesting and justify why energy utilization grows proportionally slower in the most economically developed countries than in developing countries. We found such patterns in our research.

Rehermann and Pablo-Romero [116] analyzed how the GDP per capita affects transport energy consumption, testing possible nonlinear relationships between variables. The research concerned 22 Latin American and Caribbean countries in 1990–2014. It was found that the elasticity values of transport energy absorption, with respect to GDP per capita, do not show a tendency to decrease in the long term. Saidi et al. [117] explored the impact of transport energy consumption and transport infrastructure on economic growth by utilizing panel data on MENA countries (the Middle East and North Africa region) for 2000–2016. The research confirmed that the causal relationship between energy absorption in transport and economic growth was heterogeneous. There was different flexibility depending on the level of development of the country. Our analysis also showed that the level of economic growth affects the rate of energy consumption in transport. We have demonstrated it in the example of the EU. As demonstrated by the literature review in other countries and regions, these regularities are similar to our research.

Belke et al. [118] analyzed the long-term relationship between energy consumption and real GDP, including energy prices, in 25 OECD countries in 1981–2007. Energy absorption and economic growth are cross-sectionally correlated. The reason is regional and macroeconomic links, which are manifested through common global economic crises, mutual commercial and financial institutions and local externalities between countries or regions. There is also a division into blocs of states in the EU. One is formed by the economically developed countries of Western Europe, and the other by the developing state of the Eastern EU. Different groups of countries react differently to crises and changes, including in terms of energy consumption. In our research, such divisions were visible.

Gherghina et al. [119] examined the nexus between the main forms of transport, related investments, specific air pollutants and sustainable economic growth. The research concerned the EU countries in 1990–2016. They found that it is important to invest in modern transport infrastructure that facilitates the use of more energy-efficient methods and alternative solutions that positively impact the economy while minimizing negative externalities. This study covered the EU area. Based on our research, it can also be concluded that the key is the use of more energy-efficient methods and alternative technologies in transport. Then, energy consumption in transport will increase less than proportionally to GDP growth.

5. Conclusions and Recommendations

5.1. Conclusions

The conducted research allows for a few generalizations.

1. Total energy absorption in transport was more significant in the states with the greatest area and the highest population. Conversely, in the smallest countries, energy from transport had the largest share in total energy consumption.
2. There is a general tendency to reduce the total absorption of transport energy. This was due to the introduction of energy-saving technologies.
3. The transport structure in the EU is relatively constant. Road transport was of the most significant importance in terms of energy consumption (over 90%). The share of other means of transportation was minimal.
4. In the EU, economically developing countries have, as a rule, been catching up with highly developed states. This is evidenced by the difference in the dynamics of GDP per capita growth.
5. In energy consumption by transport per capita, the dependencies were very close to GDP per capita. The economically developing countries were the fastest in increasing energy consumption in transport per capita. In turn, highly developed states recorded slight increases and were stable in this respect. Of course, it is easy to link the results with the rate of change in GDP per capita. Transport is closely related to the economic situation. Thus, the research hypothesis was confirmed.
6. An important reason for the significant increase in energy absorption per capita in Central and Eastern Europe is taking over the transport markets by enterprises from this region as a result of offering lower rates for transport.

5.2. Recommendations

The relationship between energy consumption in transport and the economic situation has not been the subject of systematic research. There are no studies on the association between energy absorption in transport per capita and the level of economic development measured in GDP per capita. The authors found only one project of this type. Furthermore, there were no such studies related to the EU.

The limitations in conducting such academic studies are the lack of available current and detailed data on energy consumption in individual modes of transport. A possible direction of further research is linking energy absorption in transport with environmental pollution and economic development. In this case, it should be based on data concerning per capita. Additionally, the investigation of the interconnections between the various modes of transport would be interesting since EU states differ significantly in this respect. Another direction of academic analysis is the examination of dependencies occurring in regions.

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Article

Energy Consumption and Its Structures in Food Production Systems of the Visegrad Group Countries Compared with EU-15 Countries

Bartłomiej Bajan *, Joanna Łukasiewicz and Aldona Mrówczyńska-Kamińska

Department of Economics and Economic Policy in Agribusiness, Faculty of Economics, Poznan University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, Poland; asialukasiewicz1@gmail.com (J.Ł.); aldonam@up.poznan.pl (A.M.-K.)
* Correspondence: bartlomiej.bajan@up.poznan.pl; Tel.: +48-61-846-6379

Abstract: While joining the European Union (EU) in 2004, the countries of the Visegrad Group (V4) had to face a major challenge in the context of adapting to the EU standards in the field of energy use and energy efficiency. One of the sectors that heavily depends on the use of energy (mainly from fossil fuels) is the food production system, whose energy transformation is essential for future food security. The study aimed to measure the use of energy and its structures in the food production systems of the V4 countries and the EU-15 countries in relation to the implementation of the EU energy targets. The targets assumed, among other things, a reduction in overall energy use and an increase in the share of renewables in the energy mix. The proprietary method based on the assumptions of lifecycle assessment was applied to measure energy consumption in the food production systems with the use of input–output tables and energy accounts, which are part of the World Input–Output Database. The research shows a decreasing share of the food production systems in energy use of the V4 countries, while in the EU-15 countries, it remains on average at a stable, low level (around 4.4%). The discussed share for Poland averaged 8.8% in the period considered, for Hungary 7.6%, for the Czech Republic 3.8%, and for Slovakia 3.3%. The share of renewables in energy use of the food production systems is growing. However, in some countries of the EU-15, it increases at a slower pace than the assumed strategic goals, mainly in the countries that are the largest food producers in the EU. For Germany, the Netherlands, Spain, and Italy, the average deviation of the share of renewables use in the food production system from the 2020 target for the entire economy is around 12 percentage points. In the case of V4 countries, the share of renewable energy use in food production systems is close to the assumed strategic targets.

Keywords: energy use; structures; food production systems; Visegrad Group; energy mix; renewables

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1. Introduction

Growing environmental and climate problems enforce the need to search for effective solutions in the field of business activities, including agriculture and the entire food production system. It is important to manage natural resources, water, and energy sustainably [1]. In the European Union (EU), various sustainable development strategies or programs have been implemented for a long time; however, the need for improvement of the environmental situation remains great. The EU's most recent goals related to the environment are included in the European Green Deal strategic document, which aims to create a modern and, above all, resource-efficient economy that would be climate-neutral and would separate the economic growth in the EU countries from the use of natural resources [2].

The importance of saving energy and its rational use is constantly increasing currently [3]. Already in the 1990s, the need to use energy and natural resources rationally and thoughtfully was emphasized in the EU [4]. In turn, in accordance with a related directive [5] on energy end-use efficiency and energy services, the EU countries had to pursue an energy-saving target set at 9%, calculated based on the annual average energy consumption. That goal was an indicative target whose non-achievement was not associated with legal consequences; moreover, individual countries could set for themselves higher targets than 9% of energy savings.

The Czech Republic, Hungary, Poland, and Slovakia, which are members of the Visegrad Group (V4) and joined the EU in 2004, had to face a major challenge in the context of adapting to the applicable energy-saving standards. Although joining the EU was associated with generally positive implications for those four countries [6], there was a difficulty related to the necessity to adapt to energy and climate goals in the course of changes introduced in that area. In turn, the EU-15 countries have had at least a decade of official actions to improve their energy situation.

In 2007, the EU authorities set key targets for the use of energy from renewable sources and for improving energy efficiency [7]. By 2020, 20% of the energy used in the EU had to come from renewable sources, and it was planned to improve energy efficiency with a reduction in energy consumption. The energy efficiency target was set at 20%, and in 2012, it was enacted by the adoption of the Energy Efficiency Directive [8]. In practice, this meant that energy consumption had to be reduced in the EU. To achieve the energy efficiency target determined by the EU, the member countries had to set their national indicative targets based on either primary or final energy savings or energy use.

The reduction of energy demand is also one of the five dimensions of the Energy Union Strategy, which was established in the European Commission's communication on 25 February 2015, entitled "A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy" [9]. According to another directive related to energy efficiency [10], that efficiency should be considered a key strategic element and the main criterion to make future investment decisions on energy infrastructure in the EU. In turn, taking into account the EU's target for 2030, which is included in the directive on the promotion of the use of energy from renewable sources [11], starting from 1 January 2021, the share of energy from renewable sources in the gross final consumption of energy by each member state should not be lower than the baseline share, that is, the share from 2020. The basic share that the member countries have to follow is also the target share of energy from renewable sources that the EU nations were supposed to achieve by 2020. All states, except Malta and Luxembourg, have set their targets at 13% or above. Having analyzed the V4 countries, the above-mentioned goal is set at 15% in the case of Poland, 14% for Slovakia, and 13% each for the Czech Republic and Hungary.

The assessment of the national plans designed by each member state and associated with energy and climate [12] shows an increasing pace of the transformation related to energy and climate. The evaluation results indicate that the share of renewable energy in the EU could reach 33.7% by 2030, exceeding the current target, which is at least 32%. In contrast, in terms of energy efficiency, the present situation is still unsatisfactory because, at the current pace of change, the gap between the target set for 2030, which assumes a reduction in energy consumption by 32.5%, and the forecasted reduction is to be approximately 3 percentage points.

Efficient energy use is also one of the basic requirements for sustainable agriculture [13], more so since, with the increase in the world population, it is important to boost global food production, which is highly dependent on the use of energy, which is mainly obtained from fossil fuels [14]. Energy is used throughout the food supply chain, starting from the production and use of agricultural inputs, and then moving to processing, packaging, and distribution to the final consumer. However, such high dependence on energy along the entire food chain raises concerns about the impact of energy prices on food prices, as well as national food security and a country's dependence on imported energy [15]. Additionally, in agriculture and the entire food production system, relatively low energy efficiency of production can be observed [16]. The demand for energy throughout the supply chain also causes low efficiency of food systems; according to some estimates, it is necessary to use as much as 10 kcal of energy to produce 1 kcal of food through all stages of the food chain [17]. Additionally, the limitations related to the availability of non-renewable energy sources, particularly fossil fuels such as oil, coal, and natural gas, including the rising costs of their exploration, exploitation, and transportation, create uncertainty in the efficient energy use [18–20]. According to numerous forecasts, at least until 2050, the production of global energy will continue to depend on fossil fuels [21]. Despite the declining amount of net energy production from fossil fuels as a result of the increasing energy inputs necessary to extract them [22], that value is still higher than the net energy production from renewable energy sources [23,24]. Although there has been an observed increase in the production of energy from renewable resources in recent years, it is still insufficient to cover the energy demand [25].

Taking into account the EU regulations related to saving energy, as well as the significant dependence on energy throughout the food production system, the EU countries will increasingly face a major challenge to ensure food security while reducing energy consumption and improving the efficiency of its use. In this regard, the V4 countries, who joined the EU in 2004 as relatively poor countries, faced a much more difficult task, particularly in comparison to the EU-15 countries [26], as the V4 countries were more dependent on the EU's financial resources that were used to support the development of their economies [27]. Moreover, the V4 countries were significantly distant from the EU-15 countries on the level of development and the results of agricultural production, which influence the entire food production system. Basic indicators, such as gross income per farm, labor, and production productivity or the value of assets per unit of land, remained at a lower level than the EU average [28]. Apart from the above, a significant difference in agricultural productivity was noticed between the EU-15 countries and the states that joined the EU in 2004; consequently, discrepancies in energy efficiency between those two groups of countries were observed [29,30].

The countries of the Visegrad Group were characterized by higher energy consumption, lower energy efficiency, and low investment in research and development [31]. This is because the V4 countries had invested in energy-intensive heavy industry [32] and focused on cheaper energy sources (coal, oil) [33]. Thus, they still significantly diverge from the situation in the EU-15 countries. Therefore, energy and climate policy is perceived as a sensitive area for many countries, especially those in Central and Eastern Europe, where most of these countries are still highly dependent on fossil fuels [34,35].

In turn, the required transition to greater use of energy from renewable sources in the V4 countries will result in higher costs than in Western European countries, for example, due to the large number of people employed in mining in countries such as Poland, the Czech Republic, and Slovakia, as well as due to the lower standard of living in the V4 countries compared to Western Europe, which will make these countries more sensitive to rising energy prices [36]. Although it is believed that higher energy prices have a positive effect on lower energy consumption by forcing investments in more energy-efficient technologies, significant price increases and differences in energy prices between countries may have a negative impact on production costs in countries with higher prices, and consequently, they may result in the weakening of the competitiveness of these economies [37]. Additionally, the increase in energy prices is reflected in higher food prices due to rising transport costs [38].

This study aimed to measure the use of energy and its structures in the food production systems of the V4 countries and the EU-15 countries in relation to the implementation of the EU energy targets. In the study, a proprietary method was used, with the application of an input–output model, to measure energy consumption in a food production system. The structures of energy consumption in the food production systems of the assessed countries were compared in terms of their similarity. Subsequently, the analyzed countries were divided into subsets according to the highest similarity of the assessed structures.

The literature does not lack research on energy consumption in the economy of the V4 and EU-15 countries [36,39–41] or more narrowly in agriculture [42–44]. However, few studies focus on the entire food production system going beyond agriculture [45,46], and none of them directly concern the relatively less-developed countries, such as the V4 countries. In such countries, often the sectors, directly and indirectly, responsible for food production have a higher share in the economy, and therefore their influence on the final results regarding the achieved energy targets at the level of the entire economy is greater. The conducted study is therefore to fill the research gap in this area and highlight possible flaws and fields for improvement of the energy policy pursued.

The remainder of this article is divided as follows: Section 2 presents a review of the literature on energy consumption in food production systems. Section 3 provides a description of the data used and the applied research methods. Section 4 covers the results of the research on energy consumption in the food production systems of the analyzed countries. Moreover, it presents the energy consumption structures in food production systems and their analysis as well as the related discussion. Finally, Section 5 consists of a summary and conclusions.

2. Literature Review of Energy Consumption in Food Production Systems

Energy is a key determinant for yielding the appropriate amount of crop. On one hand, a too-low energy intake can lead to very poor and unsatisfactory yield and consequently create an overall higher energy demand per ton of harvested product [45]. On the other hand, a sudden increase in energy use does not bring immediate benefits when it comes to yield. Therefore, farmers are usually interested in improving energy efficiency by saving energy and thus lowering operating costs [46]. The correlation between energy and agriculture is becoming increasingly important, for instance, because of climate change; at the same time, global consumption of agricultural energy is increasing as a result of population growth and the limited area of agricultural land [47,48]. A significant amount of agricultural production is being processed; in this respect, energy is essential, for example, to preserve food and increase its physical availability for a longer period or to reduce the loss in the amount of crop. Activities related to food processing range from post-harvest operations and the simplest methods of preservation to modern processing practices [49].

It is important to be aware that the energy required to produce the final food product does not only come from direct consumption but also involves indirect flows of energy. Indirect flows of energy include the accumulated value of energy used to produce the inputs and services necessary for the various stages of food production [50]. Both direct energy use (e.g., necessary for field works) and indirect energy use (e.g., to produce fertilizers and seeds) affect the final energy efficiency of production [51–54]. It is important to note that both the intensification and the globalization of agricultural production result in an increase in energy consumption by agriculture that comes mainly from fossil fuels, threatening the improvement of energy efficiency [55]. Examining the issue from the opposite perspective, due to the use of fossil fuel energy and the emergence of complex industrial systems, the high-income countries have developed their production on a large scale and have increased labor productivity. On one hand, future restrictions related to the extraction of fossil fuel may be a factor inhibiting food production; on the other hand, they stimulate the development of the food production system in search of alternative energy sources [56,57].

Fossil energy not only plays a significant role in food production in all developed societies but is also a determinant of food supply in developing countries. Fossil fuels are used to improve the factors that are crucial for agriculture, particularly labor productivity, by boosting the level of mechanical power used in agriculture and enhancing land productivity by increasing the availability of inputs [58]. In many studies, food production has been claimed to be a sector responsible for a significant share of total energy consumption [59]. Regarding the EU, it is estimated that the entire food chain (agriculture, processing, packaging, and transport), accounts for up to 17% of total energy consumption [46].

Food processing is one of the most energy-consuming stages in food production. It is estimated that the amount of energy used to process food is on average approximately three to four times greater than the energy used for primary production [60]. However, the differences in the ways that food is processed make it quite difficult to identify the trends of energy consumption at this stage [61]. The energy use by the food industry varies from country to country and also depends on the type of manufactured product [62]. One of the issues in this respect is the use of inefficient processing technologies [63–65]. The low productivity and the technological differences that can be observed in food processing are also often the causes of high energy consumption in the food industry. This phenomenon is mainly noticeable in less developed countries [66].

One of the proposed solutions to improve energy efficiency and to protect the natural environment is to change agricultural practices by introducing organic farming [67,68]. In the European Green Deal [2], it is also emphasized that food production causes a reduction in natural resources and environmental pollution. For this reason, it is important to make changes in this area, such as modernizing agricultural practices and increasing the share of organic crops to constitute 25% of the total agricultural land in the EU by 2030.

Although organic agriculture is considered productive and sustainable [69–73] and consumes less energy [74], it is estimated that it cannot provide enough food to satisfy the entire world population [75,76]. Technological development, changes in crop management, and renewable energy also play a significant role in increasing energy efficiency in agriculture [45,77]. In the case of the food industry, the optimization of technological processes is considered the main solution to help reduce energy consumption. Although some energy costs cannot be avoided, such as in cooling, freezing, or even cooking, the appropriate way that technological processes are managed can lead to significant savings [46]. Therefore, in many studies on the food industry and its energy consumption, the application of new technologies and their potential to save energy are often analyzed [78–81]. Although the introduction of new technologies and the modernization of production processes reduces the costs of agricultural production as well as increases production efficiency [82], production systems are becoming more and more complex and require high investment costs [83], which may prove to be a problem for less developed countries.

Regarding energy consumption in the economies of the V4 countries, since their accession to the EU, a trend similar to that of the rest of the EU states has been observed. There has been a gradual shift from solid fuels to an increased share of renewable energy sources in the energy mix [41]. In their analysis of the EU countries, Aydoğana and Vardara [44] point out that increasing the use of renewable energy is necessary to maintain the development of the agricultural sector, and it is also important to reduce fossil energy consumption and to protect the natural environment in a better way. Given that energy consumption also leads to greenhouse gas emissions, the EU countries need to succeed in reducing their emissions. Mohammed et al. [84] state that the majority of the EU countries, except Spain, have recorded a significant reduction in greenhouse gas emission in the agricultural sector, and the largest reductions of the emission were observed in the United Kingdom (UK), Germany, and France. According to Waheed et al. [85], an increase in energy consumption and greenhouse gas emissions may positively affect economic growth, but it leads to an increase in the costs associated with environmental degradation. According to Karkacier et al. [86], there is a strong relationship between energy use and agricultural productivity. However, Briam et al. [87] point out that more energy-intensive activities do not necessarily increase greenhouse gas emissions; moreover, efficient energy management is important in terms of reducing production costs and the risks associated with sudden changes in energy prices or energy supply shortages. Energy efficiency is also crucial to improving the sustainability of food processing, as pointed out by Wang [88].

Moreover, Florea et al. [42] indicate the high importance of renewable energy in the context of sustainable agriculture. Based on these authors' analysis covering the period 2000–2017, for the central and the eastern European countries, the share of renewable energy in final energy consumption has increased in all assessed countries, with the lowest share observed in the case of the V4. Rokicki et al. [43] have also proven that renewable energy consumption has increased in the EU countries; energy use has been reduced in agriculture in those states as well. While studying the EU countries over the period 2005–2018, in terms of, among other things, energy consumption in agriculture by source, the above-mentioned scientists have also observed an increase in electricity consumption and a decrease in fossil energy use, which is considered a positive aspect in terms of energy efficiency. As Wu [89] points out, the increase in energy efficiency should contribute to the reduction of the differences in development among the regions. Taking into account the discrepancies between the V4 countries and the EU-15, which are visible in their food production systems, Wu's point should be considered an important aspect of the economic development of the analyzed countries.

3. Materials and Methods

Energy consumption by the food production systems in the V4 countries and the EU-15 countries were analyzed using the World Input–Output Database (WIOD) [90], which contains input–output tables for each analyzed country, covering the period 2000–2014. All tables in the WIOD (Release 2016) were created with an application of a uniform methodology to ensure comparability across countries. Each table contains financial flows between 56 sectors of the economy, classified following the International Standard Industrial Classification, Revision 4 (ISIC Rev. 4). The details regarding how the tables in the WIOD are constructed can be found in the studies of Dietzenbacher et al. [91] and Timmer et al. [92]. The data on financial flows from the input–output tables were cross-referenced with the information on energy consumption developed by the Joint Research Centre of the European Commission, which can be found in the database of the WIOD Environmental Accounts, updated for the period 2000–2016 [93]. The data in the WIOD Environmental Accounts were created for the same economic sectors as in the case of the WIOD Release 2016. The data provide information on energy consumption from 12 different sources for all 56 sectors. In the analysis, the 'emission-relevant energy use' was taken into account to avoid double counting of the energy consumed in cases when particular energy sources were transformed into other sources (e.g., coal transformed into coke and coke oven gas). In the adopted approach, non-energy use of energy commodities was not considered (e.g., naphtha for the production of basic chemicals or bitumen for the production of asphalt). Furthermore, the sources of energy consumption were aggregated to eight, and finally, the following sources were distinguished: petroleum products; coal, coke, and crude oil; natural gas; other gases; renewables and nuclear energy (including biofuels); waste; electricity and heat; and other sources.

All calculations were made for four two-year periods: 2000–2001, 2005–2006, 2010–2011, and 2015–2016. It should be noted that there are the same time intervals between those periods, and the research period was limited by the availability of the latest data on energy consumption. The separation of the periods allowed the authors to examine the situation in the V4 countries before they acceded to the EU (the period 2000–2001), immediately after the accession (2005–2006), and later on. As the data in the input–output tables are only available for the period until 2014, it was assumed that the structure of financial flows in the food production system did not change significantly for each of the countries over the period 2015–2016. Therefore, the energy consumption of food production systems in the period 2015–2016 was calculated based on the input–output structure from 2014 and energy consumption in the period 2015–2016.

To calculate energy consumption in food production systems, a proprietary method was used based on the assumptions of the input–output material flow analysis, which is an element of the lifecycle assessment methodology. That kind of approach allowed the comparison of the data on financial flows from the input–output tables with the data on energy consumption by individual sectors and the calculation of energy use at each stage of food production [94]. Energy consumption in the food production system was divided into three aggregates, corresponding to the structure of the food chain:

I. Agriculture supply. In this aggregate, indirect energy consumption in agriculture is measured, which comes from, among other things, the production of fertilizers and plant protection products, the manufacture of machinery and other materials, as well as the services used in agriculture.

II. Agriculture. This involves the measurement of direct energy consumption in agriculture.

III. Food industry. This deals with the measurement of direct energy consumption in food processing.

The first step of the calculation was to determine the coefficients of energy use for each sector, separately for each source of energy consumption:

$$CEU_i = EU_i \ / \ X_i \quad (1)$$

where CEU_i denotes the coefficient of energy use for sector i, EU_i represents the energy use of sector i, and X_i signifies the output of sector i.

To calculate indirect energy consumption in agriculture (aggregate I), it was necessary to determine the portion of the energy used by economic sectors from the production of materials and services supplied to agriculture. For this purpose, the previously calculated coefficients of energy consumption for each sector were multiplied by the corresponding values of agricultural supply, which were found in the input–output table. Energy consumed as part of agricultural self-supply was subtracted from the obtained value because, being part of the production, it was considered to belong to aggregate II:

$$EU_I = \sum_{i=1}^{n} (z_{ia} * CEU_i) - (z_{aa} * CEU_a) \quad (2)$$

where EU_I denotes the energy use of aggregate I, i = 1, 2, ... , n represents the economic sectors, z_{ia} refers to the financial flow (input) from sector i to agriculture (a), z_{aa} signifies agriculture self-supply, and CEU_a denotes the coefficient of energy use in agriculture.

The value of energy consumption in aggregate II is equal to the value of energy consumption in agriculture, which was found in the WIOD Environmental Accounts, updated for the period 2000–2016. Meanwhile, the value of energy consumption in aggregate III was calculated by subtracting the value of energy consumption resulting from the flow of supply from the food industry to agriculture from that of the energy consumed by the food industry, which was included in the account of aggregate I:

$$EU_{III} = EU_f - z_{fa} * CEU_f \quad (3)$$

where EU_{III} denotes the energy use of aggregate III, EU_f represents the energy use in the food industry, z_{fa} refers to the financial flow from the food industry to agriculture, and CEU_f is the coefficient of energy use in the food industry.

Then, an analysis was performed in terms of the similarity of the structures of the sources of energy consumption in the V4 and the EU-15 countries. The similarity of structures was calculated using the structure diversity ratio based on the Manhattan distance, defined as follows:

$$V = \frac{\sum_{i=1}^{k} |\alpha_i - \beta_i|}{2} \quad (4)$$

where V signifies the ratio of structural diversity, α represents the value of the i-th component of the first structure, β denotes the value of the i-th component of the second structure, and k refers to the number of components of the analyzed structure.

The values of the ratio of structural diversity that are closer to 0 indicate that the studied objects (e.g., countries) are more similar to one another in terms of the analyzed structure, where 0 indicates identical structures regarding the studied phenomenon. In turn, a value of 1 indicates that the analyzed structures completely differ from one another. Because the ratio of structural diversity is normalized in the interval [0, 1], its changes can be interpreted in percentages; for instance, a 0.01 decrease in the ratio can be interpreted as an increase in the similarity of the analyzed structures by 1 percentage point.

The obtained results on structural diversity were presented in the form of a symmetric matrix $[v_{jp}]$, comparing the structures of the sources of energy use for each pair of countries (the j index is used to indicate the rows, and p is used to indicate the columns of the matrix). Diagonal entries of the matrix are equal to 0 because they are the results of a comparison of a country's structure with itself. Following the above, the vector elimination algorithm was used to divide the countries into subsets of similar structures of energy use. As described by Bajan and Sowa [95], the vector elimination procedure consists of several consecutive stages:

1. The diversity threshold γ value is calculated.
2. Matrix $[v_{jp}]$ is converted into matrix $[w_{jp}]$ so that

$$w_{jp} = \begin{cases} 0\, if < \gamma \\ 1\, if\; v_{jp} \geq \gamma \end{cases} \tag{5}$$

3. The sum of the entries in each row of the matrix $[w_{jp}]$ is calculated.
4. The largest value indicates the element (country) that is the least similar, at a certain γ value, to the largest number of other objects (countries). That object is eliminated by removing the corresponding row and column.
5. The sums are recalculated in the rows of the reduced matrix, resulting in the elimination of another object.
6. The elimination procedure is repeated until all components of matrix $[w_{jp}]$ are equal to 0. This is the way that Group 1, whose objects (countries) demonstrate the highest structural similarity, is created.
7. The procedure is resumed from Stage 3 with the use of the set of objects eliminated during the creation of Group 1.
8. The procedure is repeated until all objects are grouped.

The γ threshold was calculated based on the comparison of intra-group variances with the population variance for particular components of the structure [96]. That method requires the repeated performance of the vector elimination procedure at various γ values. The values are selected from the $[\overline{v}, \overline{v} - S_v]$ interval:

$$\overline{v} = \frac{2\sum_{j=1}^{r}\sum_{p>j} v_{jp}}{r(r-1)} \tag{6}$$

where $\overline{v}$ denotes the average value of non-diagonal entries in the structure diversity matrix $[v_{jp}]$, and r represents the number of compared objects (countries). The above leads to the creation of the following equation:

$$S_v = \frac{2\sum_{j=1}^{r}\sum_{j,p}\left|v_{jp} - \overline{v}\right|}{r(r-1)} \tag{7}$$

where Sv denotes the mean deviation of non-diagonal entries in the structure diversity matrix $[v_{jp}]$.

To determine the optimum threshold value of γ, measures of grouping quality for each component of the structure were calculated at various values of γ. It was assumed that the subsequently established values from the interval would vary by 0.01. Therefore, each grouping would belong to the sequence $\gamma_l = \overline{v} - S_v, \overline{v} - S_v + 0.01, \ldots, \overline{v}$. The quality measure for each l-th grouping for particular components of structure i can be expressed using the following formula:

$$F_i(\gamma_l) = \frac{\sigma^2_{i(pv)}/(r-1)}{\sigma^2_{i(igv)}/(r-m-1)} \tag{8}$$

where $\sigma^2_{i(pv)}$ signifies the population variance of the *i*-th component of the structure, $\sigma^2_{i(igv)}$ denotes the intra-group variance of the *i*-th component of the structure, and *m* represents the number of identified groups at a given γ_l. The above leads to the creation of the following equations:

$$\sigma^2_{i(pv)} = \frac{1}{r}\sum_{j=1}^{r}\left(a_{ij} - \overline{a}_i\right) \tag{9}$$

where a_{ij} represents the value of the *i*-th component of the structure of the *j*-th object, $\overline{a}_i$ denotes the arithmetic mean of the value of the *i*-th component of the structure for the *j*-th object, and

$$\sigma^2_{i(igv)} = \frac{1}{r-m}\sum_{g=1}^{m}\left(n_g - 1\right)\sigma^2_{gi} \tag{10}$$

where n_g denotes the size of the *g*-th group, and σ^2_{gi} represents the variance of the *i*-th component of the *g*-th group, calculated according to the following formula:

$$\sigma^2_{gi} = \frac{1}{n_g - 1}\sum_{j\,\in\, I_g}\left(a_{ij} - \overline{a}_{gi}\right)^2 \tag{11}$$

where I_g represents the set of objects that belong to the *g*-th group, and $\overline{a}_{gi}$ denotes the arithmetic mean of the value of the *i*-th component of the structure for the *j*-th objects that belong to the *g*-th group.

The value for which the sum of grouping quality measures for particular components of the $F_i(\gamma_l)$ structure is the highest is considered the optimum value of γ. A higher grouping quality measure means a higher probability of inclusion component *i* into the group and, therefore, higher homogeneity among the identified groups.

The calculations related to the similarity of the structures of energy consumption in the V4 and EU-15 countries were done for the first and the last analyzed periods (i.e., 2000–2001 and 2015–2016), as the changes in energy consumption structures occur at a relatively slow pace. In both cases, the optimal threshold values of γ were determined individually. In this way, for each studied period in each group, the countries were as similar as possible in terms of the structure of the sources of energy consumption.

4. Results and Discussion

4.1. Characteristics of Energy Consumption in the Food Production Systems of the Assessed Countries

The calculations related to the similarity of the structures of energy consumption in the V4 and EU-15 countries were performed for the first and the last analyzed periods (i.e., 2000–2001 and 2015–2016) as the changes in energy consumption structures occur at a relatively slow pace. In both cases, the optimal threshold values of γ were determined individually. In this way, for each studied period in each group, the countries were as similar as possible in terms of the structure of the sources of energy consumption.

The amount of energy consumption in food production systems largely depends on the populations of the studied countries, which affect the production volume. Therefore, a comparison of the absolute values of energy consumption among the countries does not provide significant information about the importance of food production in this regard. The direction of changes in the value of energy consumption in food production systems seems to be important, which, according to the performed calculations, is the same as the direction of changes in the share of the consumption in the total amount of industrial activities of the V4 countries (Figure 1). The situation is similar in terms of the average values for the EU-15 countries, except for the period 2015–2016, during which the share of energy consumption of food production systems in the energy consumption of total industrial activities decreased while the amount of the consumption increased. The literature on the subject points out that energy consumption is closely related to food productivity [97] and that energy consumption and the value of agricultural production show a positive correlation [43]. In turn, the share of energy consumption in food production systems in the total energy consumption may be influenced by an individual country's economic development, which is related to the observed positive correlation between energy consumption and GDP [98]. The less-developed countries are characterized by a higher share in the economy of sectors related to food production [99], which also affects the relatively higher share of those sectors in the overall amount of energy consumption. That correlation is confirmed by the results for Hungary and Poland, showing that the share of energy consumption in food production systems in the energy consumption of total industrial activities was the highest among all V4 countries (Figure 1). The share had been declining steadily in the case of Poland, from nearly 11% in the period 2000–2001 to over 7% in 2015–2016. In Hungary, the value ranged from 8.7% in the period 2000–2001 to 6.8% in 2010–2011.

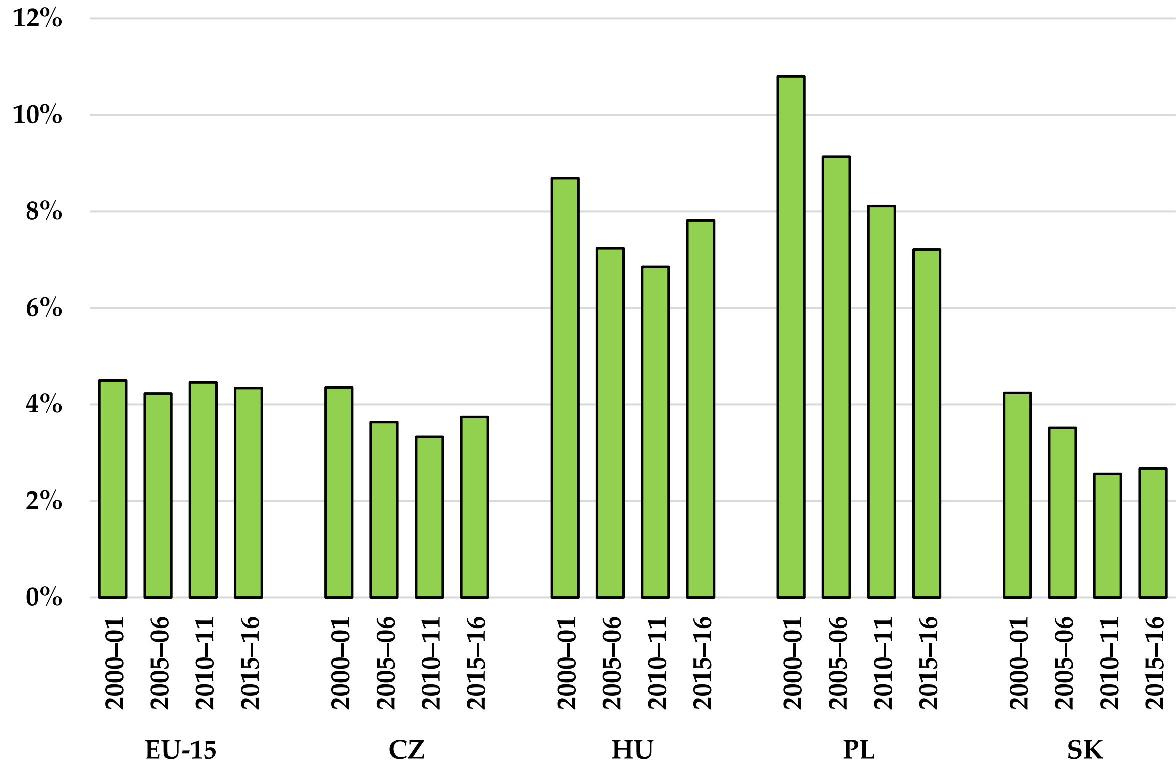

Figure 1. The share of energy consumption in food production systems in total energy consumption by industrial activities. Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

The discussed share is also influenced by other factors, such as the directions of production, its intensity, or climatic conditions (which strongly affect energy consumption in agriculture), as well as the applied technology. In the EU-15 countries, the average share of food production systems in the energy consumption of total industrial activities oscillated between 4.2% and 4.5% and was higher than the corresponding shares in the Czech Republic and Slovakia. This is because, among other things, the EU-15 countries include both the southern countries, characterized by a large share of food production sectors in the production of the economy, and the northern countries, where that share is relatively lower [99]. In turn, the Czech Republic and Slovakia are characterized by a relatively low share of agribusiness in the economy.

The results of the research on the energy intensity of agricultural land in the studied countries partially correspond to the outcomes presented above (Figure 2). By far, the lowest values of energy consumption per unit of the agricultural area were recorded in Slovakia (on average, 7.45 TJ/1000 ha of agricultural land). A higher level of energy intensity was noted in the Czech Republic and Hungarian agriculture (9.6 and 9.05 TJ/1000 ha of agricultural land, respectively), where the analyzed indicator increased significantly in the last of the analyzed periods. In contrast, in the EU-15 countries, the indicator remained at a higher level than in the Czech Republic, Hungary, and Slovakia in the period 2000–2011 (on average, 11.4 TJ/1000 ha of agricultural land), while over the period 2015–2016, the value of the indicator fell below the level recorded in the Czech Republic. The highest energy intensity of agricultural land was recorded in Poland (on average, over 15.5 TJ/1000 ha of agricultural land). Such a high energy intensity of Polish agriculture is mainly attributed to the fragmented agrarian structure and the relatively slow technical change in the countryside [43]. In the literature on the subject, it is often pointed out that the differences in energy intensity are also caused by the direction of production. It is indicated that animal production is more intensive than plant production, and the above applies not only to agriculture but also to processing [50]. However, in the V4 countries, which are post-Soviet countries, the pace of technological change and the ongoing economic transformation are also of great importance when it comes to the level of energy consumption.

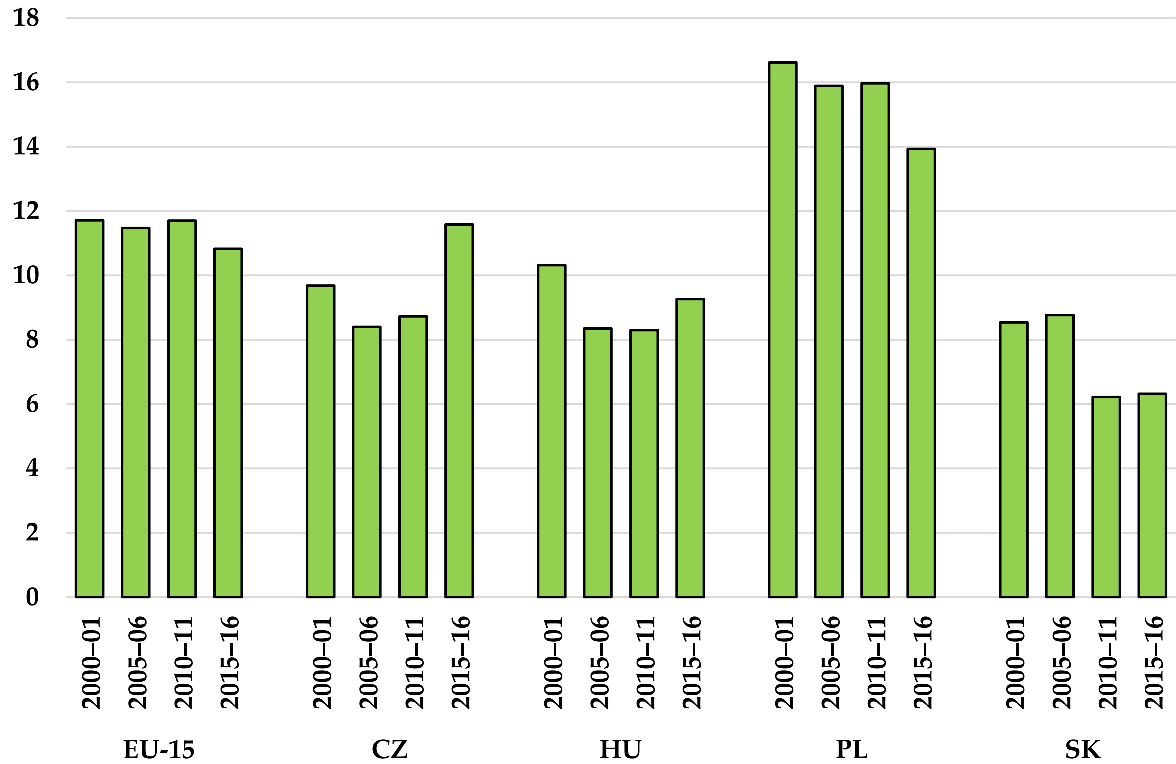

Figure 2. Energy intensity of agricultural land (TJ/1000 ha UR). Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

The presented level of energy intensity of agriculture in the V4 countries differed from that of the EU-15 countries. However, regarding the economic energy efficiency of agriculture, which is measured by the value of food produced per unit of energy, the V4 countries vastly differed from the EU-15 states (Figure 3). It can be assumed that the reason is partly the wage rate, which determines domestic demand for food and the amount of money that the consumer is willing to pay for it; however, as integration between the countries progresses, that effect should disappear because the common market is governed by the law of one price [100]. The economic energy efficiency of agriculture increased significantly in Poland and Slovakia over the analyzed period but rose at a slower pace in Hungary. Of all V4 countries, only in the Czech Republic did that indicator remain at a similar level over the studied period. As for the EU-15 countries, the value of the indicator grew steadily, remaining at a level of at least USD 50 per TJ of energy consumption, higher than in the case of the V4 states over the entire studied period.

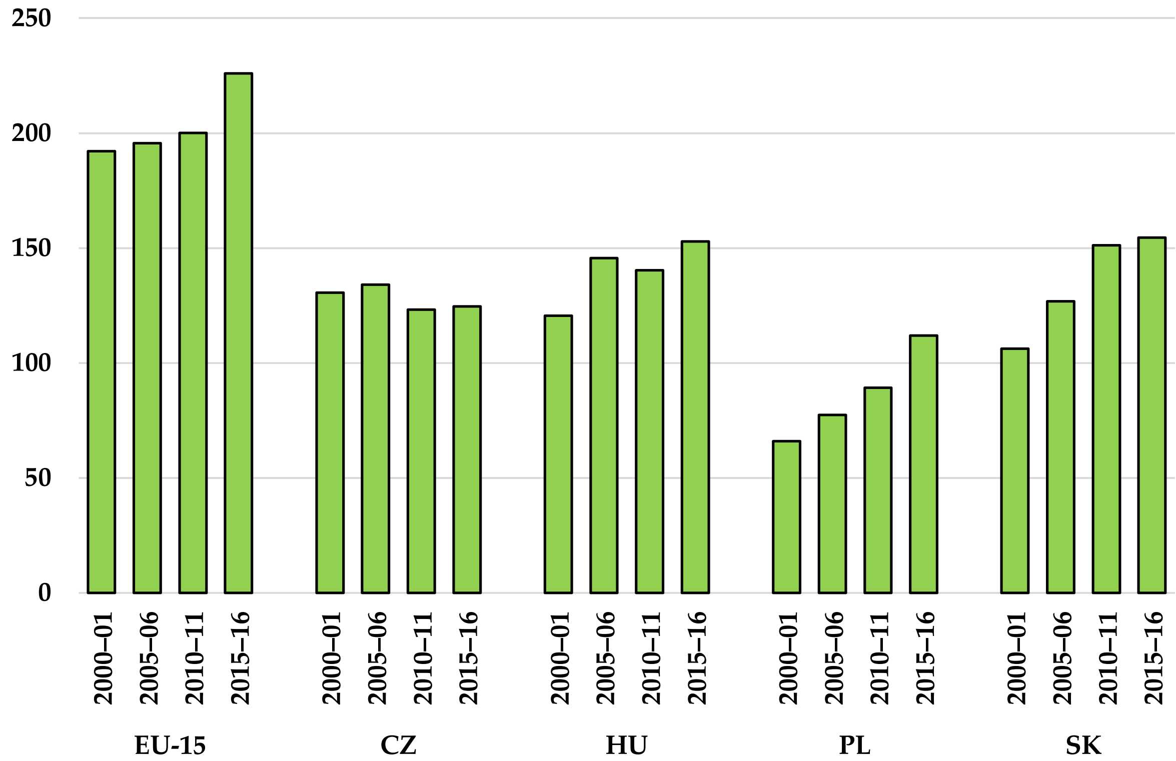

Figure 3. Economic energy efficiency of food production in agriculture (USD in constant prices from 2014-2016/TJ). Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

The energy efficiency achieved at the agricultural production stage strongly determines the energy consumption in the entire food production system; however, the share of agriculture in the energy consumption in the entire food production system varies among individual countries (Figure 4). In the EU-15 countries, the food industry consumed the largest amount of energy in the food production system (42% on average in the analyzed period). A slightly smaller share of energy was consumed by agriculture (approximately 38%), while indirect energy consumption in agriculture accounted for approximately 20% of energy consumption in the entire food production system of the EU-15 countries. That structure was subject to slight fluctuations over the studied years but remained relatively constant over time.

In the case of the V4 countries, the structure of energy consumption by sector vastly differed. In Poland and Hungary, a relatively low share of the food industry in the energy consumption in the food production system was recorded; however, the value of that share increased over the analyzed period. In the case of Slovakia, the country recorded a high share of indirect energy consumption in agriculture, which may be related to the relatively high level of material intensity in agriculture. In contrast, the structure of energy consumption by sector in the food production system of the Czech Republic was the most similar to those of the EU-15 countries, partly because the Czech Republic is on average the most similar to the EU-15 countries in terms of economic development. In the literature on the subject, it is emphasized that in the more economically developed countries, the share of the food industry in the total amount of the production of the food chain is higher; consequently, its share in the energy consumption in the food production system is also greater [101]. The second important determinant of energy consumption in the food industry is technology, whose weaker development results in relatively low energy efficiency, which leads to over-proportional values of energy consumption to the performed production [66]. This situation is observed in the majority of developing countries [102].

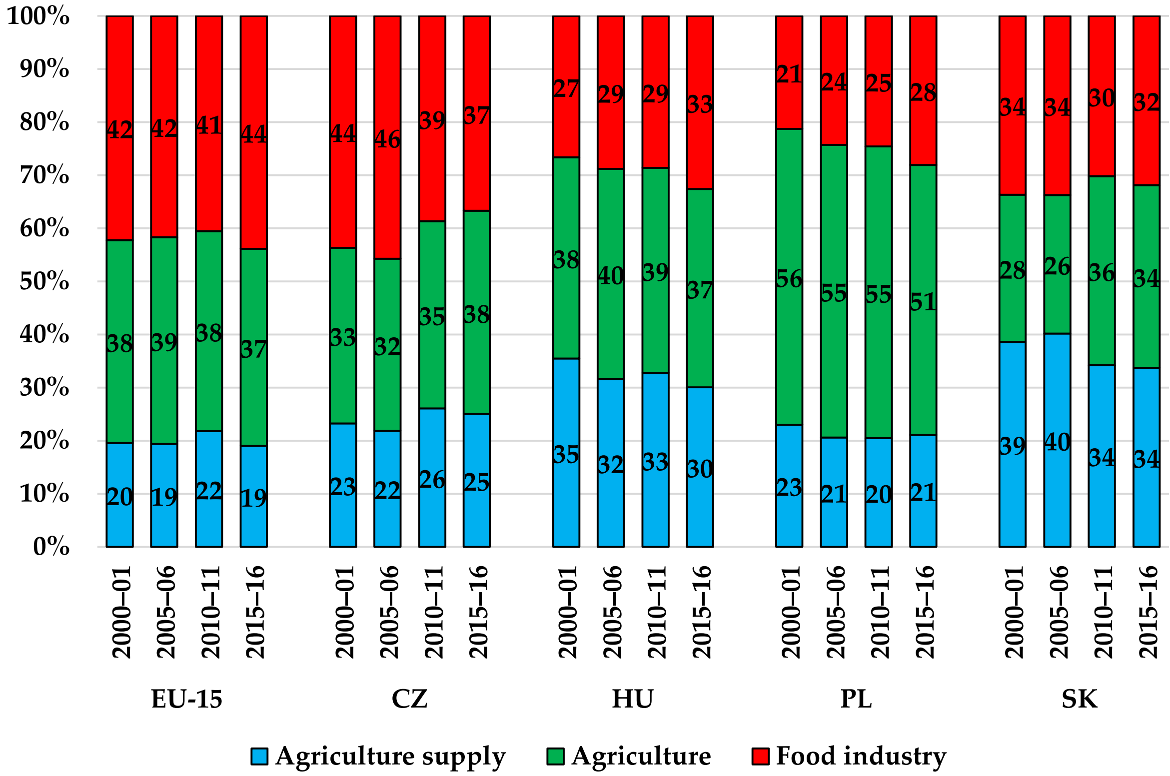

Figure 4. The structure of energy consumption by production sectors. Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

4.2. Structures of Energy Consumption in Food Production Systems by the Source of Energy

As observed based on the calculations, the characteristics of energy consumption differ in each of the analyzed countries. However, the most important aspect from the perspective of the EU strategy related to energy use is the structure of the energy sources. From the standpoint of the strategic documents mentioned in the introduction section, of particular importance is the need to increase the share of energy from renewable sources in the total energy consumption or reduce the consumption of energy from solid fuels, which cause the greatest degradation of the natural environment and are the sources of greenhouse gas emissions to the atmosphere [103].

The calculations prove that the V4 countries are characterized by a diversified structure of the sources of energy consumption in food production systems, which is becoming increasingly homogeneous over the years (Figure 5). Historically, after the transition to a market economy, Poland and the Czech Republic were the countries where energy consumption was based mainly on coal [41]. This situation is also reflected in the case of the food production system. Especially in Poland, the energy from coal had a high share in the examined structure. In the Czech Republic, the share of energy from coal in the food production system was also significant although much lower than in Poland. The assessed structures of energy consumption in the Czech Republic, Hungary, and Slovakia evolved in such a way that they were very similar in the period 2015–2016. Moreover, the structures were almost the same as the average structure of the sources of energy consumption in food production systems in the EU-15 countries, where the share of petroleum products, natural gas, and electricity predominated. From the perspective of the set targets, the shares of renewable energy consumption in the discussed structures of the Czech Republic, Hungary, and Slovakia should be assessed positively. In the food production systems of the above-mentioned countries, the general targets set at the level of the economy for 2020 are being close to fulfilled; at the same time, the values are greater than the average in the EU-15 countries in this respect. A significant increase in the share of renewables was observed primarily in the Czech Republic, which (according to the analysis of the detailed data) was mainly due to the increase in the use of energy from biofuels since 2010–2011. A similar situation was noticed in Slovakia; however, its share of renewables in the energy consumption in the food production system did not increase but remained at a level similar to the 2005–2006 period. However, these results may be partially related to the low use of renewable energy sources in food processing in the EU, indicated in some studies [46]. As the share of the food industry in the energy consumption of the food production system in the V4 countries is on average lower than in the EU-15 countries, it may also influence the share of renewable energy sources in the energy mix.

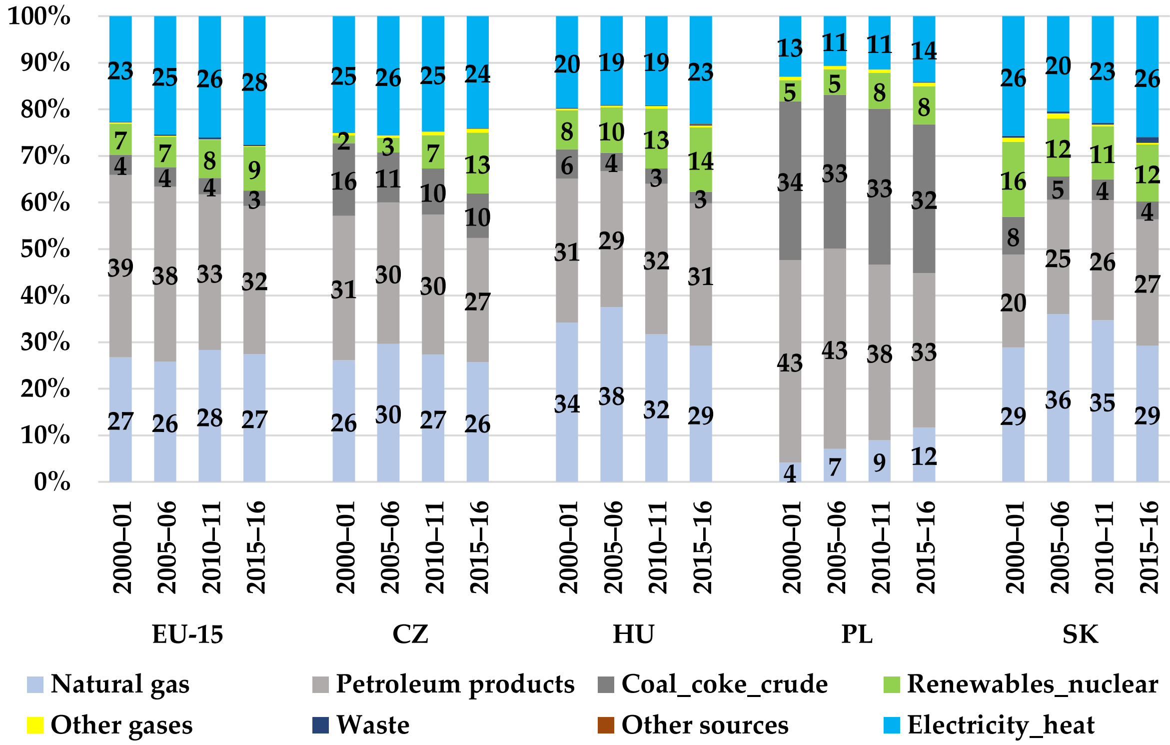

Figure 5. Structure of the sources of energy consumption in food production systems. Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

It should be noted that, according to the literature, the prices of individual sources have an impact on the structure of energy consumption [104]. In recent years, the prices of renewable energy sources have dropped significantly, especially solar and wind energy [105]. Roser [106] shows that electricity prices expressed in the levelized costs of energy from 2009 to 2019 dropped the most in the case of renewables. The price of electricity from photovoltaic declined by 89% in these 10 years, and at the same time, the price of onshore wind declined by 70%. Moreover, the price of gas dropped around 35%, and at the same time, the price of coal did not change significantly. However, the price of nuclear energy increase by 26%. The above changes of prices partially influence the choice of the source of the energy used, as they are related to its long-term profitability. In the case of the V4 countries, this thesis is confirmed by Sulich and Sołoducho-Pelc [107], who argued that the reason behind their rapid growth of energy used from renewable sources is the fall in its price. In contrast, the price of petroleum fuels depends on the world price of crude oil, which has been highly volatile since the global financial crisis of 2007–2009, peaking in 2010–2013, when the prices of renewables fell rapidly [108].

Based on the calculations, clear differences in the structure of sources of energy consumption in food production systems can also be noticed in the case of the EU-15 countries. Table 1 presents the structure of sources of energy consumption in food production systems for all analyzed countries in the period 2000–2001, dividing the countries into groups according to the highest similarity. The groups were created with the use of the calculated structure diversity matrix (Appendix A, Table A1). The average value of structure diversity among all examined countries in the period 2000–2001 was 0.2656, while the diversity threshold value γ was set at 0.22 (Table A3), following the obtained indicators of clustering quality. Therefore, the countries whose structural diversity was less than 0.22 were considered similar. This implied that the structures of the sources of energy consumption in food production systems in the period 2000–2001 were considered similar when the level of similarity was at least 78%.

Table 1. Structures of energy use (%) in the food production systems in 2000–2001 (γ = 0.22).

Country	Othsourc	Waste	Othgas	Renew_ Nuclear	Coal_Coke_Crude	Electr_ Heatprod	Natgas	Petrol_ Products
Group 1								
AT	0.0	0.3	0.2	8.2	1.7	17.6	22.1	50.0
BE	0.0	0.4	0.5	12.0	4.5	21.5	12.6	48.5
DK	0.0	0.4	0.0	4.1	10.0	25.2	20.5	39.8
ES	0.0	0.1	0.1	8.0	3.4	19.9	18.1	50.4
FR	0.0	0.1	0.2	9.7	3.8	18.0	25.6	42.6
IE	0.0	0.0	0.0	0.5	4.9	19.4	16.6	58.5
IT	0.0	0.0	0.1	1.6	1.3	20.0	28.4	48.4
LU	0.0	0.4	0.0	0.8	0.2	33.0	17.4	48.2
Group 2								
DE	0.0	0.1	0.8	7.1	8.8	16.9	26.8	39.5
GB	0.0	0.0	0.3	5.7	2.7	23.3	40.1	27.8
CZ	0.0	0.1	0.5	1.7	15.6	25.0	26.2	31.0
SK	0.0	0.4	0.9	16.0	8.1	25.7	28.9	20.0
HU	0.0	0.1	0.4	8.4	6.3	19.7	34.2	30.9
Group 3								
GR	0.0	0.0	0.0	8.6	7.3	16.1	3.5	64.4
PT	0.0	0.0	0.0	7.2	1.8	17.4	3.8	69.7
Group 4								
FI	0.0	0.1	0.1	14.1	8.0	29.5	5.5	42.8
SE	0.0	0.3	0.4	32.4	1.1	26.4	8.0	31.5
Group 5								
PL	0.0	0.0	0.7	4.5	34.1	13.0	4.2	43.5
Group 6								
NL	0.0	0.5	0.3	1.0	3.0	38.7	44.2	12.2

Based on the calculations, already in the period 2000–2001, the Czech Republic, Slovakia, and Hungary were characterized by structural similarity in the sources of energy consumption in food production systems compared with the rest of the analyzed countries. These three countries were placed in the same group (number 2) as Germany and the UK. That group was characterized by relatively high shares of natural gas in the discussed structure, with a relatively low share of petroleum products in energy consumption. Similar relations were observed in Group 1, which included Austria, Belgium, Denmark, Spain, France, Ireland, Italy, and Luxembourg. The difference was a relatively higher percentage of consumption of petroleum products and a lower percentage of the use of natural gas in Group 1. However, a more detailed analysis of the structure diversity matrix (Table A1) shows high similarity in the sources of energy consumption in food production systems between the countries in Group 1 and Group 2. In turn, Group 3 included Greece and Portugal, which were the countries with the highest share of petroleum products in the analyzed structure. Group 4 included Finland and Sweden, which were characterized by a low share of natural gas and a relatively high share of electricity in the structure of energy consumption in food production systems. Group 5 only had Poland, which was classified separately due to its large share in the examined structure of energy derived from coal compared with the other assessed countries. The last group, Group 6, only had the Netherlands, a country characterized by the greatest concentration in the structure of sources of energy consumption in the food production system. This country had the highest share of energy derived from electricity and natural gas in comparison to the other examined countries and at the same time the lowest share of petroleum products. According to the obtained results, the Netherlands was the least similar to the other countries in terms of the analyzed structure.

The similarity concerning the structure of the sources of energy consumption in the food production systems of the studied countries changed over time. In the period 2015–2016, the average value of the diversity ratio of the assessed structures, calculated based on the values for all analyzed countries (Table A2), decreased by approximately 0.01 points compared with 2000–2001, now 0.2567 (Table A3). This means an increase in the average similarity of structures by approximately 1 percentage point, which is a small value achieved over 15 years, especially taking into account the existence of common goals related to the transformation of the energy structure at the EU level. However, the threshold value γ (based on which the optimal division of the countries into groups was done) clearly decreased. In the period 2015–2016, the threshold value was 0.18, which means that similar countries were considered to be those whose diversity in the structure of sources of energy consumption in the food production system was not greater than 18%.

Based on the conducted calculations, in 2015–2016, Group 1, characterized by similarity in the examined structures, included Germany, Denmark, France, and three of the V4 countries—the Czech Republic, Slovakia, and Hungary (Table 2). These countries had a relatively low share of energy consumption from petroleum products and, at the same time, a fairly high share of natural gas in the examined structure. It is worth noting that the mentioned V4 countries were characterized by a structure of sources of energy consumption in food production systems that was similar to those of the two largest food producers in the EU (France and Germany). In this group, a relatively high level of diversification of the sources of energy consumption is observed, which is considered one of the conditions for energy security [109].

Group 2 was formed by Spain, Italy, Portugal, and Luxembourg, which were the countries with a relatively low share of natural gas and a high share of petroleum products in the structure of the sources of energy consumption in food production systems. These countries were also characterized by a relatively low share of renewable energy in the discussed structure. Group 3 included Belgium and the Netherlands, with the highest share of energy from natural gas and at the same time, the lowest share of petroleum products in the energy mix. Finland and Greece, which belonged to Group 4, were characterized by a low share of energy from natural gas and a high percentage of the share of energy from renewable sources in the energy consumption in the food production system. Group 5 comprised Austria and the UK, which were characterized by a low percentage of energy consumption from petroleum products and, at the same time, a great diversification of the sources of energy consumption, with a high percentage of natural gas, electricity, and renewable sources in the examined structure. The other three groups represented individual countries that differed from the rest of the analyzed states in terms of the structure of the sources of energy consumption in food production systems. These were Poland (Group 6), where the consumption of energy derived from coal was still predominant; Sweden (Group 7), where the largest amount of energy came from renewable sources, which should be positively assessed in the light of the EU's strategic objectives; and Ireland (Group 8), whose structure of energy consumption in food-producing sectors remained heavily dependent on petroleum products.

Table 2. Structures of energy use (%) in the food production systems in 2015–2016 (γ = 0.18).

Country	Othsourc	Waste	Othgas	Renew_ Nuclear	Coal_Coke_Crude	Electr_ Heatprod	Natgas	Petrol_ Products
Group 1								
DE	0.0	0.5	0.2	5.0	7.6	24.1	28.0	34.6
DK	0.0	0.4	0.0	9.6	5.9	28.9	22.4	32.9
FR	0.0	0.1	0.1	12.9	2.5	24.5	25.6	34.3
CZ	0.0	0.1	0.8	13.1	9.5	24.1	25.7	26.7
SK	0.0	1.2	0.4	12.2	3.9	25.9	29.2	27.1
HU	0.1	0.2	0.4	13.8	2.5	23.2	29.2	30.6
Group 2								
ES	0.0	0.0	0.0	7.4	1.3	25.5	16.8	48.9
IT	0.0	0.4	0.1	4.6	1.6	29.6	22.7	41.1
PT	0.0	0.1	0.0	5.7	2.0	29.4	18.6	44.1
LU	0.0	0.3	0.0	5.6	0.1	39.3	17.7	37.0
Group 3								
BE	0.0	0.6	0.3	11.4	1.3	27.9	44.3	14.3
NL	0.0	0.5	0.2	4.7	2.1	33.0	48.2	11.3
Group 4								
FI	0.0	0.4	0.2	17.4	6.2	43.2	3.3	29.2
GR	0.0	0.6	0.0	14.0	8.1	29.9	8.7	38.5
Group 5								
AT	0.0	0.4	0.1	23.1	0.7	29.5	24.5	21.7
GB	0.0	0.1	0.2	14.8	1.9	28.0	35.0	20.0
Group 6								
PL	0.0	0.1	0.8	8.2	31.9	14.2	11.7	33.1
Group 7								
SE	0.0	1.4	0.2	36.4	0.4	36.3	8.4	16.9
Group 8								
IE	0.0	0.1	0.0	3.4	3.5	22.2	12.4	58.4

The changes observed over the years are mainly related to a greater diversification of the sources of energy in food production systems, as well as an increase in the consumption of renewable energy. These findings are consistent with the general targets for the economies; although based on the calculations, the issue of energy transformation in food production systems mainly concerns some of the EU-15 countries, not the V4 countries. The main problem involves the achieved low indicators of the share of consumption of energy from renewable sources compared with the assumed targets at the national level. This issue primarily concerns Germany, the Netherlands, Ireland, Spain, Italy, Portugal, and Luxembourg. Of all major food producers in the EU, only France and Poland are missing in this group. However, in Poland, the situation is also not ideal, which is mainly due to the slow pace of transformation related to coal consumption. The other V4 countries are characterized by a high percentage of consumption of energy from renewables. As shown by different studies, the increase in the share of energy consumption from renewable sources in the case of the EU countries has a strong negative correlation with the possession of their fossil fuel resources [110]. For this reason, the countries that do not own any resources are more likely to depend on sources of renewable energy [111]. In light of the results for food production systems, no clear positive correlation is observed between economic development and the percentage of energy derived from renewable resources, which was indicated by numerous studies in the case of the total energy use [112–114].

According to the literature on the subject, food production in the EU-15 countries has remained at a relatively stable level, while the amount of energy allocated for that purpose has decreased [115]. As shown by the results of the present research, the share of energy consumption in food production systems in the energy consumption of total industrial activities has also declined or remained at the same level. The structures of energy consumption in the food production sectors have changed similarly to the structures of energy use of the entire economy of the EU countries. In analyzing the EU strategy regarding the use of energy, Watkins [116] points out that it was focused mainly on the increased consumption of natural gas or electricity. In that context, a strategy of diversification of the sources of the supply of natural gas was introduced, which was influenced, among other things, by the political tensions related to the cooperation with Russia [117]. Dubský et al. [118] note that the implementation of the above-mentioned strategy takes place, regardless of the related increase in the costs of natural gas. Matsumoto et al. [119] indicate that the level of energy security in the EU increased over the period 2000–2014 even though the dependence on imports increased [120]. As shown by the current research, in many EU countries, a large share of energy use derived from natural gas is observed, which is a relatively low-emission source, so it could be also considered as an element of the strategy under implementation.

5. Conclusions

The pace of energy transformation of the food production system is slower in a large number of the EU-15 countries in relation to the targets assumed for the entire economy. It can be noticed, first of all, in the use of renewable energy resources. If the set targets are to be met at the level of food production sectors, perhaps greater incentives for the use of renewable energy sources should be introduced as part of the framework of the Common Agricultural Policy. However, this recommendation does not only apply to farms but also to the food processing companies, in which case the development of production technology is also important. In this context, the high share of the use of renewable energy in the energy consumption in the V4 countries' food production systems should be well assessed, as Poland was the only one that deviated from the targets assumed for 2020 (the difference in this respect was around 7 percentage points for 2015–2016). In turn, the Czech Republic, Hungary, and Slovakia are close to fulfilling the assumed general targets for the economy, in the case of their food production systems. Taking into consideration 2015–2016, in the case of the Czech Republic and Hungary, the targets have been already fulfilled. In the case of Slovakia, the difference between assumed targets for 2020 and the share of renewables in the energy mix of the food production system was less than 2 percentage points. Additionally, the structures of the sources of energy consumption in EU food production systems are becoming increasingly diversified, which should be assessed positively in light of the strategies adopted at the EU level. In the period 2015–2016, a large concentration of the used sources of energy was observed only in Ireland.

A certain limitation of this study was the fact that the created groups of similar countries, in terms of the structure of energy consumption, had a high sensitivity to the assumed level of the threshold value. The method adopted in the study minimized that issue. However, there were still situations where some countries with higher similarity in the analyzed structures could be placed in different groups than those with which they showed greater resemblance.

Future research should focus on extending the present analysis to include a breakdown of the sources of energy use in individual aggregates of the food production system, which could show other interdependencies not noticed so far. Another interesting direction of research would be an analysis of the energy efficiency of food production systems in EU countries, which is of great importance in the final value of energy consumption.

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Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: http://www.wiod.org/database/niots16 (accessed on 1 July 2021) and here: https://ec.europa.eu/jrc/en/research-topic/economic-environmental-and-social-effects-of-globalisation (accessed on 1 July 2021).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Structure diversity matrix of energy use sources in the food production systems in 2000–2001 (γ = 0.22).

	DE	AT	BE	DK	ES	FI	FR	GB	GR	IE	IT	NL	SE	PT	LU	CZ	PL	SK	HU
DE	0	0.12	0.19	0.10	0.15	0.23	0.07	0.20	0.26	0.21	0.14	0.40	0.35	0.31	0.25	0.15	0.29	0.20	0.12
AT	0.12	0	0.11	0.16	0.05	0.24	0.08	0.25	0.21	0.14	0.09	0.45	0.33	0.20	0.16	0.26	0.33	0.30	0.19
BE	0.19	0.11	0	0.17	0.07	0.14	0.13	0.29	0.19	0.14	0.16	0.49	0.25	0.21	0.16	0.28	0.30	0.29	0.23
DK	0.10	0.16	0.17	0	0.15	0.17	0.14	0.22	0.29	0.19	0.17	0.38	0.30	0.33	0.16	0.12	0.29	0.22	0.18
ES	0.15	0.05	0.07	0.15	0	0.20	0.10	0.26	0.19	0.10	0.10	0.46	0.31	0.19	0.13	0.26	0.31	0.30	0.20
FI	0.23	0.24	0.14	0.17	0.20	0	0.20	0.35	0.22	0.27	0.29	0.49	0.21	0.27	0.21	0.29	0.27	0.27	0.29
FR	0.07	0.08	0.13	0.14	0.10	0.20	0	0.20	0.25	0.18	0.11	0.40	0.32	0.27	0.21	0.20	0.32	0.23	0.13
GB	0.20	0.25	0.29	0.22	0.26	0.35	0.20	0	0.44	0.33	0.21	0.20	0.34	0.43	0.31	0.18	0.47	0.19	0.09
GR	0.26	0.21	0.19	0.29	0.19	0.22	0.25	0.44	0	0.16	0.29	0.64	0.39	0.07	0.31	0.40	0.28	0.44	0.35
IE	0.21	0.14	0.14	0.19	0.10	0.27	0.18	0.33	0.16	0	0.14	0.48	0.40	0.18	0.15	0.28	0.34	0.39	0.28
IT	0.14	0.09	0.16	0.17	0.10	0.29	0.11	0.21	0.29	0.14	0	0.37	0.38	0.27	0.13	0.20	0.36	0.28	0.18
NL	0.40	0.45	0.49	0.38	0.46	0.49	0.40	0.20	0.64	0.48	0.37	0	0.51	0.64	0.36	0.32	0.66	0.29	0.29
SE	0.35	0.33	0.25	0.30	0.31	0.21	0.32	0.34	0.39	0.40	0.38	0.51	0	0.39	0.33	0.33	0.45	0.29	0.31
PT	0.31	0.20	0.21	0.33	0.19	0.27	0.27	0.43	0.07	0.18	0.27	0.64	0.39	0	0.30	0.44	0.33	0.50	0.39
LU	0.25	0.16	0.16	0.16	0.13	0.21	0.21	0.31	0.31	0.15	0.13	0.36	0.33	0.30	0	0.26	0.38	0.36	0.31
CZ	0.15	0.26	0.28	0.12	0.26	0.29	0.20	0.18	0.40	0.28	0.20	0.32	0.33	0.44	0.26	0	0.34	0.18	0.15
PL	0.29	0.33	0.30	0.29	0.31	0.27	0.32	0.47	0.28	0.34	0.36	0.66	0.45	0.33	0.38	0.34	0	0.49	0.41
SK	0.20	0.30	0.29	0.22	0.30	0.27	0.23	0.19	0.44	0.39	0.28	0.29	0.29	0.50	0.36	0.18	0.49	0	0.16
HU	0.12	0.19	0.23	0.18	0.20	0.29	0.13	0.09	0.35	0.28	0.18	0.29	0.31	0.39	0.31	0.15	0.41	0.16	0

Table A2. Structure diversity matrix of energy use sources in the food production systems in 2015–2016 (γ = 0.18).

	DE	AT	BE	DK	ES	FI	FR	GB	GR	IE	IT	NL	SE	PT	LU	CZ	PL	SK	HU
DE	0	0.23	0.27	0.09	0.18	0.32	0.08	0.21	0.19	0.24	0.12	0.29	0.45	0.16	0.18	0.11	0.28	0.11	0.10
AT	0.23	0	0.21	0.16	0.28	0.27	0.15	0.12	0.25	0.39	0.20	0.29	0.21	0.24	0.25	0.16	0.43	0.14	0.16
BE	0.27	0.21	0	0.24	0.35	0.41	0.23	0.10	0.36	0.46	0.29	0.10	0.37	0.32	0.34	0.23	0.50	0.17	0.20
DK	0.09	0.16	0.24	0	0.16	0.23	0.08	0.18	0.14	0.26	0.09	0.30	0.35	0.12	0.15	0.11	0.27	0.11	0.12
ES	0.18	0.28	0.35	0.16	0	0.33	0.16	0.29	0.18	0.12	0.11	0.40	0.41	0.07	0.15	0.24	0.32	0.22	0.21
FI	0.32	0.27	0.41	0.23	0.33	0	0.27	0.32	0.17	0.38	0.31	0.45	0.25	0.30	0.22	0.26	0.39	0.27	0.28
FR	0.08	0.15	0.23	0.08	0.16	0.27	0	0.15	0.17	0.25	0.12	0.32	0.37	0.15	0.18	0.08	0.30	0.08	0.05
GB	0.21	0.12	0.10	0.18	0.29	0.32	0.15	0	0.27	0.40	0.23	0.19	0.31	0.26	0.29	0.15	0.44	0.10	0.12
GR	0.19	0.25	0.36	0.14	0.18	0.17	0.17	0.27	0	0.24	0.17	0.43	0.30	0.15	0.18	0.19	0.28	0.21	0.21
IE	0.24	0.39	0.46	0.26	0.12	0.38	0.25	0.40	0.24	0	0.19	0.48	0.49	0.16	0.25	0.32	0.34	0.31	0.29
IT	0.12	0.20	0.29	0.09	0.11	0.31	0.12	0.23	0.17	0.19	0	0.30	0.40	0.05	0.11	0.20	0.35	0.18	0.17
NL	0.29	0.29	0.10	0.30	0.40	0.45	0.32	0.19	0.43	0.48	0.30	0	0.41	0.34	0.33	0.32	0.56	0.26	0.29
SE	0.45	0.21	0.37	0.35	0.41	0.25	0.37	0.31	0.30	0.49	0.40	0.41	0	0.39	0.32	0.37	0.52	0.35	0.37
PT	0.16	0.24	0.32	0.12	0.07	0.30	0.15	0.26	0.15	0.16	0.05	0.34	0.39	0	0.10	0.23	0.33	0.20	0.20
LU	0.18	0.25	0.34	0.15	0.15	0.22	0.18	0.29	0.18	0.25	0.11	0.33	0.32	0.10	0	0.26	0.35	0.23	0.23
CZ	0.11	0.16	0.23	0.11	0.24	0.26	0.08	0.15	0.19	0.32	0.20	0.32	0.37	0.23	0.26	0	0.29	0.07	0.08
PL	0.28	0.43	0.50	0.27	0.32	0.39	0.30	0.44	0.28	0.34	0.35	0.56	0.52	0.33	0.35	0.29	0	0.34	0.32
SK	0.11	0.14	0.17	0.11	0.22	0.27	0.08	0.10	0.21	0.31	0.18	0.26	0.35	0.20	0.23	0.07	0.34	0	0.05
HU	0.10	0.16	0.20	0.12	0.21	0.28	0.05	0.12	0.21	0.29	0.17	0.29	0.37	0.20	0.23	0.08	0.32	0.05	0

Table A3. The grouping quality measures for each γ value from the sequence in 2001–2002 and 2015–2016.

Specification	2001–2002		2015–2016	
	γ	Grouping Quality	γ	Grouping Quality
$\overline{v} - S_v$	0.1722	18.54	0.1687	21.47
$\gamma_l = \overline{v} - S_v$, $\overline{v} - S_v + 0.01, \ldots, \overline{v}$	0.1800	18.54	0.1700	21.47
.	0.1900	18.35	0.1800	22.60
.	0.2000	15.58	0.1900	17.95
.	0.2100	15.58	0.2000	18.58
.	0.2200	19.84	0.2100	18.43
.	0.2300	19.84	0.2200	16.26
.	0.2400	18.81	0.2300	13.05
.	0.2500	18.81	0.2400	13.05
.	0.2600	16.41	0.2500	14.25
$\overline{v}$	0.2656	16.41	0.2567	14.90

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Renewable Energy Producers' Strategies in the Visegrád Group Countries

Adam Sulich [1,*] and Letycja Sołoducho-Pelc [2]

[1] Department of Advanced Research in Management, Faculty of Management, Wroclaw University of Economics and Business, 53-345 Wroclaw, Poland
[2] Strategic Management Department, Faculty of Management, Wroclaw University of Economics and Business, 53-345 Wroclaw, Poland; letycja.soloducho-pelc@ue.wroc.pl
* Correspondence: adam.sulich@ue.wroc.pl

Abstract: Companies that belong to the energy sector can use Sustainable Development Goals (SDGs) for their strategies and diversify electrical energy production with reverence to the natural environment. This article aims to analyze sustainability strategy types among the Visegrád Group (V4) countries' energy producers, who decided to generate electrical energy from the renewable resources. This research uses an inductive inference approach supported by a literature study and deductive reasoning supported by a statistical reference method. The main finding is that the energy producers from the V4 group have a common direction of evolution in their strategies. This change is based on a growing share of renewable energy sources to achieve environmental excellence strategies. The lack of renewable energy sector organizations' strategies translates into disappointment with the goals pursued by these organizations. The significance of this study lies in an explanation of how sustainability strategies compare at a firm and country-level in a proposed classification. The analysis can open future research areas to examine development of strategies in the renewable energy sector.

Keywords: Hellwig's method; sustainability strategies; sustainable development; Visegrád Group; sustainable strategic management; the renewable energy sector

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1. Introduction

The energy sector worldwide is crucial for the economic development. Electrical energy producers are involved in the economy because energy sources impact prices of energy goods and services [1]. Future development strategies apply to all organizations, especially those that counteract environmental pollution and climate change [2]. There are organizations that implement sustainable strategies [3] towards sustainable development (SD) despite their main activities [4]. Therefore, increasing investment in Renewable Energy Sources (RES) as a part of strategy can contribute to achieving chosen Sustainable Development Goals (SDGs) among electrical energy producers [5] in different countries [6]. SDGs can also set the course for sustainable strategies in electrical energy sector companies [7]. However, electrical energy production is the main cause of climate change [8] and accounts for the majority of global greenhouse emissions [9]. Any future effort to achieve the SDGs will thus generate demand for more energy [10,11]. The Renewable Energy (RE) sector is the basis for green technology investments [12] and together with the nonrenewable energy sector, it creates the backbone for domestic economy development [13]. There are multiple examples of technology innovations in biomass, wind, solar and hydro power generation worldwide [14]. Achieving SD through the use of RES to mitigate the unfavorable effects of climate change can generate direct and indirect economic benefits [15]. Therefore, some energy producers have decided to generate electrical energy from RES [16]. The importance of energy sector companies is indisputable, and their efforts towards achieving SDGs serve as a model for other organizations in other sectors of the economy [17,18]. Successful implementation of the chosen sustainability strategy level among renewable electrical energy suppliers can influence the domestic economy. On the other hand, if there is a lack of strategy it translates into disappointment with the SDGs pursued by these organizations.

The aim of the paper is to analyze types of sustainability strategies formulated among the Visegrád Group (V4) energy producers who decided to produce electrical energy from RES [19–22]. Inspiration were strategies derived from the RE sector [5] and discussions related to consistency of management style [23]. In this paper, we consider nuclear energy as clean energy but not renewable. The Visegrád Group is a political group formed by four central European countries Czechia (CZ), Poland (PL), Slovakia (SK) and Hungary (HU), which all belong to the European Union (EU) [24]. An important common feature of the V4 countries is the fact that energy transformation in these countries began later than in other EU member states [25].

With this purpose, our work is structured as follows. In the first place, the paper develops a theoretical framework within a literature review that covers the main subjects: sustainable development, sustainability strategies and related terms. Then, a brief description of the electrical energy production sector together with RE sector development conditions in the V4 is discussed. In this part, a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) of the Visegrád Group countries RE sector is presented. In the third part of this paper, the materials and methods are described along with the results and discussion. In the conclusions, comprehension of strategies and evolution-based classifications are discussed. This classification constitutes the authors' theoretical and practical contribution to the science. The presented work develops a quantitative empirical study comprising four different countries' perspectives for the strategies in the RE sector among their main energy producers. The study is based on business data and opens a new level of cross-border comparisons among energy producers. The paper ends with conclusions and possible future study proposals, along with listed limitations and practical business, environmental and social implications.

2. Literature Review

In this paper, the authors focus mostly on the RE sector and its development conditions in the Visegrád Group without describing the whole energy production sector in detail in relation to other energy sources and technologies. The scope of the literature review is renewable electrical energy generation development conditions and sustainability strategies.

2.1. Sustainable Development and Related Terms

SD is an approach to build a common future through such human activity which meets the "needs of the present and future generations" [26,27]. SD is also a concept of quality of life with an unlimited time horizon because its assumptions are based on natural laws, are timeless and universal [17,18,28,29]. The concept of SD is a counterbalance to the "brown economy", which is based on fossil fuels and has resulted in environmental degradation [28]. The "brown economy" is known for its negative environmental impact due to the inability to overcome the current ecological crisis. The energy demand is growing, associated with the growing demand for natural resources and resulting in an increasing amount of harmful waste. The search for solutions to reconcile growing energy needs with environmental resources and protection is still ongoing [29].

SD approaches differ between countries, regions and organizations, but for all of them achieving a balance between output and input within the natural environment is a priority. Thus, SD is based on the ability to use renewable resources, reduce pollution and avoid reduction of nonrenewable assets [12]. For many years, natural resources have been exploited and, as a result, environmental problems have become common global issues. Modern economic growth is driven mainly by the exploitation of natural resources that results in environmental degradation. The energy sector and related industries struggle to achieve SDGs and, paradoxically, their activities are in opposition to the SD assumptions.

The world community has adopted SD as a concept based on the three defined pillars of sustainability: environment, economy and society [30]. These three aspects are essential and have been developed to be more applicable to business policy and strategy. However, elements of the SD idea [31] are related to business development issues within the focus of Sustainable Strategic Management (SSM). Therefore, the idea of Environmental Sustainability (ES) emerged from the consolidation of environment and business sustainability [32]. ES assumes maintaining the business integrity and ecological balance of the natural environment system [33]. Such a balance is possible, assuming that people consume natural resources at a rate and with amounts that complement each other [12]. ES depends on the maintenance of natural capital to meet people's current needs, while protecting raw materials for future generations [34]. On the other hand, ES assumes that waste can be stored as a future resource and be used when the proper technology is developed [35]. Therefore, the cleaning and removal processes for environmental services must be maintained and improved in the future [12,34]. There are other dimensions of SD, including economic and social systems. Economic Sustainability is the capacity to operate at a defined economic level [36,37], while Social Sustainability (SS) is the ability of a society [38] to perform at a higher level of wellbeing [13,39]. The evolution of strategic management for sustainable development incorporates strategic perspectives of corporate sustainability management and introduces [40] sustainable strategic management (SSM). SSM connects all possible approaches to SD, defined or indicated by the three SD pillars [4].

The need to achieve SDGs, build a balance with the environment and strengthen the organization's competitiveness led to the synergy of sustainable development and SSM strategy [27]. The concept was derived from ecological trends such as the influence of business on the natural environment, protection of natural resources, social trends and business management and strategy [41]. SSM assumes strategically importance processes for the organization that meet social responsibility criteria, harmony with the cycles of nature and economic competitiveness [42]. Combination of the economic and environmental goals included in SSM leads organizations towards sustainable competitive advantage [43].

2.2. Sustainability Strategies

Lack of SD achievement can be induced by nonstrategic approach in organizations. Therefore, the main problem is to transfer SDG ideas and assumptions into SSM and business practice [44]. Additionally, many sustainability strategies (in scientific publications also known as 'sustainable strategies') have been developed and described to solve environmental problems, but many have not been implemented [5]. The problem with SSM is implementation of strategies consistent with the type industry and natural environment conditions [23]. Although the idea of SD is popular with politicians, business leaders, entrepreneurs and societies, its implementation causes many problems in business practice [45]. Therefore, there is the tendency to use the same strategic approaches in many different economic sectors. The implementation of SSM faces various barriers, but the most critical problem is related to the process of changing the organization's management [27] and management style, and is associated with consistency of strategy type [44,46]. According to this article, strategy-type consistency means internal and external consistency between an organization's activities, management style, decision making, culture, the values of the organization and the implemented strategy. Difficulties in maintaining consistency result from management in a changing environment, where management is constantly transformed under the influence of a large number of different factors important to competitive advantage [47]. It can be assumed that strategy type consistency is the capability to balance economic, social and environmental dimensions combined with industry type. This balance should facilitate the strategy's implementation by ensuring management's harmonization with the strategy [48]. The evolution of the SSM approach has led to the recognition that environmental and social performance [42,49] is as important as an organization's economic performance [50].

A sustainability strategy is not limited to the planning of future activities [51]. Furthermore, strategic initiatives in organizations should be broader in many areas [52]. "Sustainable organizations demonstrate successful long-term performance aimed the restrictions imposed by economic, social, and environmental systems by developing a strategy that sustainably generates and captures value into the future" [53]. Sustainability strategy increases the company's value and shapes the organization's success in the long term [54]. There is a need to indicate that for many production organizations reduction of pollution is a major problem because it is associated with the limitation of anthropopressure and is associated with production cycles. Reduction of pollutions emission is not enough to achieve a sustainable competitive advantage over the longer term [55].

There are different sustainability strategy levels among organizations and administrative units [27]. These sustainability [27,50] or sustainable [56] strategies are focused on the internal conditions of processes and compliance with external conditions (frame) formulated by government environmental management and SDGs implementation. Various types of sustainability strategies can be implemented within SSM (Figure 1). Sustainability strategies represent the different levels of the implementation of SDGs [57]. The levels range from basic environmental strategy, pro-ecological strategy, and finally the full engagement and consistency of management with SDG,s which is the green strategy [7]. Therefore, there are three types of sustainability strategies differentiated on coherence degree in SDG implementation concerning natural environment protection [58,59]. Based on this division, there are also fewer and more engaged organizations in the SDGs, which reflect their involvement in natural environment protection (represented by an arrow in Figure 1).

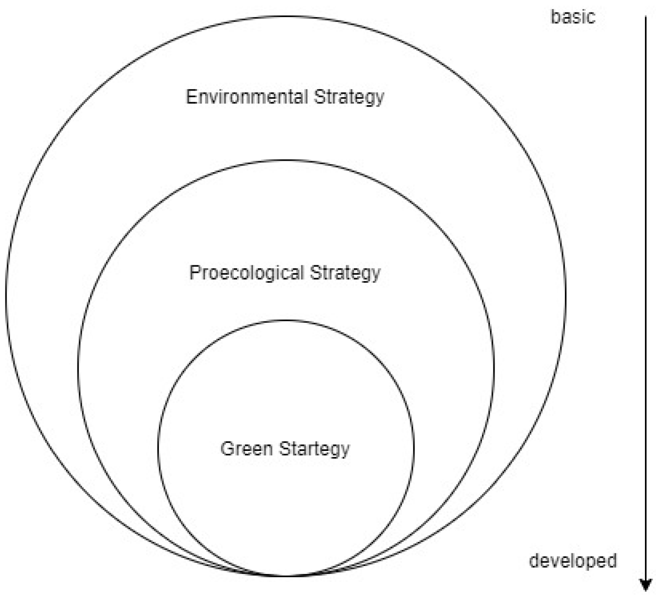

Figure 1. Relationship between sustainability strategies and management approaches. Source Authors' elaboration.

Environmental strategy is implemented by organizations that adapt to the environmental requirements legislated, and environment management formulated, by government [57]. It can be considered as a basic and minimum version of environmental measures that must be executed and met by organizations to avoid legal and financial consequences [60]. This type of strategy has obligatory implications and must be adopted by all organizations. The environmental strategy defines the organization's processes that impact the environment and points to environmentally-friendly practices [23]. In this strategy, organizations specify how they shape relations with the natural environment, and they adopt strategic attitudes [61]. The environmental strategy should be adapted to the circumstances of the organization's internal and external business environment conditions [23]. The environmental strategy can be used at a country level as well at the organization level, and it can be developed towards the next levels of sustainable strategies.

Proecological strategy concerns involvement in activities that go beyond the norms established by law and assumes the realization of chosen SDGs and treats them as sustainable strategic measures. Besides the obligatory law regulations, there are formal internal and external certificates, or industry standards, developed in this strategy level, which are not obligatory but voluntary [31]. Proecological strategy has a tactical nature and creates a connection between operational (environmental strategy) and strategic level (green strategy). Its purposes in organizations or in country-based strategies [42] are to enhance improvement of the natural environmental conditions or reduce anthropopressure (the negative impact of all human activity). On the other hand, if measurement of pro-ecological strategy implementation processes is not possible, there is no sustainable strategic management at this level [17,49]. However, if the development of a single government or organization's proecological strategy does not bring results, then action is required towards the next level of sustainability strategy [62].

The green strategy is most developed (Figure 1), which enhances quality of life by using new technological and organizational solutions and supporting green industry development. This type of strategy involves the almost maximum possible number of SDGs in the organization's activities. The practice of green strategy requires the involvement of top management and focusing their attention on the decision-making process related to the environment [43]. The choice of a green strategy is mainly due to internal factors, shaped by the commitment of the organization's management to consistency between management style and goals induced by the SD idea [23]. "A green strategy implies a proclivity to collaborate with stakeholders concerning environmental improvements, share information with competitors concerning environmental improvements, emphasize environmental improvements rather than short-term economic gains, and emphasize environmental improvements as a means of increasing earnings" [63].

2.3. Electrical Energy Production Sector—Selected Characteristics

Electrical energy has great importance for economic and social development and quality of life [64]. It is also assumed that energy demand will grow on a global scale in the near future [65]. Nowadays, for the majority of countries, energy production is based on coal combustion diversified by nuclear energy (recognized as clean energy) and some portion of RES [66]. The dominance of coal as a fuel has strategic political and socio-economic importance [61,67]. The electric power industry burns coal, emits pollutants and produces solid wastes that damage the environment and cause large-scale changes to the landscape. Despite modification of the technology of generating electrical energy from coal, and improvement in processes related to reclaiming exhaust gases, coal combustion still harms the environment [68]. The majority of electricity producers are state-owned enterprises. These companies not only produce energy in their facilities but also distribute it because they possess the required infrastructure. Therefore, this economic sector harms the environment mainly due to electrical energy production processes and related direct hazards. This industry also shapes and changes the landscape during energy generation (renewable installations), transfer, distribution and retail of electricity. The transmission of electrical energy is managed by each country's transmission system operator [69]. Each operator within to the Visegrád Group belongs automatically [70] to the Central Europe Energy Partners, and they also belong to the European Union organization Union for the Coordination of Production and Transmission of Electricity (UCPTE).

Despite numerous declarations by politicians and leaders of business organizations involved in the energy sector, Sachs [71] drew attention to the problems and failures in implementing the idea of SD, especially in electric energy production practice [15]. On the other hand, when analyzing the possibilities of organizations such as energy producers, one can indicate the chances of implementing strategies that consider the needs of the natural environment. A beneficial development alternative for organizations operating in the energy sector is implementing strategies to reduce the negative impact on the natural environment. In this approach to the strategy, the most critical problems to be solved are pollution and waste generated during the energy production process and increasing power generation efficiency. Enterprises implementing environmentally-friendly strategies have a wide range of possibilities ranging from activities with a low impact on environmental protection to comprehensive initiatives built with a long-term perspective and considering the organization's ecological responsibility [72].

The implementation of different sustainable strategies (Figure 1) is related to technological progress, which has provided a new ecological solution [18]. This shift has also forced companies to slowly withdraw from the so-called 'linear economy' approach [5]. The first strategies were characterized and named as 'end of pipe' technology-based solutions. These early strategies were based on the dilution of wastes and pollutions to meet the basic legal requirements for environment management imposed by the government [5,30]. To implement environmental strategy, energy producers' techniques dealt with emissions and were based on the limitation of pollution emission in uncomplicated processes.

Many companies invested significant amounts of money for environmental compliance [51]. The most important aspect for them was to increase process productivity [18]. Nowadays "it is considered that pollution and waste are a sign of low process efficiency" [5]. Therefore, electrical energy producers try to increase energy production effectiveness and implement clean production related to the proecological strategy.

Some companies from Standard and Poor's group involved in energy production [51], obtained a costly competitive advantage in a short time by reducing the emission of pollution [51]. Technological or process changes requires greater financial expenses than organizational shifts [51,73]. However, from a financial perspective [74], initial decrease of pollution yields the greatest results [51]. When the degree of emission approaches zero pollution, capital expenditures grow in a significant way. This is associated with an ever-deeper change within the organization. It is also necessary that the result of the main business process (product of service) is environmentally friendly. Then, the organization has both clean processes and clean products [57]. This includes a progressive change from process greening towards SSM [75].

Complementing one of the chosen sustainability strategy types should be the attitude of the whole company with aims toward SD. It is possible to specify strategy types due to the method of achieving harmony between the natural environment and organization or business environment [26,58,63]. Electrical energy producers often implement renewable energy technologies to diversify their energy production process and try to deliver more green electricity [65]. Such a change in power production is a result of the adopted type of sustainability strategy.

2.4. Renewable Energy Sector in the V4

Energy production in Central Europe is traditionally based on nonrenewable energy sources [76]. The V4 energy sector is historically rooted in fossil fuels, which occur abundantly in these countries, and among them are some of the biggest coal producers (Poland possesses the ninth largest coal deposits in the world). In electrical energy production in Central Europe, two major fuels are significant: hard coal and nuclear energy [77]. Changes in electrical production are moving towards more renewable energy in electricity production [15,17,66]. Therefore, the electrical energy generation subsystems in the Visegrád Group of countries is mixed and encompasses power plants, industrial power plants and heating plants, hydroelectric power plants, wind power, biomass and biogas [78]. Access to electrical energy is a criterion of wealth, as it determines economic and social development. Surprisingly, in the EU, the lowest rate of energy used per capita is achieved by Hungary (approx. 100 GJ per year) and Poland (approx. 115 GJ per year) [79,80]. It can be assumed that limited access to electricity determines the low wealth of a society and undermines the development of economies [81]. In the Visegrád Group of countries, there are active foreign investors and conventional energy producers who decided to develop their portfolios in the renewable energy sector. These investors are Axzon (biogas plants), Dalkia (biomass combustion), EDF, EDP Renewables, E.ON, GDF Suez (wind farms) and RWE, that along with the domestic companies are also investing in renewables [82].

In **Czechia**, primary electrical energy production is based on the use of fossil fuels [83]. The Czech Republic uses coal and lignite for approximately 47% of its electricity production and is second in Europe after Poland (73.6%) [84]. Czechia was the fourth-biggest net electricity exporter in the EU in 2018, after France, Germany and Sweden [85]. However, the country's energy security is based on coal and lignite as conventional energy sources. Apart from coal (53%), the country uses nuclear energy (35%) and renewable energy (12%) [86]. Czechia coal consumption records a decline in favor of biofuels, waste combustion and nuclear energy [87]. The largest electricity producer in Czechia is ČEZ (České Energetické Závody), and there are four much smaller producers: Severní Energetická, Sokolovská Uhelná, Elektrárny Opatovice and Teplárna Kladno. Electricity generation from renewables is driven by biogas, biomass, and solar (around 25% each), followed by water energy (around 18%). The remaining electricity production is covered by other RES, especially wind projects [87]. The fastest-growing renewable source of electricity in Czechia is photovoltaic power plants. The reason is the fall in the price of solar panels and the possibility of storing electricity. According to plans, by 2030 wind energy should cover one-third of electricity demand, whereas the development of biogas plants is subject to restrictions due to odors. Considering the various barriers that hinder the development of RES in Czechia, legislative restrictions are the most important [83].

In **Hungary,** the renewable energy sector has a small share in electricity generation and is dominated by biomass producers [80]. The energy sector in Hungary is mostly privatized, despite the largest company, MVM (Magyar Villamos Művek) group being owned by the state [88]. In Hungary, conventional electricity generation comes mostly from nuclear (49.3%) and coal (8.5%), with natural gas contributing to nearly a quarter of the total electricity generated in Hungary in 2018 [89]. In Hungary, around 10% of electricity production came from RES in 2018. Recognition that solar energy is particularly important for the development, means photovoltaic panels have been developed. The most important sources of renewable energy are solar energy and biomass, and wind energy has become much less important [90]. In Hungary, 4.5% of renewable energy is produced, and electricity from renewable sources is mainly supplied by hydro and geothermal power plants [80].

In **Poland,** investments in renewable energy sources are developing rapidly despite regulatory barriers. The largest companies in Poland operating in the energy sector are PGE (Polska Grupa Energetyczna), Tauron, Enea, Energa and ZE PAK (Zespół Elektrowni Pątnów Adamów Konin). Therefore, the biggest renewable energy sector is constituted of listed electrical energy suppliers with Polish branches. The four key players the renewable energy market are PGE, Tauron, Enea and Energa [58]. Some changes influence the renewable energy sector development in this country. The geographic conditions favor wind power plants, but the majority of renewable energy is generated by hydropower plants [91]. Hydropower development is expected to be mainly based on the use of existing damming structures to produce electricity [92]. Another opportunity is favorable changes in law (prosumers energetics) that make more organizations and households interested in photovoltaic panels. This creates a new strategy, considering a for the prosumer client in the electricity generation processes [15]. In Poland, various sources of renewable energy do not play an important role in energy production [82]. The use of wind energy has developed little, while the use of solar energy is growing faster [93].

In **Slovakia,** the electricity market is relatively small compared to other EU countries [94]. Almost 55% of energy production is supplied by nuclear power stations, 21% by conventional power stations, 14.4% by hydroelectric stations and 8.9% from other renewable sources [95]. Slovakia is considered one of the most energy-consuming economies in the EU countries [96]. In Slovakia, the major player in the electricity producer sector is Slovenské Elektrárne (SE). Slovakia is a relatively water-rich country, boasting many natural lakes, dams and rivers that support various water-intensive operations such as tourism, manufacturing and power generation [97]. Therefore, in Slovakia, hydropower is the most significant renewable energy source, accounting for around 40% of total energy production [95]. Geothermal waters and biomass plants are used to a small extent, while the possibilities of using solar energy, and thus solar panels and photovoltaic power plants, are growing [98].

A SWOT analysis (Figure 2) can be used in the RE sector to facilitate the selection and implementation of a sustainability strategy. Then, the results can be used to determine how strengths and development opportunities influence the process of achieving competitive advantage and reflect the sector's situation [99]. The analysis indicates weaknesses and threats which V4 countries have to eliminate or mitigate to provide better conditions for renewable energy organizations' development. Then, these organizations can project their strategy using strengths and opportunities, and avoid major problems [100]. Figure 2 presents the elements of the SWOT analysis for renewable energy sector industry development created by the electrical energy producers in V4 countries. The result of this analysis can be presented as similarities and differences.

Strengths	Weaknesses
• Renewables targets are in place, as the V4 are signatories of the UN Framework Convention on Climate Change and other documents. • The V4 governments are on the route to set up a support mechanism for renewable energy. • EU funds and legislative support for infrastructure investment. • Visible renewables development in recent years. • The proximity and ties between the V4 countries enable easier transfer of knowledge, technology and best practices in the implementation of a sustainability strategy. • Increasing the V4 countries regions' energy security through the diversification and decentralization of energy sources. • A growing number of experienced workers in the construction industry. • Local economy supports and a growing number of green jobs. • New methods of generating energy allow for the EP and the climate, reducing pollutants' emission and increasing energy security. • Relatively low level of investment start-up costs and quick capital return	• The V4 countries remain heavily reliant on coal for electricity generation due to the EU's largest coal reserves, resulting in high carbon dioxide emissions. • The energy sector and mining industry are the biggest parts of the V4 countries domestic economies. • Great organizational barriers and unfavorable administrative framework (law) stagnate the use of renewables. • Over-trust on EU support to drive renewable energy sector growth. • Regulatory instability in the V4 countries. • There is no common organizational unit for the V4 countries specializing in renewable energy, managing cooperation between countries, and collecting information on renewable energy sources and possibilities. • There is existing technical and environmental potential left unused (water, wind, and solar power generation). • Higher direct costs of energy production from renewable energy sources than production of energy generated from fossil energy sources. • Limited possibilities of connecting renewable energy installations to electricity, gas, and heating networks.
Opportunities	**Threats**
• Highly favorable climatic conditions for wind, water, and solar power generation. • The V4 countries are dedicated to RE goals established by EU declarations. • Close economic cooperation between V4 countries conditioned by proximity reduce costs related to energy transmission between countries. • Promoting Renewable Energy to increase public awareness of environmental protection. • Increasing the production rate of electricity with low CO2 intensity, mainly from renewable energy sources. • Potential for the improvement of existing power plants. • Potential law changes could energize the sector. • The new renewable energy law could provide at least some regulatory certainty. • There is potential development of small-scale household renewables innovations, which are supported by the government. • Increase in energy prices due to increased demand and limited supply of fossil sources.	• The growing interest in atomic energy can decrease the V4 countries renewables potential. • Worsening the relationships with the EU. • Various legislative restrictions on renewables development. • The governments are not interested in any EU regulations that make domestic electricity prices higher. • The coal industry can remain strategically important for the country's economy, which can lead to favor coal-fired generation over renewables. • Low public awareness of energy management, the importance of energy efficiency and energy-saving possibilities. • Different legal regulations on renewable energy sources in each of the V4 country. • Indirect subsidization of fossil fuel prices.

Figure 2. SWOT analysis of the V4 renewable energy sector. Author's elaboration based on [5].

Factors influencing the development of the RE sector and the directions of their impact on renewable energy producers were examined in the presented SWOT analysis. Similarities are identified among V4 countries, and each has developed some sustainability strategies [76]. What is more, among Visegrád Group countries, forecasting the future and planning in the long-term can improve the state of the environment in the next 10 or 20 years [6]. These have set their development goal to become carbon neutral by 2050. This eco-approach is promoted by the EU; therefore setting pro-eco policies may be motivated by the money offered by the EU for investments in the renewable energy sector [68]. All of the V4 countries are quickly improving their renewable energy industries, and their geographic locations and environmental conditions create good circumstances for increasing use of renewable energy [101]. The analysis presented in Figure 1 shows that there is a huge potential for the development of the renewable sector in the Visegrád Group. Development conditions for the V4 countries' renewable energy sources are convoluted and mainly rely more on external environmental factors than internal conditions.

One of the most important connections between these countries is membership in European Union. The EU's aims in terms of energy are clear. These objectives are reduction of CO_2 emissions, development of renewable energy sources, an increase of efficiency and creation of a European energy market. Considering the EU's goals with the priorities of various sectors of the energy market will be a major threat for each of the V4 countries, especially since the objectives of the EU mean moving away from coal. This raises the question of the role of the mining industry in the future. There is an attempt to protect the mining industry by combining it with the energy industry, so that extraction costs of mining are reduced.

There are differences among the Visegrád Group countries in the renewable energy sector. For example, in Hungary and Czechia, the ecological awareness of residents and the willingness to implement proecological investments are growing, but this trend is less visible in Slovakia and Poland despite huge campaigns and education spending [77]. In Czechia, the renewable energy sector is divided almost equally between biogas, biomass, solar power and other types of renewable energy generation [6]. Contrasts are visible in various technologies used to achieve set goals for the renewable energy sector [1], and differences between them may result from different stages of the country's development or a different sustainability strategy implementation level [102]. The energy sector depends on the geographical location of the country, which results in differences between countries in adopting various energy generation technologies. For example, different climate conditions may either support or make renewable projects difficult or impossible to accomplish.

3. Materials and Methods

The subjects of the study were the main conventional energy produces in the Visegrád Group countries that decided to generate electrical energy from RES. This paper excludes nuclear energy as renewable energy; therefore, data related to this type of energy were not subject to analysis. Following the RE sector's transformation, the six energy producers emerged in the countries studied (Table 1). In Poland there are four main energy producers: PGE (Polska Grupa Energetyczna), Tauron, Energa and Enea. These companies have different characteristics related to RE generation, CO_2 emissions, and shares in the electricity market in Poland. Unlike Poland, in the other Visegrád Group countries, there is only one main energy producer in each state. In Czechia the main producer of the energy is ČEZ (České Energetické Závody). In Slovakia it is SE (Slovenské Elektrárne), and in Hungary the main energy producer is MVM (Magyar Villamos Művek). Besides these companies, there are foreign investors for both conventional and renewable energy producers, which market shares, but these are players in all V4 member states. All companies listed in Table 1 are the biggest energy producers and hold stakes in the Visegrád group's RE market [103]. The dominance of single organizations in Hungary, Slovakia, and Czechia is due to the fact that in these countries a significant amount of the electric energy is generated in nuclear power plants. The aim of this research was to research energy producers' sustainability strategies in the Visegrád Group countries. The common points of their sustainability strategies, based on the indicators for monitoring implementation, are listed in Table 1. The data were obtained from the companies' integrated reports. A quantitative research statistical reference method (the Hellwig's method) was implemented. The indicators presented in Table 1 were selected based on the Fitch Solutions reports [91].

Table 1. Basic indicators for monitoring the sustainability strategy in 2019.

Measured Characteristic	Symbol	Company Name (Country Symbol)						
		PGE (PL)	Tauron (PL)	Enea (PL)	Energa (PL)	CEZ (CZ)	SE (SK)	MVM (HU)
Generation of electric energy from renewable energy sources (TWh)	x_1	1.7	1.4	2.3	1,4	15.4	16.8	16.4
Number of retail customers (millions)	x_2	5.3	5.7	2.6	3,2	8.5	2.45	4.2
Share of total domestic production of electric energy (%)	x_3	41.0	8.3	18.0	12.0	61.0	80.0	50.6
Renewable energy source installation power (MW)	x_4	650.0	852.0	443	500	864.0	408.1	466.7
Annual volume of CO_2 emissions (M tons)	x_5	55.0	18.5	10.5	3.4	27	18.8	13.3

Source: Authors' elaboration based on companies' integrated reports.

The reference method involves the determination of a synthetic variable being a function of the normalized features of the data input set. The essence of this method lies in a procedure according to which, from the explanatory variables in the matrix, a combination of variables is selected. Moreover, this method allows measurement and comparison of variables of different sizes and dimensions because a data standardization procedure is used. The purpose of the method is to compare the level of sustainability strategies among companies of the Visegrád Group countries that decided to produce electrical energy from RES. Indicators were defined by Eurostat [104] because their compatibility with the SDGs was accepted in the companies' reports. The variables used in calculations were assigned by the symbol x with the number noted as a lower index. As a result, total number of five variables was determined in this way [58].

Secondary data from the year 2019 collected by the companies' integrated reports were used for the calculations, which ensured the comparability and reliability of the data. The reason for the choice of the reference method, especially the zero unitarization method [105], was the presentation of current sustainability strategies in the V4. Moreover, the application of the standard method allowed for the verification of the obtained results in the comparison with countries having similar development [30,106], as described in the literature [107]. Since the set of independent characteristics contains variables that cannot be aggregated directly using appropriate standardization, normalization formulas were applied. Among the formulas, the method of zero unitarization was selected to standardize the process based on the interval of a normalized variable. Variables that positively influence the described phenomenon are called stimulants (x_1–x_4). The only variable with the symbol x_5 is a destimulant. Indicators were selected for the standardization process based on the following formulas:

$$\text{for stimulants}: \; z_{ij} = \frac{x_{ij} - \min\left(x_{ij}\right)_i}{\max\left(x_{ij}\right)_i - \min\left(x_{ij}\right)_i} \tag{1}$$

$$\text{for de} - \text{stimulant}: \; z_{ij} = \frac{\max\left(x_{ij}\right)_i - x_{ij}}{\max\left(x_{ij}\right)_i - \min\left(x_{ij}\right)_i} \tag{2}$$

where:

z_{ij} is the normalized value of the j-th variable in the i-th country;
x_{ij} is the initial value of the j-th variable in the i-th country.

Diagnostic features normalized in this way take the value from the interval (0;1). The closer the value to unity, the better the situation in terms of the investigated feature; the closer the value to zero, the worse the situation.

In the next step, the normalized values of variables formed the basis for calculating the median and standard deviation for each of the countries studied. Median values were determined using the formulas:

$$\text{for even numbers of observations}: \ Me_i = \frac{Z\left(\frac{m}{2}\right)_i + Z\left(\frac{m}{2}+1\right)_i}{2} \tag{3}$$

$$\text{for odd numbers of observations}: \ Me_i = Z\left(\frac{m}{2}+1\right)_i \tag{4}$$

where: $z_{i\ (j)}$ is the j-th statistical ordinal for the vector $(Z_{i1},\ Z_{i2}, \ldots,\ Z_{im})$, i = 1, 2, . . . , n; j = 1, 2, . . . , m.

The standard deviation was calculated according to the following equation:

$$S_{di} = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(z_{ij} - \overline{z})} \tag{5}$$

Based on the median and standard deviation, an aggregate measure w_i of the sustainability strategies was calculated for each country:

$$w_i = M_{ei}(1 - S_{di}); w_i < 1 \tag{6}$$

Values close to unity indicate a higher level of the sustainability strategy in the V4 member state, resulting in a higher rank. The aggregate measure places a higher rank on countries with a higher median of features describing the specific country, and those with a smaller differentiation between the values of features in the chosen state, as expressed by the value of the standard deviation [107]. The procedure selected for evaluating the sustainability strategy levels provided a multidimensional comparative analysis. Such an analysis allowed for a comparison between the Visegrad Group countries and grounds for classifying them into four groups (Table 2), where $\overline{w}$ is the mean value of the synthetic measure and S is the standard deviation of the synthetic measure.

Table 2. Sustainability strategies aggregate measures comparative analysis.

Group	Mathematical Characteristic	Meaning	Dominant Strategy
I	$w_i \geq \overline{w} + S$	high level	environmental excellence
II	$\overline{w} + S > w_i \geq \overline{w}$	medium-high level	zero-waste strategy
III	$\overline{w} \geq w_i \geq \overline{w} - S$	medium-low level	cleaner production strategy
IV	$w_i < \overline{w} - S$	low level	'end of pipe'

Source: Authors' elaboration.

The biggest energy producers in the Visegrad Group countries play the main role in sustainability strategies in these countries. The differences between conventional energy producers who decided to generate energy from the RES reflect the disparities between the countries in which they operate.

4. Results

According to the calculated w_i values, the V4 countries were assigned to one of the groups concerning their sustainability strategy level. In Table 3, the main energy producers from each country (countries symbols in brackets) are presented.

Table 3. Results for the V4 countries main energy producers.

Company Name (Country Symbol)	Indicators' Symbols and Values					Measure
	x_1	x_2	x_3	x_4	x_5	w_i
CEZ (CZ)	54	8.5	61	864	27	0.64
Tauron (PL)	1.4	5.7	8.3	852	18.5	0.86
PGE (PL)	1.7	5.3	41	650	55	0.32
Energa (PL)	1.4	3.2	12	500	3.4	0.41
MVM (HU)	16.4	4.2	50.6	466.7	13.3	0.95
Enea (PL)	2.3	2.6	18	443	10.5	0.27
SE (SK)	16.8	2.5	80	408.1	18.8	0.37
Avg. value	13.4	4.6	38.7	597.7	20.9	0.68
Std. dev.	19.2	2.1	27.1	193.6	16.7	0.20
Var. Coeff.	143.1	47.0	70.1	32.4	80.0	0.00

Source: Authors' calculations.

The results presented in Table 3 show that the largest generation of electrical energy from RES in 2019 was in the Czech Republic, followed by Slovakia, Hungary and Poland. The number of retail customers is the highest in Poland, then in the Czech Republic, Hungary and Slovakia. The share of total domestic production of electrical energy has the highest percentage in Slovakia, followed by Poland (four companies contributed 79.3% in total), the Czech Republic and Hungary. Renewable energy source installation power is the highest in Poland (2445 MW in total), and lower in Czechia, Hungary, and Slovakia. On the other hand, the annual volume of CO_2 emissions is the highest in Poland, then in Czechia, Slovakia and Hungary.

The analysis shows that there are countries in which main energy producers implement different sustainability strategy levels (Table 4).

Table 4. Groups of the V4 countries based on the main energy producers' strategies.

Group	Countries	Values of w_i for Countries
I	Czechia (CZ)	0.95
II	Poland (PL)	0.55 *
III	Hungary (HU)	0.37
IV	Slovakia (SK)	0.27

Source: Authors' calculations; * calculated as an average value.

5. Discussion

The SWOT analysis presented in Figure 2 shows that there is potential for the future development of the RE sector in the Visegrád Group countries. Energy producers examined in this study belong to the Visegrád Group countries' states corporations. These organizations have common projects and cooperate with other renewable energy sector companies. Furthermore, favorable legislative changes (prosumer energetics) encourage a growing number of households' adoptions of renewable energy sources (e.g., photovoltaic panels). The role of the client in this process requires a change in strategy based on a new customer approach [108]. An evaluation of the sustainability strategy levels by measuring the effects of energy sector company indicators was based on the reference method [105], modified by the authors from its use in macroeconomic development research. A difficulty in analyzing the renewable energy sector in V4 countries is the deficit of harmonized data allowing comparison between countries and checking of the dynamics of changes over the years.

There are distinct tendencies that support growth of the RE sector in the Visegrád Group countries which are the largest beneficiaries of EU capital and support [91]. Many producers of electrical energy have implemented different levels of sustainability strategies because of growing ecological trends in business [5]. The multidimensional evolution of the strategies in the energy sector is shown in Table 5. Sustainability strategies in the RE producers' sector in the V4 countries are similar to the relationships presented in Figure 1, as in the third column showing sustainable strategies typology [109]. These strategies are a result of three pressure directions on the electrical energy producers. The first has a legal character, the second is the economic pressure of clients and the third is social opinion related to energy production hazards. However, changes in strategy are usually forced by external requirements imposed by legislation at the level of a country or a superior international organization. This external pressure is still applied, and it is even increased by the occurrence of environmental degradation.

Energy sector companies can choose between a broad spectrum of sustainable strategy levels (Table 5). There is a basic, minimum approach characterized by the organizations which implement the "end-of-pipe strategy" [51,110], which reflects the legal requirements for all companies. The "end of pipe" strategy refers to an environmental strategy characterized by isolation and a competition-oriented approach [111]. According to the Worthington's classification, there are other names for this approach, such as indifferent stage or defender position (organization self-defense) [57]. A characteristic feature from the point of view of implementing SDGs in the technological process is the occurrence of dirty processes and dirty products/services. The isolation strategy (minimum-level strategy) is based on minimalization of interactions between the natural environment and the organization (businesses environment) [112]. This strategy decreases the stability of the organizational system and is related to the limited interaction of the organization with the natural and business environment.

A cleaner-type production strategy can also be incorporated into the environmental strategy. Not paying attention to redundancy, organizations implement dirty processes but offer a clean product or service [108]. The redundancy strategy is based on maintaining access to various resources by the organization. These resources allow organizations to survive in crises and avoid short-term adaptation [113]. Due to access allowing restoration of stability at the interface between the organization and the environment, the system can operate in a partially independent manner, both from initial knowledge and the possibility of later obtaining reliable information about the environment. This strategy type encompasses proactive and crisis preventive approaches that stay in accordance with sustainable strategy topologies described by Worthington [57].

There is also the so-called "zero strategy" (also called the "no waste" strategy), which qualifies as the proecological strategy [57]. This strategy assumes an adaptive approach and implementation of clean processes and clean products/services. Adaptability is the potential for the organization to change itself or change its surrounding. This change allows at least some of the lost effectiveness to be regained.

Developing all the above-mentioned sustainable strategies leads to environmental excellence [114], or a green strategy. A green strategy is related to the natural environment, is built on SD and expresses greening of the organization. A green strategy assumes cooperation within the network. Then, the organization can obtain an environmental leadership position [57], not just a sustainable competitive advantage. The organization's technological process is optimal, as both the processes and products/services are clean.

In the literature, there are many sustainable strategy typologies, and the most common is the evolutionary one based on technological progress. This type of development is focused on better environmental protection. The authors of this paper extended a new classification of proecological strategies, as presented in Table 5. These multiple stages or types of sustainable strategies are considered in the strategic management literature. They vary between three and five elements; however the most popular consist of four levels [57]. According to the Hart classification, these are end-of-pipe, pollution prevention, product stewardship and sustainable development [115]. These levels are in accordance with the authors' proposition in Table 5. As listed by Worthington, four element stages or positions [57] are related to the findings of Verbke and Buysse [110].

Table 5. Strategies evolution-based classifications.

Popular Name of the Strategy	Characteristic	Sustainability Strategy Types	Sustainable Strategic Management Approach and Focus on Green Response	Strategy Model
The "end of pipe" strategy	The main aim of this strategy type is to dilute or disperse all emissions to the environment to be legally compliant, but nothing more than simple treatment is performed.	Environmental	Isolation and Competition	Dirty processes and dirty products/services
Cleaner production strategy	The main objective of an organization is to comply with the law because of cleaner production and, if possible, to treat but not eliminate wastes before the end of the production cycle.		Redundancy	Dirty processes and clean product/service
Zero waste strategy No waste strategy	This strategy aims to design a process (production or service) to avoid material losses, so all wastes are reused or recycled. This strategy is ahead of the law because it not only minimizes emissions but also eliminates them.	Proecological	Adaptation	Clean processes and clean product/service
Green strategy Environmental excellence strategy	The basis for this strategy is a conviction that other organizations can use some wastes more effectively or process them better, i.e., "someone's trash is someone else's treasure". This strategy aims to connect all supply chains into a bigger ecosystem to allow other organizations to use recovered resources (previously seen as waste) in their processes with new possibilities.	Green Strategy	Cooperation and Networking	

Source: Authors own elaboration based on: [58,111,116].

6. Conclusions

Even though the SD idea is 50 years old, it has developed more in theory than in practice. Lack of interest and skills in implementing the concept means that there are no measurable social, economic and environmental results. It may even be stated that since the 1970s, social, economic and ecological inequalities between countries and regions have deepened. Despite the declarations and implementation of proecological initiatives, companies' actions are chaotic and inconsistent.

In this paper, research on the RE producers' strategies is limited to the V4 group intentionally. It was assumed that due to historical, political, economic and geographical conditions, companies from these countries would operate in a similar business environment and conditions. This, however, limits research results to countries from the Visegrád Group, where we can make comparisons among countries at a similar level of development. In the study, we did not measure the degree of translation of the SDGs into the implementation of the strategy, and only chosen measures were compared, which means that the study focused on selected, comparable indicators reported by the energy producers in the renewable energy sector.

The novelty of this work covers several aspects presented in the research. The authors presented a new view on renewable energy producers' strategies in the Visegrád Group Countries. The starting point for the considerations was the theory of sustainable development and sustainable strategic management. The authors proposed a new concept of sustainability strategies for companies that can choose between an environmental strategy, a pro-ecological strategy, and a green strategy (Figure 1). Contribution to science is a factor in the strategy types that energy sector companies can choose. The authors highlighted the wide range of opportunities associated with different levels of energy support in environmental efforts, from end-of-pipe to environmental excellence (Table 5). The authors used a statistical reference method (Hellwig's method) based on data gained from the businesses. There are few similar types of research on renewable energy producers based on business data and calculated with Hellwig's method. Other authors using this method in different contexts usually based their studies on the administrative level comparisons and classifications into groups or ordering in ascending/descending orders.

This study contributes to sustainable strategic management (SSM), sustainability strategies and SDG research. The observations in this study were limited to the degree of implementation of SDGs, so future research is required in this area. Indicated problems result from inadequate SSM [49] and the lack of implementation of strategies. Therefore, it is not so much the strategy implementation declaration that matters, but the strategy implementation process. The selection of strategic goals that positively impact the environment is essential only when this is translated into the strategy implementation.

Concerning practical implications, one should pay attention to several problems. The need to transition electricity generation from fossil fuels to renewable energy sources should be reflected in the implementation of SDGs in energy producers' strategies. The use of electricity generated from fossil fuels depletes natural resources and degrades the environment. Despite declaring the intention to reduce energy demand, there is an increase in electricity consumption in the world, still obtained mainly from fossil fuels. This increase in demand for electricity is driven by economic development. Growing investments in the energy sector, and use of RES, can be seen as a way to achieve energy independence among Central European countries. Therefore, all Visegrád Group countries are strong proponents of the diversification of energy supplies and transit routes and try to enhance and support the energy sector transition. These countries are building mutual network connections to enhance the region's security and reduce the negative effects of one-sided dependency. Therefore, fossil fuel and "brown-based" international policy lead towards strong dependencies when renewable energy sources promise independence. All the initiatives of the Visegrád Group energy producers are aimed at supporting energy stability in the Central European region. There is development capacity for the renewable energy sector based on sustainable strategies within the SD movement, and there is also space for the greening the electricity producers by a green strategy.

Regarding social implications, it is worth paying attention to new opportunities related to shaping consumer behavior. Information about electricity producers' strategies can be an essential factor in influencing consumer choices. The growing requirements of customers as to the composition of products and production processes has been reflected in the creation of labels confirming compliance with social criteria. Similarly, consumers using electricity can decide on the choice of supplier, bearing in mind the company's commitment to respect for the natural environment and implementing sustainability strategies. Thus, consumers are able to find out about renewable strategies and make more aware of energy supplier choices.

The assessment of the RE sector development conditions leads to the conclusion that only the state can take the risk of the transformation of the energy sector towards greener and sustainable practices and based on RES. The reasons are the scale of the investments and regulations associated with energy production. The state is a major stakeholder, or owner, of the power plants, suppliers, and related distribution infrastructure which constitute the energy producer companies studied in this research. In this study, we encountered multiple misunderstandings, and false or unchecked information, in the reports of the energy sector in the Visegrád Group countries. The most reliable data used in our research were expensive reports, which, in our opinion, restrict important information for decision-making processes.

In the Visegrád Group topics related to the transition towards a green economy, such as aspects of electromobility, have gained attention in recent years. However, implementation is an illusion, since the majority of generated energy comes from nonrenewable resources. Only an increase in RES can reduce the emissions generated by energy-related economy sectors. The problem is that nuclear energy is considered safe and ecofriendly among the V4 societies, despite the hazards associated with it. In domestic statistics, this type of energy is also classified as renewable, which effectively changes the internal electricity market image of Slovakia, Czechia and Hungary.

An opposite approach is when organizations choose a green strategy that responds to legal requirements and results in the organizations adopting an active attitude towards environmental protection and management evident in green decisions. Changes in technology support changes in the proecological and green strategies in the natural environment. Organizations face the choice of various technological solutions related to the chosen organization's development strategy. On the other hand, technology allows protection of scarce resources and an open perspective for resource-based strategies. These green strategy-driven organizations do much more than required by law and their actions are not based on fear of penalties. Organizations that implement green strategies represent a type of strategic thinking that looks far into the future and translates their strategic goals into a specific management style that is consistent with a sustainability strategy level.

Developing the RE sector can not only reduce negative impacts and protect the natural environment, but it is also possible to act towards energy independence from big suppliers of energy providers and producers in the region [106]. The energy sector is especially involved in the economy because RES can impact prices of goods and services and shape wellbeing.

Accelerating the development of RE requires creating a new conceptual framework, where the basic tool for the usage of SDGs is the implementation of the strategy. We recognized the possibility of a future research direction dedicated to the SWOT analysis for each V4 country's electrical energy sector. To increase the effectiveness of strategy implementation, it is necessary to research the organization in the V4 group regarding difficulties related to the implementation of sustainability strategies. A possible research avenue is to study how to implement a corporate environmental strategy, or green strategy, and propose tools to measure this process. This can reveal possible new approaches to sustainability strategy level implementation related to the research presented in this paper.

Such analysis can also open future research areas to examine development of strategies in the renewable energy sector.

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Differentiation and Changes of Household Electricity Prices in EU Countries

Tomasz Rokicki [1,*], Piotr Bórawski [2], Barbara Gradziuk [3], Piotr Gradziuk [4], Aldona Mrówczyńska-Kamińska [5], Joanna Kozak [5], Danuta Jolanta Guzal-Dec [6] and Kamil Wojtczuk [7]

1 Institute of Economics and Finance, Warsaw University of Life Sciences, 02-787 Warsaw, Poland
2 Department of Agrotechnology, Agricultural Production Management and Agribusiness, Faculty of Land Management and Agriculture, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; pboraw@uwm.edu.pl
3 Department of Management and Marketing, Faculty of Agrobioengineering, University of Life Sciences in Lublin, Akademicka 13, 20-950 Lublin, Poland; barbara.gradziuk@up.lublin.pl
4 Polish Academy of Sciences Institute of Rural and Agricultural Development, 00-330 Warsaw, Poland; pgradziuk@irwirpan.waw.pl
5 Department of Economics and Economic Policy in Agribusiness, Faculty of Economics, Poznan University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, Poland; aldonam@up.poznan.pl (A.M.-K.); joanna.kozak@up.poznan.pl (J.K.)
6 Department of Economy, Faculty of Economic Sciences, Pope John Paul II State School of Higher Education, Sidorska 95/97, 21-500 Biała Podlaska, Poland; d.guzal-dec@dydaktyka.pswbp.pl
7 GazTank Małgorzata Wojtczuk, ul. Mickiewicza 17A, 05-816 Michałowice, Poland; wojtczukkamil@gmail.com
* Correspondence: tomasz_rokicki@sggw.edu.pl; Tel.: +48-22-59-342-59

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Abstract: The paper's main purpose is to identify the differentiation and variation of electricity prices for households in EU countries. The specific objectives are to highlight the directions and differentiation of price changes in EU states, determine the degree of volatility (or stability) of electricity rates, and establish the correlation between electricity prices for household consumers and economic and energy parameters. All members of the European Union were chosen for this project as of 31 December 2019 (28 countries). The analyzed period covered the years 2008–2019. The source of collected information was the thematic literature review and the data from Eurostat. Descriptive, tabular and graphical methods, constant-based dynamics indicators, coefficient of variation, Kendall's tau correlation coefficient, and Spearman's rank correlation coefficient were used to analyze and present the materials. It was determined that higher electricity prices for households in the EU states were associated with better economic parameters. Developed countries must have higher energy rates because they will ensure energy transformation, i.e., implementing energy-saving technologies. In the EU, electricity prices for household consumers showed little volatility, but that variability increased in line with the surge of the volume of household energy consumption.

Keywords: electricity prices; households; EU countries; directions of price changes

1. Introduction

Electricity is obtained by burning fossil fuels such as hard coal, lignite, oil, and natural gas. In addition to such conventional sources, energy is also obtained from renewable resources such as wind, solar power, water, and geothermal heat. Such heterogeneity results in different energy production costs. There are also variabilities between countries regarding the structure of energy sources [1–10].

The creation of a common electricity market in the European Union has been going on for almost 30 years. Actions and regulations are mainly based on EU agreements and objectives. EU energy policy is based on three pillars: competition, security of supply, and sustainable development. Energy security includes aspects such as availability of supply, affordability, and sustainability [11–13]. There are also important goals such as reducing greenhouse gas emissions, increasing the consumption of energy produced from renewable sources, improving energy efficiency, and expanding electricity connections [14–20]. On the one hand, the electricity policy focuses on the liberalization of the entire sector, while on the other hand, it concentrates on development towards more innovative and more sustainable electricity sector [21–27]. All goals were introduced gradually and evolved. The first energy package in 1996 assumed the separation of generation from transmission and distribution, competition in electricity generation, opening the market for large consumers, non-discrimination in access to the grid, and the obligation to provide a safe, reliable, and efficient service by the distribution system operator [28]. The second energy package of 2003 dealt with competition in the retail market for households, unbundling of network activities, the creation of national electricity regulators, and the obligation of the distribution system operator to provide information enabling efficient access to the network [29]. The third energy package assumed the definition of retail supplier switching procedures, the procedures for ownership unbundling of transmission system operators, emphasizing the importance of modernizing the electricity distribution network, and the significance of smart grids and energy efficiency [30]. The 2010 strategy focused on achieving energy efficiency targets and implementing low-carbon technologies [31]. In 2011, targets were set for 2050 for a low-carbon economy [32]. Another document from 2015 concerned supporting the previous goals in the field of EU energy policy [33]. One should also mention the 2016 document on renewable electricity [34].

Electricity is a classic example of a homogeneous commodity. Homogeneous goods (services) can be characterized as physically indistinguishable or perceived as identical in the eyes of the consumer. Since the customer cannot differentiate one product from another it becomes very hard for the seller to compete. Therefore, the consumer can compare prices in different areas and periods. Since 1999, customers have been free to choose their electricity supplier. They have a very large selection in this regard. The area is served by a single operator and by a large number of participants. Energy rates can even vary within the same area. It is the customer who has to seek the best price for himself actively. However, studies show that such activities were not very common. Most often, customers were served by the local operator. Studies have found that only households informed about the tariffs are sensitive to price modifications, in the case of uninformed households the electricity demand is completely price inelastic [35–42]. That is why the EU is taking action to change this. Citizens should take action and be responsible for the energy transition by actively participating in the market. They can choose tariffs as needed but also try to change their electricity consumption patterns. For example, they can use energy to a greater extent during periods of lower grid load. However, information services are needed to achieve these effects [43–48].

In the future, consumers will be prosumers, i.e., they will produce electricity on their own and feed its surplus into the grid. Micro-networks will be created that are isolated or connected to the main network. As a result, prosumers will achieve better economic efficiency by reducing operating costs, and at the same time, contributing to the improvement of the natural environment. However, such transformation takes time [49–60].

Electricity prices is the topic of research in the field of wholesale markets. Many researchers are concerned with the electricity rates in the futures markets. Therefore, energy is the subject of the trade [61–65]. There is very little research about retail prices that relates to private households. In Moreno et al. [66], the authors investigate the determinants which affect the electricity rates in wholesale markets. However, they indicate that the impact on the determinants of household prices is unclear. In the studies by Verbic et al. [67] the relationship between the retail electricity price and energy intensity was examined, but only for households consuming 2500–5000 kWh per year. Waddams Price and Zhu [68], in the paper on the example of the British market, state that the retail electricity market has been subject to free-market laws since the end of the 20th century. Energy distribution companies were divided into regions, but they could also compete in other territories. Nevertheless, companies focused more on securing their position in their region than on acquiring new clients in other territories. It also caused problems, such as a greater impact on energy prices in a given area by one or two companies. As a result, the prices were higher than in the case of competition with multiple companies. Additionally, according to Giulietti et al. [41] the problem is the behavior of consumers who consider it too costly to find a new electricity supplier. Littlechild [69] states in his research that competition in the market is often understood as price competition. The European Commission uses this approach in relation to the retail electricity market. A well-functioning market will require some form of regulatory intervention, but the legal constraints should not be strong.

In many countries, energy prices are part of electoral policies and promises. For example, in Great Britain, the Conservative party promised a tariff protection cap and the Labor party a price cap that would ensure low energy rates [70]. Therefore, there are differences between countries. Another reason is price asymmetry, i.e., prices are more responsive to rising costs than falling costs. With rising electricity rates, households look more for a cheaper solution than falling prices [71–77]. Additionally, households are generally reluctant to change their electricity contract. In Sweden, only 15% of households changed their contracts every year. It is also a problem for policymakers [78]. There are significant financial benefits to shifting tariffs [79]. The moment of changing the contract is also important [80]. There are very few studies that determine that consumers are not paying attention to the price changes. These customers also do not want to receive personalized information on their energy consumption and costs. Such a situation takes place only until a certain threshold is exceeded. Then there is a reduction in energy absorption [81–83]. Other studies confirm the impact of personalized information sent directly to a specific consumer on reducing energy consumption. This effect continued for a long time. Information comparing the absorption of electricity in a given household to neighbors or the national average and moral factors were of particular importance on energy consumption. The price factors were of much less importance [84–91]. This research can influence the choices of decision-makers in the scope of proposed tariffs and shaped pricing policy. Such solutions are already used in the Western Europe [92–94].

There is a lack of research relating retail electricity prices to the parameters of the economy and other factors related to the energy sector. The presented article may fill the resulting research gap.

The paper's main objective is to identify the differentiation and variation of electricity prices for households in EU states. The specific goals are to show the directions of price changes and differentiation in this regard in EU countries, determine the degree of volatility (or stability) of electricity prices, and establish the correlation between electricity prices for household consumers and economic and energy parameters.

Determining the regularities that are present may be useful for policymakers with influence on the electricity markets. The research can also be treated as preliminary for further analysis. Taking the example of the most developed economies, it can be determined what future electricity retail prices in developing countries may become. As a rule, models and regularities are duplicated. Much depends on the level of economic development of the country. Additionally, the division of households into groups shows how the retail price degression is applied depending on electricity consumption. This phenomenon occurred in most EU states. Of course, there were exceptions. Based on these studies, in-depth investigations can be made in the future.

Two hypotheses were put forward in the paper. According to the first one, the level of electricity prices intended for households in the EU states was closely related to the economic situation in a given country, but the strength of this relationship decreased with higher electricity absorption in households. The economic situation was determined by parameters such as: total and per capita GDP value, total and per capita household expenditure, the size of exports and imports. The second hypothesis was that electricity prices for household consumers showed little volatility, but this variability increased with the growth in household energy consumption, especially in the group of economically developed countries.

The limitation of the study is the availability of information. Data was aggregated by country. There were no complete details available for specific regions. Additionally, the data was provided on a semi-annual basis, in line with reporting to statistical offices. In most EU countries, retail energy prices are rarely changed. Therefore, the information used can be considered as sufficient. The division into groups of households according to the amount of energy consumption during the year was also imposed. The given limitations should not affect the interpretation of the obtained test results.

2. Materials and Methods

All members of the European Union were chosen for this project as of 31 December 2019 (28 countries). The analyzed period covered the years 2008–2019. The sources of collected information were the thematic literature review and the data from Eurostat. Descriptive, tabular and graphical methods, constant-based dynamics indicators, coefficient of variation, Kendall's tau correlation coefficient and Spearman's rank correlation coefficient were used to analyze and present the materials.

The research was divided into stages. Figure 1 shows a diagram of the conducted research.

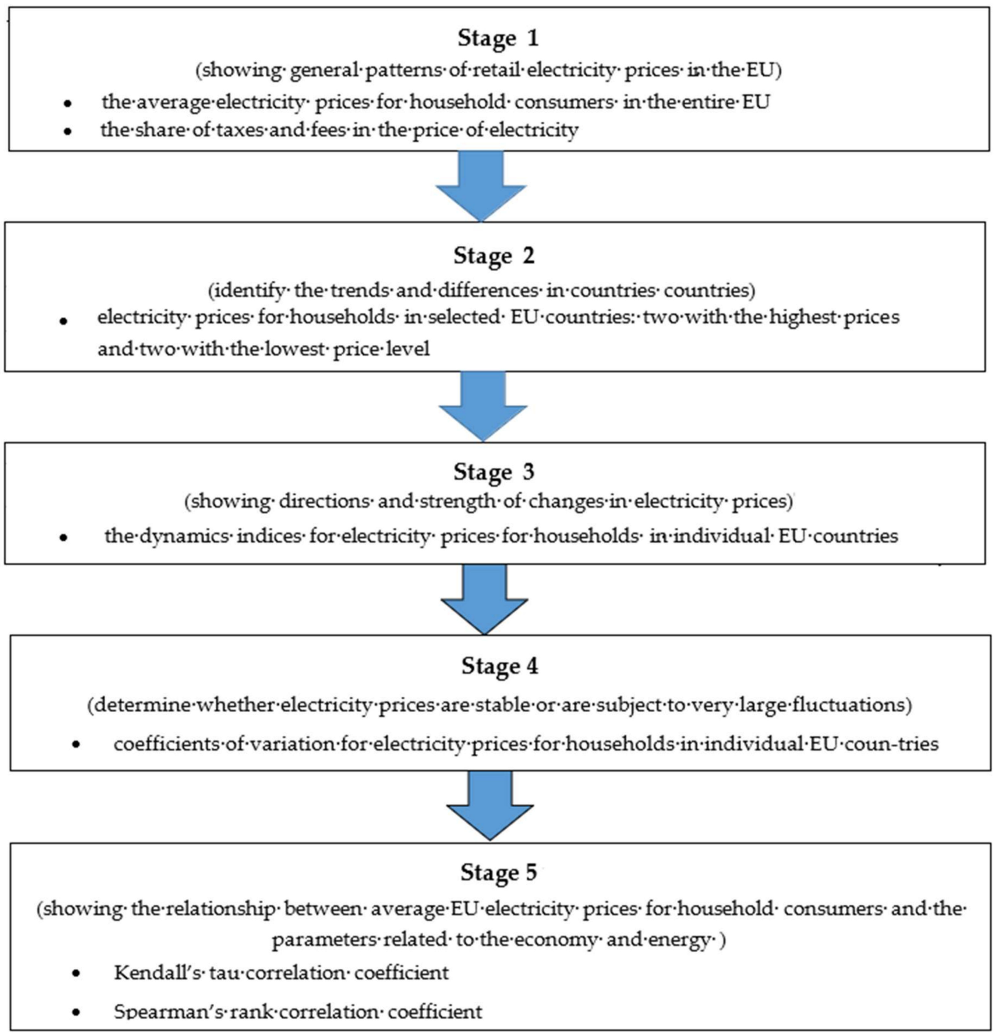

Figure 1. Diagram of the conducted research.

The first stage of this project portrays the average electricity prices for household consumers in the entire EU in 2008–2019. In addition, the share of taxes and fees in the price of electricity was also presented. In both cases, the prices were depicted in five groups of households differing in the volume of electricity consumption during the year. This approach was also used in subsequent stages of the research. This section provides an overview of the general patterns of retail electricity prices in the EU.

In the second phase of the research, electricity prices for households in selected EU countries were presented, i.e., two with the highest prices and two with the lowest price level. As a result, it was possible to determine trends and differences in countries that are on two different poles in the level of retail prices of electricity.

In the third stage, the dynamics indices for electricity prices for households in individual EU countries were estimated. As a result, the data concerning strength and directions of changes in electricity rates was obtained.

The dynamics index with a fixed base can be estimated as follows [95]:

$$i = \frac{y_n}{y_0} \text{ or } i = \frac{y_n}{y_0} \cdot 100\%, \tag{1}$$

where:

y_n—the amount of the occurrence in a certain period,

y_0—the amount of the occurrence during the reference period.

In the fourth phase, the variation coefficients for electricity prices for households in individual EU states were calculated. As a result, it was possible to determine whether electricity prices are stable or are subject to substantial fluctuations.

The variation coefficient marked as C_v eliminates the unit of assessment from the standard deviation of a set of digits. It is done by obtaining the quotient of standard deviation divided by the arithmetic mean. Formally, for sequence of N numbers, the variation coefficient is calculated as follows [96]:

$$C_v = \frac{S}{M}, \tag{2}$$

where:

S—the standard deviation from the exemplar set of numbers,

M—the arithmetic mean of the exemplar set of numbers.

In the fifth stage, the relationship between average EU electricity prices for household consumers and the parameters related to the economy and energy were analyzed. The parameters were purposefully selected based on the literature review. Introduced parameters indicate all the most significant aspects associated with the economy of a particular country and the level of energy development. Thanks to this research project, it is possible to determine the importance of parameters and their strength of association with retail electricity prices. In this phase of the project, two non-parametric tests were applied to define the correlation between the variables. The former one is Kendall's tau correlation coefficient. It is established on the difference between the probability that two variables fall in the same sequence (for the interpreted data) and the probability that these factors are different. This coefficient fluctuates in the range of values <−1, 1>. Value 1 means complete match, value 0 indicates no match of order, and value −1 indicates the complete opposite. The Kendall coefficient suggests not only the robustness but also the direction of the interdependence. It is a good tool to represent the similarity of the ordered sets of data. The following formula can be used to calculate Kendall's tau correlation coefficient [97]:

$$\tau = P[(x_1 - x_2)(y_1 - y_2) > 0] - P[(x_1 - x_2)(y_1 - y_2) < 0]. \tag{3}$$

The given formula evaluates Kendall's tau based on a statistical sample. First, all possible pairs of the observed population are combined. Next, the pairs are split into three possible units:

P—compatible pairs, when the analyzed factors within two observations fluctuate in the same trend, i.e., either in the first observation both are higher than in the second, or both are less significant;

Q—incompatible pairs, when the factors differ against each other in the opposite trend, i.e., one of them is more significant for this observation in the pair, while the other is smaller;

T—related pairs in the case of one of the variables having equal values in both observations.

The Kendall tau coefficient is then calculated from the following formula:

$$\tau = \frac{P - Q}{P + Q - T}. \quad (4)$$

Moreover,

$$P + Q + T = \binom{N}{2} = \frac{N(N-1)}{2}, \quad (5)$$

where:

N—the sample volume.

The pattern can be quantified as:

$$\tau = 2\frac{P - Q}{N(N-1)}. \quad (6)$$

The latter form of non-parametric tests is the Spearman's rank correlation coefficient, which describes the strength of the correlation of two characteristics. It is used to analyze the relationship between quantitative traits for the small amount of observations. Spearman's rank correlation coefficient is estimated according to the following formula [98]:

$$r_S = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)}, \quad (7)$$

where:

d_i—the disparity between the range of the corresponding factors x_i and feature y_i (i = 1, 2, . . . , n)

The Spearman's rank coefficient fluctuates in the range $-1 \leq r_s \leq +1$. A positive number indicates a positive correlation, while a negative digit indicates a negative correlation. The more similar modulus (absolute value) of the correlation coefficient, the more robust the correlation between analyzed variables.

The following techniques were used for data presentation: descriptive, tabular, and graphic.

3. Results

3.1. Medium Electric Prices for Households in the EU Together

Electricity prices for households in the member states of European Union are grouped by category according to the amount of consumption. There are five clusters. Firstly, the average electricity prices for household customers in all EU countries in 2008–2019 are presented (Figure 2). The prices were given on a semi-annual basis. By far the highest electricity prices were in the case of the lowest consumption, up to 1000 kWh per year. The more electricity was consumed by the households, the lower the price for 1 kWh. Such a regularity seems logically justified and results from the economy of scale. Nevertheless, the disproportions between prices in individual classes were visible, especially in households consuming the least energy and those with the highest consumption. In the following years, the differences deepened. In 2008–2019, energy prices in households consuming up to 1000 kWh increased by 53% to EUR 0.38 per kWh. This increase was slightly smaller in the next group (from 1000 to 25,000 kWh) (46%). In the next group, i.e., 2500 to 5000 kWh, prices increased by 37%, and in the following two (from 5000 to 15,000 kWh and above 15,000). kWh) by 33 and 30% respectively.

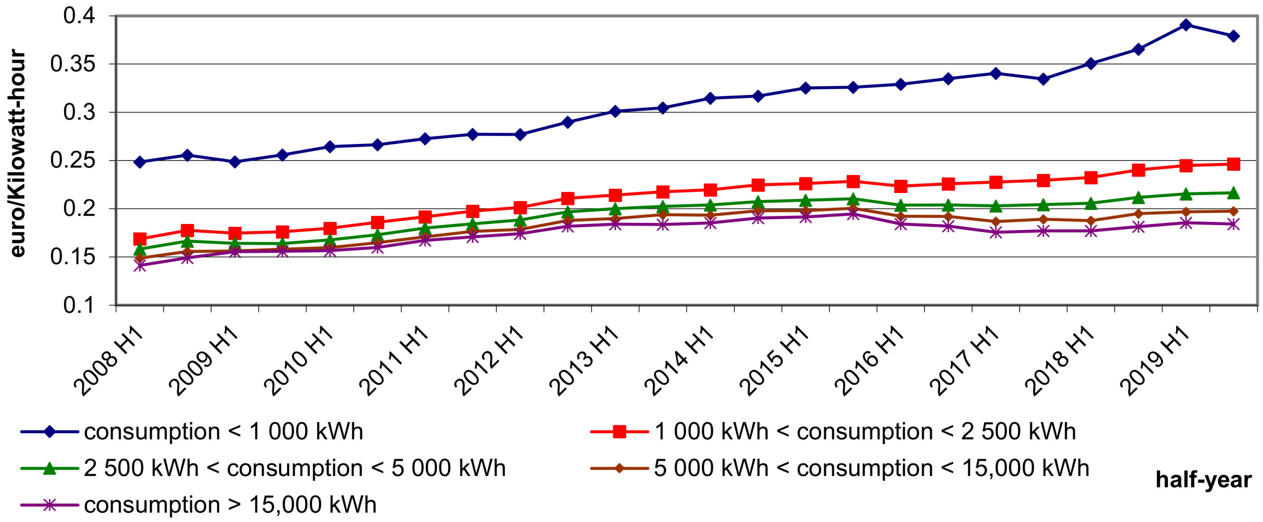

Figure 2. Electricity prices for private customers in European Union in 2008–2019.

The share of taxes and tariffs in the price of electricity supplied to private households was also determined (Figure 3). It was by far the highest in the case of households with the highest electricity consumption. A regularity was found according to which the higher the consumption of electricity, the more taxes and charges were included in the price of energy. Additionally, the disproportions deepened. In 2008, in households consuming up to 1000 kWh in the price of energy, there were 29% in taxes and fees, and in 2019 as much as 32%. On the other hand, in households with the highest electricity consumption (over 150,000 kWh), these shares amounted to 40% in 2008 and 43% in 2019, respectively. It can be concluded that higher energy consumption was burdened with relatively higher taxes, although the unit energy price was lower compared to households with low energy consumption.

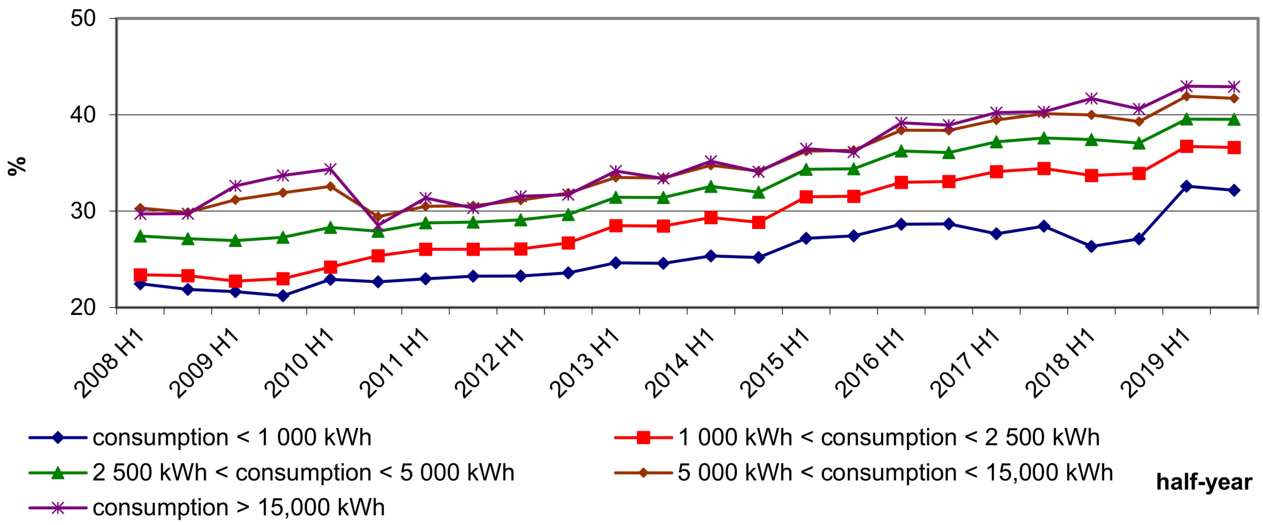

Figure 3. The contribution of levies and taxes in electricity prices for private customers in European Union in 2008–2019.

3.2. Electric Prices for Households in Selected EU Countries

Electricity prices for private households varied. It could also be the case in the direction of changes. There was no country with the highest electricity prices in each consumption group. In order to select examples of countries for a more detailed analysis, the investments received by individual countries in each of the groups in terms of energy consumption were compared. The highest electricity prices for households were in Germany. In 2019, this country was in the first positions in the groups of 1000–2500 kWh and 5000–15,000 kWh, second in 2500–5000 kWh and above 15,000 kWh, and fourth in the group below 1000 kWh. Another state with very high electricity prices was Denmark, ranking 1st, 2nd, 3rd, 4th, and 11th in individual groups. The same was done in the case of countries with the lowest electricity prices for households. It was a little easier in this case. Bulgaria was last in the EU in all groups in terms of consumption volume, while Hungary was in the penultimate place respectively.

In Germany, the electricity prices intended for households in the group with the smallest consumption volume, i.e., up to 1000 kWh, were the highest (Figure 4). Additionally, the differences between extreme groups deepened. Electricity prices in Germany in the 1000 kWh group increased by 34%, and in the over 15,000 kWh group by only 24%. The share of taxes and tariffs in the price of electricity in Germany in 2008 was 31% in the group with consumption up to 1000 kWh and 41% in the group with consumption above 15,000 kWh. In 2019, it was 40 and 61%, respectively. Therefore, it can be concluded that the increase in electricity prices in Germany was largely due to the increase in taxes and fees.

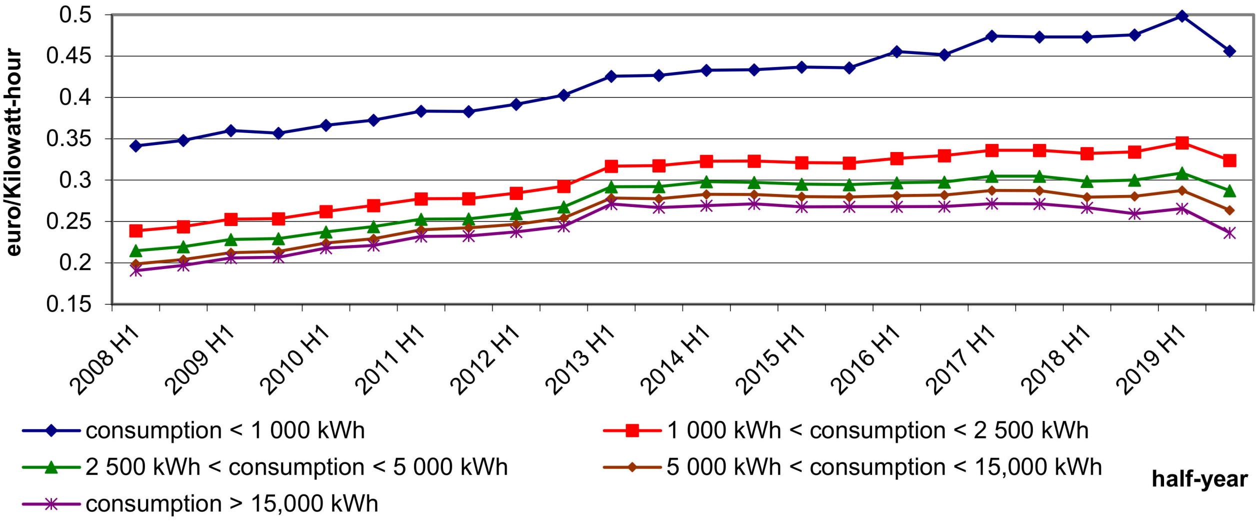

Figure 4. Electricity prices for private customers in Germany in 2008–2019.

In Denmark, in 2008–2019, there was a 9% drop in electricity prices for private households consuming the highest volumes, i.e., over 15,000 kWh (Figure 5). In the group with the lowest consumption, up to 1000 kWh, electricity prices increased by 26%. As a result, the disparities widened even more. In the case of Denmark, the prices in 2008–2014 in the groups with the lowest energy consumption, i.e., up to 1000 kWh and 1000–2500 kWh, were at the same level. It was similar in the given period in the two groups with the highest consumption, i.e., 5000–15,000 kWh and above 15,000 kWh. Since 2015, there have been differences in electricity prices between the five groups differing in terms of consumption. In Denmark, in 2008, in the price of electricity intended for households, taxes and charges accounted for 54% of this price in the group with consumption up to 1000 kWh, and 59% in the group above 15,000 kWh. In 2018, it was 55 and 56%, respectively. The tax burdens and charges for the electricity price in the group consuming more than 15,000 kWh decreased and slightly increased in the group with the lowest energy consumption.

One of the lowest electricity prices for private households was in Hungary (Figure 6). In addition, in this state in 2008–2019, there was a decrease in energy prices in all groups. On average, it was 30%, but it was the highest in energy consumption above 15,000 kWh (a decrease by 33%). Additionally, the differentiation by the group has become less and less visible. Price levels, especially in 2019, were almost identical. In Hungary, there was also a small fraction of taxes and tariffs in the price of electricity intended for private households. In 2008, it was 17–18% in individual groups, and in 2019, 21%. Still, it must be remembered that this is a relative share, and energy prices have fallen. The tax burden on consumers has not changed in real terms, taking into account only the absolute value.

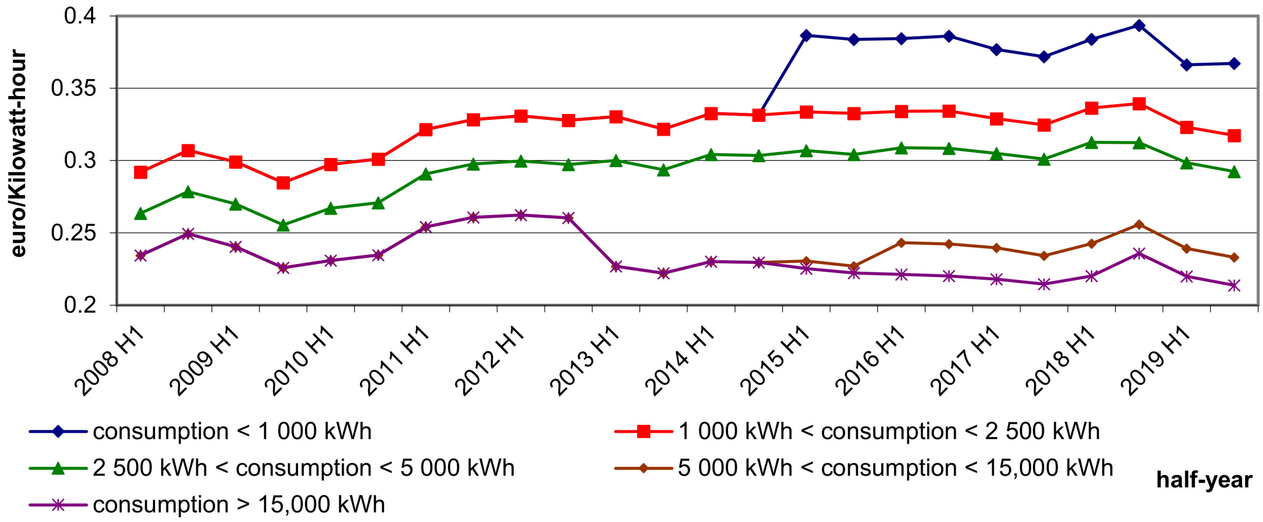

Figure 5. Electricity prices for household consumers in Denmark in 2008–2019.

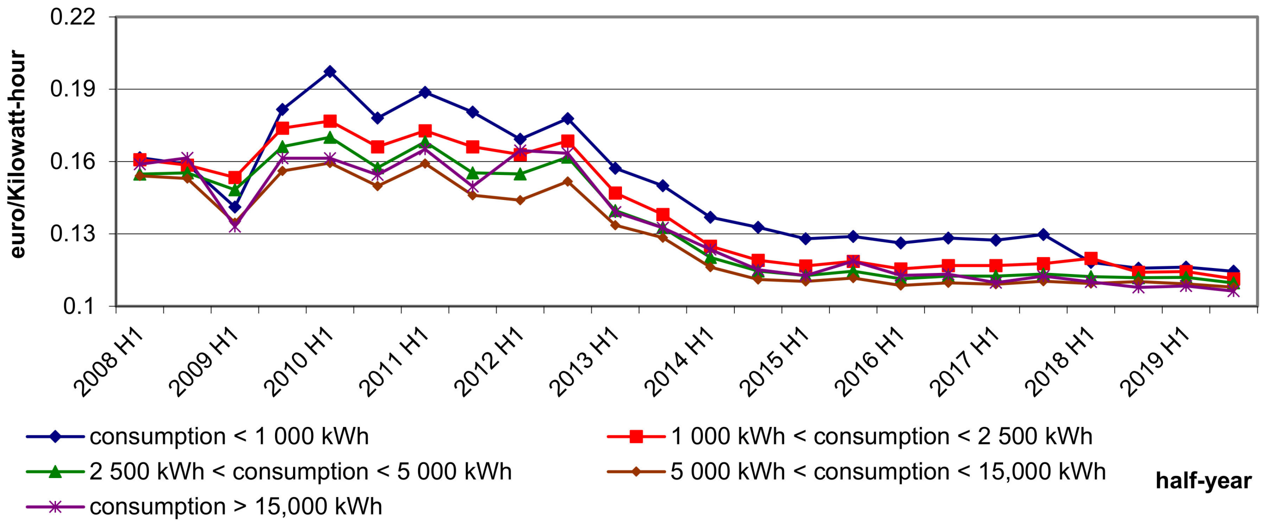

Figure 6. Electricity prices for private customers in Hungary in 2008–2019.

Definitely, the lowest prices of electricity for households were in Bulgaria (Figure 7). Although in 2008–2019 electricity prices soared by 32–37% in individual groups, the prices were still the lowest in the entire EU. In the case of Bulgaria, there were also no big differences in electricity prices between private households with different consumption volumes. It also results from the approach of the state and energy companies to the pricing policy. The share of taxes and charges in the energy price did not change in this country and amounted to 17%.

The presented examples of countries show some models of electricity pricing for households. In countries with the highest electricity prices, there was a significant differentiation of the price level depending on the volume of energy consumption. Additionally, prices were systematically growing there, and there was a very large share of taxes and fees in the price of electricity. On the other hand, in the countries with the lowest electricity prices, there was little variation between clusters in terms of the volume of energy absorption. Very low taxes and fees were also applied. Maybe that is why electricity prices were very low. The differences resulted from trends in prices, because in Hungary they fell by 30%, while in Bulgaria they increased by over 30%. Therefore, the directions of price changes were different.

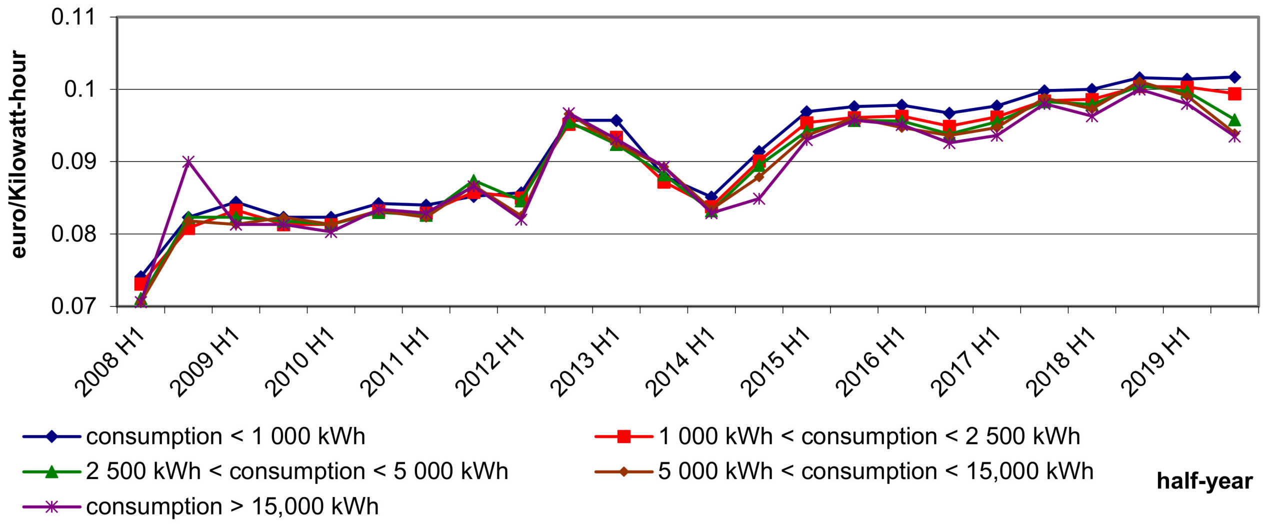

Figure 7. Electricity prices for private customers in Bulgaria in 2008–2019.

3.3. Directions of Changes of Electric Prices for Households in EU Countries

In the next stage, the dynamics indicators for electricity prices intended for private households were calculated. Similarly, the division into clusters according to the consumption volume was applied. As the basis the level of prices from 2008 was applied (Table 1). The results were ordered in descending order due to the dynamics for the smallest volume of electricity consumption, i.e., up to 1000 kWh. Electricity prices have risen in most EU countries over the past 11 years. In addition to the aforementioned Hungary and Denmark, there were also declines in Ireland. The most significant increase in electricity prices was recorded in Malta for households consuming up to 1000 kWh. Prices there increased more than six times. There was only one energy supplier in Malta, which could have had the most significant impact on such a large increase in energy. On the contrary, the level of energy prices doubled in Latvia, Great Britain, and Estonia. In Latvia and Estonia, the markets were dominated by single energy suppliers with a large market share, 63% and 80%, respectively, in 2019. In Great Britain, the largest supplier had around 20% of the market share. The shifts in electricity prices may also result from energy policies implemented by individual EU states. Each country should be analyzed individually due to the existing socio-economic circumstances. In general, the largest increases in electricity prices occurred in the economically developed countries of Western Europe. The largest price drops or the smallest increases in developing economies of Central and Eastern Europe. In these countries, there was more significant public pressure to keep electricity prices lower.

3.4. Variability of Electric Prices for Households in EU Countries

Then, the coefficients of variation for electricity prices intended for households were calculated. The results, as before, were presented in five groups differing in the volume of energy consumption. The results concern the years 2008–2019 and have been ordered in ascending order according to the volatility of electricity prices in the group of households consuming up to 1000 kWh per year (Table 2). Electricity price volatility was not too great. In many countries, the price change took place twice a year, and the amplitude of these changes was small. As a result, the prices slightly deviated from the average price over the period. The largest price fluctuations occurred in Latvia, Malta, Greece, and Belgium. Slovakia, Poland, the Czech Republic, Croatia, and Bulgaria were the most stable countries regarding energy prices for households. These were economically developing countries that wanted to ensure the stability of electricity prices to their citizens. In general, there was no universal trend for all EU states. The reason, except from diverse economic development and applied government policies in these countries, could also be the various levels of energy development, the pressure of society, as well as the social consent to apply various charges in the price of energy, e.g., for the development of renewable energy.

Table 1. Dynamics indicators for electricity prices for household consumers by volume of consumption in EU member states in 2008–2019 (year 2008 = 100).

Countries	Dynamics Factors for Household Consumers in 2008–2019				
	<1000 kWh	1000–2500 kWh	2500–5000 kWh	5000–15,000 kWh	>15,000 kWh
Malta	752.36	239.74	131.42	115.97	231.69
Latvia	268.82	204.48	194.77	189.88	199.24
United Kingdom	212.31	160.22	151.58	149.00	136.42
Estonia	194.87	176.87	173.34	170.53	182.06
Spain	186.34	186.54	175.26	160.60	151.18
Belgium	179.96	142.68	145.03	148.59	131.53
Finland	175.43	167.19	145.79	143.95	141.17
Italy	169.54	159.86	115.26	100.69	103.78
Cyprus	167.31	134.43	125.62	121.79	118.53
France	163.45	157.90	157.71	164.56	168.28
Slovenia	162.59	157.64	145.25	136.30	126.44
Greece	162.27	177.26	148.14	129.56	146.76
The Netherlands	161.61	136.34	116.17	109.58	109.05
EU	152.56	145.97	136.83	132.66	130.29
Austria	145.17	122.34	116.58	111.84	106.80
Luxembourg	142.76	116.30	109.36	105.15	138.23
Lithuania	141.00	142.89	145.81	149.50	150.46
Sweden	140.31	128.98	122.26	118.79	111.64
Bulgaria	137.25	135.98	134.74	133.00	132.44
Germany	133.59	135.62	133.75	132.60	123.91
Romania	132.81	132.28	133.93	137.68	134.60
Czechia	129.05	123.61	126.34	134.65	147.50
Denmark	125.72	108.66	110.97	99.40	91.17
Portugal	113.48	142.54	147.17	156.24	157.78
Slovakia	105.56	109.03	111.54	116.29	130.74
Poland	104.55	110.61	109.29	116.16	113.42
Croatia	103.46	128.73	133.74	138.39	141.36
Ireland	92.56	151.84	143.92	140.52	133.60
Hungary	70.85	69.28	70.87	70.02	66.90

Table 2. Coefficients of variation for electricity prices for private customers by volume of consumption in EU states in 2008–2019.

Countries	Coefficients of Variation for Electricity Prices for Household Consumers				
	<1000 kWh	1000–2500 kWh	2500–5000 kWh	5000–15,000 kWh	>15,000 kWh
Slovakia	0.05	0.06	0.06	0.08	0.09
Poland	0.06	0.06	0.06	0.07	0.07
Czechia	0.07	0.07	0.08	0.08	0.11
Croatia	0.07	0.10	0.08	0.08	0.09
Portugal	0.08	0.13	0.15	0.17	0.18
Bulgaria	0.09	0.08	0.08	0.08	0.08
Denmark	0.10	0.05	0.06	0.05	0.06
Germany	0.11	0.11	0.11	0.11	0.11
Sweden	0.11	0.08	0.07	0.07	0.07
The Netherlands	0.11	0.14	0.08	0.06	0.21
Romania	0.11	0.11	0.11	0.11	0.12

Table 2. *Cont.*

Countries	Coefficients of Variation for Electricity Prices for Household Consumers				
	<1000 kWh	1000–2500 kWh	2500–5000 kWh	5000–15,000 kWh	>15,000 kWh
Lithuania	0.12	0.12	0.12	0.13	0.14
Luxembourg	0.12	0.05	0.04	0.05	0.08
EU	0.13	0.11	0.09	0.09	0.08
Austria	0.13	0.06	0.04	0.03	0.04
Finland	0.14	0.13	0.09	0.09	0.09
Slovenia	0.17	0.12	0.10	0.08	0.06
Hungary	0.17	0.17	0.17	0.15	0.17
France	0.18	0.14	0.14	0.15	0.15
Estonia	0.19	0.17	0.16	0.15	0.16
Ireland	0.20	0.14	0.11	0.10	0.09
Italy	0.22	0.13	0.07	0.11	0.17
Cyprus	0.22	0.20	0.18	0.18	0.19
Spain	0.24	0.17	0.15	0.13	0.12
United Kingdom	0.25	0.16	0.14	0.15	0.15
Belgium	0.26	0.16	0.15	0.16	0.17
Greece	0.27	0.23	0.17	0.15	0.14
Malta	0.27	0.19	0.14	0.10	0.20
Latvia	0.30	0.20	0.18	0.17	0.17

3.5. Relation between Electric Prices for Households and the Economic and Energy Parameters in the EU

Kendall's tau and Spearman's rank correlation coefficients were computed to find the relationship between the prices of electricity intended for households in the EU and the economic and energy parameters (Tables 3 and 4). $p = 0.05$ was used as marginal value of the level of importance. Irrelevant results are highlighted in the table as red font. Correlation coefficients were computed for the entire EU for the whole period of 2008–2019. The research project attempted to check the correlation, which does not suggest that a given factor impacts on another but that there is a significant or minor relationship. In the case of electricity prices for households, the calculations were made using the average annual prices in particular groups that differ in the volume of energy consumption. Electricity prices for private customers were normally distributed. For example, the distribution of electricity prices was also given for households consuming between 2500 and 5000 kWh per year, i.e., for the middle group according to the volume of consumption (Figure 8).

For most parameters, strong association with electricity prices intended for households was found. This relationship was strong or very strong in most cases. Strongly positive relationships were found in the relation of electricity prices and all economic parameters. It was not important whether the parameters apply to the entire EU as a political group or apply per capita. It can therefore be concluded that a higher standard of living was associated with higher electricity prices. The societies of economically developed countries are wealthy and can accept higher energy prices. In contrast, in developing countries, the society is poorer, and people only accept lower electricity prices to match their incomes. Higher imports were also associated with higher consumption. On the other hand, exports proved that the obtained funds were obtained, for example, for the import of goods. Additionally, along with the increase in energy absorption by households, the strength of the association between electricity prices and economic parameters decreased. Such results were noticed in both tests.

Table 3. Kendall's tau correlation coefficients between energy economy parameters and the electricity prices for private customers in the EU.

Tested Parameters	**Kendall's Tau Correlation Coefficient**									
	<1000 kWh		**1000–2500 kWh**		**2500–5000 kWh**		**5000–15,000 kWh**		**>15,000 kWh**	
	τ	***p*-Value**	**τ**	***p*-Value**	**τ**	***p*-Value**	**τ**	***p*-Value**	**τ**	***p*-Value**
Correlation coefficients between electricity prices for household consumers and										
GDP value	0.939	0.001	0.909	0.001	0.758	0.001	0.606	0.008	0.515	0.024
Final consumption expenditure of households	0.939	0.001	0.909	0.001	0.758	0.001	0.606	0.008	0.515	0.024
Export of goods and services	0.939	0.001	0.909	0.001	0.758	0.001	0.606	0.008	0.515	0.024
Import of good and services	0.909	0.001	0.879	0.001	0.727	0.001	0.576	0.011	0.485	0.034
GDP per capita	0.939	0.001	0.909	0.001	0.758	0.001	0.606	0.008	0.515	0.024
Final consumption expenditure of households per capita	0.939	0.001	0.909	0.001	0.758	0.001	0.606	0.008	0.515	0.024
Total energy consumption	−0.151	0.451	−0.182	0.373	−0.333	0.115	−0.485	0.024	−0.515	0.016
Energy productivity in Euro per kilogram of oil equivalent	0.970	0.001	0.939	0.001	0.788	0.001	0.636	0.005	0.545	0.016
Energy productivity in Purchasing power standard (PPS) per kilogram of oil equivalent	0.970	0.001	0.939	0.001	0.788	0.001	0.636	0.005	0.545	0.016
Share of renewable energy in gross final energy consumption	0.999	0.001	0.970	0.001	0.818	0.001	0.667	0.003	0.576	0.011
Share of renewable energy in gross final energy consumption of electricity	0.999	0.001	0.970	0.001	0.818	0.001	0.667	0.003	0.576	0.011
Greenhouse gas emissions intensity of energy consumption	−0.999	0.001	−0.970	0.001	−0.818	0.001	−0.667	0.002	−0.576	0.008
Final energy consumption in households per capita	−0.595	0.006	−0.629	0.004	−0.687	0.002	−0.595	0.006	−0.565	0.009

Another group of parameters concerns energy indicators. A very high positive correlation was found between electricity prices for households and energy production yield in Euro per weight unit of oil equivalent and energy production yield in purchasing power standard (PPS) per weight unit of oil equivalent. The purchasing power standard parameter already considered the differences between countries resulting from different product prices and different levels of wages, i.e., differences in the purchasing power of the society. As a result, the situation in individual countries was somewhat more realistic. Electricity prices were also high in countries with high energy productivity. As a rule, higher productivity was associated with a higher level of economic development. Electricity was not the key factor in many countries, so the total energy consumption parameter was less important. The negative relation was significant only in the case of groups of households consuming more energy. In the parameter related to energy consumption per capita, there were significant negative relationships in all groups of farms. The level of renewable energy utilization in electricity production was significant. In turn, considering the extent of renewable energy utilized in the total energy production, the dependencies were significant. Along with the growth of energy absorption by households, the strength of the relationship between electricity prices and energy parameters decreased. A very strong and negative relationship was found between the energy consumption and the intensity of greenhouse gasses emissions. Lower emissions of greenhouse gases corresponded to higher electricity prices. As a rule, economically developed countries use less harmful technologies to the environment, and those developing countries paid less attention to environmental aspects, including greenhouse gas emissions.

Table 4. Spearman's rank correlation coefficients between energy economy parameters and the electricity prices for private customers in the EU.

Tested Parameters	Spearman's Rank Correlation Coefficient									
	<1000 kWh		1000–2500 kWh		2500–5000 kWh		5000–15,000 kWh		>15,000 kWh	
	r_s	*p*-Value	r_s	*p*-Value	r_s	*p*-Value	r_s	*p*-Value	r_s	*p*-Value
Correlation coefficients between electricity prices for household consumers and										
GDP value	0.979	0.001	0.972	0.001	0.895	0.001	0.762	0.001	0.671	0.050
Final consumption expenditure of households	0.979	0.001	0.972	0.001	0.895	0.001	0.762	0.001	0.671	0.050
Export of goods and services	0.979	0.001	0.972	0.001	0.895	0.001	0.762	0.001	0.671	0.050
Import of good and services	0.972	0.001	0.965	0.001	0.888	0.001	0.741	0.001	0.650	0.050
GDP per capita	0.979	0.001	0.972	0.001	0.895	0.001	0.762	0.001	0.671	0.050
Final consumption expenditure of households per capita	0.979	0.001	0.972	0.001	0.895	0.001	0.762	0.001	0.671	0.050
Total energy consumption	−0.182	0.100	−0.189	0.100	−0.406	0.100	−0.662	0.050	−0.678	0.050
Energy productivity in Euro per kilogram of oil equivalent	0.993	0.001	0.986	0.001	0.909	0.001	0.776	0.001	0.685	0.050
Energy productivity in purchasing power standard (PPS) per kilogram of oil equivalent	0.993	0.001	0.986	0.001	0.909	0.001	0.776	0.001	0.685	0.050
Share of renewable energy in gross final energy consumption	0.999	0.001	0.993	0.001	0.916	0.001	0.783	0.001	0.692	0.050
Share of renewable energy in gross final energy consumption of electricity	0.999	0.001	0.993	0.001	0.916	0.001	0.783	0.001	0.692	0.050
Greenhouse gas emissions intensity of energy consumption	−0.999	0.001	0.993	0.001	−0.916	0.001	−0.783	0.001	−0.692	0.050
Final energy consumption in households per capita	−0.788	0.001	−0.806	0.001	−0.872	0.001	−0.781	0.001	−0.739	0.010

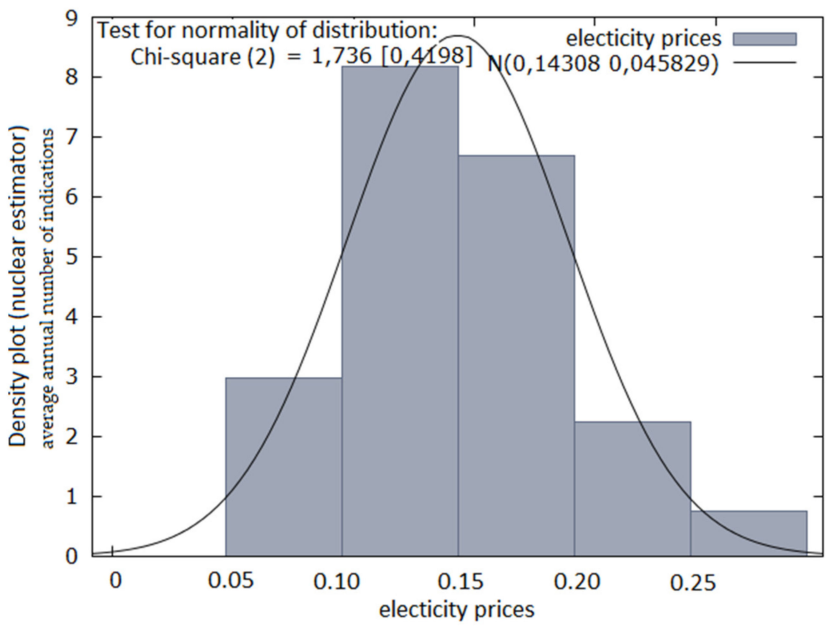

Figure 8. Graph of kernel density estimation for electricity prices for household consumers in a group consuming 2500–5000 kWh in EU in 2008–2019.

4. Discussion

In developed economies' markets, renewable energy resources (especially wind and solar power) reduced electricity prices, and increased their variability. With a small share of renewables, the price volatility decreased [99–107]. The study of the authors of the article also confirmed these dependencies because Western European states, with higher percentage of renewable energy in total energy, were represented by greater electricity prices than Eastern EU states with a lower contribution of renewable energy. The differences in electricity prices in individual countries result from the approach to their determination. Often, the electricity price depends on the node rather than market conditions, i.e., over or under energy. Marginal costs that vary with the technologies and energy sources used are also taken into account. The price of electricity is increasingly dynamically set in real-time depending on energy demand and supply [108–112]. Therefore, there are significant differences in the price of electricity in Western European states, depending on the amount of consumption. In the price of electricity there are also included taxes and tariffs that reflect external environmental costs and effectively reduce energy consumption. Thus, many countries have a double dividend that stimulates economic activity while reducing emissions. Such systems were more effective in economically developed countries than in developing countries [113–117].

In the short run, the low price of electricity may favor economic development. However, the low price of electricity, in the longer term, will encourage expansion of energy-intensive industries with low added value, which is not good for the optimization and modernization of the industrial structure. Therefore, the policy of low electricity prices is detrimental to sustainable economic growth in the long term. [118–121]. In the study by the authors of this article, a fairly clear division between developing countries with low electricity prices and economically developed countries with high prices was found. Rising electricity prices are forcing countries to invest in improvement of energy efficiency. Promoted technologies were based on renewable energy that stimulates economic growth [122–125]. The presented relationships are consistent with those obtained during the research of the authors of the article.

Research of other authors also found a high dependence of GDP per capita on energy consumption and electricity prices in households. A higher level of DGP per capita was associated with better energy consumption and higher electricity prices [66,126]. Raising electricity prices in many countries is an effective method of increasing energy efficiency. It is performed by using various types of taxes and levies as part of the electricity price [127–130]. There is a belief that electricity prices should take into account all externalities and thus affect consumers. Such an impact is possible, especially in economically developed countries [131].

In the future, electricity prices will be affected by changes taking place in the energy market. Virtual power plants will be created, connecting scattered producers of renewable energy. Thus, intelligent energy networks will be created, and the system will be highly decentralized [132–134]. The structure of devices that use electricity will also change. The greatest consumption will be related to devices using information technology, including mobile. Households will, in a way, depend on these devices and will agree to the prices of electricity. However, the innovations introduced in this industry contribute to the greater energy efficiency of the devices used [135–139].

5. Conclusions

The conducted research allowed for drawing several conclusions:

1. Electricity prices in the EU grew steadily. However, there were differences in these rates depending on the volume of consumption. The more electricity a household consumed per year, the less it paid for 1 kWh. These regularities were not always met in individual countries, especially in developing countries in Central and Eastern Europe such as Hungary and Bulgaria. Hungary was one of the few countries where electricity prices fell;

2. Across the EU, electricity prices were growing fastest in households consuming the least energy, i.e., up to 1000 kWh, and the slowest in households with the highest consumption, i.e., above 1000 kWh. As a result, the disproportions between prices in these groups of households increased. Such regularities occurred especially in highly developed countries such as Denmark and Germany;
3. The highest prices of electricity intended for households were generally found in economically developed states of Western Europe and the lowest in economically developing states of Eastern EU. This is because socio-economic factors are of great importance here;
4. Higher electricity prices for households were associated with better economic parameters of the country, but the strength of this relationship decreased with increasing electricity consumption in households. Thus, the first hypothesis was confirmed. These results confirm the regularity according to which developed countries must have higher energy prices because they will ensure energy transformation, i.e., the implementation of energy-saving technologies. At low prices, such actions would not be economically justified. In highly developed economies, the percentage of taxes and tariffs in the price of electricity was much higher than in developing countries. In Western Europe, there was a differentiation in the amount of taxes and charges depending on the volume of electricity consumption. As a rule, the load increased along with the growth in the amount of consumption. Societies in these countries were more prosperous and aware, so they agreed to additional taxes due to higher energy consumption;
5. Electricity prices for households in the EU countries were not subject to large fluctuations. They were most stable in developing economies, such as Slovakia, Poland, and the Czech Republic, and least stable in highly developed countries such as Malta, Belgium, and Great Britain. Overall, in the EU states, electricity prices for household consumers showed little variability, but the volatility increased with the growth of the level of household energy absorption, especially in the group of highly developed countries. Thus, the second hypothesis was confirmed;
6. Price changes may result from national policy and the type of energy market in a given country. For example, in the countries with dominant position of one energy supplier, there may have been significant increases in electricity prices. On the contrary, governments of individual states can also influence electricity prices in other countries, especially where the pressure of society to maintain lower electricity prices is greater;
7. Subsequent research may focus on the relationship between energy prices and the implementation of climate policy in individual countries. One can compare individual countries with each other or groupings of countries. Countries can also be grouped according to the level of economic development. Research may also focus on the importance of various types of taxes in the price of energy. By definition, this type of taxes should be spent mostly on improving energy efficiency, i.e., restructuring the energy sector. Such actions, in turn, will affect the implementation of climate commitments by individual countries.

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Article

Assessment of the Economic Efficiency of the Operation of Low-Emission and Zero-Emission Vehicles in Public Transport in the Countries of the Visegrad Group

Sławomir Stec

Department of Economics, Faculty of Management, Rzeszów University of Technology Ignacy Łukasiewicz, 35-959 Rzeszów, Poland; s.stec@prz.edu.pl

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Abstract: Transport is one of the key sectors of the European economy. However, the intensive development of transport caused negative effects in the form of an increase in the emission of harmful substances. The particularly dramatic situation took place in the V4 countries. This made it necessary to implement solutions reducing emissions in transport, including passenger transport. Such activities can be implemented in the field of implementation of low-emission and zero-emission vehicles for use. That is why the European Union and the governments of the Visegrad Group countries have developed numerous recommendations, communications, laws, and strategies that order carriers to implement low- and zero-emission mobility. Therefore, transport organizers and communication operators faced the choice of the type of buses. From an economic point of view, each entrepreneur is guided by the economic efficiency of the vehicles used. Hence, the main aim of the article was to conduct an economic evaluation of the operational efficiency of ecological vehicles. As more than 70% of vehicles in use in the European Union are still diesel driven, the economic efficiency assessment was also made for vehicles with traditional diesel drive. To conduct the research, the method of calculating the total cost of ownership of vehicles in operation was used. As a result of the research, it was found that electric buses are the cheapest in the entire period of use (15 years), and then those powered by CNG. On the other hand, the cost of using hydrogen buses is the highest. This is due to the high purchase prices of these vehicles. However, the EU, as well as the governments of individual countries, support enterprises and communication operators, by offering them financing for investments. The impact of the forecasted fuel and energy prices and the planned inflation on operating costs was also examined. In this case, the analyses showed that the forecasted changes in fuel and energy prices, as well as the expected inflation, will significantly affect the costs of vehicle operation and the economic efficiency of using various types of drives. These changes will have a positive impact on the implementation of zero-emission vehicles into exploitation. Based on the analyses, it was found that in 2035 hydrogen buses will have the lowest operating costs.

Keywords: Visegrad Group; energy efficiency; social and economic aspects of energy; economic efficiency; low emissions; zero emissions

1. Introduction

Transport, as highlighted in the Transport in the European Union—Current Trends and Issues [1] report, is a key sector of the European economy. It provides products and services both to citizens and economic operators of EU Member States, including the V4 countries and to their trading partners. It is an important instrument for ensuring mobility, contributing to the free movement of people in the internal market. According to EU data, covering 27 Member States, 10.1 million people were employed in the transport department in 2017, which accounted for 5.38% of the total number of employees.

In turn in passenger transport, in 2017, more than 2 million people were employed, which constituted 1.08% of the total number of employees. The structure of employment in transport in the V4 countries is similar. The largest number of people employed in transport per all employees was in Hungary—5.73%, and the lowest in Slovakia—4.50%. When it comes to people employed in passenger transport, the most people work in this sector in Hungary—1.13% of the total number of employees, and the least in Slovakia—0.62%.

It should be added that in 2017 the number of people employed in transport in the entire EU increased by 1.2 (percentage points) compared to 1995 and by about 0.2 (percentage points) compared to 2015 [2]. According to Eurostat data, the transport department successfully increased its share in the gross domestic product (GDP) of the EU from 4% in 1995 to over 5% in 2019. Unfortunately, the COVID-19 pandemic, which hit the transport department quite hard, caused the share in 2020 to drop by 1.6% in GDP. The Czech Republic and Slovakia were the most severely affected, where the decline was at the level of −2.2% and −2.3%. On the other hand, in Poland, there was a decrease of −0.7%, while in Hungary the level of the share of transport in GDP did not change [3].

The development of transport also translates into the dynamics of changes in passenger transport. Between 1995 and 2018, the number of passengers in the EU-27, expressed in passenger-kilometers (pkm), increased by 31.5% [2]. Forecasts show that passenger transport in 2018–2050 will increase by approx. 32.5% [4].

However, the successful development of transport brings with it negative effects in the form of increased air pollution. This is the transport, including passenger transport, that generates a significant part of harmful substances, including non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM) $PM_{2.5,}$ and PM_{10} [5]. The report published in 2020 by the European Environment Agency (EEA) shows limit values of air quality exceeded in 2018 in most EU Member States. Therefore, PM_{10} in 20 countries; $PM_{2.5}$—6; O_3—20; NOx—16; BaP—14. Unfortunately, the countries belonging to the Visegrad Group (V4) are in the lead in these statistics, as in the countries, standard levels of each harmful substance have been exceeded [6]. Transport is also a major contributor to greenhouse gas emissions, ranking second after the energy generation sector. In 2019, around 30% of the CO_2 emitted in the EU, was generated by transport. Road transport is the most responsible for 72% of all transport emissions [7]. Unfortunately, in this regard, the situation is constantly becoming worse. From 1995 to 2018, CO_2 emissions in transport in the EU increased by 23.6%, but in the last decade, there was a slowdown, as in 2018 transport generated 2.5% more CO_2 into the atmosphere than in 2010 (Table 1). The situation is even worse in the V4 countries. In Poland, the increase in CO_2 emissions from transport in 2018 compared to 1995 amounted to as much as 181%. In the Czech Republic and Hungary, the emission growth dynamics in the presented period amounted to approx. 85%, and in Slovakia to 41.8%. Similar to the EU, also in the V4 countries, a decreasing dynamic of the increase in greenhouse gas emissions have been observed.

Table 1. CO_2 emissions by transport in the V4 and EU countries.

Country	1995	2010	2018	% 2018/1995	% 2018/2010
EU 27	876.4 661.9 *	1056.4 763.4 *	1083.1 777.0 *	123.6 117.4 *	102.5 101.8 *
Czech Republic	10.8	17.6	20.1	186.1	114.2
Hungary	7.9	12.2	14.6	184.8	119.7
Poland	24.3	50.9	68.3	281.1	134.2
Slovakia	5.5	7.5	7.8	141.8	104.0

* Road transport; Source: own study based on Eurostat data [2].

Given the systematic increase in the level of greenhouse gas emissions in this sector, which is carrying the risk of undermining the results of EU action, it is becoming increasingly important to build a model of sustainable mobility to achieve climate goals. The model aforementioned is built based on the majority are the CNG buses, numerous legal documents published both at the European level and in the individual Member States. The laws, regulations, communications, and strategies are the that affect the dynamic development of low- and zero-emission transport, as well as to other solutions helping to reduce the negative impact on the natural environment. The greatest development in this area took place in public transport, and above all in bus transport. Buses and coaches are the most popular means of passenger transport in the EU, serving cities, suburban and rural areas. They are also the most cost-effective and flexible forms of public transport, requiring minimal investment in launching new lines or routes. According to the United Nations, Economic Commission for Europe, buses, and coaches are defined as "vehicles with at least four wheels, designed and constructed for the carriage of passengers, and having more than eight seats in addition to the driver's seat" [8]. With one bus that can replace 30 cars on the road, buses help reduce traffic congestion. According to the Driving Mobility for Europe, 55.7% of all journeys by public transport in the EU (32.1 billion trips per year) are made by the city and suburban buses. Buses on average travel 511.4 billion kilometers in the EU (8.5% of passenger transport by land) [9].

Consequently, many of the activities, aimed at building the model of sustainable mobility, will be directed towards the bus and coach market. We can already see successful increasing activities in this area. Carriers invest in low-emission and zero-emission vehicles. Electric buses are becoming more and more popular, and the share of those powered by hydrogen is gradually increasing in the structure of vehicles. Virtually every carrier plans further investments in rolling stock, which will have to meet more and more stringent environmental requirements. It should be noted, however, that most decisions about choosing a specific type of vehicle, and most of all the type of its fueling, are based on cost calculation. Therefore, in this article, the main goal was to assess the economic efficiency of operating buses with various drives, with particular emphasis on low-emission, and zero-emission vehicles in the V4 countries. Additionally, an assessment of the direct and indirect costs related to the purchase of these vehicles was carried out. The research allowed us to obtain an answer to the question concerning the choice of the most effective direction of investments in ecological rolling stock, taking into account the micro and macroeconomic indicators in the discussed countries.

Accordingly, in the article, the following structure is introduced. The first part deals with the theoretical aspects of the development of low- and zero-emission transport. This section presents statistical data on the development of this sector in recent years in the V4 countries compared to the EU. The second part presents the materials and methods to develop this topic. At the end of the work, the results of the research were published and a discussion was held on them. The final part of the article consists of conclusions and a summary.

2. Development of Low and Zero-Emission Transport in the Countries of the Visegrad Group

In the introduction, it was noted that transport is responsible for around 25% of total greenhouse emissions in the EU resulting from human activities. Through this source, nitrogen oxides (especially nitrogen dioxide), suspended particles of PM_{10} and $PM_{2.5}$ fractions (dust particles), carbon monoxide, and hydrocarbons enter the air [10]. All pollutants have many negative effects on human, animal, and plant health. Therefore, the aforementioned policy of the EU, but also all the Member States, began to be based on activities aimed at reducing air pollution by transport, as well as on public transport promotion. The European Commission and the European Parliament play a special role here, and these institutions pass many legal acts aimed at reducing the negative impact of transport on the environment. In 2011, the European Commission issued a White Paper on the future of transport by 2050 and set out a vision to reduce greenhouse gas emissions caused by transportation by at least 60% by 2050 compared to 1990. By 2030, it aims to reduce greenhouse gas emissions in this sector by approximately 20% compared to the 2008 level [11]. In turn, the European Low-Emission Mobility Strategy of 2016 set the goal of improving the transport system, accelerating the introduction of low-emission fuels, and switching to low- or zero-emission vehicles [12]. The next Commission document of 2018 entitled "A Clean Planet for All: A European long-term strategic vision for a thriving, modern, competitive and climate neutral economy" identified as an important policy objective to guide the EU transition to a clean economy, and to zero gas emissions greenhouse by 2050. The strategy also stresses the need for a systems approach and underlines the importance of the transition to low-emission and zero-emission vehicles, emphasizing the role of electrification and renewables [13]. Another important document is the Directive 2009/33/EC, updated in 2019, on the promotion of clean energy-efficient road transport vehicles, which supplements the horizontal regulations of the European Union [EU] on public procurement. By introducing the obligation to take into account—when awarding public contracts for road transport vehicles—the energy factor and environmental impact during the vehicle's life cycle, it is to stimulate the market for clean and energy-efficient vehicles, contribute to the reduction of CO_2 emissions and air pollutant emissions, and increase energy efficiency [14]. In 2018, the implementation of the Green Deal for Europe began, which obliges all 27 EU Member States to transform Europe into the first climate-neutral continent by 2050. Consequently, emissions reductions of at least 55% are expected by 2030 compared to 1990 [15]. Following the Green Deal for Europe, a Strategy for Sustainable and Smart Mobility was developed in 2020—Europe's transport on the way to the future, to ensure a sustainable and resilient European transport system. It is thanks to the implemented changes in transport systems that it will be possible to achieve the overarching goal of a 90% reduction in transport-related emissions by 2050, thus fulfilling the commitment to climate neutrality. Gradually, until 2050 incl., all buses on the roads of Europe are to be emission neutral [16].

Based on EU legislation, the member states also regulate the issues of striving for environmentally friendly transport development. It is also the case in the member countries of the 1991 V4. The Czech Republic, Hungary, Poland, and Slovakia, which have a shorter period of membership in the EU than most countries, are striving efficiently to implement all policies, including transport policy.

In the Czech Republic, the most important strategic document in the field of transport is the Transport Policy of the Czech Republic for the period 2021–2027 with a perspective until 2050. This strategy regulates virtually every aspect related to sustainable transport, but significant attention has been paid to public transport as well as increasing the share of low-emission vehicles in transport [17]. In Hungary, the National Energy Strategy until 2030 is an important document that indicates the energy policy goals in the field of transport. The document emphasizes the need to meet the EU requirements concerning the reduction of pollutant emissions from transport and the introduction of the required indicators for low and zero-emission vehicles [18]. In addition, lot of space on adjusting the necessity of changes in transport was devoted to the National Climate Change Strategy 2008-2025. In particular, it focuses on reducing transport emissions by rationalizing and reducing transport and transport needs, developing cycling and walking, improving the share of public transport users, and promoting environmentally friendly transport [19].

In Poland, the most important document in the field of transport is the Strategy for the Sustainable Development of Transport until 2030, in which the priority of, inter alia, promoting sustainable transport, as well as reducing the negative impact of transport on the environment [20]. In turn, particular emphasis on the electrification of transport was placed in the Energy Policy of Poland until 2040 developed in 2020 [21].

In Slovakia, the Transport Development Strategy of the Slovak Republic is in force until 2030. The authors adopted the main goal to be the public transport development by increasing the attractiveness of its alternative forms. Additionally, it focuses on the electrification of railways and urban public transport as well as the introduction and construction of infrastructure for alternative energy sources in transportation [22].

The above-mentioned activities of the EU and individual V4 countries lead to the building, inter alia, a low-carbon economy model. A key element in this respect will be the dissemination of zero-emission vehicles, renewable and low-emission fuels, and related infrastructure, it will also apply to the entire bus and coach market. As indicated in the introduction, buses are the basic link of public transport, responsible for more than half of all passenger transport. There were 756,000 buses on the EU roads in 2018 (Table 2).

Compared to 1995, the number of these vehicles increased by 11.5%. The most used buses and coaches are in Poland—119 thousand. Poland also recorded the highest growth dynamics in the number of buses. In 2018, there were 39.3% more of them than in 1995. A slight increase in the number of buses was recorded in the Czech Republic. In this country in 2018, there were 22,000 of these vehicles and it was 7.3% more than two decades earlier. On the other hand, in Hungary and Slovakia, the number of buses in service fell by around 7%.

Table 2. The number of buses and coaches in use in the V4 countries and the EU in 1995–2018.

Country	1995	2010	2018	% 2018/1995	% 2018/2010
EU 27	678.1	707.6	756.0	111.5	106.8
Czech Republic	20.5	20.4	22.0	107.3	107.8
Hungary	20.5	17.6	19.1	93.2	108.5
Poland	85.4	97.0	119.0	139.3	122.7
Slovakia	11.8	9.4	9.1	77.1	96.8

Source: own study based on Eurostat data [2].

The average age of the EU bus fleet in 2019 is over 11.7 years (Figure 1). Compared to the years 2017 and 2018, the age of buses in the EU countries increased by 0.1 years [2]. The oldest buses run in Poland, the average age of which is 15.6 years, while Slovakia has the youngest fleet of buses, where the average age of buses is 11.4 years. The advanced age of vehicles is decisively influenced by the owners of small transport companies, who often cannot use external funding to purchase new vehicles. Many small entrepreneurs buy used buses from public carriers or Western European countries. Therefore, when analysing the statistical data on the purchase of city vehicles, which are most often made by local governments, one can notice fairly high growth dynamics in the field of younger vehicles. Therefore, in the example of Poland, it can be concluded that the number of buses in public transport aged 0–3 years increased in 2017–2019 from 15.9% to 26.2%. Thus, the number of the oldest vehicles, over 10 years old, fell from 43% to 37% [23]. Similar trends are observed in the remaining V4 countries.

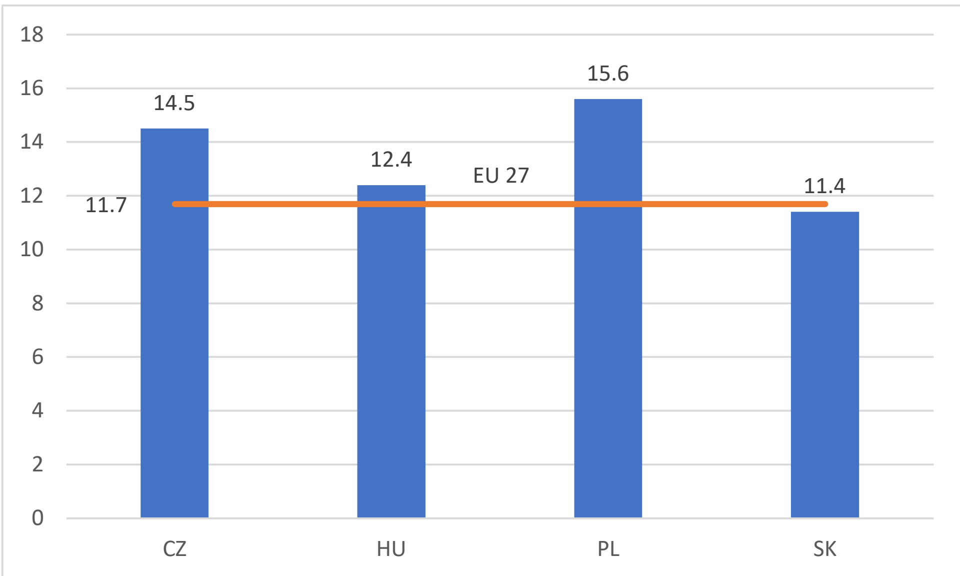

Figure 1. The average age of buses and coaches in operation in the V4 and EU countries in 2019. Source: own study based on ACEA [23].

The relatively advanced age of the vehicles in use translates into the fact, that most of these buses are diesel-powered and their engines do not meet the highest EURO 6 emission standards. According to the data of the Chamber of Commerce for Urban Transport, in 2019 in Poland, only 34% of city buses are vehicles with a drive meeting EURO 6 standards or emission-free. Another 32% of vehicles met the EURO 5 standard. Satisfying is the fact that there were only 0.8% of substandard vehicles [23]. It should also be noted that bus manufacturers estimate the age of vehicle operation at 15 years. Given the above, a significant number of vehicles should no longer be driven on European roads, especially in Poland and the Czech Republic.

When analyzing the data of newly registered buses and coaches, it can be welcomed that the sales of vehicles with diesel engines are falling, unfortunately, it is happening slowly (Table 3). In 2018, as much as 95.4% of buses powered by diesel were registered in Europe. In 2019, a slight decrease was recorded, by nearly 1%. Revolutionary changes took place in 2020, as the number of registered diesel vehicles dropped to almost 73%. On the other hand, in the V4 countries, the lowest number of diesel buses is registered in Poland. In 2018 it was less than 80%, and in 2020 it was only about 73%. Unfortunately, the worst situation is in Hungary. In this country, more than 95% of diesel buses are still being registered. Likewise, a high percentage of these vehicles are being registered in Slovakia. The situation is slightly better in the Czech Republic, as in this country the number of newly registered diesel vehicles has fallen by around 14% over the last two years.

When analyzing other types of drives in the context of new vehicle registration, there is a noticeable increase in new buses with hybrid, electric, and other alternative fuels, mainly CNG, in Europe. It is the CNG group of vehicles that is responsible for the largest increase in new buses powered by alternative fuels—from 3.3% to 11.4%. The significant growth dynamics was also noticed when purchasing hybrid buses. There was an increase of 8.8% compared to the previous year.

Table 3. Newly registered buses and coaches in the V4 and EU countries, by type of propulsion in 2018–2020.

Country		Petrol	Diesel	Hybrid Electric	Electric	Natural Gas	Other + Unknown
EU 27	2018	0.8	95.4	0.3	0.3	2.7	0.4
	2019	0.8	94.5	0.7	0.6	2.7	0.6
	2020	0.02	72.9	9.5	6.1	-	11.4 **
Czech Republic	2018	0.0	93.1	0.0	0.1	3.5	3.3
	2019	0.0	89.2	0.1	0.3	6.7	3.8
	2020	0.0	79.8	0.0	0.5	-	19.7 **
Hungary	2018	0.3	97.4	0.5	0.1	1.6	0.0
	2019	0.3	97.5	0.5	0.1	1.3	0.2
	2020	1.0	95.5	0.0	3.5	-	0.0 **
Poland	2018	3.5	79.4	0.2	0.3	1.2	15.5 *
	2019	3.4	79.7	0.3	0.3	0.7	15.6 *
	2020	0.0	72.9	2.1	13.7	-	11.3 **
Slovakia	2018	0.4	94.0	0.0	0.5	2.7	2.4
	2019	0.4	94.5	0.0	0.5	2.5	0.3
	2020	0.0	91.4	0.0	0.0	-	8.6 **

* The majority are the CNG buses; ** From 2020, ACEA also includes natural gas vehicles in this group; Source: own study based on ACEA [9,24,25].

In turn, in the V4 countries, the most favourable situation is in Poland. This country is a leader in the implementation of new electric vehicles. In 2020, electric vehicles accounted for as much as 13.7% of all new vehicles in this segment. It was an increase compared to the previous year, by as much as 13.4%. This increase in electric vehicles translated into a decline in purchases of vehicles with other alternative drives by around 4%, but it remained at the European average level anyway. In the Czech Republic and Slovakia, there is a noticeable increase in registrations of new low-emission buses. Electric buses, on the other hand, are still less popular. On the other hand, in Hungary, there was a slight increase in the electric buses purchase. In 2020, they accounted for 3.5% of new vehicles. As you can see, still nearly three-quarters of all new buses sold in the EU run on diesel. This is mainly due to the high purchase costs of new vehicles, as well as the need to invest in additional infrastructure. The implementation of CNG-powered buses or electric buses is associated with the construction of additional infrastructure that will enable the refuelling and charging of these vehicles. An even greater challenge, the implementation of hydrogen-powered vehicles is. Hydrogen is the most abundant chemical element on Earth. It is used in the refining and petrochemical industries. However, for several years, efforts have been made to popularize its use in commercial vehicle drives. In the case of a hydrogen vehicle, the vehicle is driven by electric motors as it is the hydrogen cells that generate the electricity that powers the vehicle's propulsion system. The drive does not affect driving the vehicle. A hydrogen vehicle has the advantage over an electric bus in that it can cover a much longer distance on one refueling. For example, the new Solaris Urbino 12 hydrogen bus needs only a few minutes of filling to cover more than 350 km. However, a hydrogen drive requires a greater financial contribution than an electric vehicle. Refueling with hydrogen, as mentioned, takes only a few minutes, and an electric vehicle requires up to several hours of charging. For now, electro-mobility is more popular, even though hydrogen is the most abundant element on the Earth and belongs to the group of the cleanest biofuels [26]. However, this type of power supply will be gradually implemented in Europe. The forecasts made by the UITP Vehicle Equipment Industry Committee in 2017 as part of the ZeEUS project regarding the expected share of buses with various drive's types on the market in 2020–2030 suggests a clear decline in the use of diesel, mainly in favour of battery technology, as the dominant electric bus technology. It is also believed that there will be a stable demand for CNG and plug-in hybrids as a technology transition between diesel and zero-emission technologies, as well as a gradual increase in the use of hydrogen in fuel cells (Figure 2).

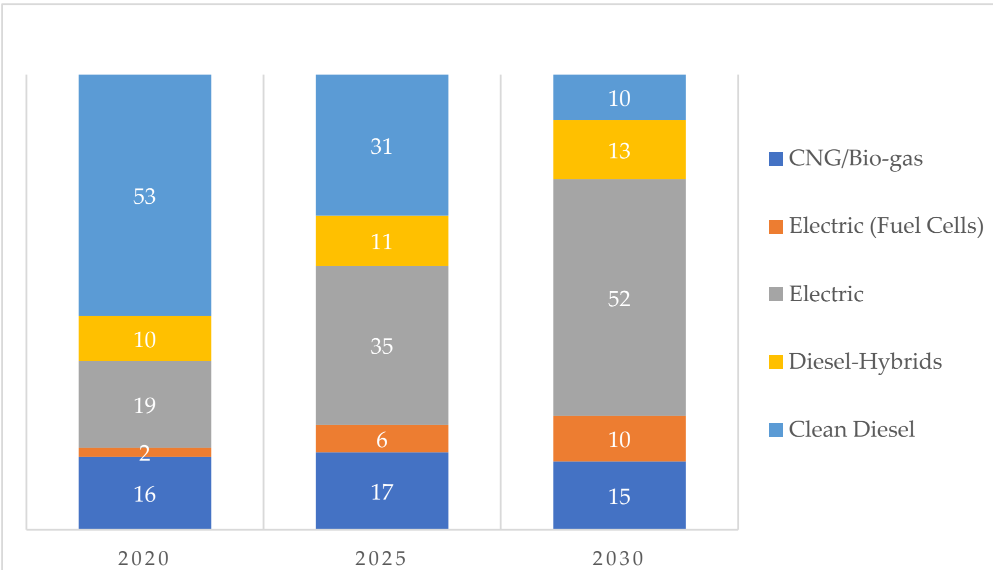

Figure 2. Forecasts of newly registered buses with alternative drive types in Europe in the years 2020–2030; Source: ZeEUS/UITP (VEI)—2017 [27].

3. Materials and Methods

The main direction of the research was to evaluate the economic efficiency of operating buses with various drive types, with particular emphasis on low-emission and zero-emission vehicles. Buses with a hybrid drive and CNG-powered buses were selected among low-emission vehicles. On the other hand, vehicles include buses with electric drive and buses running with electric motors powered by electricity generated by hydrogen cells. For the sake of simplicity, the article uses the concept of hydrogen buses. Since in the studied countries and the entire EU there is still a significant number of vehicles powered by internal combustion engines, for comparison, vehicles with diesel engines have been selected too. Maxi buses with a length of 12 m and mega-articulated buses with a length of 18 m were selected for the analysis. Additionally, an assessment of the direct and indirect costs related to the purchase of these vehicles was carried out. Before starting detailed research, analyses of the development of the low-emission and zero-emission buses market in the V4 and EU countries were carried out based on the literature on the subject, as well as mass statistics data provided by European and national research and statistical institutions. In order to obtain an answer to the formulated research problem, methods of processing and interpretation of the collected knowledge were used in the form of a descriptive method, a tabular-descriptive analysis method, and a graphical presentation.

In turn, the Total Cost of Ownership method was used to assess the efficiency of bus operation in individual V4 countries (TCO). It is a method that sums up all the costs of the vehicle, from its purchase, through use, to disposal. TCO analysis allows evaluating the direct and indirect costs associated with the purchase. It gives an opportunity to illustrate the total amount of costs related to the use and possession of the purchased means of transport. To estimate the total cost of maintenance, in addition to the purchase cost, maintenance costs are also included, which include fuel and/or energy costs, insurance, service, and repair costs [28].

Total Cost of Ownership can be written as the following equality:

$$C_{TCO} = C_V + N_V \times \ (C_P + C_S + C_O) \quad (1)$$

where C_{TCO} is the total cost of the vehicle (€), C_V—vehicle purchase cost (€), N_V—service life of the vehicle, C_P—costs directly related to the implementation of transport tasks (€/year) (costs of wear of spare parts and consumables, costs of wear of tires, costs of fuel consumption, driver's salary), C_S—costs directly related to the implementation of servicing tasks (€/year) (costs of ongoing repairs, periodic inspections, battery costs), C_O—other operating costs (€/year) (vehicle insurance, taxes, and fees).

The total cost of ownership was calculated for the operation period of vehicles of 20 years for diesel buses and 15 years for other drives. The length of the bus operation period was adopted based on the experience of carriers and manufacturers' recommendations.

3.1. Assumptions Adopted for the Financial and Economic Analysis

Investment costs in the form of the cost of purchasing rolling stock have been adopted on the basis of the analysis of the results of tenders for selected carriers from individual V4 countries in 2021. To obtain reliable data, the average purchase cost of a given type of vehicle was calculated based on 8 completed bus deliveries, taking into account the type of drive and capacity. Thus, a total of 80 deliveries were analyzed. It should be noted that the suppliers of individual buses were primarily the largest suppliers and manufacturers of buses in the V4 countries (MAN, VOLVO, Mercedes-Benz, SOR, Solaris Bus and Coach, Autosan, BYD). Similarly, the cost of estimating battery replacement in electric buses and the cost of plug-in and pantograph chargers have been adopted based on the analysis of the results of tenders for selected carriers from individual V4 countries in 2021. Since the prices of the offered vehicles, batteries, and chargers were quite similar, the same costs were assumed for all analysed countries. It should be added that the cost of replacing the battery in an electric bus is 30% of the value of the new vehicle. In turn, the cost of purchasing a plug-in charger for free overnight charging is 33,000 € and it is the necessary cost of purchasing one charger for one bus. On the other hand, pantograph chargers cost approximately 121,000 € [29]. Only the costs of the first charger will be included in the analysis. Pantograph chargers service several vehicles a day, therefore the unit investment cost will not significantly increase the operating costs of one vehicle. These costs are presented in Table 4.

Table 4. The average cost of purchasing a city bus, taking into account the type of drive and capacity (€).

Vehicle Class	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
maxi (12 m)	230,000	275,000	530,000	263,000	625,000
mega (18 m)	395,000	475,000	800,000	420,000	935,000

Source: own study based on the results of tenders in the V4 countries.

3.1.1. Forecasted Operating Costs

The basic assumptions adopted in the development of the operating cost analysis:

- The base year is 2021. In the case of diesel-powered buses, the analyses were performed until 2040. In turn, for the remaining vehicles, the analyses cover the years 2021–2035.
- Wholesale fuel prices were adopted as of 1 July 2021, for individual countries based on the available reports (Table 5).
- Wholesale diesel prices in the following years are based on Konoema's long-term forecasts [30], which assume a steady increase of 10% per annum until 2026, and from 2027, diesel prices are accepted at a constant level.
- Wholesale prices of CNG gas, according to forecasts, will be indexed in reference to diesel prices, therefore a similar price increase of 10% until 2026 is assumed and CNG prices from 2027 are assumed constant [29].
- Electricity prices in the following years were adopted based on the forecasts of the Institute for Renewable Energy, where a constant increase in prices by 4.0% until 2025 was assumed; and from 2026 by 3.2% [31].
- Hydrogen prices in subsequent years were adopted based on analyses by Bloomberg New Energy Finance, which assumed a drop in prices by 4.0% by 2030 and then by 2.1% [32].
- The amount of operational work was assumed at the level of 70,000 km per one bus per year. This consists of the daily length of the bus route 225 km. Most carriers operate the vehicle 6 days a week.
- The average consumption of fuels and energy was adopted based on the experiences of communication operators from Poland (Table 6).
- The average tire wear for one bus was calculated based on the experience of Polish communication operators.
- The number of drivers—it was assumed that there are two drivers per one bus. Average drivers' salaries are based on industry reports available in each country.
- In the case of service costs, tire replacement, driver salary costs, vehicle insurance and taxes, the inflation rate was taken into account according to the assumptions of the national banks:
    - Czech Republic (2022—2.3%; 2023—2.0%; from 2024, inflation is assumed to be 2.0%) [33]
    - Hungary (2022—3.0%; from 2023, inflation is assumed to be 3.0%) [34]
    - Poland (2022—3.3%; 2023—3.4%; from 2024, inflation was assumed to be 3.4%), [35]
    - Slovakia (2022%—1.8%; 2023—2.5%; from 2024, inflation was assumed to be 2.1%) [36]

Table 5. Wholesale fuel prices in the V4 countries as of 1 July 2021 (€).

Fuel Type	Unit of Measure	Czech Republic	Hungary	Poland	Slovakia
Diesel	L	0.980	0.966	0.935	0.919
CNG	m^3	0.770	0.760	0.692	0.960
Electricity	kWh	0.076	0.075	0.083	0.062
Hydrogen	kg	7.824	7.840	7.000	7.200

Source: own study based on the prices of major fuel distributors in a given country.

Table 6. Average fuel and energy consumption by buses.

Fuel Type	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
	L/100 km	L/100 km	kWh/100 km	m^3/100 km	kg/100 km
maxi (12 m)	41.3	30.0	110.0	41.0	8.5
mega (18 m)	53.0	46.5	140.0	50.1	10.8

Source: own study based on the experiences of communication operators from Poland [37].

3.1.2. Costs Directly Related to the Implementation of Transport Tasks

The costs directly related to the implementation of transport tasks, including the cost of wear of spare parts and consumables, were developed based on the experience of carriers from the V4 countries (Table 7). As in the case of bus purchases, the amount of these items is convergent, therefore the same costs for all countries have been assumed. The calculations have been based on information on the costs of materials per 1 km. The cost of tire wear is based on 10,000 km, assuming a tire replacement cost of 660 €. The tire life was assumed to be 150,000 km.

Table 7. Basic assumptions for unit operating costs in the operating period as of 1 July 2021 (€).

The Type of Cost	Country	Unit of Measure	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Costs Directly Related to the Implementation of Transport Tasks							
Cost of consumption of spare parts and consumables	V4	€/km	0.11 * 0.15 **	0.12 * 0.16 **	0.09 * 0.12 **	0.12 * 0.16 **	0.10 * 0.13 **
Tire wear cost	V4	€/10,000 km	264 * 352 **	264 * 352 **	264 * 352 **	264 * 352 **	264 * 352 **
Average driver salary	CZ	€/driver	1212	1212	1212	1212	1212
	HU		1142	1142	1142	1142	1142
	PL		1208	1208	1208	1208	1208
	SK		1300	1300	1300	1300	1300
Costs directly related to the implementation of maintenance tasks							
Costs of carrying out repairs of current periodic inspections	V4	€/year	6500	6000	5600	6400	5600
Other operating costs							
Vehicle insurance	CZ	€/year	950	950	950	950	950
	HU		700	700	700	700	700
	PL		920	920	920	920	920
	SK		1000	1000	1000	1000	1000
Taxes and fees	CZ	€/year	180 * 290 **	180 * 290 **	180 * 290 **	180 * 290 **	180 * 290 **
	HU		480 * 600 **	480 * 600 **	480 * 600 **	480 * 600 **	480 * 600 **
	PL		578.5	578.5	578.5	578.5	578.5
	SK		230 * 350 **	230 * 350 **	230 * 350 **	230 * 350 **	230 * 350 **

* for a maxi vehicle (12 m); ** for a mega vehicle (18 m); Source: own study based on the experience of communication operators from the V4 countries, legal provisions in force in a given country from the V4 group.

3.1.3. Costs Directly Related to the Implementation of Maintenance Tasks

The costs directly related to the implementation of maintenance tasks were calculated similarly. They were based on the experience of carriers. Insurance costs, on the other hand, were adopted based on the experience of communication operators from individual

V4 countries. In addition, the costs of taxes and fees have been adopted based on the regulations of the country in the V4 group.

4. Results and Discussion

In the first stage of the research, the total cost of vehicle ownership was calculated. As mentioned in the previous chapter, these costs include, apart from operating costs, also the costs of purchasing vehicles, and in the case of electric buses, also the costs of battery replacement after 8 years of use and the costs of purchasing a plug-in charger. In addition, in the case of hybrid buses, the cost of purchasing batteries after 8 years of operation was also taken into account. In the case of electric buses, the cost of the battery is 30% of the bus purchase price, and in the case of hybrid buses—10%. In line with the assumptions, inflation was taken into account for service costs, drivers' salaries, tire purchases, insurance, and taxes. Forecasts of changes in fuel and energy prices have been considered too. Thanks to this, it will be possible to determine the influence of these factors on the economic efficiency of particular types of drives during the entire period of operation. A summary of the total cost of ownership is presented in Table 8. The lower operating costs of hybrid, electric, and CNG buses (by approx. 30%) compared to diesel buses are mainly due to their operating period. The experience of carriers, as well as the recommendations of manufacturers, shows that diesel-powered buses are used for 20 years, while the remaining vehicles will be used for about 15 years.

Table 8. The total cost of ownership of maxi buses (12 m) with different drive types in the V4 countries (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	2,183,025.52	1,544,134.28	1,586,534.64	1,545,308.17	1,912,730.03
Hungary	2,265,689.93	1,564,219.09	1,608,512.60	1,719,035.24	1,938,187.98
Poland	2,312,871.42	1,609,614.50	1,678,964.38	1,582,775.28	1,938,949.70
Slovakia	2,192,682.22	1,558,294.10	1,608,025.28	1,709,067.28	1,912,001.11

Source: own study.

When conducting research, it is worth pointing out the structure of individual costs (Figure 3). The largest group of costs are operating costs, including fuel costs and remuneration for vehicle maintenance. Then there are costs of, taxes and insurance. However, as can be seen, the salary costs for each type of drive are around 30%. However, in the case of fuel and energy costs, the lowest share is in the case of electric buses (approx. 7%). On the other hand, the largest share of fuel costs in the TCO structure is fuel for diesel buses—38%. For other drives, fuel costs account for around 30% of total costs. Then there are the costs of taxes and insurance. The third significant group of costs is the group of investment costs. The highest costs in the entire structure are related to the purchase of electric vehicles (35%) and hydrogen-powered vehicles (33%). The lowest share of investment costs in the total cost of ownership of maxi (18 m) buses with different drive types in the V4 countries (€) occurs in the case of diesel buses.

The vehicle-kilometer costs presented in Table 9 clearly show that the use of hydrogen-powered buses is much more expensive than in the case of other drives. In addition, such a situation applies to all analysed countries. On the other hand, the cheapest vehicles to use in the Czech Republic are hybrid buses and CNG-powered buses. In turn, in Hungary, Hybrid vehicles will be the cheapest to use, followed by electric vehicles. In Poland, CNG-powered vehicles will be the cheapest to operate, and then hybrid vehicles. On the other hand, in Slovakia, hybrid vehicles will be the cheapest to operate, and CNG the most expensive. In addition, this is what distinguishes this country from the others, because, in the case of the Czech Republic, Hungary, and Poland, buses powered by traditional diesel fuel are the most expensive after hybrid vehicles.

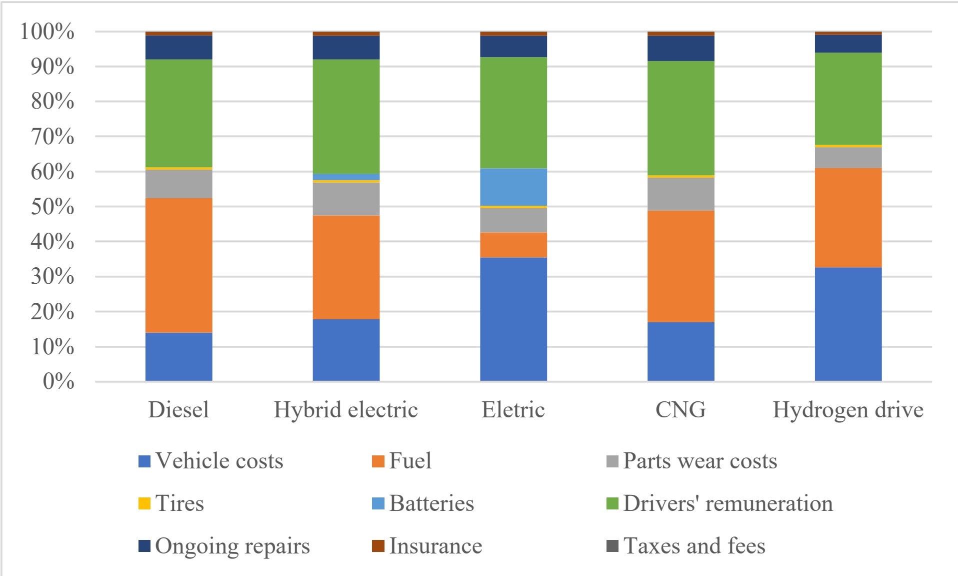

Figure 3. The structure of costs of implementing and operating buses, by type of drive on the example of maxi (12 m) buses in the Czech Republic; Source: own study.

Table 9. Cost of vehicle-kilometer maxi buses (12 m) with different drive types in the V4 countries for the entire period of vehicle operation (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.56	1.47	1.51	1.47	1.82
Hungary	1.62	1.49	1.53	1.64	1.85
Poland	1.65	1.53	1.60	1.51	1.85
Slovakia	1.57	1.48	1.53	1.63	1.82

Source: own study.

As with maxi buses, the total cost of ownership of articulated buses is highest for diesel (Table 10). CNG buses and hybrid buses are the cheapest in operation. The high operating cost of diesel vehicles is also due to their 5-year longer operation. Electric buses will be the cheapest of the zero-emission vehicles.

Table 10. The total cost of ownership of maxi (18 m) buses with different drive types in the V4 countries (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	2,666,272.86	2,069,599.06	2,010,401.24	1,865,314.51	2,418,153.93
Hungary	2,727,184.07	2,090,211.33	2,035,209.85	2,075,700.65	2,447,150.12
Poland	2,792,942.30	2,127,042.41	2,107,931.02	2,105,559.30	2,431,195.54
Slovakia	2,661,651.92	2,068,566.00	2,026,585.57	2,056,409.94	2,406,134.14

Source: own study.

In the above analysis, the different operation period of the vehicles makes the comparison a bit difficult. Therefore, vehicle-kilometer costs for articulated buses are presented. In addition, the vehicle-kilometer costs for large-capacity buses indicate significant differences and relatively high operating costs of zero-emission vehicles (Table 11). When comparing the vehicle-kilometer costs of large buses to those of standard buses, it is noted in some cases that the operating costs of diesel-powered articulated buses are lower than those of hybrid, electric, or CNG buses. This is mainly due to the purchase price of the vehicles themselves. At this point, it can be added that in the case of electric buses, the cost of pantograph chargers has not yet been taken into account, and in the case of hydrogen-powered buses, the costs of the charging infrastructure have not been included (refuelling station and electrolyser). Similarly, in the case of other types of vehicles, the cost of CNG charging infrastructure or traditional fuel stations was not included in the calculation. The pantograph charger basket costs approx. 100,000 €. An investment in a hydrogen refueling station for 50 buses costs approximately 5,100,000 €. Additionally, there is a need to buy an electrolyser worth approx. 7 million €. On the other hand, a CNG refueling station with a capacity of 1200 m^3/h costs almost 1 million € [38].

Table 11. Cost of a vehicle-kilometer of mega buses (18 m) with different drive types in V4 countries for the entire period of vehicle operation (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.90	1.97	1.91	1.78	2.30
Hungary	1.95	1.99	1.94	1.98	2.33
Poland	1.99	2.03	2.01	2.01	2.32
Slovakia	1.90	1.97	1.93	1.96	2.29

Source: own study.

In the initial part of the article, it was emphasized that most carriers, when deciding to invest in new rolling stock, pay attention primarily to the purchase costs and operating costs. Taking into account the costs of investment in a vehicle power infrastructure, it can be concluded that most carriers may take into account economic bills and will choose diesel vehicles. In addition, it was so until recently, because the statistical data presented in Section 2 on the dynamics of changes in the bus structure in individual V4 and EU countries, taking into account different types of drives, clearly indicate that diesel buses are still the most frequently purchased vehicles. However, the issued communications, directives, and strategies by the EU and the governments of the V4 countries, clearly indicate the timing and guidelines for changes in the implementation of low- and zero-emission mobility. This is mainly due to high investment costs. In the costs of purchasing buses presented in Table 5, vehicles with zero-emission drives are much more expensive than others. In the case of electric buses, this is twice the cost of diesel vehicles, and in the case of a hybrid bus, it is even three times higher. In addition, the infrastructure for powering and refueling these vehicles should be built from scratch. However, to enable carriers to adapt to the requirements of implementing low- and zero-emission vehicles, the EU offers the possibility of co-financing the purchase of vehicles as well as refueling and powering infrastructure for buses. At the time of writing this article, consultations and work on the construction of aid programs in the 2021–2027 financial perspective are still ongoing in the EU. Therefore, there are no specific and certain assumptions regarding the amount of funding for the purchase of the vehicles in question. However, in order to illustrate the impact of co-financing for the purchase of buses on the total cost of ownership, and above all on the cost of vehicle-kilometer, co-financing levels were adopted based on media information from consultations conducted in individual V4 countries. On this basis, it was concluded that the highest funding is planned in most countries for the purchase of hydrogen buses. It is planned that the carrier will be able to obtain funding for the purchase of these types of buses even at the level of 90%. In the case of electric buses, the level of funding may vary between 70–90%. Experts who believe that hydrogen technology should be developed are lobbying for each year lower funding for the purchase of electric vehicles. Therefore, for this calculation, it was assumed that the co-financing rate will be 80%. There are more and more opinions that CNG buses should not be considered low-emission buses. Thus, it is suggested to gradually reduce the funding for these vehicles. Therefore, for this calculation, the level of funding was assumed at 50%. In the case of diesel-powered buses and hybrid buses, on the other hand, there is a clear message that it will no longer be possible to obtain any funding for their purchase. Thus, the subsidies for the purchase of these vehicles were not included in the calculations below.

Taking the above-mentioned subsidies to the purchase of low- and zero-emission buses resulted in a clear change in the bus-kilometer cost calculated based on the total cost of ownership. As shown in Table 12, the cost of implementing and operating electric vehicles has decreased. However, CNG vehicles still generate the lowest costs among green and hybrid vehicles. After obtaining funding, electric vehicles will be the cheapest to operate, followed by hybrid vehicles. Moreover, the publicly available information shows that it will also be possible to obtain high funding for the construction of the infrastructure supplying the above-mentioned vehicles.

Table 12. Cost of a vehicle-kilometer of maxi buses (12 m) with various propulsion in the V4 countries for the entire period of vehicle operation (in the case of obtaining financing for the purchase of the vehicle in €).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.56	1.47	1.08	1.35	1.29
Hungary	1.62	1.49	1.10	1.51	1.31
Poland	1.65	1.53	1.17	1.38	1.31
Slovakia	1.57	1.48	1.10	1.50	1.29

Source: own study.

A similar situation occurred in the case of articulated buses (Table 13). It is worth noting that the cost of implementing and operating hybrid buses has decreased significantly and is even lower than CNG buses. In the case of subsidization, the cost of one vehicle-kilometer of a hydrogen bus is approximately 15% lower than that of a diesel bus. Without funding, this cost is approximately 15% higher. The subsidy for the purchase of electric vehicles is also beneficial. Thanks to this, they are the cheapest in operation. Despite the lower funding for the purchase of CNG buses, it still makes them attractive compared to diesel and hybrid buses.

Table 13. Cost of a vehicle-kilometer of mega buses (18 m) with different drive types in the V4 countries for the entire period of use of the vehicle, if subsidized (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.90	1.97	1.28	1.58	1.50
Hungary	1.95	1.99	1.30	1.78	1.53
Poland	1.99	2.03	1.37	1.81	1.51
Slovakia	1.90	1.97	1.30	1.76	1.49

Source: own study.

The above analyses show that co-financing for the purchase of ecological vehicles will have a beneficial effect on the increase in the economic efficiency of the operation of low-emission and zero-emission buses. In the event of obtaining a high subsidy for the purchase of hydrogen-powered vehicles, as well as the decreasing prices of hydrogen alone, the operation of this type of bus will be more economical than that of CNG-powered buses.

The next stage of the research was to analyze the impact of the forecast changes in fuel and energy prices, as well as the forecast inflation in individual V4 countries. In the part discussing the research methodology, the assumptions of the forecast changes in the prices aforementioned as well as inflation were indicated, based on which the annual operating costs of particular types of buses were calculated in the base year (2021) and the final year of operation (2035). For the correctness of the results, in the case of diesel buses, the operation of which is expected to be 5 years longer than that of other vehicles, the fifteenth year of operation was also assumed. The comparison was made based on a vehicle kilometer. It should be noted that the cost of purchasing vehicles was not included in the calculation.

In the base year, the lowest vehicle-kilometer cost was found for the operation of electric vehicles (Table 14). On the other hand, hydrogen-powered vans are the most expensive to operate. The single vehicle-kilometer cost is twice as high as for electric buses. On the other hand, the operating costs of hybrid buses are comparable to the costs of using CNG buses.

Table 14. Cost of a vehicle-kilometer of maxi buses (12 m) with different drive types in the V4 countries, calculated on the basis of the first year of operation (2021) (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.07	0.95	0.71	0.98	1.30
Hungary	1.05	0.93	0.,68	0.96	1.28
Poland	1.05	0.95	0.73	0.96	1.24
Slovakia	1.07	0.97	0.73	1.09	1.28

Source: own study.

In the last year of operation, which took into account the forecast changes in fuel and energy prices as well as inflation, quite significant changes can be observed (Table 15). Well, the anticipated reduction in the price of hydrogen will make this type of vehicle the most economical in all V4 countries. The calculations are also favorable for electric buses, but their operating costs will increase by 90 to 100%. This is due to the anticipated increases in energy prices.

It is also worth paying attention to the differences between operating costs in different countries. In the base year, the highest cost of vehicle use is expected in Slovakia. In turn, in 2035, in Slovakia, the lowest operating costs of all types of buses are expected. This can be explained by the expected low inflation and price stability since it is the only country from the V4 group in which the euro currency functions.

Table 15. Cost of a vehicle-kilometer of maxi buses (12 m) with different drive types in the V4 countries, calculated on the basis of the last year of operation (2035) (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.50	1.38	1.24	1.37	1.24
Hungary	1.60	1.46	1.32	1.61	1.32
Poland	1.65	1.54	1.43	1.50	1.37
Slovakia	1.51	1.40	1.27	1.55	1.25

Source: own study.

In the case of using different mega-class buses in the base year, a similarity to the situation of maxi buses can be noticed. Here, too, the costs of using hybrid buses in 2021 are twice as high as electric buses (Table 16). The operation of diesel buses is relatively high. However, it should be remembered that the costs of building the refueling and charging infrastructure were not considered in the calculation.

Table 16. Cost of a vehicle-kilometer of mega buses (18 m) with different drive types in the V4 countries, calculated on the basis of the first year of operation (2021) (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.23	1.17	0.77	1.11	1.52
Hungary	1.20	1.14	0.75	1.08	1.50
Poland	1.21	1.15	0.79	1.20	1.44
Slovakia	1.23	1.17	0.79	1.23	1.49

Source: own study.

In the case of mega-class buses, in the last year of their use, the cost of the vehicle-kilometer for diesel, CNG, and electric vehicles will also increase (Table 17). The biggest increases are forecast for electric buses. In turn, the expected reductions in hydrogen prices, despite inflation, will make these buses the most economical.

Table 17. Cost of a vehicle-kilometer of mega buses (18 m) with different drive types in the V4 countries, calculated on the basis of the last year of operation (2035) (€).

Country	Diesel	Hybrid Electric	Electric	CNG	Hydrogen Drive
Czech Republic	1.75	1.73	1.47	1.54	1.39
Hungary	1.83	1.82	1.55	1.82	1.48
Poland	1.90	1.89	1.66	1.89	1.52
Slovakia	1.75	1.74	1.49	1.75	1.40

Source: own study.

As can be seen from the above analyses, the forecast changes in fuel and energy prices, as well as the expected inflation, will significantly affect the costs of vehicle operation and the economic efficiency of using various types of drives. These changes will have a positive impact on the implementation of zero-emission vehicles into operation. Furthermore, it is worth noting that the analyses of vehicles powered by engines emitting gases or dust do not include charges for the introduction of gases or dust into the air. Currently, it was assumed that the purchased vehicles will meet the Euro 6d ISC-FCM standard, which, among other things, requires the installation of devices recording real fuel or electricity consumption. Furthermore, this standard indicates that the NOx emission level is set at 80 mg/km for diesel vehicles. In normal traffic, however, it can be exceeded a maximum of 1.43 times, previously 2.1 times. In 2023, the ratio is to be tightened. Moreover, there is a CO_2 emission standard in force at a level of 95 g/km. However, work is already underway on the Euro 7 standard, which will further tighten the standards. Unofficial information indicates that the NOx emission limit (nitrogen oxides) is to be 30 mg/km (let us remind—now 80 mg/km). Carbon monoxide (CO) emissions would then drop from 1000 mg/km to 300 mg/km and from 500 mg/km to 100 mg/km for diesel vehicles [39]. This may mean that currently purchased vehicles will not meet the implemented standard, and the carrier will have to pay for emissions. For example, in Poland, fees are calculated as the product of the fuel consumed (Mg) multiplied by a fee rate for a given year, set by the Minister of Climate for a given year. In addition, these charges significantly increase the operating costs of these vehicles, making zero-emission vehicles more profitable.

5. Conclusions

Undoubtedly, transport is one of the key sectors of the European economy. For over two decades, a gradual increase in the number of people employed in this sector has been noticeable, but first of all, attention should be paid to the over 30% increase in the number of passengers transported. The forecasts carried out, indicate their further growth in the next 30 years. However, such an intensive development of transport brings negative effects in the form of an increase in the emission of harmful substances. It is in the V4 countries where the higher emissions of NMVOC compounds, nitrogen oxides NO, carbon oxides, particulate matter has been noted. The situation in the V4 countries is particularly dramatic in terms of CO_2 emissions caused by transport, as, for example, in the Czech Republic and Hungary, the increase in 2018 compared to 1995 was around 85%. It was even worse in Poland, where an increase of over 181% was recorded.

The above alarming statistics contributed to the activities of the EU and individual countries, which make recommendations in the form of various legal documents, ordering all member states to significantly reduce pollutant emissions. It translates, inter alia, on the need to implement measures to reduce emissions in transport, including passenger transport. In addition, such activities can be implemented in the field of introducing low and zero-emission vehicles into operation.

Based on statistical data, the average age of this group of vehicles in the EU is 11.7 years, while in the Czech Republic, Hungary and Poland it is higher. This means that there are vehicles that do not meet strict emission standards on the roads of Europe. Moreover, in Poland, the average age of vehicles is 15.6 years, and most manufacturers recommend the use of their vehicles for 15 years. Therefore, carriers face the necessity to replace their bus fleet, but each newly purchased vehicle, following the guidelines, should have a low or zero-emission propulsion status. For example, in Poland, the Electro-mobility Act [40] requires local governments with over 50,000 inhabitants to residents that the share of zero-emission buses in the fleet used is to be:

- 5% from 1 January 2021
- 10% from 1 January 2023
- 20% from 1 January 2025
- 30% from 1 January 2028

This gives rise to the fact that transport organizers and communication operators will consider the choice of the type of buses.

From the economic point of view, every entrepreneur, when purchasing buses, will be guided by the economic efficiency of the vehicles used. Therefore, it becomes necessary to commission cost-benefit analyses of the implementation of low- and zero-emission vehicles. Among these vehicles, CNG-powered buses, considered low-emission vehicles, are currently the most popular, followed by electric buses as zero-emission vehicles. Hydrogen-powered vehicles, on the other hand, are still at the stage of technological development.

The analyses of the total cost of ownership show that CNG-powered buses are the cheapest in the implementation and use of green vehicles. It even emerges that the annual vehicle-kilometer costs of these vehicles in the Czech Republic, Poland, and Hungary are lower than those of traditional diesel vehicles and hybrid buses. Higher operating costs of CNG buses in Slovakia compared to other vehicles are associated with higher gas prices (high tax). The total cost of ownership, on the other hand, is lowest in the Czech Republic and Hungary.

Although the cost of using buses with a diesel engine is not the lowest, carriers buy such buses due to the high costs of the vehicle charging infrastructure.

However, the EU, as well as the governments of individual countries, support enterprises and communication operators by offering them financing for investments. Even though in the current period, there is no defined budget and detailed aid programs for the coming years, the announcements show that the highest co-financing will be available for investments in hydrogen-powered buses and electric buses, and to a lesser extent for low-emission buses. On the other hand, carriers will not receive any support for the purchase of diesel vehicles. This will significantly increase the economic attractiveness of new investments in low-emission and, above all, zero-emission transport.

Currently, in the case of zero-emission vehicles, electric buses are more economical in this case. Their operation is definitely cheaper compared to hydrogen buses. It is worth noting that this applies to both buses with standard capacity (maxi—12 m) and large-capacity buses (mega—18 m). The difference in operating costs is quite significant, as the use of hydrogen-powered buses is about 25–30% more expensive than electric buses. These high costs of using hydrogen vehicles are mainly influenced by the purchase price of these buses. These buses are approximately 15–20% more expensive than electric vehicles. This high purchase price is also caused, among others, by the initial stage of the development process, as hydrogen technologies are only just leaving the prototyping stage. As is well known, any new technology entails high investment costs. This was also the case with the initial production stage of electric buses. In this case, however, the problem of high operating costs is the need to use high-capacity batteries, as well as the need to replace them after 8 years of use.

Finally, it is worth pointing out that the forecasts of fuel and electricity prices show that diesel and CNG will increase by approx. 10% until 2026. This price should stabilize later. In the case of electricity, forecasts indicate a price increase of approx. 4% annually until 2025, and then by approx. 3.2% per year. On the other hand, in the case of hydrogen prices, it is expected that the price of this fuel will initially decrease by about 4% annually, and after 2030, by about 2.1%. Hence, fuel prices, nearly 30% of the total cost of ownership, will be a key element in selecting the most cost-effective vehicles. In addition, in this case, in the perspective of 15 years, hydrogen-powered buses well fare.

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energies

Article

The Energy Efficiency of the Last Mile in the E-Commerce Distribution in the Context the COVID-19 Pandemic

Dariusz Milewski [1] and Beata Milewska [2,*]

[1] Institute of Management, University of Szczecin, 8 Cukrowa St., 71-004 Szczecin, Poland; Dariusz.Milewski@usz.edu.pl
[2] Institute of Management and Quality, WSB University in Poznan, Powstańców Wielkopolskich 5, 61-895 Poznan, Poland
* Correspondence: beata.milewska@wsb.szczecin.pl

Abstract: The e-commerce industry has been developing extremely dynamically for many years. This development was intensified during the COVID-19 pandemic. According to the research conducted by the authors of this paper, in Poland, during the pandemic, the number of delivered parcels increased 20–100%, depending on the courier company. The research of the authors of this article focused on the energy efficiency of the last mile, which is very important for the efficiency of the entire delivery process to customers. As the authors calculated, the last mile can consume over 70% of energy of the whole distribution channel. The article presents the results of research concerning the energy efficiency of deliveries performed by couriers and express companies in Poland. Two models of distribution used Poland have been compared—direct deliveries to final customers, and deliveries to parcel lockers. The research methods are interviews with the managers and couriers, analysis of the literature, and the simulation method. According to the results of the simulations performed by the authors, distribution with the use of parcels lockers can help reduce the consumption of fuel even by 74–87% per parcel or 36% per m^3. Apart from this, the authors calculated the impact of scale of operations on the energy efficiency of the transport processes on the last mile, which is an indirect effect of the growth of the e-commerce market, caused by the pandemic. Based on the results of the original research of the authors, it can be assessed that the growth of the number of the delivered parcels during the pandemic resulted in the consumption of fuel per one parcel being reduced in some cases by over 36%. The novelty of the authors' research is that the conducted simulations regarded not only the efficiency of the processes, but also the energy consumption in delivering parcels at the last mile and during the pandemic.

Keywords: e-commerce; last mile; parcel lockers; efficiency of logistics processes; energy efficiency; economies of scale; simulation of logistics processes; COVID-19

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1. Introduction

E-commerce has been developing for many years. This development has been accelerated by the pandemic. In the EU-27, whereas total retail sales diminished by 17.9%, e-commerce sales in April 2020 increased by 30%, compared with April 2019 [1]. This increase is related to the growth of the courier and express services market.

In Poland, the market of courier and express services grew from PLN 4.5 billion in 2015 (EUR 1.08 billion) to 7.9 in 2019 (EUR 1.89 billion) [2] (increase by 39%). The growth was caused by the growing volume of parcels in the e-commerce market. In 2020, online sales in Poland increased by almost 26% and already accounted for 14% of the retail market in Poland [3]. Thus, the effects of the pandemic for this sector of the economy turned out to be positive. Not only did the turnover in this market increase, but the pandemic has also expanded the scope of the e-commerce market (new firms, consumer segments, e.g., elderly) and products (shift from luxury goods and services to everyday necessities, e.g., groceries) [4].

The growth of the e-commerce market causes an increase in transportation. The problem is particularly important in the so-called "last mile", where deliveries are made to various customers, sometimes with a low payload and less efficient vehicles (e.g., vans and trucks) with a lower load capacity than in deliveries to large stores, e.g., discount stores [5,6]. Other factors specific to the e-commerce industry also affect the efficiency of transportation processes. A question arises here: what may be the consequences of the increase in transport to internet customers for energy consumption and in consequence to quality of life and social costs?

However, it can be assumed that the market growth will allow for the achievement of economies of the scale in transport (better use of capacity and shorter routes per 1 vehicle). In addition, the e-commerce industry uses innovative solutions aimed at increasing delivery efficiency, such as parcel lockers or alternative fuels.

The e-commerce market influences energy consumption in various ways. The more efficient the operations, the bigger the efficiency of the consumption of energy and the lower the negative impact on the environment. The type of energy used at each stage of the parcel delivery processes is also important. This is a significant problem as operators are starting to use alternative energy sources (e.g., electric vehicles). The transition from traditional technologies to, for example, the use of biofuels also requires a change in the supply chains of these fuels, which also consume energy [7]. Thus, the impact of the e-commerce industry on energy consumption and the natural environment is of a diverse, direct, and indirect nature.

The problem of the impact of the supply chain strategies of production companies and their suppliers on the economic efficiency of logistics and production processes on the one hand, and on energy consumption on the other hand, has been the subject of studies presented in the literature. For example, Vandana et al. [8] developed a model that allows to calculate the level of production at which energy consumption is optimal. The energy consumption can be controlled by the production rate. It complements traditional cost accounting with environmental and emission issues.

The environmental impact of supply chain models has also been studied by other authors. The issues that were the subject of these studies, and which were included in the models developed by individual authors, are: the positive impact of increasing the flexibility of supplies on the possibility of reducing waste [9], and a strategy to repair defective products to reduce waste [10]. This issue in relation to various decision problems was also the subject of other studies [11–13].

The simulations carried out by the authors of this article concern the problem of energy consumption, not in entire supply chains and not in production companies, but in the distribution services sector—in the e-commerce industry and in the last mile. The results of the performed calculations fill the gap in the literature, the more so because they were carried out in the context of a pandemic.

The issue of the development of the e-commerce industry and the effects of this development is very wide. However, the intention of the authors of the article was to focus on the problem of the impact of this development on energy consumption, assuming that traditional fuels are used to power delivery vehicles. Studies concerning the process performance on the last mile of e-commerce were conducted, but were carried out before the pandemic. The research conducted by the authors thus fills the knowledge gap regarding the effectiveness of these processes and the impact on energy consumption in the new reality created by the pandemic.

The aim of this article is to present the impact of the models of e-commerce deliveries and the increase in the scale of operations on the energy efficiency of the deliveries on the last mile, on the basis of the authors' own research.

The essence of the problem addressed by the authors is contained in the following questions:

- To what extent can the use of parcel lockers help to improve the delivery process in the e-commerce industry and, consequently, to reduce energy (fuel) consumption?

- Does the impact of the development of the e-commerce market result in the economies of scale and thanks to that in the decrease in the energy consumption in the transport processes?

  Authors tried to find answers to the above questions.

2. The Literature Review

The pandemic had a significant impact on the e-commerce market and, consequently, on the courier and express services market. Turnover in the e-commerce industry has increased significantly; however, the increases vary on individual markets, in individual companies, including companies dealing with the deliveries of goods to final recipients. Higher turnover results in greater transports, which raises concerns about the impact of this market on the quality of life of residents. However, for example, a study in Madrid showed that the number of parcels delivered to customers in the central district doubled, but an increase in pollution was lesser than the growth of e-commerce [14]. The question arises therefore whether this is due to economies of scale? Are the delivery processes more efficient (better use of capacity, time) when more parcels are delivered?

However, the problem is very complex. In recent years, there has been an increase in the number of low-tonnage vehicles (light goods vehicles up to and including 3.5 tones gross weight), which are in many cases poorly utilized. However, it should be borne in mind that while goods are delivered to warehouses or distribution centers of retailers with high-tonnage (i.e., more efficient) vehicles, the final distribution to stores is carried out by medium-tonnage vehicles. Thus, the economic and environmental benefits of traditional distribution channels do not have to be greater than in e-commerce. In addition, customers of retail shops often use ineffective individual motorization. This problem, in relation to external costs transport, has already been the subject of the authors of this article [15].

Factors which influence the efficiency of deliveries in e-commerce are: seasonal peaks in demand, reduced lead times, meeting delivery time windows, first-time delivery failure rates, high levels of product returns [16,17], fragmentation of freight shipments [18–20], increase in customer demands for service quality [21], and different sizes of shipments and their packaging.

A high level of returns is an important problem. Returns for the fashion segment in 2013 accounted for more than 18% of all parcels [22]. From logistics point of view interesting is of course how this problem generates additional trips. Additional trips can be also caused by customers themselves. A considerable share of customers (even 50%) first visit a shop before ordering goods via Internet [23].

The situation is also not improved by the fact that the infrastructure is often not adapted to this type of distribution of goods in cities [24].

The most frequent problem which customers in the Visegrad Four countries (Poland, Slovakia, Czechia, Hungary) face when online shopping was that the delivery time of goods was longer than it was stated by the seller on the store's website. The highest incidence of problems with online shopping was reported in 2015 in Hungary (40%), in 2017 in Poland (18%), and in 2019 in the Czech Republic (28%) [25].

If the e-commerce market is small, the problem may be the lack of critical mass in a given region, especially on the "last mile", which in that case can be very long [26].

The last mile is regarded as the most expensive section of distribution of goods [27,28]: its cost can amount up to half of total logistic costs [29] and contributes to an increase in social costs [30].

Rural deliveries can be three times more expensive than urban ones [31,32]). However, in urban areas external costs are higher [33].

New effective solutions are needed, which are effective both from the point of view of operators, users, and society, and, therefore, solutions that will meet the requirements of sustainable development [34–36]. Organizational, technology-enabled, and data technique-enabled innovations [37] can help improve efficiency of the last mile deliveries [38,39]. They include: urban consolidation centers [40–42], crowdsourcing [43–46], pickup points, parcel lockers [47], automated technologies, robots [48–50] "mobile warehouse" [51], reception boxes [52], drones [53], autonomous vehicle deliveries [54], such as autonomous cars [55], and bike deliveries [56]. Technologies aimed at increasing the efficiency of deliveries and reducing the negative impact on the environment are implemented and tested [57–59], such as alternative fuels (e.g., biodiesel), and the use of electric vehicles (EVs) for home deliveries [60,61]. For example, the analysis conducted in Milan proved that the use of electric vehicles (EVs) leads to a decrease in greenhouse gas (GHG) emissions to 54% [62].

Research is underway to solve the problem of congestion in cities caused by the increase in transport carried out by courier companies. One such interesting concept is the use of underground railways to distribute parcels [63]. Another solution, which can improve the efficiency of the last mile deliveries in e-commerce, can be smart parcel stations (SPS), which have been widely deployed in several countries [64]. The innovations have the potential to reduce externalities generated by the last-mile delivery activities [65,66]. Research conducted in Poland shows that parcel lockers can help reducing negative environmentally impact by reducing the number of deliveries in the city area, in some cases even tenfold [67]. However, under conditions that the parcel lockers found in the vicinity of homes, on the way from work and in places where it is possible to park a car [68]. Another interesting information is that in traditional delivery system, a courier is able to deliver 60 parcels in a distance of 150 km, whereas in the system with parcel lockers—600 parcels in just one day, with a travel distance of about 70 km. Similar results were achieved in other analyses [69].

However, the specificity of a given market is important. For example, research conducted in Brazil showed that 70% customers are willing to walk up to 1000 m to a parcel collection point (drugstores, gas stations, post offices, supermarkets, and malls) [70], whereas 95% of pedestrians and 48% of car drivers would agree to collect their goods within 2000 m (30 min or less). Finally, 52% of car drivers are willing to travel up to 5000 m to retrieve purchased goods in CDPs. However, as authors stated, these limits are more representative of the Brazilian reality and differ from those stated in the literature.

Although there are opinions that e-commerce has a negative impact on external costs, the results of the studies indicate the opposite. For example, research in Italy showed that e-commerce can have 10–30% lower energy consumption and CO_2 emissions compared with traditional retail [71,72].

Research conducted in Japan in the book market showed that in e-commerce, considerably more energy per book is used than conventional retail in dense urban areas, because of additional packaging in courier services. On the other hand, more energy can be consumed in suburban and rural areas due to the inefficiency of personal automobile transport [73]. Overall consumption at the national level is nearly the same: 5.6 megajoules (MJ) per book for e-commerce and 5.2 MJ per book for traditional retail [74].

The research conducted in the USA showed that, when customers order films online, less energy is consumed (33%) and less CO_2 (40%) is emitted than in traditional retailing [75,76].

The problem of the impact of the development of the e-commerce industry on individual motorization (and, consequently, on social costs) in cities was also the subject of research of M. Stinson et al. [77]. According to the results of the study, although e-commerce has generated an increase in parcel truck delivery trips, the net effect of e-commerce is a reduction in fuel consumption due major via shopping trip reductions.

3. Materials and Methods

The considerations presented by the authors are based on the results of the original research supported by the analysis of the literature.

The authors conducted telephone interviews with courier companies in Poland and with couriers themselves. The interviews were conducted in July and August 2021.

Interviews were conducted with representatives of two courier companies UPS (deliveries to customers' homes) and INPOST (deliveries to parcel lockers) and five couriers who work for these companies and for GSL company (deliveries to customers' homes). This made it possible to compare alternative parcel distribution systems. People taking part in the study were informed about the purpose of the study and gave their consent to the interview and publication of the study results. During the interview, these people were asked 7 open-ended questions (free-form interview). The replies were very extensive; one interview lasted about 1 h. Couriers had at least several years of experience, usually with more than one courier company. Two couriers interviewed also worked in the UK (2020 year) and Germany (2021). Couriers also compared the situation on the e-commerce market before the pandemic and currently during the pandemic. All couriers delivered parcels in urbanized areas.

The main purpose of the interview was to obtain data to simulate energy consumption for two typical models of last mile deliveries in Poland.

To justify the importance of the issues undertaken by the authors, the calculations of the consumption of energy on the last mile have been conducted. Results are presented below. The authors elaborated following formula of the consumption of fuel on a given section of the whole route of a parcel:

$$Cpp = (Cpv*D)/(C*U) \quad (1)$$

where:

Cpp—Unit consumption of fuel [l/km/parcel]
Cpv—Consumption of fuel by a given vehicle [l/km/vehicle]
D—Distance [km])
C—Capacity [parcels]
U—Utilization of the Capacity

The above formula has been used also in the calculations, results of which are presented in the Section 4 of this article.

The assumptions for calculations are in Table 1 and results of the calculations are presented in Table 2.

Table 1. Assumptions for calculations.

Capacity of a Vehicle	Consumption of Fuel
[parcels/vehicle]	[l/km]
100	0.15

Source: Own calculation based on the data from transportation market.

Table 2. Simulations of consumption of petrol in an e-commerce supply chain.

Supply Chain Stage	Capacity	Distance	Consumption of Petrol [L/km]		Share
	[Parcels]	[km]	per Vehicle	per Parcel	
From a supplier to a DC	1125	400	0.38	0.14	21.7%
"Last mile" (From DC to receivers)	100	325	0.15	0.49	78.3%

Source: Own calculation based on the data from transportation market.

Under assumed conditions the consumption of fuel on the last-mile section stands for the biggest part of the consumption of fuel per parcel on the whole route (78.3%). The basic reason is that final deliveries from a Distribution Centre to recipients are performed with the usage of smaller transport means, whereas to the Centre in the more economical full truck load mode (e.g., 24 tons of a load). Therefore, the efficiency of the processes on the last mile is important, and this the reason authors deal with this problem.

4. Results of the Research

4.1. Stages of the Conducted Research

On the basis of interviews, two basic models of the deliveries on the last mile in Poland have been identified: direct deliveries to homes of customers and deliveries to parcel lockers. These models are described in Section 4.2.

Next, the authors described for comparison how delivery parcels are performed in Germany and the UK (Section 4.3).

In the next stage, the authors have conducted a calculation of the energy efficiency of the deliveries on the last mile for two previously described models (Section 4.4). The intentions of the authors were to investigate which of these models are more energy efficient and to what extent. For calculations, the authors used data obtained during their own research and data from the literature. These are, for example: the number of parcels delivered by a courier during one delivery and number of addresses, consumption of fuel, a length of a route, and capacity of vehicles.

Then, the authors compared energy efficiency for two levels of demand for courier services—before and during the pandemic (Section 4.5).

Finally, conclusions were drawn (Section 5).

4.2. Models of Deliveries on the Last Mile to E-Commerce Customers in Poland

In Poland, there are two basic models of the last mile delivery to internet customers.

- Direct deliveries to homes of customers;
- Deliveries to parcel lockers.

Most courier companies in Poland use the first model—direct deliveries to homes of customers. An example of a company using this model in Poland is UPS Polska. Based on the interview, it can be concluded that in UPS number of delivered parcels indeed increased during the pandemic by 20–30%, but the capacity of the vehicles has not changed. The distances travelled by the transport means decreased, because more customers are served and one vehicle can serve smaller area. This evidently confirms of the occurrence of the phenomenon of the economies of scale, also in this industry. Furthermore, despite the increase in the number of parcels, the quality of service did not worsen.

In Poland, a big problem in deliveries to homes is the absence of the customers. Couriers do not leave parcels at the doors, and neighbors usually are not willing to receive parcels. For this reason, in many cases a courier has to deliver them on the next day.

The second model, used in Poland only by one company—INPOST, is based on the deliveries not to customers' homes, but to parcel lockers. Customers collect parcels on their own from parcel lockers. This form of distribution develops in Poland dynamically. During the pandemic, the increase in deliveries of parcels to parcel lockers was 100%. Before the pandemic, the number of parcel lockers was 7000, and nowadays it is 13,000. Presently, in cities in Poland, parcel lockers are located on average 450 m from each other. A courier visits per day only 4 parcel lockers, delivering on average 250 parcels to each parcel locker (1000 parcels delivered per day). However, if this number of parcels does not fit in one van, a courier has to perform 2–4 trips a day to a Distribution Centre.

According to information obtained from INPOST, the parcel lockers are more efficient—one parcel-locker replace 13 vans with a driver, who delivers 70–75 parcels per day, visiting 90–100 locations (the problem of the absence of inhabitants at homes). However, according to the couriers interviewed by the authors, these figures are currently slightly different, which are presented in Section 4.3.

Additionally, in this company, the capacity of vehicles is the same, such as it was before the pandemic, and is fully utilized. More and more often, electric vehicles are utilized. As for the distances, they did not change, which can be explained by the specificity of this business model. Despite the increase in the number of parcels during the pandemic, the quality of service in this company also did not worsen.

Of course, customers have to travel to parcel lockers to pick up parcels, which can contribute to the external effects of last-mile delivery. However, parcel lockers in cities are presently very densely located, which makes it possible to reach them even on foot. Above all, however, they are located near frequently visited places such as shopping centers, thus customers can pick up (and send) parcels while doing other things (e.g., shopping).

4.3. Comparison of the Models of Distribution of Parcels in Different Countries

Interesting information have been obtained by the authors during interviews with couriers in Poland, who deliver goods to customers or to the parcel lockers. Some of the responded couriers had experiences in work also in other countries—in Germany and UK. The results of these interviews indicate that logistics operations on the last mile in Poland are relatively less efficient than in Germany and the UK. In Germany and the UK, the problem of non-delivered parcels (and additional trips) is less severe than in Poland. In Germany, when a customer is not at home, the parcels are usually left with neighbors. They can also be left in a parcel collection point. In the UK, parcels are left at the door of a customer, thus the problem of the absence of a customer does not exist.

In study cases, a courier in Germany delivers about 100 parcels daily. In the UK, a courier delivers about 80—even 150—parcels daily. The pandemic also had impact on the e-commerce market in Germany—before the outbreak of the pandemic, a courier delivered 50% fewer parcels.

4.4. Comparison of the Energy Efficiency of Deliveries to Homes and to Parcels-Lockers

The authors performed calculations of the energy efficiency of deliveries to customers and parcel lockers based on the data:

(a) Presented in the literature;
(b) Obtained during their own research (interviews).

These data differ from each other, e.g., the distances covered during a day in case of different couriers, which results, e.g., from different distances to a Distribution Centre or different areas to which parcels are distributed. In the author's opinion, the reason is also that data in the literature are from the period 2011–2013, and the research conducted by the authors concerning the period in the time of the pandemic.

For the calculations based on their own research, the authors used the data most often repeated in the answers. For example, the indicated quantities were from 70 to 120 parcels, but authors used the number of 100 parcels. The number of parcels per vehicle delivered to customers' homes depends first of all on a season. Most of the parcels are delivered in December.

The authors adopted the following assumptions for the calculation:

(a) Calculations based on the data obtained from the literature ([63–65]):
    - During one day a courier has to deliver 60 parcels to customers or 600 to parcels lockers;
    - The distance to customers is 150 km/day, and in case of deliveries to parcel lockers 70 km/day.
(b) Calculations based on the data obtained by the authors during their own research:
    - During one day, a courier has to deliver 100 parcels to customers or 1000 parcels to parcel lockers;
    - In case of deliveries to homes of customers, the distances from the distribution center to the first customer's home and from the last customer's home to the distribution center is 25 km each, and the distance between customers to whom the courier delivers parcels per day is 30 km (80 km in total);
    - The distance from a Distribution Centre to a parcel locker and returning to the DC is 25 km (in total 50 km), and the distance between two parcel lockers—0.5 km;
    - Number of parcel lockers to which the courier delivers parcels per day—4;

- The number of loading operations in the distribution center per one day for a courier delivering parcels to the customer's homes—1;
- Number of loading operations in the distribution center per one day for a courier delivering parcels to parcel lockers—2 or 4 (it depends on the sizes of parcels because usually it is not possible to load 1000 parcels into a one van). Therefore, in the case of deliveries to parcel lockers, calculations have been performed for two variants in distribution:
  - Two runs—101 km/per day;
  - Four runs—202 km/per day.

This is based on the results of the research calculations which have been performed, the results of which are presented in Table 3 and compared with the results of the research from the literature.

Table 3. Comparison of efficiency of consumption of fuel of two distribution channels in e-commerce.

Source: Literature ([63–65])		**Source: [Own Research]**		
Deliveries to Homes	**Parcel Lockers**	**Deliveries to Homes**	**Parcel Lockers (V1)**	**Parcel Lockers (V2)**
Distances [km/day]				
150.0	70	80.0	102.0	202.0
Number of packages per day [pcs.]				
60.0	600	100.0	1000.0	1000.0
Consumption of petrol [L/parcel]				
0.38	0.02	0.12	0.02	0.03
Savings per parcel	−95.33%		−87.25%	−74.75%
Consumption of petrol [L/m^3]				
2.88	1.35	1.54	0.98	0.97
Savings per m^3	−53.33%		−36.25%	−36.88%

Source: Own calculation based on the data from transportation market.

Results of the calculations of the authors on the base of the data from the literature are in the first and second columns of Table 3 ([63–65]). Thanks to the use of the parcel lockers, the consumption of energy per parcel can be reduced by 95.33%.

Other results were obtained by the authors with the use of data obtained during interviews. In the first variant, savings amount to 87.25%, and in the second to 74.75%, thus they are lower than obtained with data from the literature, but still considerable. That confirms a high energy efficiency of the system with parcel lockers.

This is mainly because, thanks to the usage of parcel lockers, a courier can deliver about 10 times more parcels during a day than in the case of deliveries to homes. Additionally, the distances traveled by a courier delivering parcels to parcel lockers are usually shorter than for home deliveries. However, it depends on how many times a day a courier has to visit a distribution center due to the inability to load 1000 parcels into one van (in the studied cases, 2 and 4 times).

The authors calculated the energy savings of deliveries to parcel lockers not only per parcel, but also per m^3, in order to ensure comparability of both models. The parcels delivered to a parcel locker are usually smaller than those delivered to customers' home. The savings per m^3 are smaller but still significant—53.33% when we use data from the literature, and 36.25% for the first variant (V1) and 36.88% for the second (V2), when we use data obtained by the authors.

4.5. Economies of Scale on the Last Mile

Based on the data obtained from interviews, simulations have been conducted concerning the impact of the scale of operations on the efficiency of deliveries of parcels directly to homes.

Table 4 presents the results of these simulations.

Table 4. Impact of scale of operations on the last mile in e-commerce.

Lower Demand (before Pandemic)	Higher Demand (during Pandemic)
Distances [km/day]	
100.0	80.0
Number of packages per day [pcs.]	
80.0	100.0
Consumption of petrol [L/parcel]	
18.8	12.0
Savings	−36%

Source: Own calculation based on the data from transportation market.

Calculations have been made for two variants:

1. "Lower demand (before pandemic)";
2. "Higher demand (during pandemic)".

If demand increases, economies of scale are visible. The distances to customers are shortened from 100 km to 80 km. Apart from this, the capacity of vehicles is better utilized—there are more parcels to be delivered during the trip, at 100 in comparison with 80 before the pandemic. In effect, the consumption of fuel is lower by 36% per parcel.

5. Conclusions and Discussion

The growth of the e-commerce market results in an increase in the transport of goods, which raises concerns about an increase in social costs due to higher consumption energy. In Poland, during the pandemic the number of delivered parcels increased 20–100%, depending on the company. An especially high increase (100%) was experienced by the company INPOST, which delivers parcels to parcel lockers. Additionally, the number of parcel lockers increased by almost 100%.

According to the calculations made by the authors, delivery processes on the last mile are particularly important—the last mile can consume even over 70% of energy per parcel in the whole distribution channel. However, the impact of the deliveries on the last mile on the consumption of fuel can be minimized.

The simulations conducted by the authors of this article were based on the results of different studies, but first of all on the information and data from the transportation market.

According to the research conducted by the authors of the article, there are opportunities to increase the energy efficiency of the deliveries of parcels. The authors calculated that the biggest savings can be obtained by the use of the parcel lockers instead of deliveries to homes. In Poland, deliveries to parcel lockers are performed only by one company—INPOST. Thanks to the utilization of parcel lockers, the savings of energy consumption can reach 74–87% per parcel or 36% per m^3. Such good results are possible because a courier delivers parcels per day only to four parcel lockers, leaving in them about 10 times more parcels than a courier delivering parcels to homes. However, the energy efficiency of deliveries with the use of parcel lockers depends on the number of trips performed by a courier during one day to and from a Distribution Centre. A courier delivering parcels to parcel lockers replaces 10–13 couriers delivering to homes, depending on the distances between customers and sizes of parcels.

Another factor which has an impact on the energy efficiency of transport processes in INPOST is the introduction of electric vehicles.

Additionally, in this market, the economies of scale are visible—when the e-commerce market grows, such as recently during pandemic, the efficiency of deliveries also increases (about 36%). The routes are shorter, the vehicles are better utilized, which also decreases the negative impact on social costs and consumption of energy.

In Poland, the problem of non-delivered parcels is more severe than in Germany and the UK, which may impact the efficiency of transport (necessity of additional trips). Some of the couriers indicate the problem of overloaded vehicles.

The research also show potential for improvement, especially when different models and different markets (e.g., in different countries) are compared. This problem requires further and in-depth research.

Apart from this, in concrete situations the energy efficiency depends on many factors. Different transportation means are used in different conditions—urban spaces, crowded streets, problems with parking. The authors also did not refer to the other solutions only mentioned in the paper—models of distribution (crowdsourcing), and new technologies (e.g., automated, electric vehicles), which could further increase energy efficiency in the e-commerce on the last mile.

Taking into account all of the above-mentioned problems, further research is needed.

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Article

Energy Self-Sufficient Livestock Farm as the Example of Agricultural Hybrid Off-Grid System

Grzegorz Augustyn, Jerzy Mikulik *, Rafał Rumin and Marta Szyba

Department of Business Informatics and Management Engineering, AGH University of Science and Technology, 30-059 Kraków, Poland; gaugustyn@zarz.agh.edu.pl (G.A.); rrumin@zarz.agh.edu.pl (R.R.); mszyba@zarz.agh.edu.pl (M.S.)
* Correspondence: jmikulik@zarz.agh.edu.pl; Tel.: +48-603-353-250

Abstract: Contemporary agriculture has become very energy-intensive and mainly uses electricity, which is needed for technological processes on livestock farms. Livestock faeces are burdensome for the environment due to the release of methane into the atmosphere. This article presents the concept of a self-sufficient livestock farm as an off-grid energy circuit that is a part of the agricultural process. The key idea is to obtain an energy flow using the concept of a smart valve to achieve a self-sufficient energy process based on a biogas plant, renewable energy sources, and energy storage. During the production process, a livestock farm produces large amounts of waste in the form of grey and black manure. On the one hand, these products are highly harmful to the environment, but on the other, they are valuable input products for another process, i.e., methane production. The methane becomes the fuel for cogeneration generators that produce heat and electricity. Heat and electricity are partly returned to the main farming process and partly used by residents of the area. In this way, a livestock farm and the inhabitants of a village or town can become energy self-sufficient and independent of national grids. The idea described in this paper shows the process of energy production combining a biogas plant, renewable energy sources, and an energy storage unit that enable farmland to become fully self-sufficient through the energy flow between all constituents of the energy cycle being maintained by a smart valve.

Keywords: biogas energy; solar energy; hybrid biogas plant; renewable energy; circular economy; off-grid systems

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1. Introduction

Methane is the basic component of natural gas, the combustion of which causes less carbon dioxide emissions than is the case with other fossil fuels (coal, lignite, and peat). Methane is formed during the anaerobic digestion of organic matter. One of the major sources of methane is waste from livestock farms. Methane emitted in natural processes has a negative impact on the environment as it has a carbon dioxide equivalent of 25 times. Methane emissions can be reduced by fermenting the organic matter in biogas plants [1]. Biogas is a mixture of methane (40–85%), carbon dioxide (16–48%), and other gases present in trace amounts. The content of methane in biogas is influenced by the fat content of the substrate. Its high content results in biogas with a high methane content. The biogas yield is influenced by the fermentation temperature, retention time, substrates used, load, decomposition technology, and the pre-treatment of raw materials [2,3]. As a result of the fermentation of organic material, clean and cheap fuel in the form of biogas is produced. It can be used for heating, lighting, and powering machines [1]. Fermentation, however, is an unstable process as it may be disturbed by an increase in temperature in a fermentation chamber, overproduction of volatile fatty acids, and chemical contamination, e.g., with pesticides or heavy metals [4]. The by-product of this process is digestate, which is a valuable organic fertilizer that is a source of easily digestible nutrients for plants [3,5,6]. Biogas plants, unlike other renewable energy sources, are multi-energy systems as they produce biomethane, which, after combustion, provides electricity and heat through the process of cogeneration [5]. Electricity is usually sold to the national grid, and heat, when distributed into the local district's heating grid, is used to heat the biogas plant's buildings and the farm [7]. Cogeneration combustion is not the only possibility for the usage of biomethane. After cleaning, it can be injected into the natural gas network. In a compressed form, it can be used as a fuel for cars with CNG installations [2,3,5,8]. It can also be converted into biohydrogen in a steam reforming process.

By utilizing organic waste, biogas plants are flexible sources of energy that reduce the amount of greenhouse gases emitted into the atmosphere as they burn fossil fuels. Therefore, they are a part of circular agriculture (circular economy) and contribute to the concept of sustainable development. This concept organizes agricultural production according to the following principle: Resources—Agricultural Products—Renewable Energy Sources, with an emphasis on recycling and reuse of waste and by-products instead of traditional and extensive production [9]. Biogas plants are popular in many countries as they have an advantage over installations producing energy from the sun and wind. The production of biogas is not affected by climate-related risks. Biogas can also be stored for later use. Producing biogas from farm waste and using it for personal use is especially popular in countries with no universal access to electricity and heating networks due to large due to large distances between buildings [6,10].

The global energy industry is moving towards energy storage systems and renewable energy installations placed close to end users. Such an approach fosters greater independence from imported energy sources and diversification of energy sources [2]. Balda et al. proposed in Japan a project of a self-sufficient farm, which would generate electricity, heat, and fuel to meet its own needs. The research presents a version of a self-sufficient farm that optimizes the size of a biogas plant in accordance with its specific demand for food and fuel. In such farms, crops are used to produce food or fuel, and their residues are used to generate electricity and heat through cogeneration [11].

Due to climatic conditions and long distances, renewable energy should come from autonomous, interconnected, small biogas plants. The produced electricity and heat would be used to power and heat households. In biogas plants, raw biomass and liquid waste from cattle, pig, sheep, and poultry farms would be used as substrates. Approximately 95–99% of the generated heat energy would be used to heat housing and livestock buildings for cattle and to support the fermentation processes. About 40–42% of the electricity would be used in cattle buildings for technological processes, and the rest by biogas plants and homes [10].

In Asian [2,6,12,13] and African [1,2,6] countries, small household biogas plants, in which animal droppings are used as substrate, are popular. The fermented substrate (digestate) is transported to the fields as fertilizer with a high nutrient content [14]. Crude biogas is stored and used directly for cooking, or is used in cogeneration to produce electricity and heat. It can also be used to power absorption chillers for cooling purposes. Electricity and heat are used locally, or fed into the grid [15,16]. Purified biogas is used to power cars, buses, and trucks [1].

In the EU countries, the energy transformation is carried out in order to reduce greenhouse gas emissions, improve air quality, and stop climate warming. This is the main goal of sustainable agriculture programs in many European Union countries, including Poland. Livestock farms with biogas plants generate electricity and heat from local organic substrates. The heat is used to heat the farm buildings and to support local heating networks [17]. By generating electricity and heat in a biogas plant, the use of fossil fuels and associated greenhouse gas emissions can be reduced [5].

The support of the development of biogas plants in Germany can be observed in the form of subsidies granted to biogas plant operators. In addition to such incentives, the decision to build a biogas plant can be affected by environmental, social, and economic factors. The availability of feed for farm animals is also an important part of the decision to build biogas plants, as there is a concentration of biogas plants in regions with a high density of livestock in Germany [15].

Biogas can also be produced using biodegradable municipal waste. Such waste is an important substrate and, when combined with cattle manure in a 1:1 ratio, it can generate a large amount of biogas [13]. Biogas produced from waste in rural areas around cities has great potential to meet the energy needs of cities. In the case of combined heat and power generation, there is a problem of low heat consumption by biogas plants. On average, a biogas plant uses 50% of the heat produced. In Germany, only 10% of biogas producers use more than 50% of the heat. The remaining amount could be used to heat houses and buildings in the vicinity of the biogas plant [2].

The European Union has developed a sustainable economy plan known as the European Green Deal. The activities described therein concern, inter alia, counteracting climate change and environmental degradation. This can be achieved through a sustainable climate policy that fosters the development of a modern, resource-efficient, and competitive climate-neutral economy by 2050. Economic growth will then be independent of the use of natural resources. Such sectors as energy, transport, agriculture, construction, and all industries will be transformed. The greatest emphasis is placed on the transformation of the energy sector [18,19]. Conventional coal-fired power plants will be gradually replaced by renewable energy installations [20]. There is a methane strategy in the European Green Deal which focuses on its reduction in energy, agriculture, and waste sectors, as these are the areas where methane emissions are the highest. The use of a cross-sectoral approach will help target actions in each area, exploring synergies between sectors, e.g., through the production of biomethane released in landfills or on animal farms. Biomethane produced in biogas plants from various types of biodegradable waste such as animal faeces, green and kitchen waste, and waste from the agri-food industry, can be the catalyst for energy conversion [21]. Among the European countries, Poland also has a great potential for biogas production, given the similar natural conditions to those of Germany. According to the data collected by the Energy Regulatory Office (ERO), in March of 2021, there were 120 agricultural biogas plants in Poland with a total capacity of 117.98 MW (average power 0.98 MW) and a biogas production capacity of 490,143.199 m^3 [22]. This constitutes approximately 10% of the estimated potential at approximately 5 billion m^3 [23]. The development of biogas plants was limited by the lack of local spatial development plans, which do not take into account places for the construction of installations which use renewable energy sources. This, combined with the misconception that biogas plants need to be large, meant that they were built only in voivodeships with large farms and large livestock farms [7].

2. Renewable Energy Solutions (RES) in On-Grid and Off-Grid Micro Networks Considerations

The main disadvantage of renewable energy is its unreliability and the inability to work efficiently due to the intermittent and fluctuating nature of the processes, which usually leads to system oversizing, thus increasing the investment cost. For this reason, hybrid renewable energy systems (HRES) are built. Their popularity has grown due to the effectiveness of eliminating the disadvantages of RES systems based on a single source. A hybrid system consists of at least two power systems of different origins (renewable and fossil fuels), an energy storage unit, and electronic devices controlling them. The main advantages of HRES are greater reliability, better efficiency, increased energy storage capacity, lower energy costs throughout the life cycle, and minimization of greenhouse gas production [22,23]. Hybrid systems producing electricity can take a form of a microgrid. This is a locally controlled energy system that uses:

- different types of renewable energy sources: sun, wind, biomass, or water;
- energy generators (diesel, gasoline, biogas, and biodiesel);
- energy storage systems (batteries, hydrogen, and heat);
- loads (residential, commercial, and industrial);
- control devices (inverters and converters) [15].

There are two types of microgrids: on-grid and off-grid. The former are connected to the national power grid, the latter are autonomous and operate outside of the national power grid. The combination of photovoltaic technology and other RES with a biogas generator can be a profitable solution that may power even the most remote and sparsely populated rural areas. Such a hybrid system is optimal and less expensive than the traditional one. In off-grid networks, energy is generated by photovoltaic panels and a biogas generator, and stored in a battery bank. The batteries should have the capacity to power buildings for a certain number of days without sun, wind, or biogas [15,24].

Developing microgrids in which renewable energy is used has many environmental benefits, such as reducing the overall energy consumption, improving energy efficiency, reliability of energy supply, reducing transmission losses, voltage control, and an increased security of the energy supply. HRES support the implementation of sustainable development with the use of renewable energy [25]. The climatic risk is the occurrence of long interruptions in the supply of electricity from the national grid caused by damage stemming from weather factors, e.g., strong wind, snowfall, or freezing rain. Its occurrence and ailments are reduced by HRES microsystems independent of the national network, which are also an energy reserve for this network [26].

In rural and sparsely populated areas, terrain and economic considerations play an important role in the planning of the power grid. Attention is paid to the production of energy from renewable sources, which are easy to install, have a higher rate of energy use, lower transmission losses, and lower operating costs [24,25]. In addition, the use of environmentally friendly renewable energy sources in rural areas can reduce environmental pollution also in surrounding towns. The use of alternative energy sources makes communication more accessible and minimizes dependence on fossil fuels, which in turn reduces the negative impact on the environment [22,26].

Ghenai et al. proposed a microgrid for the city of Sharjah in the United Arab Emirates that uses renewable energy from a hybrid solar-biogas system. It consists of photovoltaic panels, a biogas cogenerator, batteries (lithium-ion batteries), as well as inverters. In the PV—Photo Voltaic system, two-axis tracking devices have been added to maximize the system's output power. The study took into account the effect of temperature on the operation of PV systems. Its efficiency decreased with increasing ambient temperature (high summer temperatures in Sharjah) and the accumulation of dust on the solar panels (desert region). The study presented a simulation and modelling analysis for the design of energy-based microgrid systems. The results showed that the hybrid system can provide up to 14% of the total annual electricity demand in the city of Sharjah, with the percentage of energy generated by photovoltaic panels being 74%, and 26%from a biogas cogenerator [27]. Hybrid grids can be used in sparsely populated areas, where large distances between farms make the construction of traditional energy networks unprofitable. The government of India took up the challenge to provide a stable and continuous power supply to all farms. For this purpose, an integrated energy system was created consisting of a wind turbine, photovoltaic panels, and a biogas generator. The systems were connected to a control panel, which transmitted the electricity to the battery. The battery was charged when the wind turbine and solar panels produced power. It was used to cover the energy needs of households. However, the capacity of the wind turbine and the PV system was insufficient to meet the buildings' needs. To meet the demand, a biogas generator was added, which became the source component of the hybrid system [28]. In response to the challenges of rural electrification in Sub-Saharan Africa, a completely renewable off-grid energy system was developed. It included wind turbines, a photovoltaic panel, and a biogas generator installed in Djounde in the north of Cameroon. The hybrid system was optimized, and the simulation performed confirmed the cost-effectiveness and environmental benefits of the proposed system compared to the existing solutions. Electricity supplied to the agricultural sector helped solve the main problem in the area, poor agricultural productivity, through the use of electrical appliances in agricultural production and processing of agricultural products [29]. In Bangladesh, a hybrid system consisting of a photovoltaic module, a biogas generator, a biodiesel generator, and an energy storage device was developed. The system established a reliable energy supply, reduced environmental pollution, ensured more efficient use of energy, and reduced maintenance costs. The HOMER (Hybrid Optimization Model for Electric Renewable) software was used to evaluate the performance of the hybrid energy system. Cow manure was used as the substrate for this biogas plant. [30]. Similarly, the research described by Buragohain et al., focused on a biogas plant using cow manure as a substrate [31]. Additionally, for the Bangladeshi areas, Chowdhury et al. designed a hybrid system consisting of PV panels, a biogas generator, and batteries to store electricity. This made the system more economical, as it could generate electricity on cloudy days. Research has shown that the proposed hybrid system is more cost-effective and reliable for rural areas [24]. Oluwaseun et al. proposed an electricity generation system that, as the previous one, was also based on PV panels and a biogas plant. In this case, manure from 1000 pigs was used as a substrate for biogas production. The research showed that electricity generated in a biogas plant is more effective and reliable for rural areas than is the case with solar energy. The results also showed that burning biogas provides more energy compared to solar energy [27]. To produce biogas in a hybrid installation, apart from animal manure, other substrates constituting biodegradable waste can be used. Such a system was designed by Habiba et al., who used kitchen waste from dormitories and hostels located on the university campus to produce biogas. PV panels were installed on the roofs of these buildings [32]. In rural areas, biomass from animal manure is readily available. Its abundance makes it a viable option to use it as a potential source of substrates for electricity generation in countries with significant amounts of animal excrement [23]. On the island of Java, a hybrid system consisting of a PV plant and a biogas plant was proposed. Electricity was produced by PV panels in the dry season (April–August) when the sunlight was the most intense (123–1075 W/m^2). The energy generated in this way could be stored in batteries and used by the inhabitants of the island when energy was not produced by PV panels. In the aforementioned biogas plant, cattle manure was used as a substrate for the production of biogas and electricity, which was obtained as a result of cogeneration. The strategy behind a hybrid system is that, while PV panels produce electricity during the day, the biogas plant generates it at night. As a result, both RES systems complement one another, constituting the optimal hybrid power system for the island [29]. Furthermore, the solution creates a system of effective distribution of energy generated from renewable sources. It is possible to build hybrid energy grids parallel to the commercial grid. This solution can make electricity successfully distributed to rural and urban areas, which would solve the electricity problem [15,29].

An important role in hybrid and off-grid solutions [24,26,29,30,33–38] and systems is played by energy storage units. The evolution of the energy market towards micro production of electrical energy and heat implicates certain problems with unpredictable energy production profiles and its balancing in hybrid systems. Energy storage units are one of the solutions to be considered in this area, as they can help with momentary energy balancing and energy production fluctuations in small and medium hybrid systems [15,28,33,39]. Such energy storages are now entering the consumer market and are commonly used with photovoltaic systems. Some of the energy storage solutions include lithium-ion batteries, battery cells, or hybrid batteries based on hydrogen technology which can accumulate electrical energy to balance unstable energy sources such as photovoltaic installations during their cooperation with power grids. Small to medium capacity energy storages can be particularly helpful for small to medium installations starting from 3 kWh up to 60 kWh, or even more for commercial markets [40]. This direction shows how to properly apply and manage energy storage solutions in small and medium renewable energy production systems to achieve better balancing and comply with local energy market regulations.

3. The Idea of a Hybrid Off-Grid Autonomous System

Hybrid, off-grid, autonomous energy systems are based on renewable energy sources such as wind, solar, and biogas, as well as energy storage options to provide uninterruptible power supply to the recipients (farmlands, households, etc.) and to satisfy their energy demands. Considerations in previous chapters show that there is a need to manage energy sources in hybrid systems to render them as independent from the national power grid as possible. The electrical energy produced by a biogas plant can be used to power the grid when variable renewable energy, such as solar or wind energy, is introduced into the energy system. This is also as biogas (methane) can be easily stored and produced on demand [8]. Biogas storage tanks are connected to an installation that transfers the product to cogeneration engines, where electricity and heat are generated. A biogas storage facility makes electricity and heat production flexible, as the storage size is directly linked to the efficiency of the biogas plant [5]. Hybridization of energy sources on a farm increases the reliability of the energy system combining two or more sources of energy. Additionally, the system can include energy storage units to create an autonomous (self-sufficient) off-grid energy system. However, such a solution requires constant management and monitoring of the parameters of the system's elements.

The idea shown in this paper combines a biogas plant and renewable energy sources, as well as an energy storage unit to create an autonomous, self-sufficient hybrid power system managing the energy flow through the use of a smart valve. The smart valve's role is to manage and provide routing between all elements of the system: the biogas plant, a renewable energy source, and the energy storage unit. Routing the correct source of energy to the recipient (households and agricultural facilities such as barns, glasshouses, and farm buildings on the farmland) as well as managing the way it is routed (directly to the recipients or to the storage device) is the key aspect of the solution.

For further considerations and simulations, our off-grid network consists of a medium size cattle farmland with 20 cows, ten households, a biogas plant, a renewable energy source using PV of 10 kWh, and an energy storage unit.

Figure 1 below presents the energy flow between all elements of the system proposed for further considerations. It is connected to the power grid. Energy and heat produced through a biogas plant are routed to the following recipients: glasshouses, farm buildings, and households. Households are connected to the system, but they do not belong to the farmland and are considered external energy loads. The biogas plant is also a direct source of energy for farmlands, as it utilizes the overproduced CH_4 and CO_2. The photovoltaic circuits constitute additional components to produce and support the facilities and individual consumers when possible. It is noteworthy that in this solution electrical energy cannot be stored, so an additional source from the power grid network is needed should the biogas plant or PV circuits produce no energy.

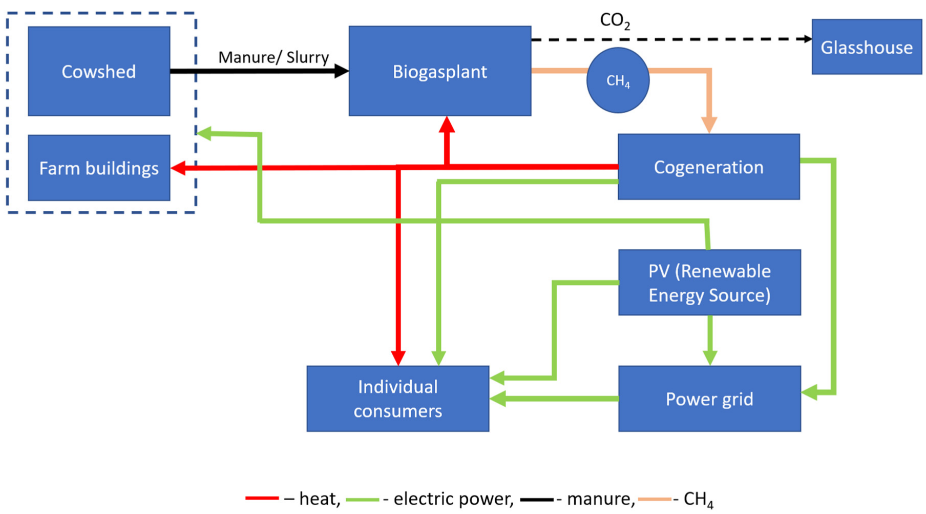

Figure 1. Diagram of energy flow (heat, electric power, manure, and CH_4)—produced on a medium-sized cattle farm with an on-grid connection.

The idea and main focus of the research is to connect all components of the system, the biogas plant, a renewable energy source, and the additional energy storage unit, in one hybrid system where the energy flow and routing are managed by a smart valve in a way that allows for autonomous off-grid functionality. This idea is shown in Figure 2.

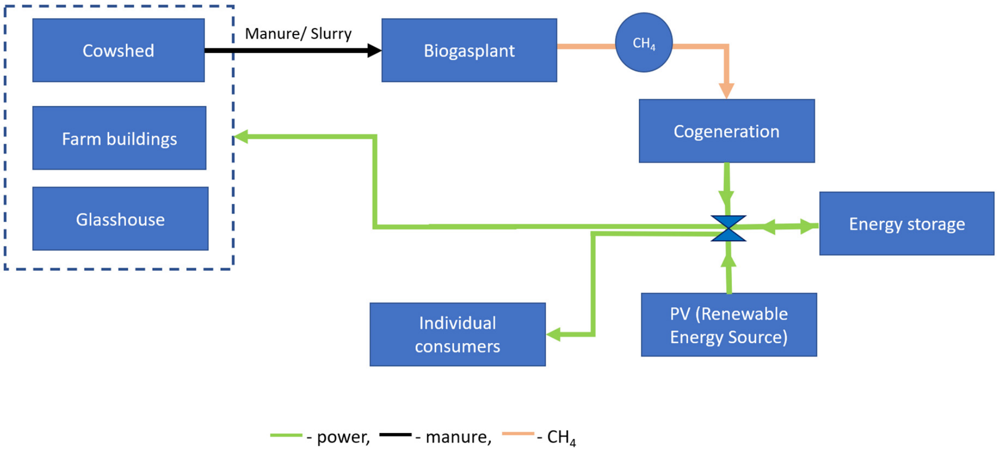

Figure 2. Diagram of electric power flow produced on a medium-sized cattle farm with an off-grid solution, an energy storage unit, and a smart valve supporting energy routing.

The smart valve plays a key role in this self-sufficient system. It manages the energy routed to/from respective elements of the system. The valve is responsible for adjusting the energy flow and the storage decisions during periods of overproduction. The operation of the valve is based on a three-way input controller with negative feedback. The energy produced by the biogas plant and a photovoltaic source is routed by the valve in two ways:

- when the energy demand from farmland and households is low or there is no demand for energy, the valve charges the energy storage unit for later usage;
- when the energy demand from farmland and households is greater than what is produced in a specified instance, the valve takes energy stored in the energy storage device as a result of the previous charging processes;
- when there is no energy produced by the system, the valve uses all energy stored in the energy storage unit.

The function of the valve is to ensure that the system is balanced so that all energy loads (farmland and households) are satisfied; in other cases, it charges the energy storage device. Its functions are based on the coefficients which are adjusted to the current energy demand, production, and storage capabilities.

The valve's operation and systems are shown in Figure 3.

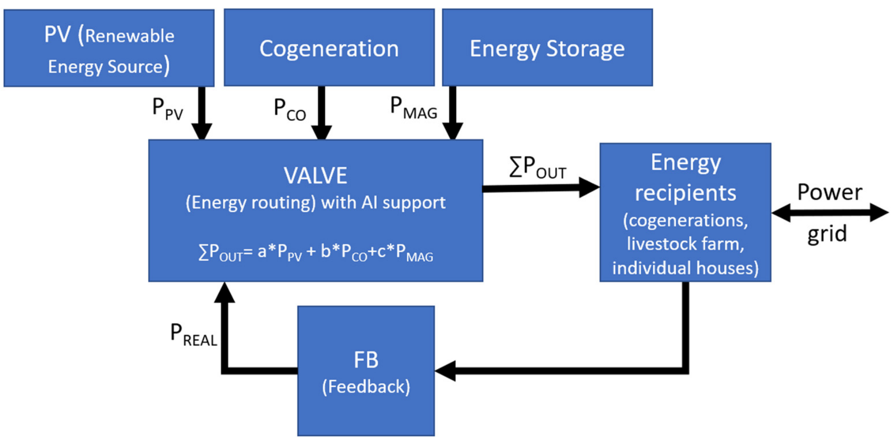

Figure 3. Energy routing through a smart valve—inputs and outputs.

In this case, we can describe its functionality based on the energy balance with its main condition:

$$P_{NET} = \sum P_{OUT} - \sum P_{REAL} \quad (1)$$

Furthermore, we can expand the equation into the following form:

$$P_{NET} = [a * P_{PV} + b * P_{CO} + c * P_{MAG}] - P_{REAL} \quad (2)$$

where: P_{OUT}—produced and stored electrical energy, P_{NET}—balanced electrical energy, P_{PV}—electrical energy from a PV source, P_{CO}—electrical energy from a cogeneration process, P_{MAG}—electrical energy from an energy storage unit, P_{REAL}—electrical energy sum for all energy recipients, and **a**, **b**, **c**—regulation coefficients based on a simulation (can be defined through a prediction and optimization process with artificial intelligence calculations including prediction, distortions, and disturbances coming from local conditions, environment, and manure/CH_4 production fluctuations).

To achieve proper operation of the system, **a**, **b**, **c** coefficients must be set up in a way to achieve the most efficient energy routing for energy received from a biogas plant (cogeneration), a PV source, or an energy storage unit. All coefficients should have values that maintain the energy balance of the system, make it fully autonomous, and—based on the energy profile from sources and loads—provide proper values to maintain the system's functionality without using external energy from a national power grid to meet the energy demands of the farmland and households.

We can see that **a**, **b** cannot be negative, as energy cannot be returned to the source, but **c** can be positive or negative, as the energy storage unit can be the receiver or the source of energy (depending on the overall capacity of the unit). In this way, we can define coefficients' limits as (3):

$$\left.\begin{array}{c} A\ \epsilon < 0,1 > \\ b\ \epsilon < 0,1 > \\ c\ \epsilon < -1,\ 1 > \end{array}\right\} \quad (3)$$

They can change over time, depending on the resolution of the data, which means that their values fluctuate within the limits based on the predictions and optimization of the energy usage and production. If there is no energy demand, all energy production is routed to the energy storage unit, which will be expressed as: **a = 0**, **b = 0**, **c = 1**, and the unit will be charged for future use to meet the momentary energy demands and requirements. It is noteworthy that when coefficient **c** is positive, the energy storage unit is charged, and when negative it becomes the power source. This is why we can balance the circuit knowing the **a**, **b** coefficients (based on the source profile) and by providing the charging profile based on coefficient **c**.

The coefficients depend on the time instance, and are connected with the biogas plant's energy production profile over time and PV energy production profile over time.

It is also a part of the process to predict and select the proper capacity of the energy storage unit to cover the energy demand of the system when energy is not produced. This will be explained and estimated during the simulation in the following chapter. When the energy production is greater than the system can accept and surpasses the capacity of the energy storage unit, energy can be routed to the power grid to be retrieved later during, e.g., service and conservation works.

Based on the considerations above, we can define the following conditions for balancing the process for an autonomous off-grid process with a smart valve as:

$$\Delta P_{NET} = 0 \quad (4)$$

which means a fully independent, self-sufficient energy system in an off-grid state.

When $P_{NET} > 0$:

- the energy storage unit is charging;

- electrical energy is released to the power grid for future retrieval when it is needed to provide support during power or servicing breaks.

This idea can be proposed to, e.g., medium or small farmlands and a certain number of households to keep the system off-grid by the efficient management using a smart valve. In this way, there is also no need for the households to use a backup power source (such as a fossil fuel based one). The following simulation will show how the process can be described based on certain values and data.

4. Simulation

The simulation will be processed using the following assumptions and based on the calculations for a specific size of farmland and number of cows:

- Twenty cows in a livestock farm located in southern Poland (Lesser Poland);
- A livestock farm defined as a regular intensive milk production farmland;
- loads defined as one production farmland and 10 individual buildings;
- 24 h operation cycle with 1 h resolution in time;
- The energy storage unit with the maximum capacity of 100 kWh and 50 kWh starting capacity, distributed over 10 individual recipients (households) where every recipient has a 10-kW standard capacity built-in; located in southern Poland (Lesser Poland);
- 10 kW photovoltaic installation in southern Poland (Lesser Poland), facing south, angled at 35 degrees, during the worst-case operation month, i.e., February.

Table 1 shows that 20 cows can generate a substantial amount of biogas which can be turned into a heat and power process very efficiently.

Table 1. Energy products from manures for a specific number of cattle.

	Number of Cows	Substrate Mg/Cow	Substrate Mg/Year	Biogas m^3/Year	Biomethane m^3/Year	Heat kWh	Heat for Fermentation kWh	Electricity kWh
Manure	20	18	360	21,600	12,960	66,290.4	143.2	42,184.8
Slurry	20	25	500	10,000	6000	30,690	9207	19,530

Own study based on Source: [41].

Considering data from Table 2, the carbon equivalent (eq.) [42–47] for manure was defined as the amount of coal that needs to be burned to generate 42,184.8 kWh of electricity for the same amount of electricity produced by a manure-powered biogas plant. The carbon equivalent (eq.) for slurry was defined as the amount of carbon that needs to be burned to generate 19,530.0 kWh of electricity for the same amount of electricity produced by a slurry-powered biogas plant.

Table 2. Estimated CO_2 emission comparison for different fuels and their carbon equivalents.

	Stock in m^3/Year or Mg/Year	Electricity in kWh	Amount of CO_2 Generated in the Production of 1 MWh in Mg	Amount of CO_2 Generated in the Production in One Year in Mg
Manure	21,600 m^3/year	42,184.8	0.56	23.70
Slurry	10,000 m^3/year	19,530.0	0.56	10.97
Carbon eq. for manure	6074.61 Mg	42,184.8	0.94	39.65
Carbon eq. for slurry	2812.32 Mg	19,530	0.94	18.35

Own study based on Source: [41].

Table 2 shows that the amount of CO_2 released to the atmosphere during the coal burning process is greater than in the respective biogas burning process. For example, biogas from manure released 23.7 Mg CO_2 into the atmosphere, while coal combustion released 39.6 Mg CO_2, both generating the same amount of electricity, amounting to 42,184.8 kWh.

On the other hand, the biogas burning process from the slurry released 10.9 Mg CO_2 into the atmosphere, and the coal combustion equivalent produced 18.3 Mg CO_2. Moreover, if we assume that 1 g of methane released into the atmosphere has an equivalent of 25 g CO_2, the combustion of methane from manure generating 42,184.8 kWh will release 23.7 Mg CO_2 into the atmosphere. In this process, 12,960 m^3/year of biomethane, which corresponds to about 226 Mg CO_2, does not reach the atmosphere. Thus, in total, for manure biogas we obtain a negative CO_2 equivalent of approximately −203 Mg CO_2. If we consider the case of biogas from slurry generating 19,530 kWh, which releases 10.9 Mg CO_2, the process prevents 6000 m^3/year of biomethane, which corresponds to about 105 Mg CO_2, from being released into the atmosphere. This amounts to the negative CO_2 equivalent from slurry biogas to stand at about −94 Mg CO_2. This shows the possible net reduction in biogas' impact on the environment and is based on the literature examples [48–51] of such negative values of the CO_2 equivalents through the usage of biogas plants or biomass itself.

Table 3 shows the possibilities of biogas production from different types of substrates of agricultural and food origin [52–54]. Manure and slurry were selected for considerations and simulations, as they are the most commonly generated waste in cattle breeding in our geographic region and are significantly harmful to the environment. For this reason, they are the primary source of methane emission into the atmosphere, but can be utilized for the production of biogas as a fuel for biogas plants (Figures 4 and 5).

Table 3. Production of biogas, biomethane, electricity, and thermal energy from selected substrates.

Substrate:	Production		Production	
	Biogas Nm^3/t	Biomethane Nm^3/t	Electricity kWh/t	Thermal Energy kWh/t
grass silage	172	93	298	372
grass fodder	60	42	134	176
fodder from laws	42	21	67	84
cattle slurry	20	12	38	48
cattle manure	60	36	117	184
pig slurry	15	9	29	36
dry chicken manure	231	119	381	476
canteen waste	145	82	262	328
fat after frying fries	827	562	1798	2243

Own study based on Source: [41].

Drawing from the assumptions above, we were able to define and use the profiles of energy production by a biogas plant and a photovoltaic installation during a 24 h cycle, which is shown in Figures 6 and 7 with a trend line. We also show the comparison of electrical energy production profiles from these sources combined during one day.

The energy production profile depends on the supply of substrate for cogeneration and the further combustion of biogas in the cogeneration process. Therefore, the energy generation process is not constant and depends on the daily operating mode of the farm (milking hours, feeding hours, and maintenance hours).

The next step in our simulation was to calculate the total of electrical energy produced over 24 h to define a 24 h profile of electrical power that can be retrieved from all power sources (Figure 8). These values are required as inputs to our virtual regulation valve.

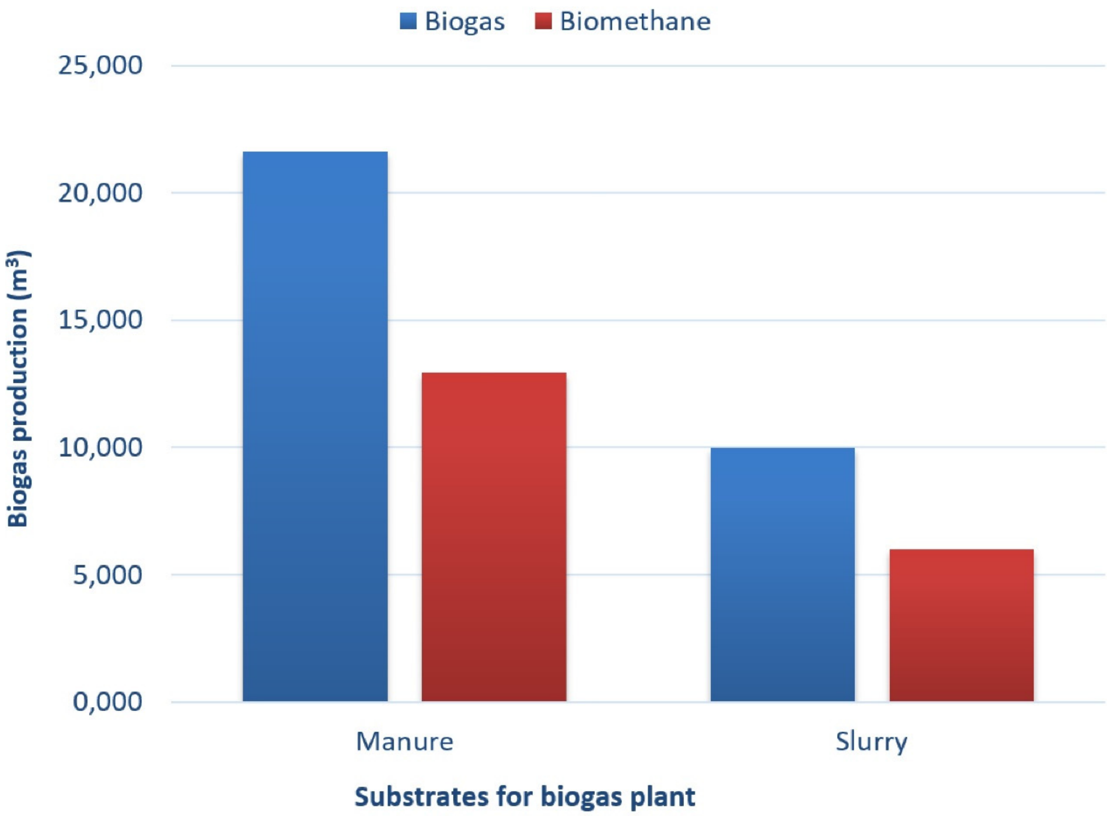

Figure 4. Biogas and biomethane production from 20 cows on farmland. Own study based on Source: [41].

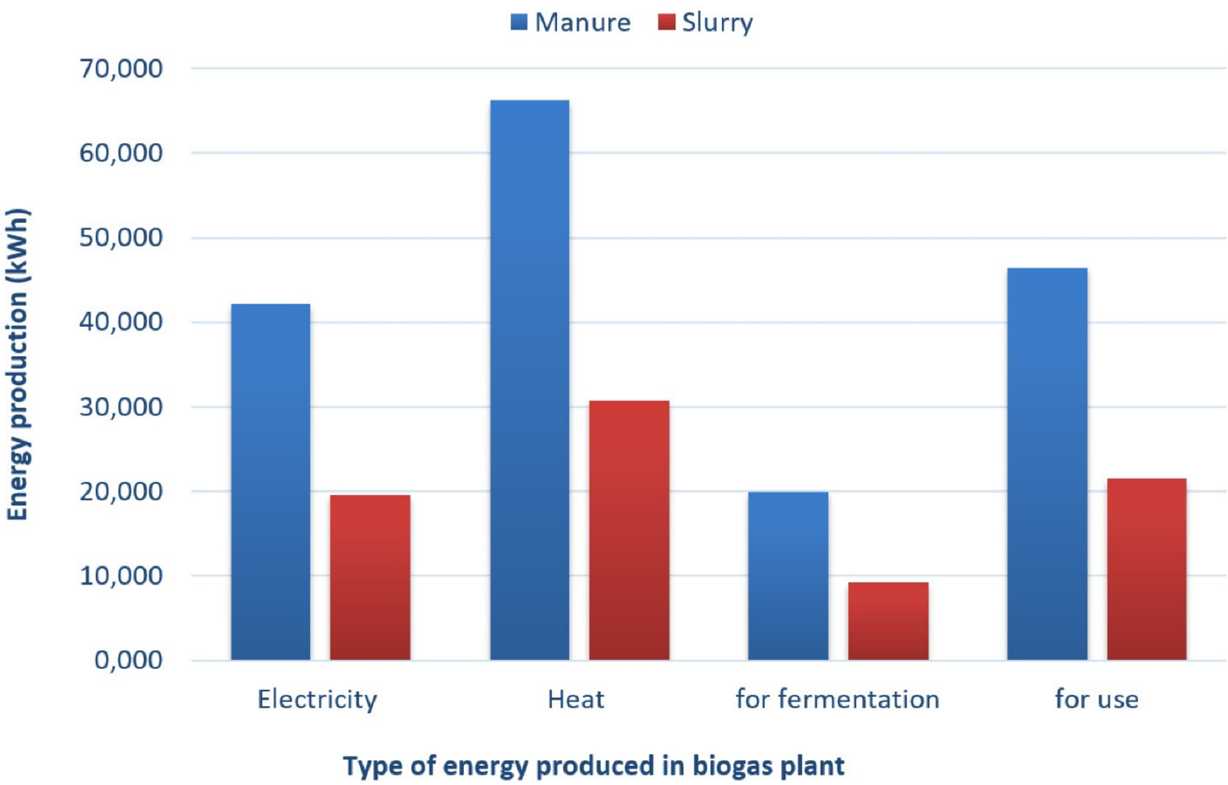

Figure 5. Heat and electric power production from 20 cows on farmland. Own study based on Source: [41].

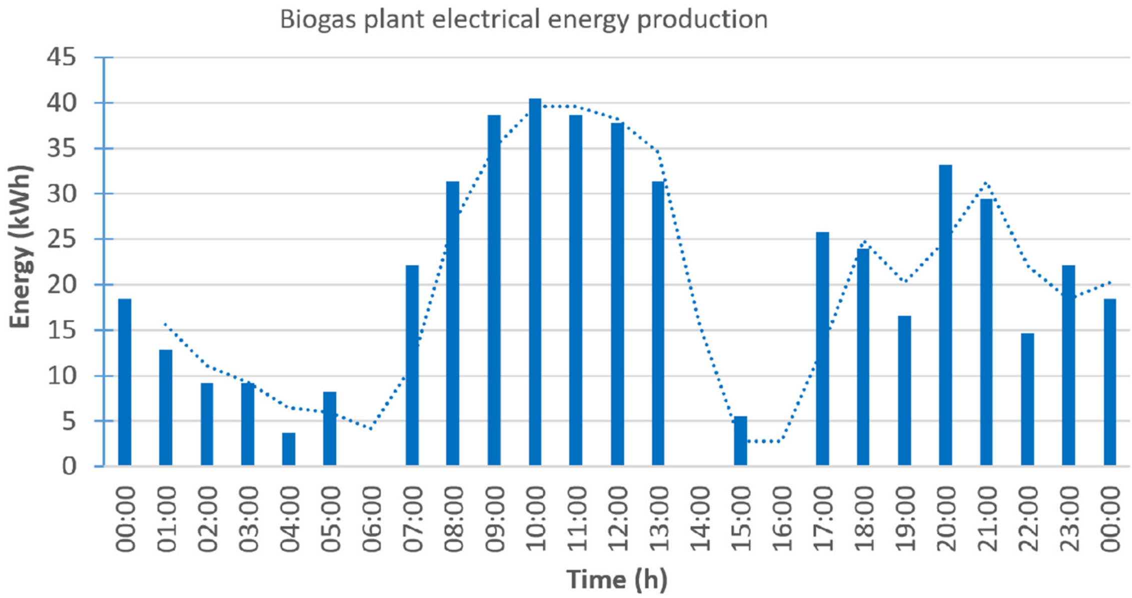

Figure 6. Biogas plant's electrical energy production profile during a 24 h cycle for farmland with 20 cows. Own study based on source [55].

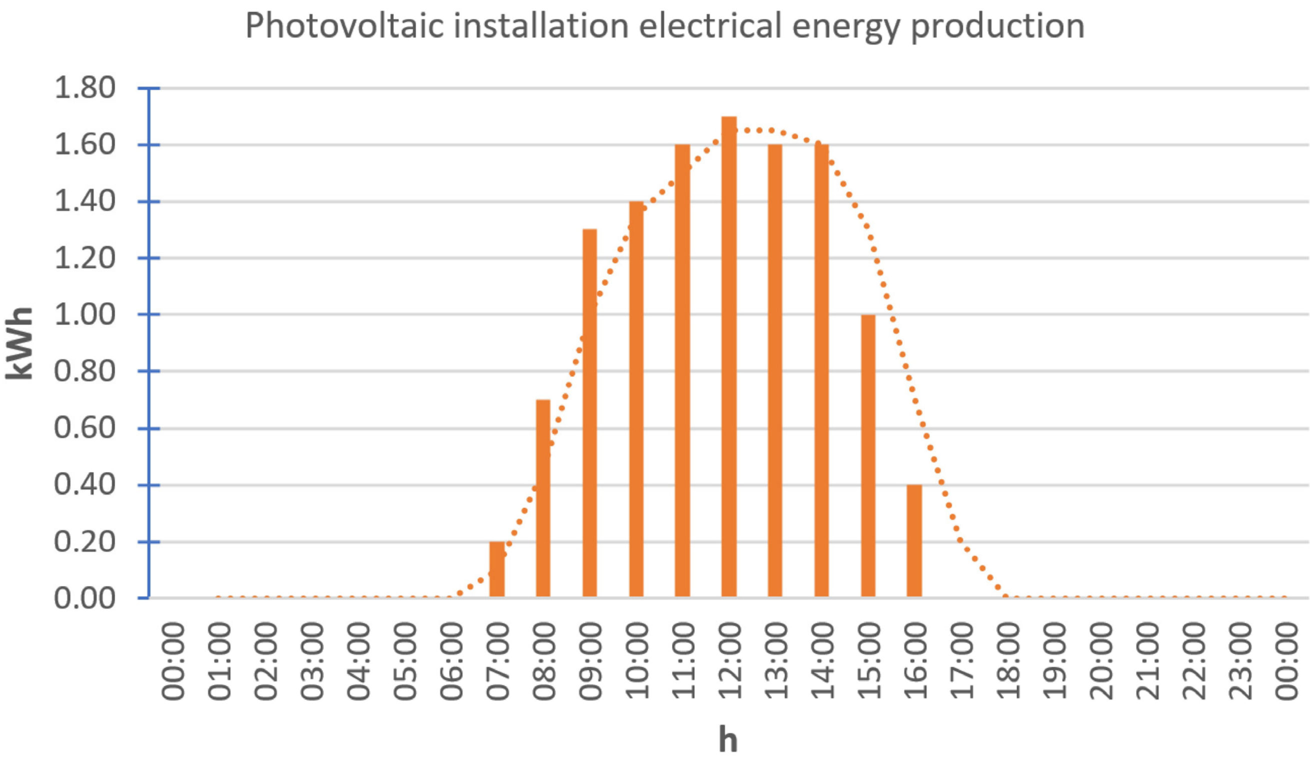

Figure 7. The 10-kW photovoltaic installation's electrical energy production profile during a 24 h cycle. Own study based on source [55].

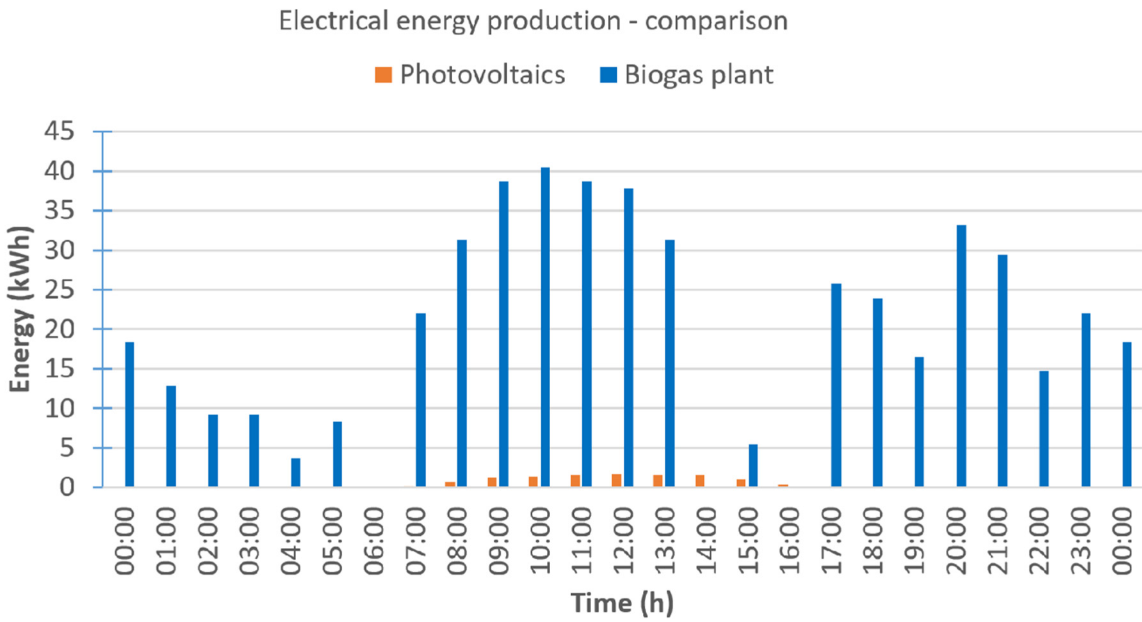

Figure 8. Electrical energy production profile comparison during a 24 h cycle. Own study based on source [55].

As a next step, we needed to define the energy requirement profile for the recipients over 24 h. Our recipients were:

- ten individual houses as the passive energy recipients with an estimated energy requirement of 379.2 kWh/day;
- loads defined as one production farmland (described above) and 10 individual buildings (as the energy recipients in the circuits-households) located in a close neighbourhood and connected with the energy distribution infrastructure.

The average size of the household is 150 m^2. These profiles (Table 4) are taken from the literature [31,55] and available sources.

Table 4. Daily electricity and electricity demand.

Time HH:MM	Production Power by Co-generation	Daily Profile of a Biogas Plant for 20 Cows	Household Demand Profile on a Working Day	Household Demand Profile of one on Saturday	Demand Profile for 10 Buildings	Production Farm Demand Profile—Dairy Intensive	Profile RES * (PV) 10 kW
	kW	kWh	kWh	kWh	kWh	kWh	kWh
00:00	350	18	0.5	0.5	10	0.9	0
01:00	320	13	0.4	0.5	8	0.8	0
02:00	210	9	0.4	0.4	8	0.8	0
03:00	220	9	0.5	0.4	10	0.8	0
04:00	100	4	0.4	0.5	8	0.75	0
05:00	40	8	0.4	0.3	8	4.0	0
06:00	60	0	0.9	0.7	18	8.8	0
07:00	500	22	0.7	0.9	14	8.7	0.2
08:00	700	31	0.4	0.5	8	7.7	0.7
09:00	820	39	0.3	0.3	6	4.5	1.3
10:00	880	41	0.3	2.1	6	3.0	1.4
11:00	850	39	0.4	2.4	8	2.3	1.6
12:00	820	38	0.45	2.2	9	2.5	1.7
13:00	600	31	0.5	2.7	10	2.6	1.6
14:00	180	0	0.6	2.2	12	2.4	1.6
15:00	100	6	0.5	1.8	10	2.1	1

Table 4. *Cont.*

Time HH:MM	Production Power by Co-generation	Daily Profile of a Biogas Plant for 20 Cows	Household Demand Profile on a Working Day	Household Demand Profile of one on Saturday	Demand Profile for 10 Buildings	Production Farm Demand Profile—Dairy Intensive	Profile RES * (PV) 10 kW
16:00	0	0	0.9	1.7	18	2.1	0.4
17:00	400	26	0.3	2.2	6	6.5	0
18:00	400	24	0.3	2.3	6	8.8	0
19:00	420	17	0.4	2.3	8	9.0	0
20:00	800	33	1.1	2.7	22	9.3	0
21:00	700	29	1.2	0.5	24	6.5	0
22:00	350	15	0.8	0.6	16	5.0	0
23:00	400	22	0.6	0.7	12	3.0	0
00:00	400	18	0.5	0.5	10	1.3	0

* RES—Renewable Energy Systems. Own study based on source [55].

The calculations are based on regular usage during a working week (Monday–Friday). These data series are shown in Figures 9–11, where we can see separate energy usage profiles for the farmland and individual recipients, as well as the summary of energy demand which will be the input for our smart valve.

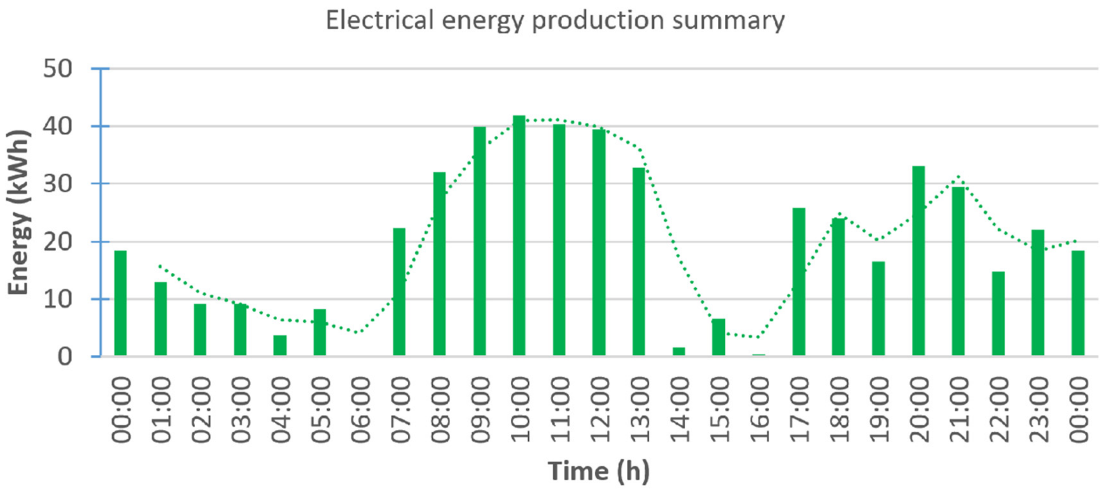

Figure 9. Electrical energy production summary profile during a 24 h cycle. Own study based on source [55].

We have defined all inputs for the simulation to outline the amount of energy needed to charge the energy storage unit and to cover the energy demands at times when energy production is unable to fulfil the recipients' needs. To properly calculate the value of the energy loading or discharging the energy storage unit, we needed to take into account the loading process of the energy storage unit.

Our idea was based on the rule that an energy surplus can be used to charge the energy storage unit in an hourly cycle. In this way, we were able to recharge and prepare the unit for a high energy demand when no energy was produced by a biogas plant or photovoltaic installation (e.g., during the night).

This can be expressed through the formula below:

$$C_n = \frac{P_{MAG_{init}}}{P_{MAG_{init}} + \sum_{n=1}^{24}\left(P_{MAG_{init}} + \cdots + P_{MAG_{n-1}}\right)} \tag{5}$$

where $P_{MAG_{init}}$—the initial energy storage value at the beginning of the cycle, n—following hour of the daily cycle from 1 to 24, and C_n—the regulation coefficient for the energy storage unit's management function of the valve.

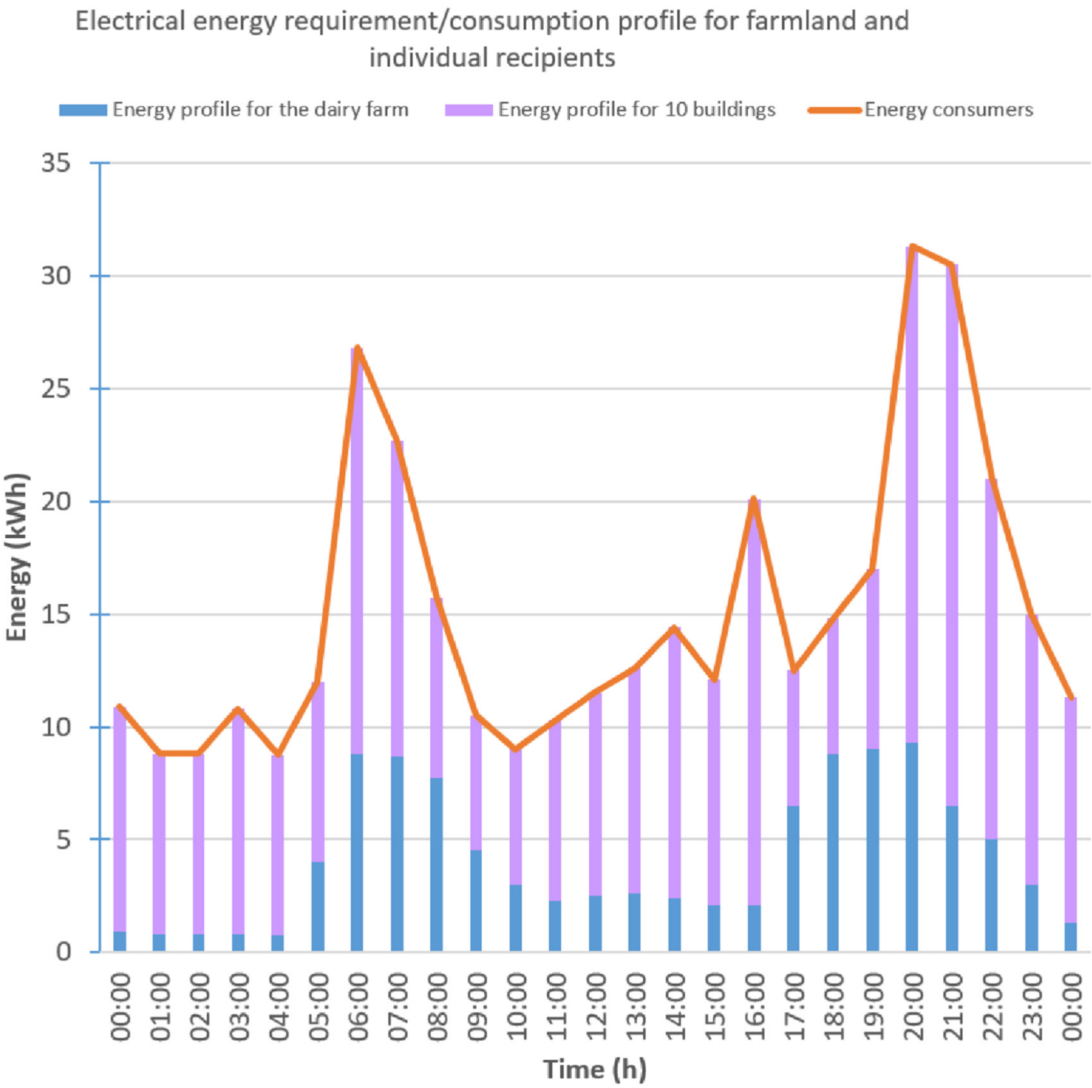

Figure 10. Electrical energy requirement/consumption profile for farmland and individual recipients and a summary of the energy usage for the analysed energy flow circuit. Own study based on source [55].

Our simulation, based on the input data, is shown in Figure 12 below. The energy storage accumulates energy when its surplus allows, and returns it to the system when the recipients need it. In the previous chapter, we mentioned that the energy storage unit's capacity selection would be estimated, and now we can see that as we store more than 40 kWh, and the storage unit needs to release energy at almost 30 kWh over 24 h, a reasonable size of the unit is twice the maximum of the energy stored or used by it. In this case, it would mean more than 80 kWh. Using the common commercial size of the storage unit, the practical approach would be to use distributed consumer size units with, e.g., a 10-kWh capacity for each recipient (household), which would grant 100 kWh of storage in total. Energy storage units with a 10-kWh capacity can be built-in in every home as a part of the system. We also need to consider the case when we start our simulation and operation with a given initial value of the energy storage unit to avoid energy shortages caused by an empty storage unit. We assume in the simulation that the initial value of the unit should be half of its full capacity, which amounts to 50 kWh. This is also included in the above formula (5).

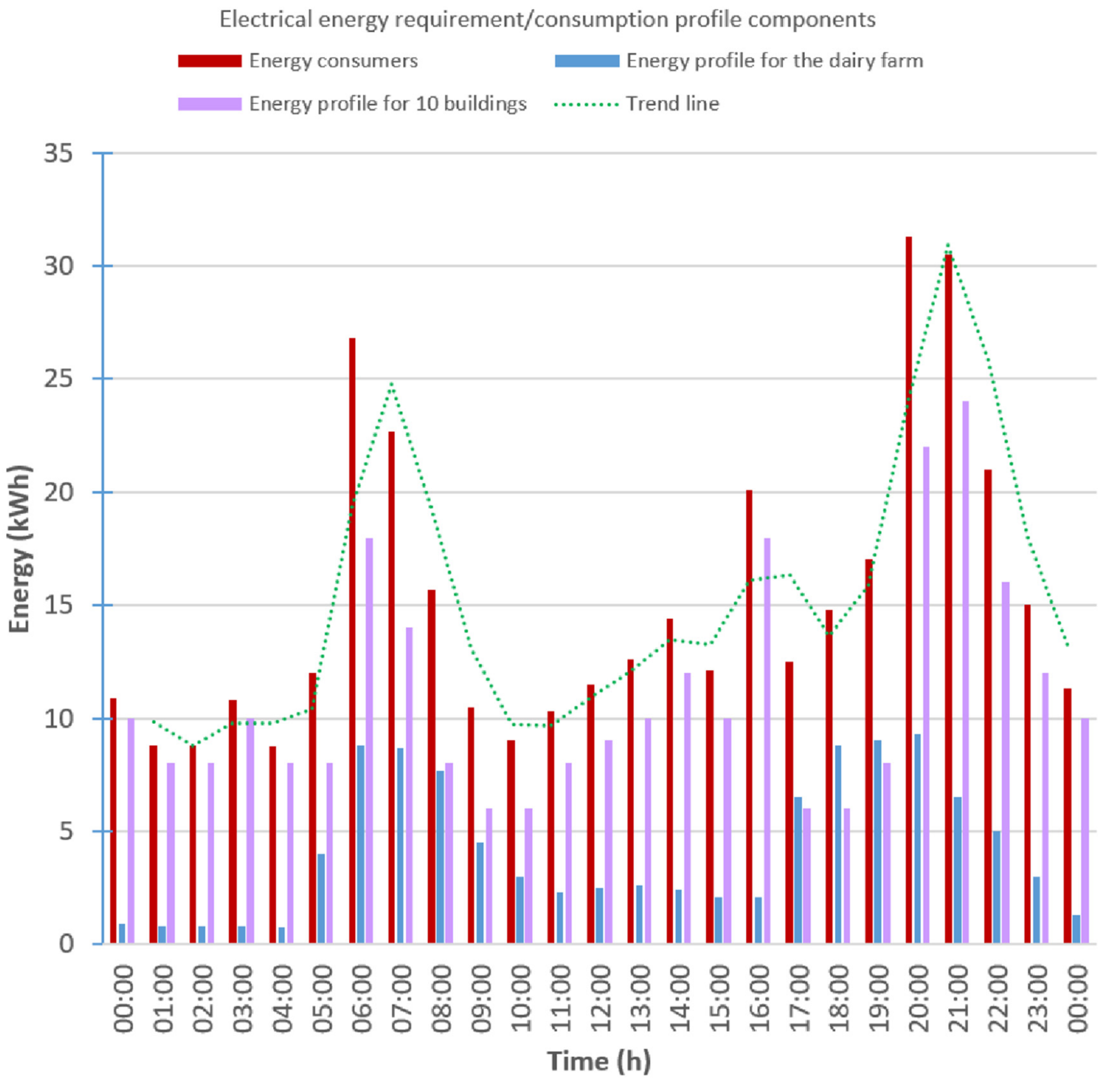

Figure 11. Electrical energy requirement/consumption profile components for farmland and individual recipients and a summary of the energy usage for the analysed energy flow circuit. Own study based on source [55].

The energy storage grid management based on the distributed 10 kWh storage network in each of the 10 homes is to be examined further, but our goal was to calculate the coefficients for the smart valve to define its operation over the 24 h cycle. This simulation of **a**, **b**, **c** coefficients is shown in Figure 13.

In our simulation, all energy from the biogas plant and photovoltaic installation is used in the system once produced, therefore the **a** and **b** coefficients are 1 or 0 in given instances. Coefficient **c** changes over time and takes values from a = [−1; 1] range, as stated before. This set of coefficients can be adjusted over time using, e.g., artificial intelligence or prediction and optimization based on profiles of usage over time for specified farmlands and the number and types of recipients. However, it is now visible that these coefficients can manage the smart valve's operation, rendering the proposed system independent from the power grid and keeping it self-sufficient in terms of energy production and consumption.

We can also notice that if we observe 2 days (48 h) as the simulation interval using the same input data, the coefficient **c** becomes stabilized, and the daily cycle repeats its profile (Figure 14). It is to be further investigated how to optimize the system and apply or adjust prediction algorithms to achieve a better match to the loads' profile and the energy storage unit's capacity.

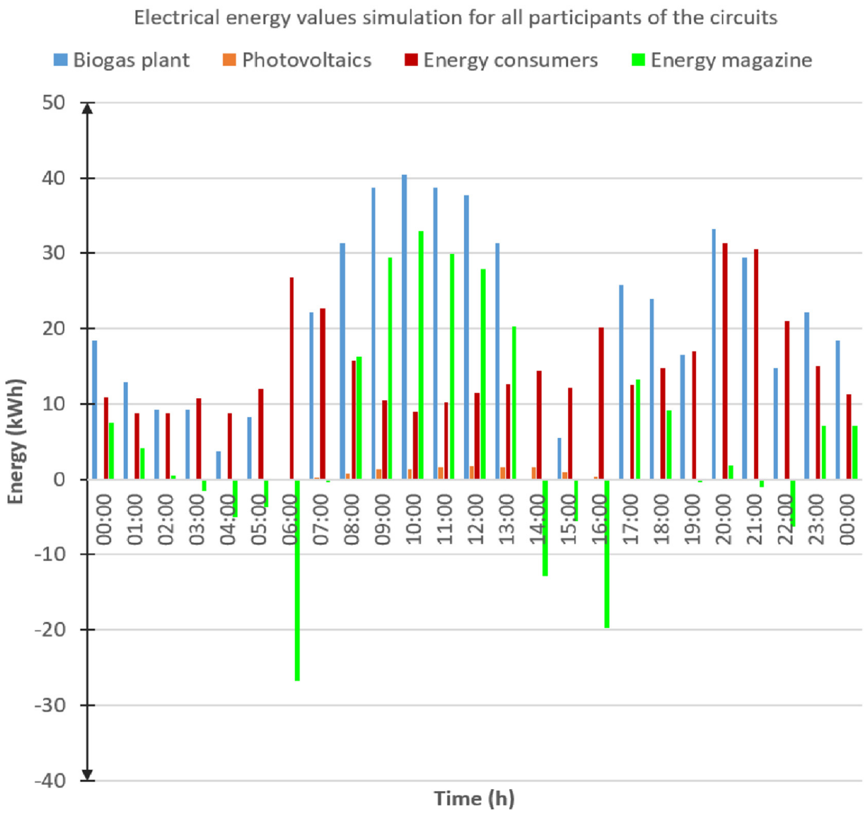

Figure 12. Electrical energy values simulation for all participants of the circuits on the virtual valve including the energy storage management.

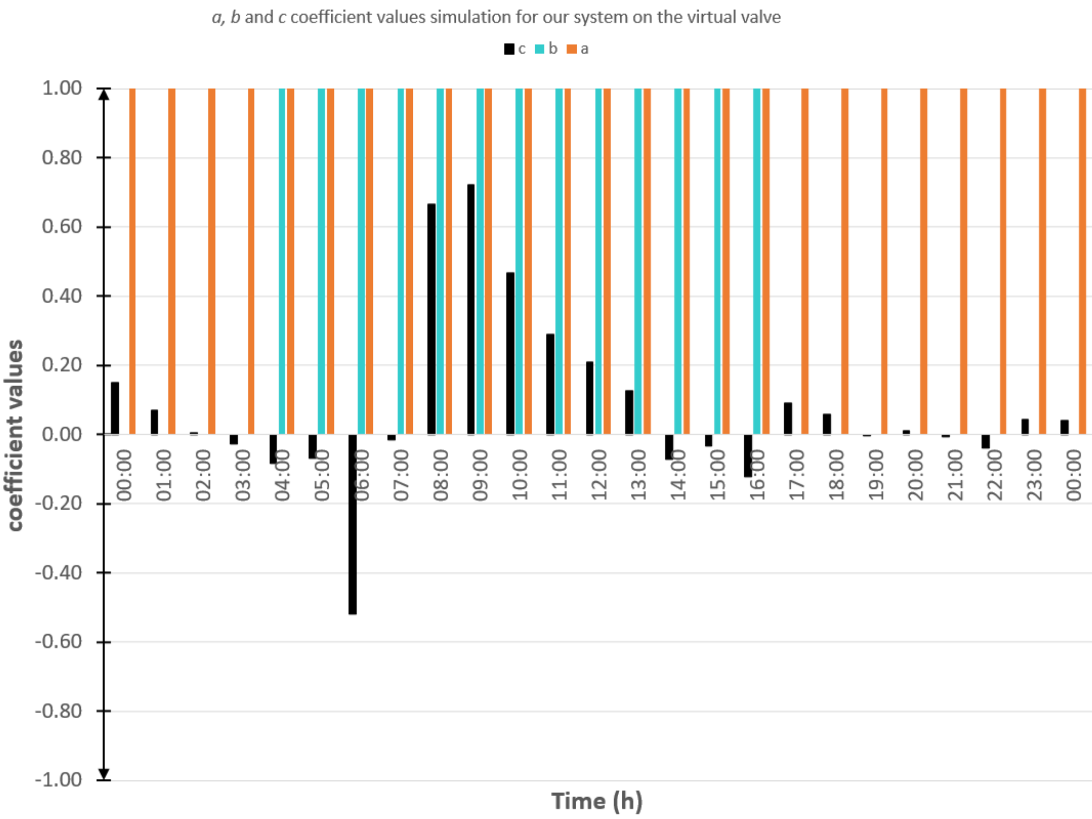

Figure 13. The **a**, **b**, **c** coefficient values simulation for our system on the virtual valve.

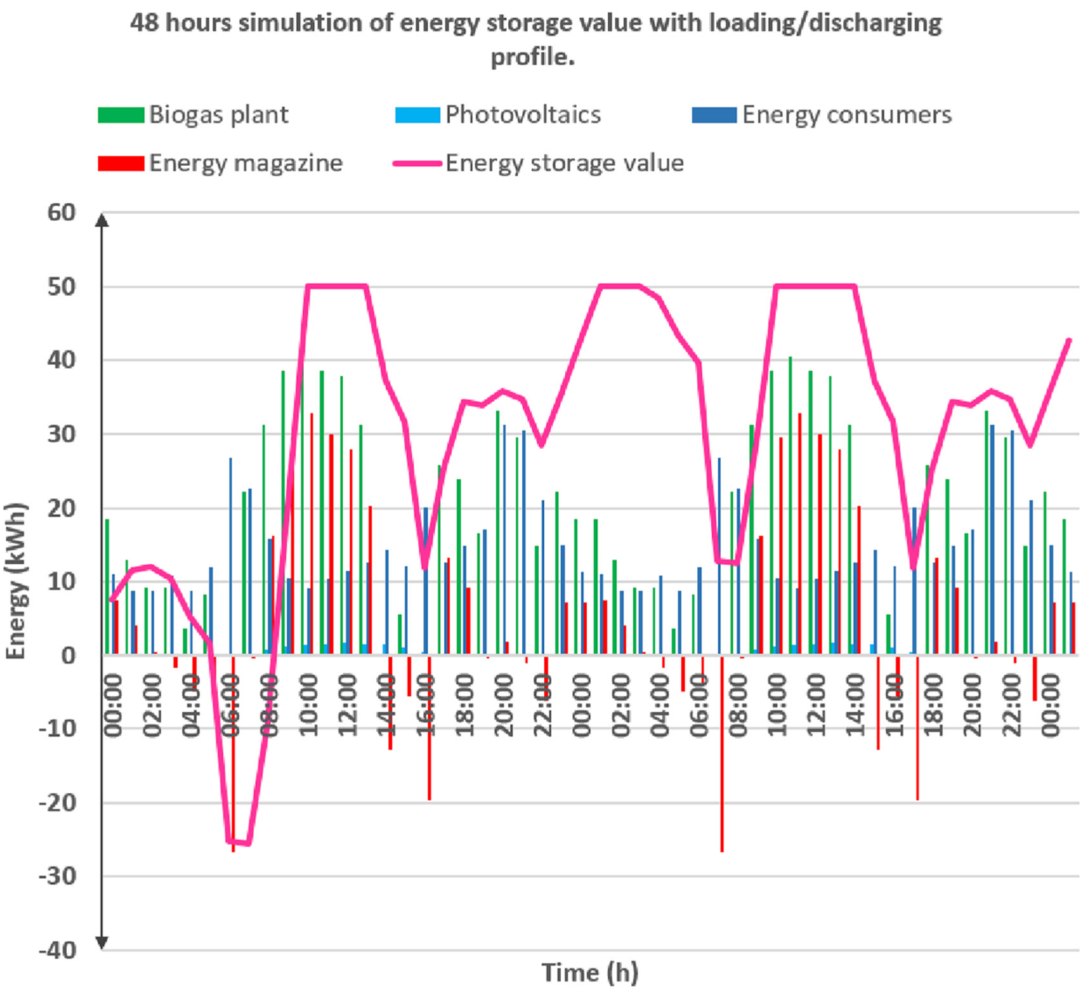

Figure 14. A 48-h simulation of the energy storage unit's value with a loading/discharging profile.

A complimentary result of the implementation of the smart valve concept to achieve an off-grid, autonomous, self-sufficient hybrid system presented above is that we can estimate the reduction in CO_2 emissions as compared to the electrical energy produced by a conventional fossil fuel powered plant covering the power requirements of the recipients in the system—the farmland buildings during operation and 10 households. The comparison of these values is shown in Table 2. As the fossil fuel powered plant, we used heat and power plant in Kielce located in the southern part of Poland, with an installed electrical power of 17.6 MW and annual electrical energy production of 91,508 MWh (as per 2020, based on data published on the website).

5. Conclusions

The idea of an off-grid, self-sufficient, autonomous hybrid system for the agricultural area with a biogas plant, supported with renewable energy PV circuits and an energy storage unit managed by a smart valve, allows for efficient energy management and nearly full usage of the biogas and biofuel production for cattle farming, and can satisfy the energy consumption needs of individual consumers (households) in the area. Even considering that it cannot be a fully off-grid solution, and an electric power network is still used as a backup for the system, proper management enabled by the smart valve capable of managing the energy flow and its distribution grants a possibility to efficiently manage the energy. The calculation and set up of the valve's coefficients, taking time into consideration, allows the system to be independent of the national power grid and ensures the full usage of the energy produced by the biogas plant and renewable energy sources. There is also no need to use additional fossil fuel sources as complementary energy sources for households or farmland buildings.

Our simulation showed that, with proper energy storage values and calculation of coefficients for the smart valve, we could achieve a self-sufficient, off-grid system that could power external recipients such as individual homes, satisfying the energy demands of farmland at the same time.

As the smart valve management plays a key role in the system, further examination and investigation are necessary to research the possibility to apply more advanced algorithms (e.g., prediction or optimization). The proposed system and calculation method for the smart valve's operation can be adapted to on-site or off-site solutions.

Renewable energy sources give a great chance not only for the creation of autonomous hybrid systems in small village areas, but also to minimize environmental pollution by removing conventional power sources based on fossil fuels, utilizing the waste produced by farmlands at the same time.

The idea of an autonomous, self-sufficient, hybrid energy system based on agricultural farmland can be extended to other types of farmlands and villages. It allows for the application of artificial intelligence to maintain energy routing and storage by applying the smart valve concept. This also allows for the addition of alternative renewable energy sources, such as wind plants or water plants, to the system. The smart valve, with its coefficients, can be used to control the process of energy routing and balancing in modern automation and control systems to provide energy management for such systems and their future versions. The idea also allows more control over balancing the process of unstable energy production from a biogas plant and renewable energy sources to supply electrical energy to the local loads (households and farmlands) to achieve a self-sufficient system with a hybrid architecture and energy storage options.

The biogas-based process additionally allows for a significant reduction in CO_2 emissions in comparison to coal combustion emissions. When we take methane's equivalent of CO_2 emissions coefficient which is released into the atmosphere, we can observe a possibility to additionally reduce the impact of methane's influence on the environment. It is clearly visible, when we use a formula where 1 g of CH_4 greenhouse gas is equal to 25 g of CO_2 greenhouse gas emissions, that the reduction in methane greenhouse gas emissions constitutes a significant reduction in a CO_2 equivalent, even considering the amount of CO_2 burned in a cogeneration process. The result of the process reduces greenhouse gas emissions, and can lead to negative CO_2 emissions equivalent.

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Determining the Power and Capacity of Electricity Storage in Cooperation with the Microgrid for the Implementation of the Price Arbitration Strategy of Industrial Enterprises Installation

Rafał Kuźniak, Artur Pawelec, Artur S. Bartosik * and Marek Pawelczyk

Department of Production Engineering, Kielce University of Technology, Al. Tysiaclecia P.P. 7, 25-314 Kielce, Poland; rkuzniak@tu.kielce.pl (R.K.); apawelec@tu.kielce.pl (A.P.); m.pawelczyk@tu.kielce.pl (M.P.)
* Correspondence: artur.bartosik@tu.kielce.pl

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Abstract: The growing worldwide costs of energy produced as a result of conventional fuel combustion, the limited capacity of the distribution grid, and the growing number of unstable installations based on renewable energy sources increase the need to implement systems of stabilization and regulate loads for end users. The battery energy storage system (BESS) that operates in the internal microgrid of an enterprise enables the management of the accumulated energy in any time zone of the day. Using a price arbitrage strategy with an electricity storage facility, we can reduce the cost of high electricity prices during peak demand periods. This study aims to determine the most effective method of setting up the capacity and electrical power of an energy storage system operating in a microgrid, in an enterprise to implement a price arbitration strategy. Such a method should include consideration of the characteristics of the demand profile of consumer systems, the charges related to electricity, and electricity storage costs. The proposed deterministic method is based on the use of a defined parameter, "marginal income elasticity". In this study, the size of energy storage refers to the power and electric capacity of BESS that are used for the implementation of the price arbitrage strategy.

Keywords: BESS management; price arbitration; shift load; microgrid; energy efficiency

1. Introduction and Review of the Literature Related to the Optimal Power and Capacity of an Electric Energy Storage System

In recent years, the energy market has seen an increase in interest in electricity storage, resulting in the development of scientific research on various working conditions and the strategies for their operation. Numerous studies have presented reviews of energy storage technologies in terms of their applications in microgrids [1–8]. Researchers presented the main functionalities that can be implemented in microgrids, including the absorption of energy from renewable sources, improvements in the quality parameters of electricity, peak shaving strategies, and price arbitrage and time shifts [9,10]. One of the main goals of the research has been to develop a methodology to achieve the optimal parameters of energy storage from an economic point of view, taking into account the investment and operating costs and the technical and economical parameters of various technologies that have potential for broad usage [11–15].

Research on the battery energy storage system (BESS) that uses deterministic and stochastic methods to determine the cost effectiveness of storage technologies was presented in previous works [16–18]. Adopted models were analyzed, including the costs of individual BESS technologies, the degradation of the capacity over time, and the losses of capacity during the discharge readiness period. The application of the integrated model to define and select energy storage parameters was presented in previous works [19–21]. These works presented models that included the implementation of thermal, electrical, and aging processes, as well as various sources and parameters that characterized the production of electricity within the microgrid. Stochastic predictive models, using 24 h wind force forecasting to optimize the power and capacity of energy storage in microgrid systems, were proposed in [22].

The problem of selecting the power and capacity of energy storage to balance microgrids, based on local results with various integrated renewable energy sources and various types of energy storage, was studied [23–26]. These studies presented mathematical models of microgrid systems with sources such as photovoltaic panels and wind turbines. On the basis of actual data characterizing the demand for electric energy, a simulation of the microgrid operation was performed, depending on the variability of electric energy demand in an island system. The use of electricity storage systems to increase the share of energy generated from renewable sources was also considered in previous works [27–30].

The issue of selecting the size of energy storage for households with their own renewable energy production systems for time-shifting functionality was discussed in an earlier study [31]. As a result of that research, it was shown that group energy storage, compensating for the flow of energy transferred to the external grid, is more profitable than individual storage systems. Studies on the maximization of expected daily economic profit, obtained using the time-shifting strategy to postpone the production of renewable energy, were presented in [32].

Korpikiewicz [33] broadly presented the conditions required for the operation of autonomous energy storage to implement a price arbitrage strategy, i.e., the use of variable energy rates throughout the day to reduce energy demand in periods of high energy prices and increase demand in periods of low energy prices. Algorithms describing the logic of determining the BESS charging and discharging cycles to optimize the operation of the system have been presented with the basic technical and operational data of BESS, which were obtained in various energy storage technologies [34].

A very important problem that should be considered when installing BESS in enterprises is the safety of the system. Particular attention should be paid to fire hazards posed by lithium-ion batteries. Therefore, the safety of BESS is the subject of intensive studies conducted by scientists [35], engineering associations [36], territorial units [37], and manufacturers who implement their own fire protection concepts [38]. Despite intensive research, there is still a lack of effective and rapid methods that could be widely used.

In summarizing the literature review, it should be noted that there are several studies on the use of BESS to implement a price arbitrage strategy. Most of the works dedicated to price arbitration focus on separated systems, supporting the distribution network and operating autonomously with constant and fixed charge and discharge values [39–41]. The models of energy storage operation presented in the literature confirm that the operating profit resulting from the use of the storage facility for price arbitrage is proportional to the total storage capacity.

In the available research, there are several studies on the profitability of an energy storage system management strategy that take into account the constraints associated with the actual energy demand and power of microgrids in production plants. Restrictions resulting from legal regulations on billing for the production of energy in a given country or in real microgrid systems may cause the benefits of using storage systems to decrease non-linearly with an increase of BESS capacity and power.

This study aims to determine the most effective method for setting up the capacity and electrical power of an energy storage system operating in an enterprise's microgrid to implement a price arbitration strategy. Our research considered the existing technical and cost limitations in real enterprises that lead to a decrease in the effectiveness of the implementation of a price arbitration strategy. This paper defines the indicators for assessing the effectiveness of this strategy, and on that basis, we propose a determination of the effective boundary for BESS size. The microgrid system of the enterprise is a separate power installation, created from the load devices, active energy storage, or generation of assets with a control-and-regulation system, that is capable of managing the energy and electric power balance within the enterprise, connected to the distribution system operator's (DSO's) network. In this study, we assumed that the microgrid system managed an electricity storage installation and industrial power load within selected companies that were connected to a medium voltage grid.

2. BESS Work Strategy, Characteristics of Companies Selected for Research, and the Chosen BESS Model

The paper analyzes the use of BESS in terms of representative functionality for the electricity market, that is, price arbitrage. Price arbitration is based on the use of daily differences in unit prices of electricity. The essence of this strategy is the storage of energy purchased from the external grid in the price valley and then unloading the battery storage to supply the microgrid loads at times when the unit energy prices are the highest. When examining the conditions of this BESS functionality, one should consider the electricity prices [PLN/kWh] based on the offers of trading companies in the competitive market and the variable rates [PLN/kWh] for the distribution services that are included in the tariff of the appropriate distribution system operator that is approved by the President of the Energy Regulatory Office (ERO). The second option is to consider electricity prices according to the rates of the Polish Power Exchange Stock Market.

For customers who are billed according to the tariffs of energy companies, price arbitrage may be applied by selecting multizone tariff groups. The most diversified prices are in the B23 tariff group. There are three time zones in this group: S1 is the morning peak, S2 is the afternoon peak, and S3 is the the rest of the day. At all hours of the day on Saturdays, Sundays, and public holidays, energy is billed in the S3 zone as the rest of the day. The distribution of hours according to UTC + 1 time (coordinated universal time + 1 h) in tariff group B23 is presented in Table 1. The multi-tariff time zones included in Table 1 are typical for Poland and are applied in the tariffs of the four largest distribution network operators in Poland.

Table 1. Distribution of time zones in the B23 tariff group for individual months in UTC+1 time. Yellow background with 1 is zone S1; red background with 2 is zone S2; green background with 3 is zone S3.

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Jan	3	3	3	3	3	3	3	1	1	1	1	1	1	3	3	3	2	2	2	2	2	3	3	3
Feb	3	3	3	3	3	3	3	1	1	1	1	1	1	3	3	3	2	2	2	2	2	3	3	3
Mar	3	3	3	3	3	3	3	1	1	1	1	1	1	3	3	3	2	2	2	2	2	3	3	3
Apr	3	3	3	3	3	3	1	1	1	1	1	1	1	3	3	3	3	3	2	2	2	3	3	3
May	3	3	3	3	3	3	1	1	1	1	1	1	1	3	3	3	3	3	2	2	2	3	3	3
Jun	3	3	3	3	3	3	1	1	1	1	1	1	1	3	3	3	3	3	2	2	2	3	3	3
Jul	3	3	3	3	3	3	1	1	1	1	1	1	1	3	3	3	3	3	2	2	2	3	3	3
Aug	3	3	3	3	3	3	1	1	1	1	1	1	1	3	3	3	3	3	2	2	2	3	3	3
Sep	3	3	3	3	3	3	1	1	1	1	1	1	1	3	3	3	3	3	2	2	2	3	3	3
Oct	3	3	3	3	3	3	3	1	1	1	1	1	1	3	3	3	2	2	2	2	2	3	3	3
Nov	3	3	3	3	3	3	3	1	1	1	1	1	1	3	3	3	2	2	2	2	2	3	3	3
Dec	3	3	3	3	3	3	3	1	1	1	1	1	1	3	3	3	2	2	2	2	2	3	3	3

In the case of enterprises in the B23 tariff group, the price arbitration strategy is based on avoiding the purchase of electricity from the external grid when the variable unit rates in PLN/kWh are the highest, according to variable fees during the afternoon peak in the S2 zone.

An important element of electricity billing that should be considered when applying the price arbitrage strategy is the capacity fee. In Poland, beginning on 1 January 2021 as part of the implementation of the capacity market, an additional component was introduced to settlements for distribution services: i.e., the capacity fee in PLN/kWh. The rate of the capacity fee is published annually by the President of the Energy Regulatory Office (ERO), along with the designated hours of peak power demand during the day, at which times this component should be added to the consumed kilowatt hours Because the amount of this fee depends on the hours of the day, it increases the daily difference in prices related to electricity consumption and affects the application of the price arbitration strategy [42].

The capacity fee in Poland, after 1 January 2021, applies to all enterprises and is charged from 07:00 to 22:00 on business days. The hours in which the capacity charge applies according to UTC + 1 are presented in Table 2.

Table 2. Schedule of hours in UTC+1, time of charging the capacity fee valid from 2021; red background on 1.

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Jan	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Feb	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Mar	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Apr	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
May	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Jun	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Jul	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Aug	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Sep	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Oct	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Nov	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Dec	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0

The price arbitrage strategy research was carried out for three different companies on the basis of the time series of the average 15 min electric load power consumed by the companies and recorded by measuring systems in an annual period. Data recorded in individual 15 min intervals were marked as load power P_{L15} [kW]. The companies selected as research subjects were marked with letters A, B, and C, to which the year of registration of the time series tested was added (2018 and 2019). The selected companies carry out production activities with the use of various technologies and in various specialties. The enterprises are powered from the medium voltage power grid. Companies A and C are characterized by a constant level of energy consumption on working days; their work is carried out in a three-shift system. Enterprise B works in two shifts, only on working days. The differences in the weekly work organization of the enterprises are visible in Figure 1, which presents the average weekly profiles of power demand in 15 min power-demand intervals.

The characteristics of the organization of the work in the surveyed enterprises and their power demands are also illustrated by the coefficients of variation in the statistics of the 15 min power consumption time series, as shown in Table 3.

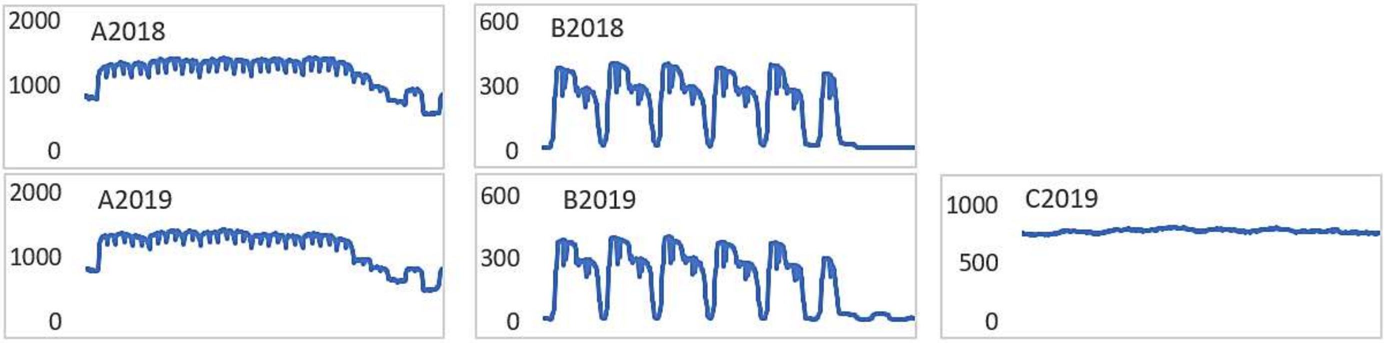

Figure 1. Comparison of the average weekly power demand profiles in [kW] for an annual period.

Table 3. Statistical data of the 15 min load power time series of the enterprises.

Enterprise Average 15 min Load Power in Year		A2018	A2019	B2018	B2019	C 2019
Maximum	kW	1822	1860	509	508	1272
Average	kW	1217	1177	208	202	786
Median	kW	1336	1361	228	205	786
Standard deviation	kW	353	434	175	174	176
Coefficient of variation		29%	37%	84%	86%	22%

Based on the regulations that govern the application of tariff rates by energy companies and the settlement rules on the energy market and the capacity market, simulations of the BESS effect for the "price arbitrage" functionality were carried out. As part of the research, analyses of the time series of parameters characterizing the operating state of BESS, which were created as a result of the simulation of its operation in the microgrid system and the size of settlement data at the point of common coupling (PCC), were carried out.

The research consisted of adopting subsequent parameters characterizing the size of the energy storage, increasing them by a fixed value, and simulating their operation for a "price arbitrage" strategy in 15 min intervals for the entire annual measurement period. To investigate the price arbitrage strategy related to electricity, the input was the increasing capacity in kWh. The results of successive "k" simulations at the given BESS capacities were the quantities that described the effects of BESS.

In the case of microgrids, price arbitrage may be carried out by charging the energy storage from the power grid operated by one of the DSOs in periods when the cost of electricity from internal microgrid sources is lowest. Energy storage is discharged through the receiving systems in periods when the cost of electricity from the DSO grid is highest. As part of the price arbitrage implemented in the microgrid, financial benefits are obtained by taking advantage of the price difference between the avoided purchase of energy from the grid during discharging and the price of energy supplied by BESS. Typical BESS operating states for the implementation of the price arbitrage strategy are presented in Figure 2.

The revenue obtained resulting from the use of BESS for price arbitration, REV_{BA}, for one charging and discharging cycle, results from the use of energy stored in the E_{BA} energy storage for the company's needs, taking into account the depth of discharge planned for the price arbitration, DoD_A, and the maximum price, C_{ESmax}, of energy not taken from the DSO grid in a given zone S, as presented by Equation (1).

$$REV_{BA} = E_{BA} \cdot (1 - DoD_A) \cdot C_{ESmax} \quad (1)$$

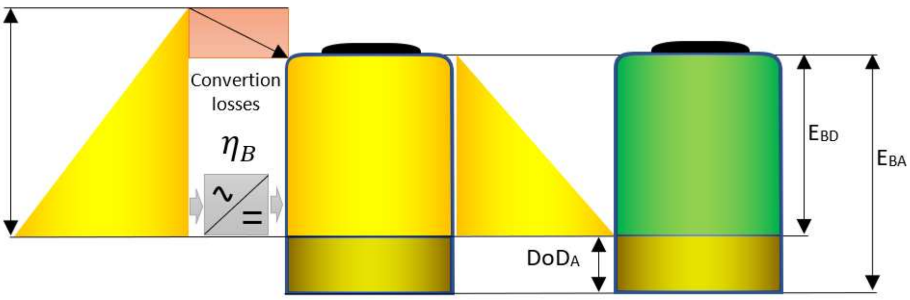

Figure 2. Examples of typical BESS operating states with markings of characteristic measures for price arbitrage.

The operating costs of price arbitration with BESS are marked as O_A for one charge and discharge cycle. The costs include charges for energy collected during BESS charging from the DSO network in the S zone at the minimum price, C_{ESmin}, on a given day. The operating costs include the efficiency of the storage system, η_B, resulting from losses related to the conversion of AC/DC and DC/AC in the charge-and-discharge cycle. This cost is written as follows:

$$O_A = \frac{1}{\eta_B} E_{BA} \cdot (1 - DoD_A) \cdot C_{ESmin} \tag{2}$$

The operating income for a single cycle, INC_{BA}, with a multi-zone tariff group, can be written as follows:

$$INC_{BA} = REV_{BA} - O_A = E_{BA} \cdot (1 - DoD_A) \cdot \left(C_{ESmax} - \frac{1}{\eta_B} C_{ESmin} \right) \tag{3}$$

If BESS is used for price arbitrage in the microgrid system, based on the energy supplied by external suppliers from the DSO's grid, the purchase of O_E electricity and the cost of providing the distribution service in the O_D variable part should be considered when calculating revenues and costs. For this reason, the income for a single discharge cycle for microgrids should be calculated by including the separate revenues and costs of electricity, i.e., REV_{BE} and O_E, and for the distribution service, i.e., REV_{BD} and O_D:

$$INC_{BA} = [(\mathrm{REV}_{BE} - O_E) + (\mathrm{REV}_{BD} - O_D)], \tag{4}$$

For a company in the B23 tariff group, the income for a given billing period resulting from the use of the storage system in n_i cycles, assuming one cycle per day and considering the discharge in the peak zones S1 and S2 and the resale of surplus energy at market prices, C_{Erk}, to the DSO grid, is calculated according to the following relationships:

$$\begin{aligned} INC_{BA} = n_i \cdot E_{BA} \Big\{ \Big[&[(1 - DoD_{S1}) \cdot C_{ES1} + (1 - DoD_{S2}) \cdot C_{ES2} + (1 - DoD_{SR}) \cdot C_{Erk}] - \tfrac{1}{\eta_B} \cdot \\ (1 - DoD_A) \cdot C_{ES3}] + \Big[&(1 - DoD_{S1}) \cdot (S_{ZS1} + S_{ZJ} + S_{Oze} + S_{kog} + S_{Pcap}) + (1 - DoD_{S2}) \cdot \\ (S_{ZS2} + S_{ZJ} + S_{Oze} + S_{kog} + S_{Pcap}) &- \tfrac{1}{\eta_B} \cdot (1 - DoD_A) \cdot (\mathrm{S}_{ZS3} + S_{ZJ} + S_{Oze} + S_{kog}) \Big] \Big\}, \end{aligned} \tag{5}$$

The unit prices of electricity, C_{ES1}, C_{ES2}, C_{ES3}, and C_{Erk}, are the prices that are accepted for settlements from the offer of electricity trading companies. The unit variable rates for the distribution service, S_{ZS1}, S_{ZS2}, S_{ZS3}, S_{ZJ}, and S_{Oze}, S_{kog}, S_{Pcap}, are calculated or adopted by the territorially competent distribution system operators in the form of a tariff approved by the President of the Energy Regulatory Office.

2.1. Assumptions Made in the Simulation Model

The simulations were carried out for enterprises A and B based on data from 2018 and 2019 (the series were marked as A2018, A2019, and B2018, B 2019) and for enterprise C based on data from 2019 (the series was marked as C2019).

The following assumptions were made for the simulation model:

1. The effectiveness of individual strategies was tested for a full one-year period.
2. Time series and validity times of individual price components were compared with UTC + 1.
3. The energy storage tested was a storage equipped with lithium-ion batteries, which resulted in the highest degree of commercialization for this type of battery [43–45].
4. To ensure the comparability of the results for all simulations, regardless of the tariff group that is used in a selected company, the same electricity price rates and the same rates for the distribution service in enterprise A in 2021 were used (tariff group B23 together with a power fee).
5. The average 15 min BESS charging power value, P_{BC}, could not exceed the contractual power, P_U, that was accepted for settlement with DSOs, considering the average 15 min load power of P_{L15} loads. This condition for each 15 min interval is described as follows:
$$P_{BC} \leq P_U - P_{L15} \tag{6}$$
On this basis, a condition was formulated defining the maximum charging power for each of the compartments:
$$maxE_{BC} \leq \frac{15[min]}{60[min]} \cdot 1[h] \cdot (P_U - P_{L15}) \tag{7}$$
6. The contractual power was assumed as the highest capacity of all registered 15 min average capacities in the examined billing period. Although this value is unknown at the time an enterprise determines the contracted capacity for a given settlement period, adopting it at the lowest level and not causing additional costs of overruns constitutes the most restrictive limitation for the use of storage capacity for the price arbitration strategy.
7. **The storage tank was unloaded only in zone S2, as this zone possess the highest unit.**
8. The rate of the S_{Pcap} capacity fee was calculated in the daily hours of peak demand for power in the power system, in accordance with the rules established by the Energy Regulatory Office for 2021.
9. The time zone for charging the energy storage, Z_C, was programmed in the hours in which the S3 zone was valid and the power fee was not applicable.
10. The energy of the discharging storage system was limited to the energy consumed by the energy receivers during the period in which the S2 zone was valid. This limitation was aimed at eliminating the discharge of the BESS "onto the DSO grid", i.e., the negative flows at the settlement point. This situation is unfavorable because electricity is sold back to the external network at prices lower than the avoided costs of its purchase.
11. With the above assumptions and the condtion described by Equation (6), the income was calculated in accordence with the following relationship:
$$INC_{BA} = n_i \cdot E_{BA} \quad \begin{gathered}\Big[(1 - DoD_{S2}) \cdot (C_{ES2} + S_{ZS2} + S_{ZJ} + S_{Oze} + S_{kog} + S_{Pcap}) \\ - \tfrac{1}{\eta_B}(1 - DoD_A) \cdot \Big(C_{ES3} + S_{ZS3} + S_{ZJ} + S_{Oze} + S_{kog}\Big)\Big]\end{gathered} \tag{8}$$
12. Charging and unloading cycles occurred in the time zones in force for the B23 tariff group, excluding statutory non-working days and holidays designated by employers.
13. As the conversion efficiency of the charge-discharge cycle, η_B, was included on the charge side, the need to modify the charging power was provided, inclusive of the power to cover the conversion losses. The efficiency of the conversion system was assumed in the calculations to be $\eta_B = 85\%$.
14. The depth of discharge was assumed to be:
$$DoD = DoD_A = DoD_{max} = 20\% \tag{9}$$

15. CAPEX costs and the BESS life cycle were not considered in the study. The analyses were limited to the operational economic effects realized by the price arbitration in accordance with the rules of electricity billing law in Poland.

3. Simulations of the Effectiveness of Price Arbitration Implemented in Microgrid Systems with the Use of BESS

The use of price arbitrage in enterprises entails a complication in programming the BESS operation control system, resulting from the need to include the complex and unpredictable profile of electrical loads. The demand for energy and power in the microgrid varies over time and results from the current demand for electricity by devices, implementing production processes, building infrastructure, servicing of communication routes, transport, social needs, etc. Additionally, it should be noted that each enterprise has a different nature of organizational and technological processes, i.e., each enterprise has its own individual specificities in running a business, which are connected with the demand for energy needs at certain times.

3.1. Indicators of the Effective Selection of Storage Capacity for Price Arbitrage

To assess the use of various BESS values for the implementation of price arbitration strategies in the enterprises, simulations were carried out. On the basis of the simulations, the implementation of the strategies was assessed. We assumed from the input data that the capacity of the E_{BA} reservoir increases step-by-step by a constant value. Thus, defined parameters were used, which were determined for each tested capacity value based on the annual measurement results. The list of defined parameters is presented in Table 4.

Table 4. Measures for the evaluation of the functioning of subsequent BESS figures for the implementation of the price arbitrage strategy.

Parameters	Description
BESS maximum discharge power [kW]	Maximum discharge power for all 15 min intervals. This power determines the current carrying capacity of the inverter in the DC/AC direction.
BESS maximum charge power [kW]	Maximum charging power for all 15 min intervals. This power determines the current carrying capacity of the inverter in the AC/DC direction.
Annual energy charged [kWh]	Total energy introduced to BESS during the year as a result of charging.
Annual energy discharged [kWh]	Total energy siphoned off from BESS during the year as a result of discharge in zone S2.
BESS capacity utilization [%]	Indicator describing the degree of utilization of the available storage capacity, determined according to the following formula: $$\text{BESS capacity utilization} = \frac{\sum_{tp=1}^{tp=35040} E_{BD,tp}}{Number\ of\ working\ days \cdot E_{BA} \cdot (1-DoD_A)}, \quad (10)$$
Annual income [PLN]	Annual REV_BA income calculated as the sum of the income for each 15 min period during the year.
Marginal income elasticity	The relative increase in income obtained by the relative increase in the BESS capacity for the next simulation "k": $$\text{Marginal income elasticity} = \frac{\frac{(INC_{BA,k}-INC_{BA,k-1})}{INC_{BA,k}}}{\frac{(E_{BA,k}-E_{BA,k-1})}{E_{BA,k}}} \quad (11)$$

Along with the increase in BESS capacity, increasingly smaller increases in annual income were observed, which were calculated as the difference between annual revenues and annual OPEX costs. In the case of microgrids, revenue is limited not only by the size of the energy storage, but also by the amount of energy consumed by the load in the price zone in which the storage is discharged and by the maximum value of the contracted capacity. As a result, the revenues do not grow linearly as they do in the case of the classic standalone

BESS operation for price arbitrage, but grow according to a curve with a decreasing slope and a linearly increasing energy storage capacity. The impact of the indicated limitations on the operation of BESS in the enterprise microgrid is illustrated by the graph in Figure 3 that shows the temporal variability of the amount of energy stored in BESS for two arbitrarily selected storage capacities, 1000 kWh and 4500 kWh, in one of the weeks characterized by the highest energy consumption by the A2019 enterprise:

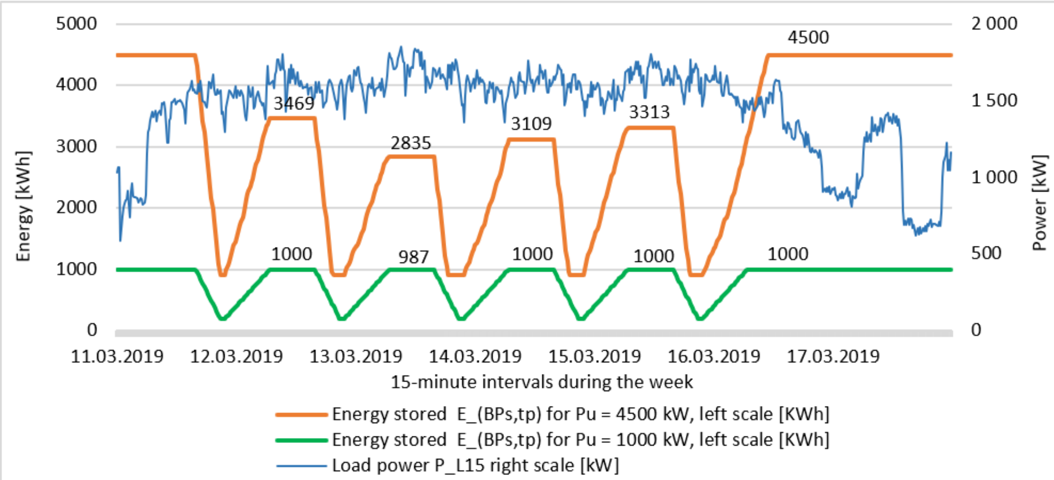

Figure 3. Cumulative state of charge BESS for 1000 kWh capacity and 4500 kWh capacity during the week with the highest load for the A2019 enterprise.

With an energy capacity of the storage system of 1000 kWh, the charging and discharging cycles were evenly distributed on the working days from 11 March 2019 to 17 March 2019. There were no limitations to this capacity that made it impossible to charge the magazine to a given value. The exception was on 13 March 2019, when restrictions related to the enterprise's microgrid resulted in incomplete recharging of the storage system to the value of 987 kWh, representing 99% of the total capacity. At the same time, virtually all energy stored in BESS (98% to 100% E_{BA}) was used for all cycles. For comparison, with an energy storage capacity of 4500 kWh, incomplete charging occurred every working day and the storage capacity was used only from 63% to 77% on these days E_{BA}.

The simulation data for one year, which was obtained using price arbitrage, together with the BESS capacity that increased in successive steps with a constant contracted capacity equal to 1860 kW, are presented in Table 5.

Table 5. Results of simulations of the price arbitrage strategy for A2019 enterprise.

BESS Capacity (Pu 1860) [kWh]	BESS Maximum Discharge Power [kW]	BESS Maximum Charge Power [kW]	Annual Energy Charged by BESS [kWh]	Annual Energy Discharged by BESS [kWh]	BESS Capacity Utilization [%]	Annual Income [PLN]	Marginal Income Elasticity [%]
100	27	10	23,059	19,600	94%	4268	
200	53	21	46,118	39,200	94%	8535	100%
300	80	31	69,176	58,800	94%	12,803	100%
400	107	42	92,235	78,400	94%	17,070	100%
500	133	52	115,293	97,999	94%	21,338	100%
600	160	63	138,349	117,597	94%	25,605	100%
700	187	73	161,405	137,194	94%	29,872	100%
800	213	84	184,461	156,792	94%	34,139	100%

Table 5. *Cont.*

BESS Capacity (Pu 1860) [kWh]	BESS Maximum Discharge Power [kW]	BESS Maximum Charge Power [kW]	Annual Energy Charged by BESS [kWh]	Annual Energy Discharged by BESS [kWh]	BESS Capacity Utilization [%]	Annual Income [PLN]	Marginal Income Elasticity [%]
900	240	94	207,518	176,390	94%	38,406	100%
1000	267	105	230,570	195,984	94%	42,672	100%
1100	293	115	253,606	215,565	94%	46,936	100%
1200	320	125	276,634	235,138	94%	51,198	100%
1300	347	136	299,645	254,698	94%	55,456	100%
1400	373	146	322,631	274,236	94%	59,711	100%
1500	400	157	345,551	293,718	94%	63,953	99%
1600	427	167	368,409	313,147	94%	68,183	99%
1700	453	178	391,219	332,536	94%	72,404	99%
1800	480	188	413,983	351,886	94%	76,618	99%
1900	507	199	436,700	371,195	94%	80,822	99%
2000	533	209	459,341	390,440	93%	85,012	99%
2100	560	220	481,894	409,610	93%	89,186	98%
2200	587	230	504,363	428,709	93%	93,344	98%
2300	613	241	526,725	447,716	93%	97,483	98%
2400	640	251	548,973	466,627	93%	101,601	97%
2500	667	261	571,084	485,422	93%	105,693	97%
2600	693	272	593,022	504,069	93%	109,753	96%
2700	**720**	**282**	**614,733**	**522,523**	**93%**	**113,771**	**95%**
2800	747	293	636,166	540,741	92%	117,738	94%
2900	773	303	657,336	558,736	92%	121,656	93%
3000	800	314	678,221	576,488	92%	125,521	92%
3100	827	324	698,778	593,961	92%	129,326	91%
3200	853	335	718,983	611,136	91%	133,065	90%

The research showed that among the proposed indicators for the use of the price arbitration strategy, the parameter of *marginal income elasticity* was characterized by the greatest volatility. This is illustrated in Figure 4.

In Figure 4a, the *characteristic point* can be determined, beyond which the character of the curve changes from moderately sloping to a curve with a significant decrease. This point, defined by the authors as the *characteristic point* of the curve, determines the value of the BESS capacity, above which its further increase is ineffective. Figure 4a shows that the *BESS capacity utilization* waveform (green) is a less indicative parameter in determining the optimal BESS capacity, as there is no clear *characteristic point* on the curve. Even more difficult is identifying the “characteristic point”, which shows the non-linearly decreasing efficiency with increasing energy storage capacity, that is caused by the *annual income parameter*, as presented in Figure 4b.

Figure 4a,b shows that after exceeding the *characteristic point*, the parameter value of the *marginal income elasticity* begins to decrease significantly, along with the constant increase in the capacity of BESS. For the same capacity increases, the parameters of *BESS capacity utilization* (Figure 4a) and *annual income* (Figure 4b) are more linear. On the basis of the simulations, a conclusion can be drawn that the effective operation is increasing the capacity of BESS to the value for which the internal limitations of the microgrids do not have a significant impact on the effect of the implementation of the price arbitrage strategy.

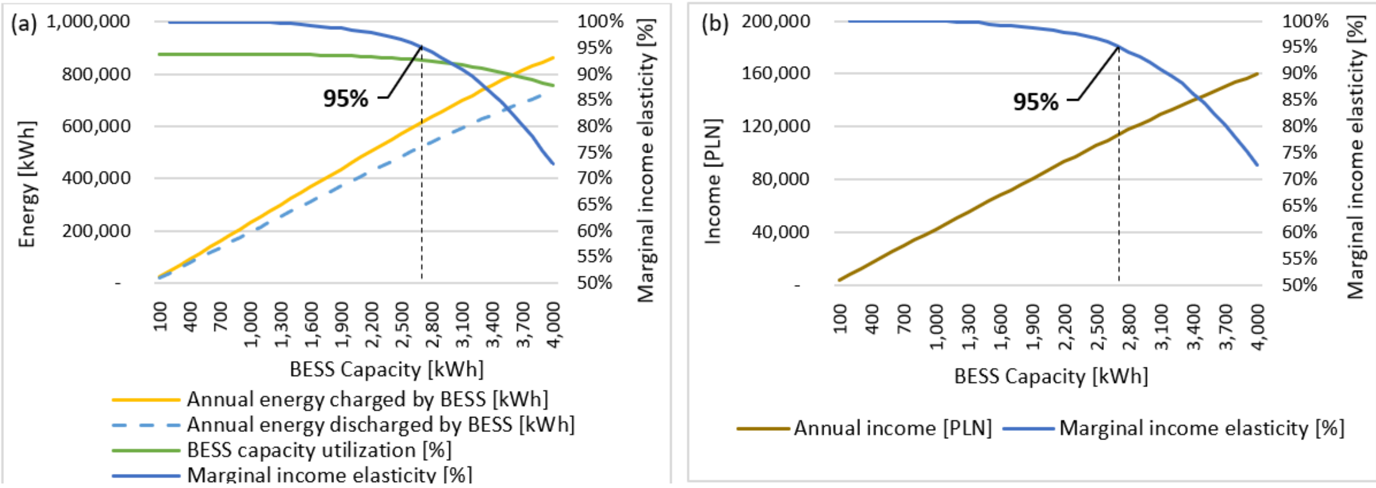

Figure 4. Results of the simulations of the price arbitrage strategy for the A2019 enterprise: (**a**) comparison of the *marginal income elasticity* parameter with the parameters of *annual energy charged*, *annual energy discharged* in kWh, and *BESS capacity utilization* in %; (**b**) comparison of the *marginal income elasticity* parameter and the *annual income* in PLN.

In this study, we arbitrarily assumed that the effective value of the BESS capacity is determined when the parameter of *marginal income elasticity* is equal to 95%. From the results presented in Table 5 for enterprise A2019, the *marginal income elasticity* of 95% was achieved with the BESS capacity equal to 2700 kWh. In the *marginal income elasticity* diagram shown in Figure 4, this point is located before the *characteristic point*. The BESS capacity of 2700 kWh can be considered as the effective size of the energy storage capacity of enterprise A2019. This capacity value corresponds to the maximum charging and discharging powers in the 15 min intervals during the year, considering the work of BESS for price arbitration and the implemented technical limitations. The maximum values of these powers, as presented in Table 5, were calculated as a result of the simulation for the BESS = 2700 kWh capacity. There was also a minimum power size of the inverters for the assumed BESS capacity, as follows:

- A discharge power corresponding to DC/AC conversion 720 kW;
- A charging power corresponding to AC/DC conversion 282 kW.

The differences between the maximum charging and discharging powers are due to the fact that the charging period is 9 h and the discharging period is 5 h to 3 h, depending on the period of the year. Therefore, it follows that the discharging current is significantly higher than the charging current.

3.2. Validation of Indicators Based on Data Obtained from Enterprises (B 2019, C 2019 and A2018)

To verify the method of determining the optimal BESS dimensions for the implementation of the price arbitration strategy using the *marginal income elasticity* parameter, the B2019 and C2019 time periods were tested in a manner analogous to the method described for the A2019 enterprise. The results are shown in Figure 5.

In enterprises A and B, only the *marginal income elasticity* parameter indicates the existence of a *characteristic point* that influences the effectiveness of the price arbitrage strategy, as shown in Figure 5. However, it can be observed in the parameter of *marginal income elasticity* in enterprise B that the *characteristic point* was more difficult to identify than it was in enterprises A and C. This difference was due to the different organization of the working hours in these enterprises. In enterprise B, on the last shift of the working day, the volume of electricity demand in the afternoon peak hours of the S2 zone decreased significantly. In these hours, which were already at low values of BESS capacity, there were cases of incomplete discharges of BESS capacity in the S2 zone. Thus, the decrease in the demand on the microgrid for electricity in the discharge zone, together with the limitation assumed in point 10 in Section 2.1, resulted in the ineffective use of price arbitrage.

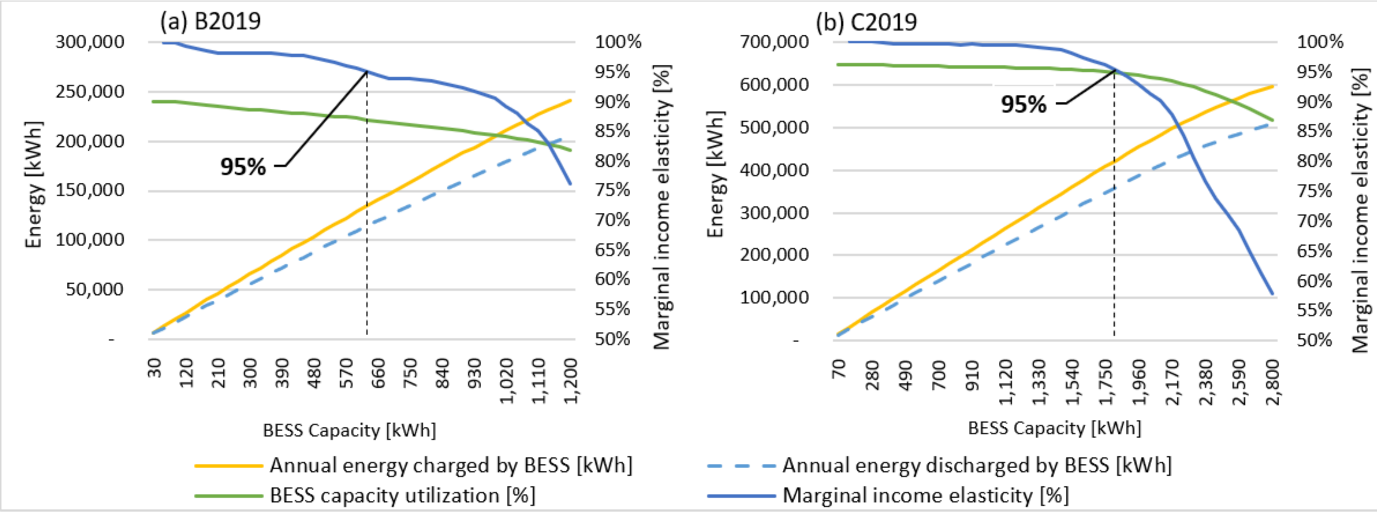

Figure 5. Results of simulations of the price arbitrage strategy: (**a**) B2019; (**b**) C2019.

The arbitrarily adopted value of 95% for the *marginal income elasticity* parameter clearly indicated the existence of an effective value of the energy storage capacity. The effective value of energy storage capacity was visible in the B2019 and C2019 graphs near or before the *characteristic point* that resulted from the limitations of the microgrid. Table 6 shows the BESS parameters in points for which the *marginal income elasticity* parameter is equal to 95%.

Table 6. Numerical results of the price arbitrage simulation for enterprises B2019 and C2018.

Enterprise	BESS Capacity [kWh]	BESS Maximum Discharge Power [kW]	BESS Maximum Charge Power [kW]	Annual Energy Charged by BESS [kWh]	Annual Energy Discharged by BESS [kWh]	BESS Capacity Utilization [%]	Annual Income [PLN]	Marginal Income Elasticity [%]
B2019	630	168	66	134,628	114,434	87%	24,916	95%
C2019	1820	485	190	422,822	360,531	95%	78,906	95%

It should be noted that the *characteristic point* in the case of enterprises B and C occurred for various parameters that characterized the use of storage capacity; for the parameter of utilization of the *BESS capacity*, it was approximately 87% for the series B2019 and 95% for the series C2019. In enterprise A, the value of this parameter was 93%. The simulations showed that the parameter of using the storage capacity (i.e., the utilization of the *BESS capacity*), did not change significantly, as evidenced by its flattened characteristics. For these reasons, it can be concluded that this parameter is not very useful in determining the value the of effective use of BESS for a price arbitrage strategy.

The indicator of optimal BESS selection for the same enterprise was also analyzed in relation to the consumption profile from the previous year. The calculation results for the data series A2018 and B2018 are shown in Figure 6.

The results from the simulations again indicated that the *marginal income elasticity* parameter remained the most sensitive. The remaining parameters, which quantified the size of the storage system for the use of the price arbitrage strategy, did not clearly indicate the existence of the *characteristic point* that could be used to determine the optimal size of BESS.

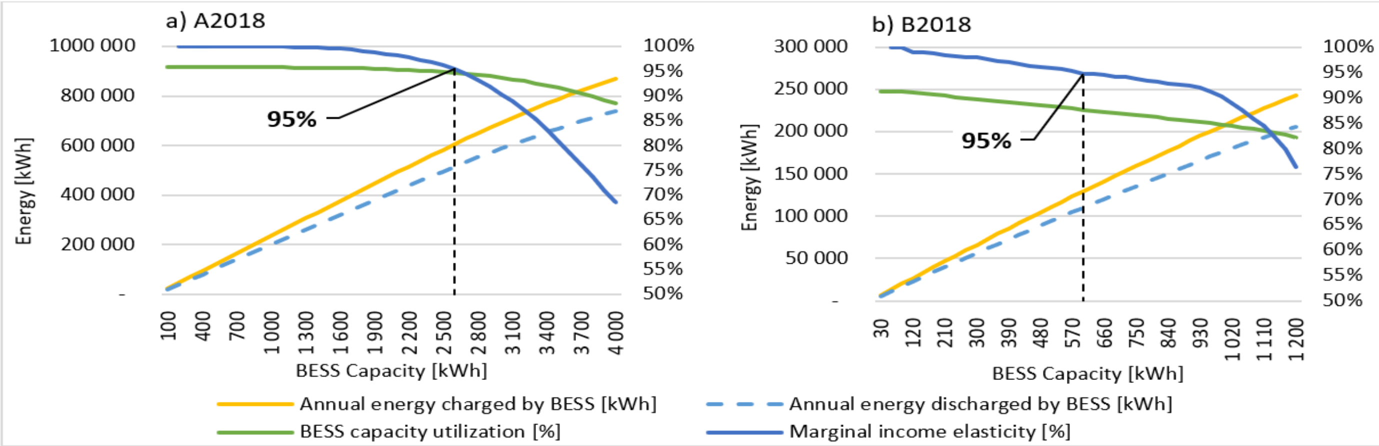

Figure 6. The results of the price arbitrage simulation for enterprises (**a**) A2018; (**b**) B2018.

By assuming a *marginal income elasticity* value of 95%, we determined the effective storage size for the arbitrage price strategy. For data series A2018, this was a BESS capacity of 2600 kWh, which is close to the 'characteristic point". For the B2018 data series, this was a BESS capacity of 600 kWh located ahead of the *characteristic point*. A comparison of the results for 2018 and 2019 for enterprises A and B is presented in Table 7.

Table 7. Numerical results of the price arbitrage simulation for the A2018 enterprise.

Enterprise	BESS Capacity (Pu 1822) [kWh]	BESS Maximum Discharge Power [kW]	BESS Maximum Charge Power [kW]	Annual Energy Charged by BESS [kWh]	Annual Energy Discharged by BESS [kWh]	BESS Capacity Utilization [%]	Annual Income [PLN]	Marginal Income Elasticity [%]
A2018	2600	693	272	604,700	513,995	95%	111,914	95%
A2019	2700	720	282	614,733	522,523	93%	113,771	95%
B2018	600	160	63	129,186	109,808	88%	23,909	95%
B2019	630	168	66	134,628	114,434	87%	24,916	95%

The data in Table 7 show that the individual parameters in 2018 and 2019 were similar. This means that each enterprise maintained its basic nature of demand in 15 min intervals in subsequent years. However, it can be seen that in the case of the same enterprise, the *marginal income elasticity* equal to 95% indicated a higher value of the optimal BESS capacity in 2019. Studies of the load profiles of the same enterprise for 2018 and 2019 showed an increase in optimal storage capacity by only one step of the set capacity in the calculations. This slight difference may be due to the different number of non-working days in the analyzed years, together with the associated Saturdays and Sundays.

For the data series A2018 and C2018, we also examined how the proposed indicator to evaluate the efficiency of selecting the size of the energy storage, defined as the *marginal income elasticity*, behaved for various contractual powers. Figure 7 shows the results of the simulation of the BESS operation, in accordance with the price arbitration strategy for the data series A2018 and B2018, during which the contractual power was increased stepwise by a constant value.

In previous studies, it was assumed that the contractual power was equal to the maximum power of all 15 min power consumptions in an annual period. This was a hypothetical value and, in fact, it was impossible to determine if there were no tools for actively lowering the consumed power. Adopting a certain level of contractual power determines the operation of the energy storage in the event of the implementation of the price arbitration strategy. The higher the contractual power, the greater the possibility of increasing the charging power.

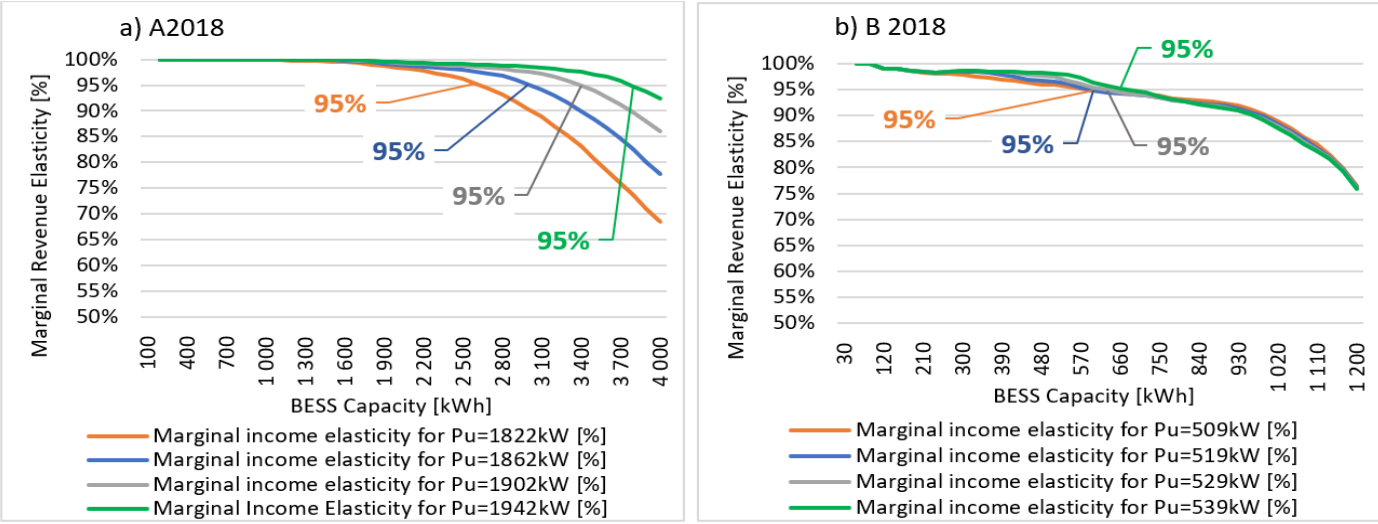

Figure 7. The results of the price arbitrage simulation with different contractual powers Pu [kW] for enterprises (**a**) A2018; (**b**) B2018.

For the A2018 data series, with the increase of the contractual power, the point of *marginal income elasticity* equal to 95% as a function of the storage capacity shifts to the right. This means that the contractual power had a significant impact on the effective use of the storage capacity. In the examined enterprise A, the increase in the contractual power resulted in a linear increase in the effective storage capacity, as shown in Figure 8a. Unlike data series A2018, the *marginal income elasticity* curves obtained for enterprise B (data series B2018) showed a weak dependence on the change in contractual power, as shown in Figure 8b). For increasing values of the contractual power, the obtained values of the ratio were the same or increased slightly.

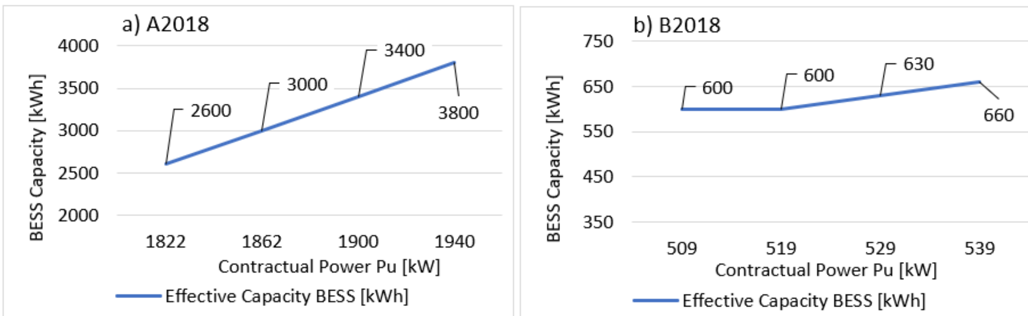

Figure 8. Effective BESS capacity with different contractual powers Pu [kW] for enterprises (**a**) A2018; (**b**) B2018.

These differences can be explained by the fact that the limitation of the BESS charging current depends not only on the contractual power, but also on the energy consumption profile during the charging zone hours. Both enterprises, A2018 and B2018, had different work organizations and differed in the level of energy consumption in the adopted Z_C charging zones. Enterprise A maintained a constant high level of energy consumption during the Z_C zone hours, and the energy consumption in the Z_C zone of enterprise B was significantly lower due to the two-shift work organization. It can be assumed that in the case of enterprise B, it was important to limit the amount of energy discharged by BESS to a value not greater than the energy resulting from the demand of internal consumers in zone S2, and that the limitation resulting from the contracted amount of contractual power was insignificant.

4. Discussion and Conclusions

Studies of real microgrid systems have shown that the nature and variability of electricity consumption by enterprises limit the effective use of price arbitrage strategies. These limitations, which are caused by the rules for billing for electricity and the instantaneous amount of energy load, determine the possibility of charging and discharging the storage system. As a result, the effectiveness of implementing the price arbitrage strategy decreases non-linearly with an increase in the BESS capacity, despite the programming of constant values of charging and discharging energies.

The limitations of the real microgrid systems mean that, for certain BESS capacity values, further increases in the energy storage capacity for the implementation of price arbitrage cease to be effective. To determine this value, the *marginal income elasticity* indicator was used. The curve of this parameter as a function of increasing BESS capacity has a characteristic point, after which the curve begins to significantly decline. Our research showed that the *characteristic point* appears near the value of the *marginal income elasticity* parameter, which is equal to 95%. Our research results showed that the application of the *characteristic point* of the *marginal income elasticity* curve to determine the size of the energy storage capacity establishes the limit of the BESS capacity, which is effective in implementing price arbitrage.

The determination of the effective size of energy storage, based on the *marginal income elasticity* parameter equal to 95%, will indicate the sizes of the effective storage capacity for the same enterprise in the following years. However, in these cases, one should consider the variability in energy and power demand caused by different numbers of days off work, as well as Saturdays and Sundays.

The effective use of energy storage capacity can be influenced by the value of the contractual power reported for settlements to DSOs, especially for enterprises with a continuous nature of production where the intensity of electricity demand does not decrease during BESS charging hours. In enterprises where production is not continuous and the organization of work occurs in one or two shifts, the amount of electricity demand of microgrid loads in the adopted period of energy discharge by BESS is of great importance for the effectiveness of price arbitrage. In cases where this demand is much lower than the maximum load value, the limitation resulting from the amount of contracted power is insignificant and the importance of limiting the amount of discharging energy of the storage system to the amount of energy that is consumed by the microgrid loads increases.

This study undertook simulations aimed at determining the power and capacity of BESS for the functionality of price arbitration. Our research had certain limitations, as outlined below.

1. The legal regulations and all of the prices mentioned in this research are only applicable in Poland.
2. This paper did not attempt to implement dynamic tariffs based on hourly SPOT market prices on the electricity exchange. A market game based on the difference in hourly electricity prices may turn out to be more effective than an alternative based on the B23 tariff group, and may constitute an important premise for further research.
3. This paper adopted the capacity fee rules applicable in 2021. Our study did not analyze the various legally permitted rules for power charges in Poland or the method of calculating power fee reductions depending on the daily power profile, which were introduced in settlements from 1 October 2021.

The following future work is intended:

1. Research on the possibility of obtaining synergy via the simultaneous use of price arbitrage strategy and strategy peak shaving. These functionalities are representative of two separate markets, i.e., price arbitrage in the electricity market, which is the domain of trading companies, and the peak shaving strategy, which covers activities in the capacity market, a consideration that is important from the point of view of distribution and transmission system operators.

2. Further research is recommended to verify the fit of the Gaussian probability distribution to the deviations of the profiles in relation to the mean value. In addition, further research is recommended for the purpose of analyzing seasonal and cyclical data.
3. In the field of price arbitration, further research is recommended to identify more precisely the *characteristic points* on the curves that are indicated in this paper, including the *marginal income elasticity* curve.
4. In future work, it is recommended that the analyses be extended to include the CAPEX costs of BESS installations and their life cycles for various electricity storage technologies.

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Nomenclature

Index	Description	Unit
t_P	15 min interval	
k	System state for the set value of the contractual power	
P_{L15}	Load power, 15 min average	kW
P_U	Contractual power	kW
P_{BC}	BESS charging power, 15 min. average	kW
S_{ZS1}, S_{ZS2}, S_{ZS3}	Variable rates for electricity distribution services for the selected time zone: S1, S2, or S3	PLN/kWh
S_{ZJ}	Quality fee rate	PLN/kWh
S_{OZE}	RES fee rate	PLN/kWh
S_{kog}	Cogeneration fee rate	PLN/kWh
S_{Pcap}	Power capacity fee rate	PLN/kWh
O_A	Operating costs of price arbitrage	PLN
O_A	Operating costs of price arbitration	PLN
O_E	BESS operating cost of purchasing electricity for charging	PLN
O_D	BESS operating cost from the variable part of fee for electricity distribution service for charging	PLN
C_{Erk}	Price of electricity fed into the DSO grid	PLN/kWh
C_{ES1}, C_{ES2},C_{ES3}	Electricity prices in the zones: morning peak S1, afternoon peak S2, and rest of the day S3	PLN/kWh
C_{ESmax}	Maximum electricity price	PLN/kWh
C_{ESmin}	Minimum electricity price	PLN/kWh
INC_{BA}	BESS income from price arbitrage	PLN
REV_{BA}	BESS revenue from price arbitrage	PLN
REV_{BE}, REV_{BD}	BESS revenues from electricity and from distribution service	kWh
E_{BA}	BESS capacity for a price arbitrage strategy	kWh
E_{BD}	BESS discharge energy	kWh
E_{BC}	BESS charging energy	kWh

E_{BAs}	Stored energy remained after discharge for the Price arbitrage strategy	kWh
Z_C	Designated charging time zone (charge zone)	hours of the day
n_i	Number of charge/discharge cycles	
η_B	BESS nominal efficiency for charging and discharging cycle	%
DoD_{s1} *i* DoD_{s2}	BESS depth of discharge in the appropriate time zones S1 and S2	%
DoD_{SR}	BESS depth of discharge related to energy fed into the DSO grid	%
DoD_A	Fixed depth of discharge for price arbitrage	
DoD_{max}	Maximum depth of discharge	%

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energies

Article

Impact of the Energy Sector on the Quality of the Environment in the Opinion of Energy Consumers from Southeastern Poland

Krzysztof Kud [1,*], Marian Woźniak [2] and Aleksandra Badora [3]

1 Department of Enterprise, Management and Eco-Innovation, The Faculty of Management, Rzeszów University of Technology, 12 Powstańców Warszawy Street, 35-959 Rzeszów, Poland
2 Department of Economics, The Faculty of Management, Rzeszów University of Technology, 12 Powstańców Warszawy Street, 35-959 Rzeszów, Poland; mwozniak@prz.edu.pl
3 Department of Agricultural and Environmental Chemistry, University of Life Sciences in Lublin, 15 Akademicka Street, 20-950 Lublin, Poland; aleksandra.badora@up.lublin.pl
* Correspondence: kkud@prz.edu.pl; Tel.: +48-600-945-954

Abstract: Limiting CO_2 emissions has been adopted as a contemporary challenge and introduced into numerous global and regional policies. The measures taken to reduce greenhouse gas emissions largely relate to the decarbonization of the economy. Changes in the Polish energy sector are a huge challenge because the energy mix is dominated by the energy derived from coal combustion. Decarbonizing the energy sector will require significant financial resources. Therefore, several questions arise: What is the social attitude to the planned changes? How do residents treat the issue of greenhouse gases? Do they perceive the relationship between energy production and the quality of the natural environment? What are their expectations regarding the transformation of the energy sector? The aim of this study was to identify the opinion of the inhabitants of southeastern Poland on changes in the energy sector and its impact on the quality of the natural environment. The study was conducted at the turn of 2020 and 2021. The survey was partial and carried out using the CAWI (Computer Assisted Web Interview) method; 1539 questionnaire forms were filled in and the sample was randomly selected. The study confirms the following research hypotheses: 1. There is social support for the view that climate change is currently one of the greatest threats to modern civilization. 2. There is a social belief that the quality of the natural environment in southeastern Poland is good compared to other regions of Poland and Europe. 3. Increasing the share of energy based on renewable energy sources is socially expected. 4. There is a social expectation of nuclear energy. It can therefore be concluded that the surveyed community accepts the direction of changes in the energy sector.

Keywords: energy sector; environmental quality; renewable energy sources (RES); nuclear energy; southeastern Poland

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1. Literature Review

1.1. European Union (EU) Policy and Community Obligations

The climate and energy policy of the European Union (EU) is long-term and aims to achieve climate neutrality by 2050. EU policy has a significant impact on changes in the Polish energy strategy [1]. In order to switch to low-emission energy, the EU is implementing its climate and energy goals for 2020 and 2030 [2]. These trends accelerate significantly and this is a challenge for energy transformations in Poland in the near future [3,4].

The Paris Agreement was concluded at the "21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21)" [5–7]. It was agreed at this conference that it was necessary to stop the increase in the global mean temperature and maintain it below 2 °C. However, it should be ensured that it does not exceed 1.5 °C. During the Polish presidency of the EU, in December 2018, the Paris Agreement began to be implemented in Poland through the so-called "Katowice Climate Package" [8]. At that time, great emphasis was placed on making this transformation fair and in solidarity. "Clean Energy for All Europeans" is an EU package that shows the way to build a single energy market and achieve the EU's 2030 climate and energy goals [2,9]. Work on it ended in 2019 [4]. The Polish government actively influenced the shaping of the final version of the European model, which will determine the future of the Polish energy market [3,10]. A further revision of the key EU regulations relating to the energy sector is anticipated in the future. This applies in particular to the long-term vision of reducing greenhouse gas emissions by 2050 [1]. The European Green Lad from 2019 is an ambitious EU strategy striving for climate neutrality by 2050 [10,11]. Poland supported the European Green Lad, but tried to take into account the basic socioeconomic aspects that exist in our country [3,12].

All global economies were hit by the coronavirus (COVID-19) pandemic in 2020 [13]. It highlighted the important role of the energy security of Poland and other European countries [9,10]. It is important that after a pandemic, investment decisions are made in the context of ecological and low-carbon economic recovery [6,7]. Both national protection tools and EU support will be undertaken in Poland [3,14]. Moreover, the manner of carrying out the transformation should take into account socially acceptable energy prices in order not to aggravate energy poverty [8,14].

At the heart of the European Energy Policy are various measures aimed at creating an integrated energy market and ensuring security of energy supplies and a stable energy sector [10,13].

In line with the provisions made in the framework of the Energy Union of 2015 [9], the five most important goals of the EU's energy policy are (i) diversification of European energy sources, ensuring energy security through solidarity and cooperation between EU countries; (ii) ensuring the functioning of a fully integrated internal energy market, allowing energy to flow freely within the EU through appropriate infrastructure and without technical or regulatory barriers; (iii) improving energy efficiency and reducing energy import dependency, reducing emissions and stimulating job creation and economic growth; (iv) decarbonizing the economy and moving to a low-carbon economy in line with the Paris Agreement; and (v) promoting research in low carbon and clean energy technologies and giving priority to research and innovation to stimulate the energy transition and improve competitiveness [2]. An EU decision introduced changes to the energy efficiency and governance policy of the Energy Union in 2019 in the context of the United Kingdom's withdrawal from the EU [11]. The European Parliament has consistently expressed its strong support for a common energy policy that includes decarbonization, competitiveness, security, and sustainable development [1,4]. The European Parliament also supports the adoption of firmer commitments to meet the EU's own goals, highlighting the fact that the new energy policy must support the EU's greenhouse gas emissions reduction target and become climate neutral by 2050 [5,15].

PEP2040 (Poland's Energy Policy until 2040) is our national contribution to the EU's climate and energy goals [14]. The energy policy of Poland adjusts our national economy to the EU regulatory conditions in accordance with national possibilities [1,6,14]. PEP2040 predicts that the low-emission energy transformation will initiate the modernization of the entire national economy, guarantee energy security, ensure a fair distribution of costs and protect the most vulnerable social groups [8,16]. The PEP2040 also includes an innovative approach to the environment and climate, which should be accepted by society [17,18]. The Polish energy transformation will be based on three pillars (Table 1) and on key strategic elements (Table 2), setting out the detailed goals of this transformation [14].

Table 1. Three pillars of the Polish energy transformation [14].

Pillar I Fair Transformation	Pillar II Emission-Free Energy System	Pillar III Good Quality Air
Transformation of coal mines	Offshore wind	Innovation of heat engineering
Reducing energy shortages	Nuclear energy	Electrification in transport
RES *-related jobs	Energy from other sources	Development of the "Dom z Klimatem" program

* RES—Renewable Energy Sources.

Table 2. Key elements of PEP2040 [17,18].

Selected Elements from the PEP2040 Program
Energy transformation
The share of coal in electricity generation
A fair transition
Increase in the share of RES
Offshore wind energy
Photovoltaics
Energy efficiency
The investment programs of OSPe * and OSDe **, active consumers, and local balancing
A nuclear power plant
The heat needs of all households
Natural gas
Decarbonized gases
Diversification of supply directions will be ensured
Improving air quality, departure from coal combustion in households development of low-emission transport
GHG *** emissions will be reduced
Reduction of the phenomenon of energy shortages.
Development of energy technologies

* OSPe—Transmission System Operator, an investment program focused on the development of renewable energy sources. ** OSDe—Distribution System Operators, an investment program focused on the development of renewable energy sources. *** GHG—greenhouse gases.

The Polish Energy Transition will therefore be fair and will take into account all social groups. It will be initiated from the bottom up and will be focused on modernization and innovation [14,16]. It will also stimulate economic development, efficiency, and competitiveness [3,18]. Table 2 shows a more detailed description of the goals contained in the three pillars.

Therefore, Poland's Energy Policy is based not only on security and ensuring the competitiveness of the economy, but also on reducing the environmental impact of the energy sector and on the optimal use of its own energy resources [14,16,18].

1.2. The Impact of Power Engineering on the Natural Environment

A resolution adopted by the General Assembly (UN) on 25 September 2015 "Transforming Our World: The 2030 Agenda for Sustainable Development" [19] sets out 17 sustainable development goals and 169 related tasks to be achieved by 2030. These goals concern five areas of the so-called 5×P: People, Planet, Prosperity, Peace, and Partnership [20]. The resolution was signed by all 193 member states of the United Nations, which undertook to monitor the achievement of goals and tasks through appropriate indicators [21,22]. In Poland, these indicators are dealt with by the Central Statistical Office [23]. When analyzing the sustainable development goals, special attention should be paid to two, namely goal 7: "Ensure access to stable, sustainable, and modern energy at affordable prices for all", and goal 13: "Take urgent measures to combat climate change and their effects" [19]. The implementation of these goals, together with the related tasks, is to significantly contribute to accelerating the reduction of global greenhouse gas emissions by increasing the share of renewable energy sources and by increasing the global efficiency of energy consumption [5]. It is also to contribute to undertaking adaptation measures to the progressive negative effects of climate change [11,17,24].

Achieving a deep reduction of greenhouse gases or even climate neutrality by 2050 will require qualitative changes in Polish Domestic Policy, going far beyond the scenarios considered in the national public debate [14], including: ensuring even twice as much electricity supply with almost complete elimination of emissions from power engineering; complete elimination of fossil fuel heating in buildings; dominating the energy mix in transport by alternatives to fossil fuels (electromobility, biofuels, synthetic fuels, or hydrogen); replacement of traditional technologies in heavy industry with zero-emission alternatives and the widespread implementation of the principles of the circular economy; large and simultaneously sustainable increase in the supply of biomass for energy purposes [17]. The main objective of the Polish Energy Policy is to develop the potential of the environment for the benefit of citizens and entrepreneurs [18]. The specific objectives will take into account the most important trends in the field of the environment, in a way that allows for harmonizing issues related to environmental protection with economic and social needs [12]. The topic of energy is included in the directions of interventions regarding the elimination of air pollutant emission sources [3]. It specifies the directions of activities that will receive support, such as investments related to increasing the share of renewable energy [14], modernization of CHP systems in order to reduce pollutant emissions [25], development of low-emission transport [26], reduction of energy losses related to its transmission, and the development of energy clusters [14,18] and transformation of municipalities into energy self-sufficient communities [12,27].

Various branches of the energy sector affect various elements of the environment in a variety of ways, including for people, animals, plants, water, air, landscape, climate, and natural resources (Table 3) [18].

Table 3. Impact on selected elements of the environment on some alternative branches of the energy sector [18].

Elements of the Environment	Influence
	Construction of nuclear power plants
Air	positive: reducing air pollutant emissions from other energy producing sources. negative: emissions of air pollutants during construction.
Water	negative: during construction, impacts on surface and groundwater may be associated with changes in water relations. negative: during operation, due to the intake and discharge of large amounts of water for the cooling system.
People	positive: by partially replacing conventional energy, it indirectly reduces the emission of pollutants into the air, and therefore reduces the negative impact on human health. negative: an (insignificant) increase in the level of ionizing radiation in the vicinity of nuclear power plants, the risk of accidents, and the associated risk of releasing larger amounts of radioactive substances, generation of radioactive waste, emission of noise, and air pollution during construction work. Negative psychological impact.
Animals	negative: land taking, impacts during construction; indirectly positive impact by reducing the emission of atmospheric pollutants from the energy sector.
Plants	negative: land taking, impacts during construction; indirectly positive impact by reducing the emission of atmospheric pollutants from the energy sector.

Table 3. *Cont.*

Elements of the Environment	Influence
Climate	positive: reduction of greenhouse gas emissions from conventional energy.
Landscape	negative: disturbing the landscape with "foreign" elements by building new cubature objects.
Natural resources	positive: reducing the use of nonrenewable resources (fossil fuels) for energy production. negative: using uranium, thorium as fuel for a nuclear power plant, and rock raw materials at the construction stage of the investment.
RES—photovoltaics and solar collectors	
Air	positive: indirect—the use of solar energy will reduce the consumption of fossil fuels and related air pollutant emissions; this will improve air quality, and in the case of solar panels also thermal comfort. negative: emissions of air pollutants during the construction of photovoltaic farms and solar panels.
Water	no impact
People	positive: improved air quality will have positive health effects; moreover, when used for heating, it will improve the comfort of the residents; it can improve energy security.
Animals	possible negative consequences as a result of the occupation of land for solar farms and solar panels, along with electricity and heat output infrastructure; impacts will depend on the location. slight negative during construction; positive due to impact on air quality.
Plants	negative: land taking and limitation of biologically active area; deforestation of forests and trees. slight negative under construction; positive due to impact on air quality.
Climate	positive: reducing greenhouse gas emissions by replacing fossil energy with renewable energy sources.
Landscape	negative: disturbance of the landscape with "foreign" elements.
Natural resources	positive: reduced use of fossil energy resources. negative: due to the consumption of raw materials for the production of devices.
RES—water and energy resources	
Air	negative: emission of fumes and dust during construction works; the negative impact is short-term and related to the implementation of the investment, i.e., carrying out construction work. positive: clean energy production.
Water	negative: during the implementation of water structures, including hydrotechnical devices, it may adversely affect the quality of water and ecosystem function below the project location; in contrast, during operation, various types of impacts on the aquatic ecosystem, both negative and in selected aspects, are possible. positive: more serious threats and significant negative impacts are related to the construction and operation of large dam reservoirs, which are associated with significant hydrological changes, deterioration of water quality in reservoirs as a result of sedimentation of pollutants, and disturbances in ecosystem function.
People	positive: clean energy production, increasing retention, delaying water runoff, and creation of recreational areas. negative: noise and exhaust emissions during work; changes in the organization of road traffic related to the implementation of the investment. The negative impact is short-term and is related to the implementation of the investment, i.e., carrying out construction works. Long-term, illusory sense of security, technical buildings in river valleys increase below the dams and flood losses accumulate.
Animals	negative: a change in water relations may result in an imbalance of ecosystems, causing animal migration and / or increasing fish mortality; in addition, ecological corridors may be interrupted—animals may be disturbed, frightened, and leave during the construction stage.
Plants	negative: interference with water conditions and taking the land for investment affect the destruction of natural habitats (in particular those dependent on water).
Climate	positive impact on reducing greenhouse gas emissions and adapting to climate change. negative: possible methane emissions from dam reservoirs aggravate this global warming.
Landscape	negative: disturbance of the landscape with "foreign" elements in space. positive: creating reservoirs.
Natural resources	negative: consumption of rock raw materials during the construction phase. positive: reducing the consumption of energy resources.

Table 3 shows that the planned development of both renewable energy sources and nuclear energy in Poland has an impact on the natural environment [14,17,24]. This impact can be both positive and negative, and short- and long-term. In contrast, it is believed that the abovementioned energy sources are mostly low-emission or zero-emission, and thus fit into the zero-emission economy of the future, not only in Poland, but also in the EU and worldwide [14,15,24].

1.3. Climate Changes and Power Engineering

According to scientists from around the world, the phenomena occurring on Earth today are very disturbing because the highest temperatures and the greatest concentration of CO_2 have been observed in the last twenty years, ever since these parameters were measured [28]. According to the data of the World Meteorological Organization (WMO) [29], the years 2010–2019 were the hottest years in the entire history of the Earth, and 2019 was one of the top three warmest years in the entire history of measurements [28]. The data presented by WMO [29] therefore show that "our planet and life on Earth are on the brink", and climate change causes a much more frequent occurrence of violent weather phenomena, which in turn also affects the existence of the world's population [30]. However, one should remember the bilateral dependence, as climate change affects the population, but also the population can contribute to this change by promoting activities related to the emission of greenhouse gases [31,32].

The results of the report of the International Panel on Climate Change (IPCC) [33] show that in order to avoid exceeding the limit of the temperature increase by 1.5 °C, only technological changes are not enough, as achieving this goal depends to a large extent on changing lifestyle to focus on reducing energy consumption [31]. Scientists claim that humanity should comply with the policy of energy efficiency in the coming years because the fate of the Earth and the planet's inhabitants will depend on it [34]. Climate change, caused by the increase in global temperature, will be felt worldwide, regardless of where they live, and it will also affect Polish residents [35]. According to the members of the International Panel on Climate Change, an increase in the mean global temperature by 2 °C will cause the Earth to face far more frequent weather anomalies, such as storms, floods, droughts, storms, fires, and frosts [29,30].

The report [30] underlines that in 2019, 409 natural disasters were recorded globally, largely as a result of climate change. These disasters resulted in losses amounting to 232 billion USD, of which 71 billion related to the payment of claims. Just five of the costliest flood disasters in the US, China, India, and Iran cost more than 53 billion USD in direct economic impact. In Poland, the droughts in 2019 burdened the economy with around 1 billion USD and largely translated into a 5% increase in food prices [36]. Additionally, it is emphasized that the occurrence of drought each year may cause a snowball effect, accumulating negative consequences and leading to, for example, soil desertification [28,35]. In contrast, it is a fact that energy is necessary in the process of creating wealth in industry and commerce, and also to achieve a proper quality of life in society [37]. Energy consumption is also a significant source of greenhouse gases produced by humanity, as about two-thirds of the global greenhouse gas emissions are the result of burning fossil fuels for the production of heat and electricity, together with transport and industry [15,31].

There is a clear relationship between energy and welfare, as measured by GDP per capita and CO_2 emissions at the same time [37]. The richer the society, the greater the consumption of energy; therefore, the thesis can be presented that with the economic development of countries, higher energy consumption and, at the same time, higher CO_2 emissions per capita take place. An example is the USA, where GDP per capita is over 63,000 USD [38]. In Poland, about 10 kg of coal, 3 L of oil, and 1 m^3 of gas are consumed per person each day, and owing to fossil fuels the way of life of the society has changed dramatically. In 2019, Poland, with a GDP per capita of USD 15,274, was 45th in the world, and the overall CO_2 emissions per capita were 35% lower compared to 1980, which resulted in 8.5 tons of CO_2-equivalent greenhouse gases and ranked the country 36th in the world [35].

In the period 1999–2019, world GDP increased by nearly 70%, which resulted in an increase in energy consumption by about 40% and by the same amount of CO_2 emissions from fossil fuel combustion [33]. It should be noted that in the 2019–2020 period, developed economies saw an average decrease of 10% in annual emissions, while in emerging and developing economies the decrease was only 4% [32]. The largest decrease was recorded in the USA (by nearly 50%) and in the European Union generally over 25%, while China saw an increase in emissions (by nearly 8%) [39,40].

In the European Union, in the years 1990–2019, the emission of the main greenhouse gases (Table 4) reached a total value of 5630 million tons, of which CO_2 emissions were the greatest (82.5%), followed by CH_4 and N_2O [32]. Over the analyzed period, a downward trend in the amount of emitted gases was observed. Generally, in 2019 it decreased by 29.1% in relation to 1990. The downward trend concerned practically all greenhouse gases except HFCs (hydrofluorocarbons), where an upward trend was recorded [33].

Table 4. Overview of emissions and removals of the EU's main greenhouse gases 1990–2019 in million tons of CO_2 [32].

Specification	1990	2000	2010	2015	2016	2017	2018	2019
CO_2 emissions (with LULUCF *)	4494	4185	3956	3530	3513	3526	3446	3296
CH_4	729	612	496	464	458	460	451	443
N_2O	407	325	259	257	256	261	257	255
HFCs **	29	53	99	106	106	105	99	94
Total (with LULUCF *)	5630	5122	4711	4251	4227	4247	4154	3994

* LULUCF—(Land Use, Land Use Change, and Forestry). ** HFCs—(hydrofluorocarbons).

When interpreting the main sources of greenhouse gas emissions in the EU in 1990–2019 (Table 5), it can definitely be stated that it is the energy sector to the greatest extent (77%), followed by agriculture and industry [15,32]. As in the case of general issuance, the main issuer sectors also recorded a downward trend in the period under review [33,39], which can also be seen in most countries (Table 6) [32].

Table 5. Overview of EU greenhouse gas emissions (million tons of CO_2 equivalent) in terms of main sources and sinks in 1990–2019 [32].

Specification	1990	2000	2010	2015	2016	2017	2018	2019
Energy	4358	4012	3801	3376	3357	3361	3282	3132
Industrial Process	530	463	397	381	381	390	380	370
Agriculture	537	459	423	433	434	437	432	429
Waste	240	228	167	142	139	138	136	135
Total (with LULUCF *)	5669	5166	4790	4335	4312	4327	4233	4067

* LULUCF—(Land Use, Land Use Change, and Forestry).

In the case of the energy sector, Large Combustion Plants (LCPs) deserve special attention, which vary in size from 50 MWt (megawatts of thermal power) to even over 2000 MWt, the very large ones account for 21% of the LCP and generate 70% of installed power. In the EU, they account for around 40% of the electricity production capacity and depend highly on fossil fuels, producing a significant amount of emissions of air, water, and land pollutants [31,37]. In this situation, many countries are wondering what direction should be taken to develop an energy policy in order to meet the growing energy needs and, at the same time, to reduce CO_2 emissions [6,15]. Scientists say that getting out of the situation is definitely not linked to the use of carbon [41]. However, is politics heading towards the end of the coal age? It definitely does not indicate this, as coal remains a significant fuel [14,31]. However, international environmental organizations in the Boom and Bust report [33,42] estimate that the number of new coal-fired power plants in 2017 decreased by 29% compared to 2016, and by as much as 73% compared to 2015.

Table 6. Energy industry: contribution of the largest and smallest emitters to CO_2 and N_2O emissions in EU countries [32].

Member State	GHG * Emissions in 1990 (kt ** CO_2 Equivalents)	GHG Emissions in 2019 (kt CO_2 Equivalents)	CO_2 Emissions in 1990 (kt)	CO_2 Emissions in 2019 (kt)	N_2O Emissions in 1990 (kt CO_2 Equivalents)	N_2O Emissions in 2019 (kt CO_2 Equivalents)
Largest issuers						
Germany	427,353	249,696	423,906	244,822	3167	2073
United Kingdom (UK)	236,325	86,521	234,721	85,404	1399	728
France	66,350	38,212	65,835	37,897	448	268
Italy	137,646	91,797	136,941	91,312	477	362
POLAND	235,395	150,707	234,294	149,912	1018	691
Smallest issuers						
Malta	1766	740	1759	739	6	0
Cyprus	1767	3293	1761	3282	4	8
EU 27+UK	167,4802	986,865	1,665,064	975,763	8543	6780

* GHG—(greenhouse gases). ** kt—kilotons.

The aim of this study was to identify the opinion of the inhabitants of southeastern Poland on changes in the energy sector and its impact on the quality of the natural environment. The answers to the following questions were sought: (i) What is the social attitude toward the planned changes? (ii) How do citizens treat greenhouse gases and climate change? (iii) Do they see the link between energy production and environmental quality? (iv) What are their expectations regarding the transformation of the energy sector?

2. The Scope and Methodology of Research

Youth education plays an important social role by shaping specific, desired attitudes [43]. Identification of the perception of the issue of the quality of natural environment may provide knowledge concerning the information gap in the topic studied. The study addressed to young people was based on the assumption that, first, since EU regulations focus on reducing CO_2 emissions and stopping climate change [24], it is worth knowing the opinion of young people regarding the perception of these changes and the possibility of stopping them. Second, since the energy sector has an impact on the natural environment [44], how do young people perceive the state of this environment on a local, national and global scale. Third, an attempt was made to identify the expectations of young people regarding the directions of state activities that should be undertaken in the field of energy management.

Broadly understood society (demos) in a democratic system basically determines the shape of the law, and thus the economy [45]. Determining the views of adult energy consumers can be used to design changes in the energy sector or to plan social education [46]. Adults, as consumers of electricity in various forms, are an important element in shaping the relationship between the economy and the natural environment [47]. The survey was to answer the following questions: Do the respondents associate the functioning of the energy sector with the issues of caring for the natural environment? How do they perceive care for the environment and what solutions do they expect from the energy sector? Is their environmental attitude related to the perception of the energy sector?

The study was conducted from October 2020 to February 2021. In October 2020, adolescents under the age of 18 were tested. In February 2021, the survey was conducted among adults. A different tool was constructed to study school youth (n = 535) by adjusting the content of the questions to the intellectual level of adolescents, and a separate tool was created for adults (n = 1004). The survey was partial; it was carried out using the CAWI (Computer Assisted Web Interview) method; a total of 1539 reliably completed survey forms were collected. The research was not probabilistic; the selection of the sample was random. At the beginning, access to the questionnaire was given to several dozen people who met the condition of residence in the research area. These people represented various social groups: school youth, workers in the manufacturing sector, farmers, officials, students, etc. Then, these people invited others to take part in the study, meeting the criteria of age and place of residence in southeast Poland. The analysis and inference were carried out separately for both groups of respondents. The inference applied only to the studied group since the selection of the sample was random. In the analyzed sample, similar to the population inhabiting the research area, there was a certain numerical predominance of women. In terms of age, the respondents belonged to the largest age group in the surveyed voivodships [23]; however, the sample was not representative and the results refer to the surveyed group of people. The research area is characterized by high quality of the natural environment and significant forest cover (forest cover in % in 2018 in Poland was 29.6, while in Podkarpackie Voivodeship 38.3% and in Lubelskie Voivodeship 23.4%) [48], high tourist potential [49], and a significant number of farms.

During the identification of attitudes and perceptions of the issues discussed in this paper, questionnaires were created containing a number of thesis formulations assessed by the respondents in terms of compliance with their beliefs. A bipolar, five-point Likert scale was used for the assessment [50]. On the scale, the value of 1 meant definitely not; 2—probably not; 3—neither yes nor no; 4—rather yes; 5—definitely yes. Statistical analyses were performed in the Statistica program..

. In the research material collected, basic descriptive statistics were calculated and the structure of assessments of diagnostic theses was analyzed [51]. Due to the selection of the sample, the research is the basis for further research and should not be generalized to the entire population of southeastern Poland.

3. Research Results

In the part of the study addressed to adolescents, 60.9% were women and 39.1% were men. Most of the surveyed people in this group (59.6%) lived in cities, while 40.4% lived in the countryside.

In the part of the research diagnosing the perception of climate change and the quality of the natural environment by adolescents, the structure of assessments of formulated theses was calculated; the results are presented in Figure 1. Formulations 1 to 4 contained theses relating to the scale of the problem related to global warming. The vast majority (74.2%) of respondents perceived global warming as one of the greatest problems of mankind. The thesis downplaying this problem was contradicted by 90.7% of the respondents (Figure 1). Theses 5–8 contained references to climate change, its specificity, and the possibilities of stopping the changes. More than half of the respondents (57.2%) believed that climate change could be stopped. A similar percentage of respondents did not support the thesis that climate change is a tool of economic struggle. In contrast, 86.2% of respondents claimed that climate change is a consequence of human activity. The data presented show that young people were sensitive to the problem of global warming—they saw the role of humans in causing climate change and hoped that it could be stopped through human efforts.

In the part of the study relating to the perception of the natural environment, it is worth emphasizing that adolescents had the highest concerns about the state of the natural environment in a global perspective. In this case, 85.4% of the respondents were concerned about the condition of the Earth's natural environment (Figure 1). In the national perspective, the concerns were lower by 60.0%, and in the perspective of the southeastern Poland region, the quality of the environment worried only 27.5% of the respondents. These results may indicate a high sensitivity to global problems, which are presented, inter alia, in the curricula.

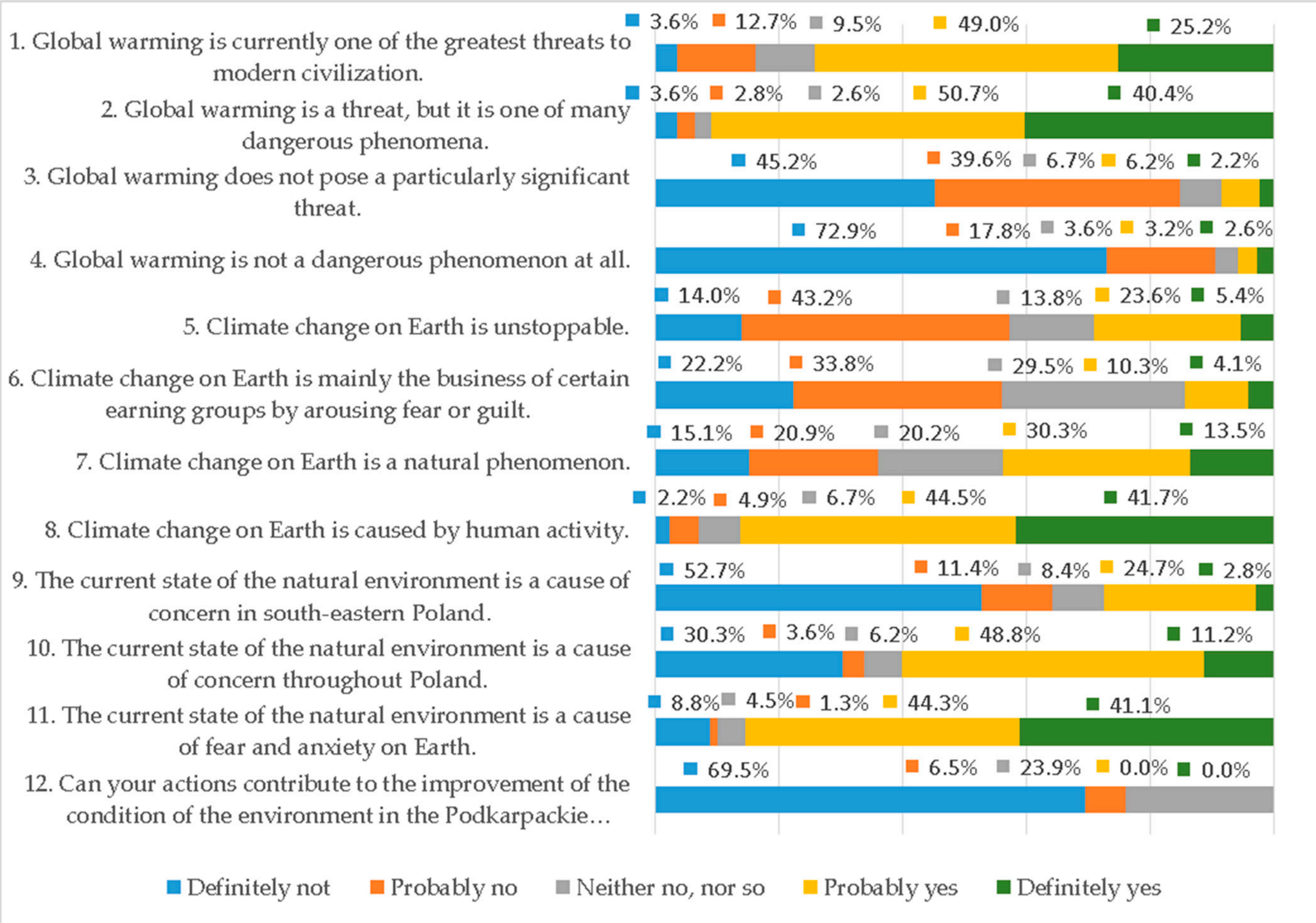


Figure 1. The structure of assessments of theses diagnosing the perception of global warming, climate change, and the quality of the natural environment by young adolescents.

Figure 2 presents the structure of assessments of theses diagnosing the perception of the directions of energy policy development by adolescents and the expected directions of state support. According to the vast majority of respondents, special attention should be focused on measures aimed at improving energy efficiency and reducing energy consumption (93.1%). Similar support (94.2%) was obtained by the thesis postulating the development of the energy sector using renewable energy sources. Young people did not support the development of energy based on gas and crude oil, especially the energy of hard coal and lignite. In contrast, 46.2% of the respondents supported nuclear energy.

Regarding the directions of state support in the area of energy management, the respondents primarily expected the development of energy using renewable energy sources (95.9%), energy-saving construction (83.4%), and high energy efficiency of manufactured devices (83.2%). The large support for the theses relating to the need to conserve energy and improve energy efficiency proves the high environmental awareness of the respondents (Table 6).

In order to learn about the perception of the benefits and disadvantages of energy production from renewable sources by respondents, a number of diagnostic theses were formulated, and the structure of their assessments is presented in Figure 3. Among the advantages of renewable energy, the improvement in air quality and the positive impact on health protection were generally most appreciated. Among the disadvantages of renewable energy, the respondents emphasized the high costs of renewable energy sources. Concerning other suggested drawbacks, the ratings were mixed. It should be emphasized, however, that there were the fewest assessments indicating a firm belief in a defect. This means that in the group studied, the general perception of renewable energy sources was positive.

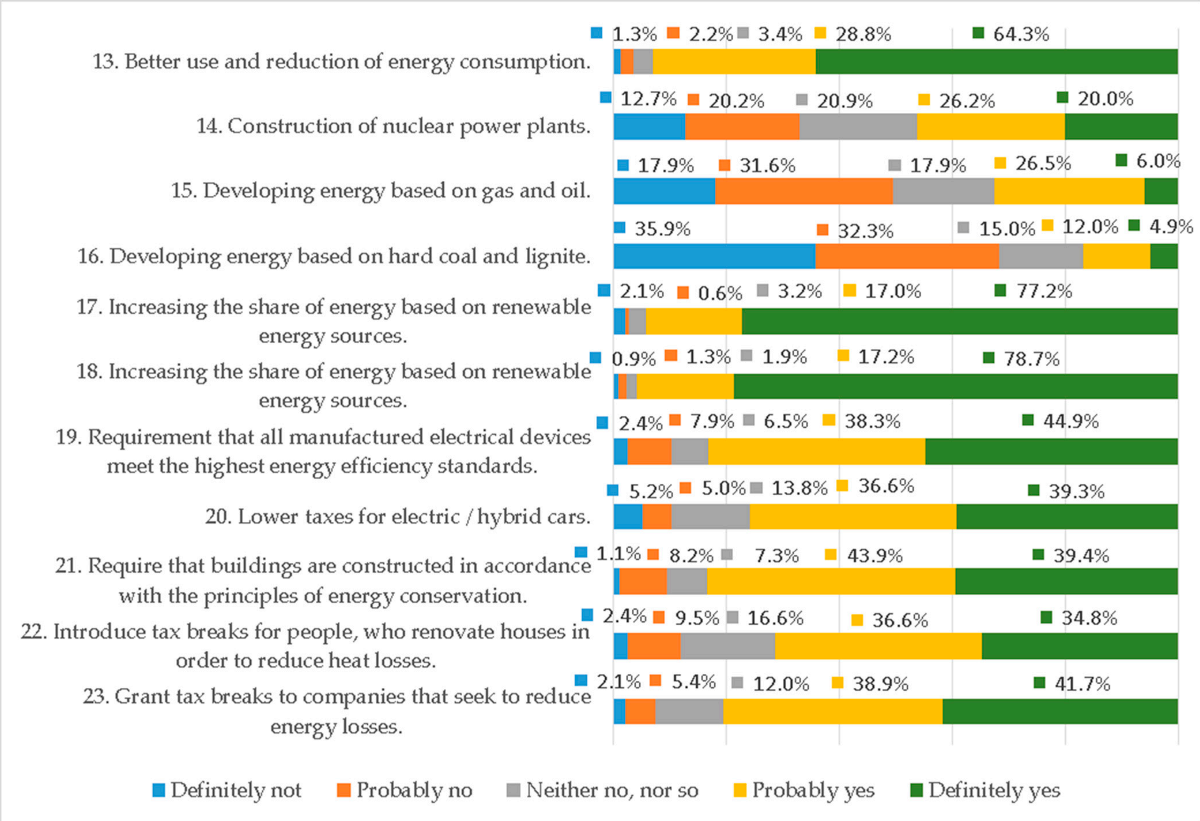


Figure 2. The structure of assessments of theses diagnosing the perception by adolescents of the directions of energy policy development and directions of state support.

In this research, an important issue was the perception of the quality of the natural environment by young people in the context of opinions on the benefits of producing energy from renewable sources. The calculated mean scores for theses relating to these issues are shown in Figure 4.

The differences between young people's concerns about the state of the environment depending on the perspective of perception were significant. The respondents had the greatest concerns about the state of the environment in the global perspective and the lowest in the local perspective. It is worth emphasizing that the surveyed adolescents assessed the possibility of personal influence on the quality of the natural environment as low (thesis 12). It seems justified to include in the curricula the role of individuals in shaping the quality of the natural environment.

The opinion on the benefits of energy production from renewable sources was positive, as evidenced by the high average scores, from 24 to 28. The surveyed youth especially counted on the improvement of air quality and a positive impact on the quality of health.

In the part of the survey addressed to adults, the age of the respondents ranged from 18 to 77 years. Geometric mean was SG = 25.96, median age (middle value) Me = 23 years, lower quartile being the limit of 25% of observations, Q1 = 21 years, and the upper quartile, indicating the limit of 75% of observations, Q3 = 30 years, modal, i.e., the most common value was 22 years. Most of the respondents were women, they constituted 57.5% of the respondents, and men accounted for 42.5%. The place of residence of the respondents is shown in Figure 5. In the group studied, 52% of the respondents lived in the countryside, and 15.7% lived in a city with more than 100,000 residents.

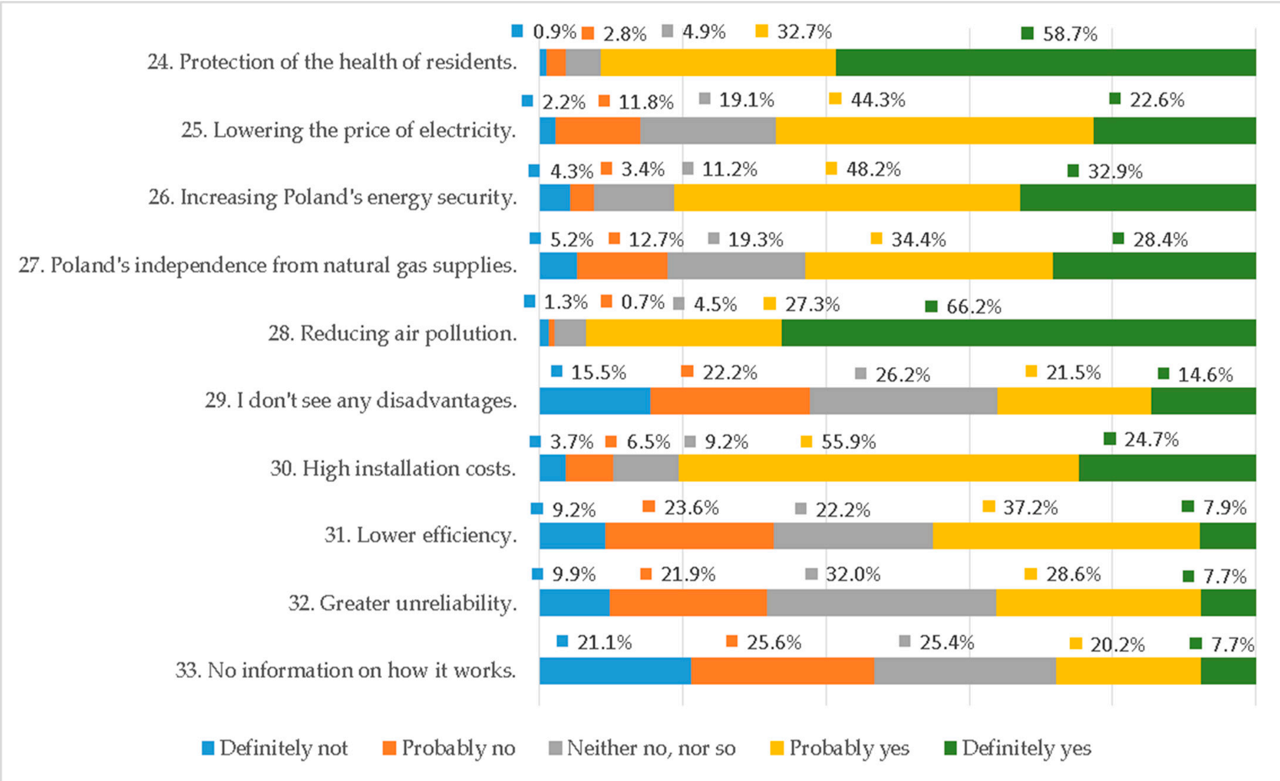
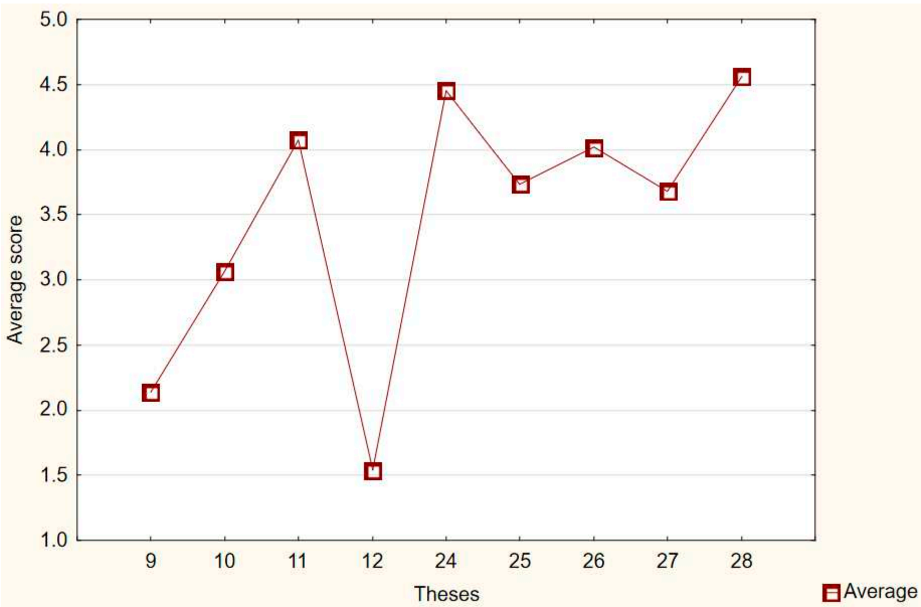


Figure 3. The structure of assessments of theses diagnosing the perception of advantages and disadvantages of energy production from renewable sources by adolescents.



9. The current state of the natural environment is a cause of global concern and local concern in southeastern Poland; 10. The current state of the natural environment is a cause of global concern and concern in Poland; 11. The current state of the environment is a cause of concern and anxiety on Earth; 12. Can your actions contribute to the improvement of the condition of the environment in the Podkarpackie Province? 24. Protection of residents "health"; 25. Lowering the price of electricity; 26. Increasing Poland's energy security; 27. Poland's independence from natural gas supplies; 28. Reduction of air pollution.

Figure 4. Average ratings relating to the quality of the environment and the benefits of energy production from renewable sources.

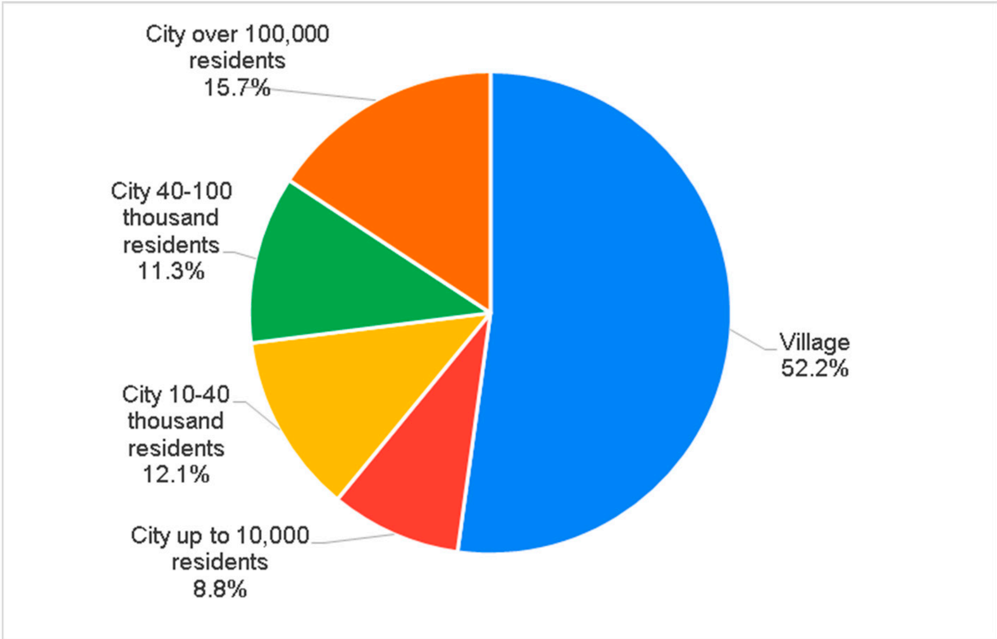


Figure 5. The structure of adult respondents by place of residence.

Figure 6 presents the structure of theses assessments used to identify attitudes and perceptions of the studied phenomena. The theses relating to the need to limit consumption and reduce CO_2 emissions were highly approved by the respondents. The former was supported by 68.6% of people, while the latter was supported by 82.7%. This means that the subjects were convinced of the decisive anthropogenic impact on global warming.

Concerning limiting the human population in order to protect the climate, 57.5% of respondents were against such actions. Thus, the respondents perceive contemporary problems, but do not see their solution in human depopulation. The assessment of the energy sector was dominated by responses clearly confirming its negative impact on the natural environment (42.0%), and 62.0% of the respondents confirmed this thesis in total. This is an interesting observation as part of this sector is renewable energy, with which the respondents hope to cover the growing energy demand (87.7%). This may mean that the respondents associate the energy sector primarily with high-emission energy sources.

Concerning the impact of nuclear power on the natural environment, there was a moderate acceptance; 37.7% of the respondents did not confirm the thesis about the negative impact of nuclear power plants on the environment. However, nearly half of the respondents (49.5%) were against the construction of a nuclear power plant in the vicinity of their place of residence (Figure 6).

The theses aimed at identifying the ecological attitude in practical terms, and relating to the purchasing attitude, i.e., conscious and moderate consumption, were highly rated. This means that most of the respondents do not buy in advance (74.2%), are convinced of the high quality of food produced using organic and traditional methods (84.7%), and are able to bear slightly higher costs of organic, safe, and wholesome food. (70.9%) (Figure 6). This means that the respondents had a formed ecological attitude.

Figure 7 shows the average ratings of theses relating to the energy sector. These data show that among the respondents there was a belief that it was possible to meet the growing energy needs with energy from renewable sources. Respondents also showed moderate concern about the negative environmental impact of the energy sector. As far as nuclear energy is concerned, the average scores were approximately 3, which meant that there was no unambiguous opinion. On the other hand, the average assessment of the thesis supporting the construction of a nuclear power plant close to the respondents' place of residence indicated moderate skepticism.

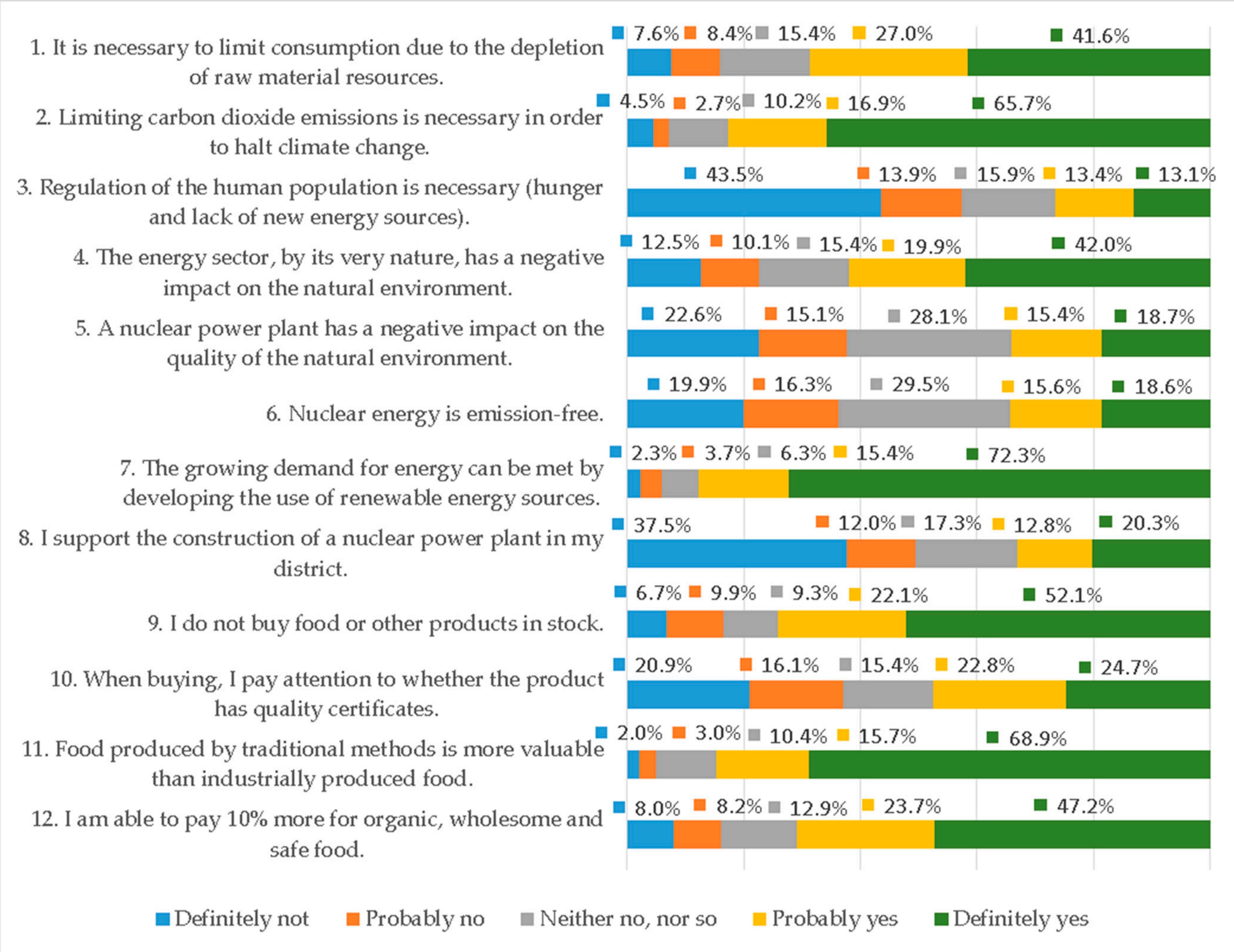
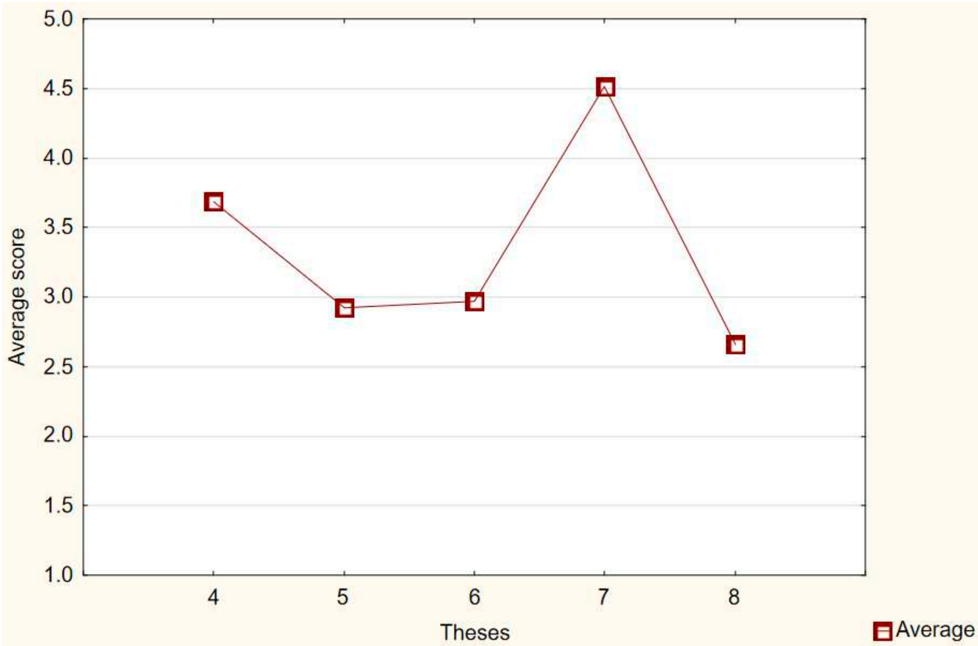


Figure 6. The structure of assessments of theses diagnosing attitudes and perception of the studied phenomena by adult respondents.

Comparing the data from Figures 6 and 7, it can be concluded that some of the respondents were afraid of nuclear power, were convinced about the negative impact of the energy sector on the environment, and had high hopes for the development of renewable energy sources. In the surveyed group, some respondents were open to nuclear energy, perceived it as emission-free, and had no concerns about the proximity of the nuclear power plant.

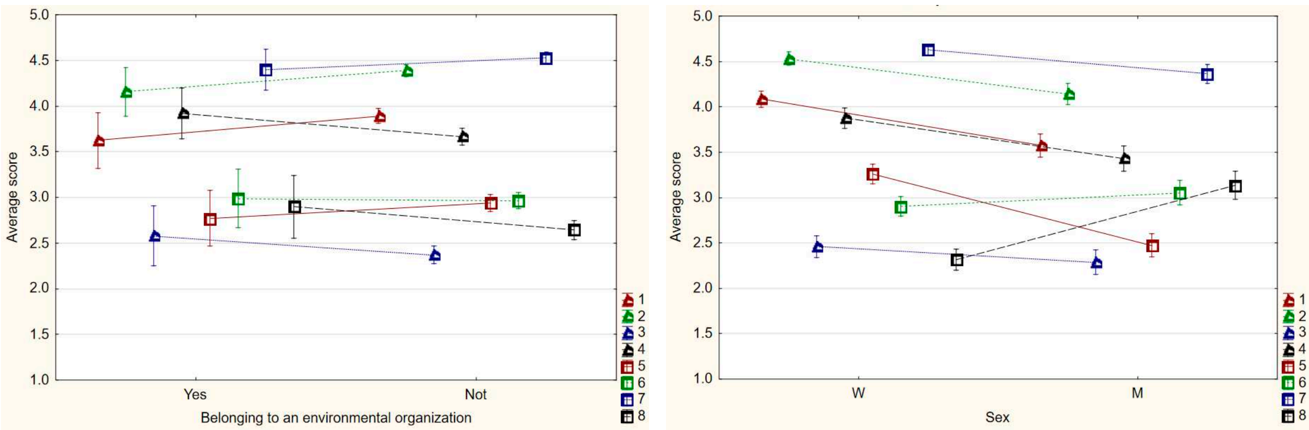
At the conceptualization stage, it was assumed, inter alia, that people belonging to social organizations, whose goals include care for the natural environment, have a higher level of ecological sensitivity. Therefore, it can be expected that their perception of the energy sector is different from that of other people not involved in social activities. In the studied group, 16.1% of people declared affiliation to social organizations that care about the quality of the natural environment.

Figure 8 shows a comparison of the average ratings of theses in groups of people belonging to pro-ecological social organizations, and those not belonging to such organizations, and by gender. It should be noted that the differences in the perception of the impact of the energy sector on the environment were smaller depending on the fact of social activity of people in pro-ecological organizations than the differences between people of different sexes. It can be concluded that in the studied group, the social activity of the respondents was not related to the perception of the impact of the energy sector on the natural environment. At the same time, the lack of such a relationship may be the result of the fact that the majority of respondents are ecologically sensitive, which is confirmed by the results presented in Figure 6.



4. The energy sector, by its very nature, has a negative impact on the natural environment; 5. A nuclear power plant has a negative impact on the quality of the natural environment; 6. Nuclear energy is emission-free; 7. The growing demand for energy can be met by developing the use of renewable energy sources; 8. I support the construction of a nuclear power plant in my district.

Figure 7. Average ratings of theses relating to the energy sector.



(**a**) (**b**)

1. It is necessary to limit consumption due to the depletion of raw material resources; 2. Limiting CO_2 emissions is necessary in order to halt climate change 3. Human population regulation is necessary due to the specter of overpopulation, hunger and the lack of new energy sources; 4. The energy sector, by its very nature, has a negative impact on the natural environment; 5. A nuclear power plant has a negative impact on the quality of the natural environment; 6. Nuclear energy is emission-free; 7. The growing demand for energy can be met by developing the use of renewable energy sources; 8. I support the construction of a nuclear power plant in my district.

Figure 8. Average ratings of theses diagnosing the ecological attitude and the perception of the energy sector categorized due to (**a**) membership in pro-ecological organizations; (**b**) sex of respondents.

The data presented in Figure 8 show that gender was important in the assessment of many issues. Differences can be seen regarding the need to reduce CO_2 consumption and emissions. Women declared greater support for these theses than men. Women also saw more of the negative impact of the energy sector on the environment, including the negative impact of nuclear power plants. The assessment of consent to build a nuclear power plant near the respondents' place of residence was different. In this case, men showed greater acceptance of this thesis.

One of the elements of the study was an attempt to learn about the expectations and preferences of the respondents in relation to the direction of development of the energy sector. The structure of expectations regarding the direction of development of the energy sector in Poland is presented in Figure 9.

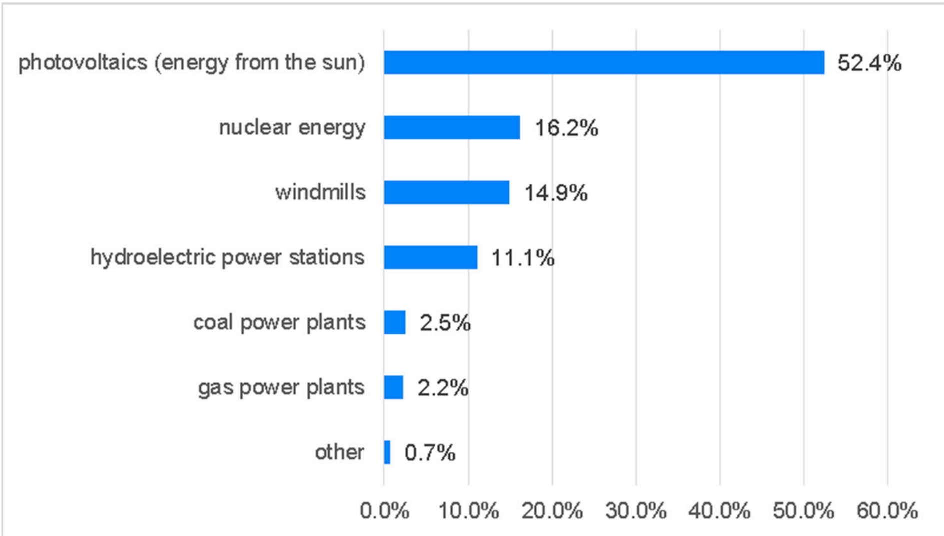


Figure 9. Respondents' expectations regarding the development of energy sources in Poland.

These data show that photovoltaic is the main expected direction of development of the energy sector (52.4% of indications). The second largest group was nuclear power (16.2%). Noteworthy is the low support for the development of coal and gas energy.

4. Discussion

As stated in the International Energy Agency's report from 2021 [15], the energy sector is responsible for about three-quarters of greenhouse gas emissions and is of key importance in limiting the effects of climate change. Reducing these emissions is to prevent further global temperature increases and halt climate change. As the report cited above shows, this will require enormous financial outlays. It is assumed that the total annual investments in the energy sector will increase to the level of 5 trillion USD (United States Dollar) by 2023, which is an additional 0.4 percentage points annually to global Gross Domestic Product (GDP). These high costs require social consensus, hence the social perception of the impact of the energy sector and social consent to undertake broad and profound changes in the current lifestyle [37].

The social perception of climate change is a fundamental issue: it can influence political decision-makers in shaping the legal order and in creating incentives and requirements for respecting the natural environment [52,53]. The surveyed youth expressed their concern about climate change and confirmed the necessity to undertake actions limiting its changes. Similar results were obtained in the first decade of the 21st century in the relatively wealthy US society. However, it was emphasized that the effect of reducing consumption and caring for the natural environment is greater when the public is well informed about the benefits of such activities [54].

The involvement of young people in activities aimed at respecting the environment and saving energy is known and largely depends on education [46,55]. Environmental education plays an important role in preventing climate change, caring for the natural environment, and transforming society towards sustainable development [56]. The surveyed youth saw the need to care for the natural environment. It showed great understanding for reducing consumption and emissions of greenhouse gases. At the same time, the quality of the local natural environment was perceived as satisfactory, and the condition of the environment was of concern, mainly at the global level. The sensitivity of young people to the problems of the quality of the natural environment is shaped by many factors. Parents [57] play an important role, but also the youth education system [58]. The results obtained show greater concern about the quality of the global environment and less concern for the local environment, and may prove that young people are highly sensitive to global problems presented in the curricula [58].

The expectations of the adolescents studied were consistent with the results obtained by other authors [43,54]. They mainly concerned the improvement of energy efficiency, the reduction of energy consumption, and especially the development of renewable energy.

In studies conducted in the USA, it was recommended to take into account the social perception of the costs of renewable energy in shaping the path of changes in the energy sector [59]. It is worth emphasizing that social conviction regarding specific actions, also in the area of climate protection, does not take into account all the variables. Often the economic costs are not widely realized, and social belief is the result of incomplete knowledge of the issue [60]. The respondents saw the economic aspect of the development of renewable energy. However, mainly the benefits of renewable energy sources were pointed out, above all, the improvement of air quality was emphasized. A similar, positive attitude towards renewable energy sources was identified by other authors [61–63].

The perception and acceptance of renewable energy sources is key to a successful transformation of the energy sector [61], hence the positive opinion of the respondents is a good predictor of this transformation. In the research conducted, pro-ecological attitudes and concern of adult respondents about the condition of the natural environment were associated with a positive attitude to renewable energy sources.

The belief of society about an anthropogenic impact on global warming is confirmed by numerous studies. The perception of environmental quality issues depends on many factors, both social and individual characteristics of people. The importance of ecological education and shaping pro-ecological attitudes are emphasized [54,64–68]. Similar relationships have been identified in studies conducted in southeastern Poland. However, the postulates of limiting the human population in order to stop climate change [69] were not confirmed in the conducted studies.

The respondents expressed different views on the impact of power plants on the quality of the natural environment. In the studied group, the functioning of the belief about the negative impact of nuclear power plants on the quality of the natural environment was identified. Such a stance is in contradiction with the studies of other authors who emphasize the high level of safety of nuclear power plants [70,71].

The literature emphasizes the relationship between the ecological attitude and the consumption of ecological products [72]. People with greater knowledge about the human–nature relationship, characterized by an ecological attitude, noticed the need to reduce consumption and emissions of pollutants. Therefore, shaping pro-ecological attitudes and the diffusion of knowledge about the real environmental effects of obtaining energy from various sources is crucial for reliable discourse and social participation in shaping the energy transformation [73].

The research shows that among the respondents, support for the development of photovoltaic energy dominates. It is an interesting result as it proves the high ecological awareness of the respondents. The positive effects of the development of photovoltaics relate to distributed generation, which does not require investment in grid infrastructure. It is worth emphasizing that in the research area, the government program for cofinancing photovoltaic installations "My Electricity" enjoyed great popularity (the largest in the Podkarpackie Province) [74]. This is a successful observation because photovoltaics have great development potential, especially in the context of new solar energy conversion technologies. It is worth mentioning that in Poland, the production of highly efficient new generation cells, perovskites, has started, which have a chance to dynamize the production of solar energy [75,76]. Therefore, it can be expected that the society in the area studied is ready to disseminate clean energy technologies. The second most important source of energy mentioned by the respondents was nuclear energy, and the third was wind energy. This means that in the group studied the support for nuclear energy is relatively high [77].

Place of residence influences the perception of the energy sector. Depending on the industrialization of the region and the type of dominant energy source, inhabitants perceive the energy sector differently [78]. Most of the people surveyed in this study 59.6% lived in cities; 40.4% lived in villages. There were no significant differences in the tendencies of perceiving the impact of the energy sector on the quality of the natural environment depending on the size of the place of residence.

5. Conclusions

The young respondents were sensitive to the problem of global warming, saw the role of man in the formation of climate change, and hoped that it could be stopped through human efforts. The vast majority of young people surveyed perceived global warming as one of the greatest problems of mankind, and the young people had the highest concerns about the condition of the natural environment from a global perspective. From the national perspective, these concerns were lower, and from the local perspective, young people were sure that their natural environment is in good condition.

In the opinion of the vast majority of the surveyed youth, the actions of the EU or the Polish state aimed at improving energy efficiency and reducing energy consumption deserve special attention. Young people did not support the development of energy based on gas and crude oil, especially the energy of hard coal and lignite. In contrast, almost half supported the development of nuclear energy and, above all, expected the development of renewable energy sources. Among young people, there was high support for theses relating to the need to conserve energy and improve energy efficiency, which may prove the high ecological awareness of the respondents.

Among the advantages of renewable energy, the young people surveyed most appreciated the improvement in air quality and the positive impact on the generally understood health protection. Among the disadvantages of renewable energy, the respondents emphasized the high costs of construction and operation of this type of energy source. There was also a strong conviction among young respondents that RES are a significant tool for reducing the negative human impact on the quality of the natural environment. It should be said that among young people, greater concern about global warming, climate change, and the quality of the environment was associated with more positive assessments of renewable energy.

The theses regarding the need to reduce consumption and reduce CO_2 emissions met with great recognition among adult respondents, so respondents were convinced of the decisive, anthropogenic impact on global warming. However, regarding the claim to regulate the human population, most respondents were against it. The respondents see contemporary problems, but do not see their solution in human depopulation.

Regarding of the energy sector, responses strongly confirming its negative impact on the natural environment prevailed among the adult respondents. This is an interesting observation as part of this sector is renewable energy, with which the respondents hope to cover the growing energy demand. This may mean that the respondents associate the energy sector primarily with high-emission energy sources.

Concerning the environmental impact of nuclear power, there was moderate acceptance among the adult group of respondents. One-third of the respondents did not confirm the thesis about the negative environmental impact of nuclear power plants. However, nearly one-half of the respondents were against building a nuclear power plant in the vicinity of their place of residence.

The research confirms the diversity of the respondents in the perception of the impact of energy on the natural environment. Some of the respondents, with pro-ecological sensitivity, were afraid of nuclear power, were convinced about the negative impact of the energy sector on the environment, and had high hopes for the development of renewable energy sources. The second part of the respondents was open to nuclear energy, saw it as emission-free, and had no concerns about the proximity of the nuclear power plant.

The sex of the respondents was of importance in the assessment of many issues. Differences were calculated concerning the need to reduce consumption and CO_2 emissions. Women declared greater support for these theses than men. Women were also more convinced of the negative impact of the energy sector on the natural environment, including the negative impact of nuclear power plants. Women showed less acceptance than men of the location of a nuclear power plant in the vicinity of their place of residence.

Among the respondents, support for the development of photovoltaic energy dominated. It is an interesting result as it proves the high ecological awareness of the respondents. The positive effects of the development of photovoltaics relate to distributed generation that does not require investment in grid infrastructure. Nuclear power was ranked second and wind power third. Therefore, the surveyed group accepts the direction of changes in the energy sector, expects the development of renewable energy and nuclear energy, and is aware of the threats related to climate change at the global level, however, especially the young group of respondents, do not identify this threat within southeastern Poland.

6. Recapitulation

Based on the research results presented in the article and their discussions with the literature, the following conclusions can be made:

1. The young people surveyed believe:
    - Climate change is currently one of the greatest threats to humanity (but not the only one), interpreting this phenomenon primarily as a threat to the world, and to a lesser extent to Poland and the region of origin.
    - Energy policy in Poland should be aimed at better use and reduction of energy consumption, and mainly towards greater use of energy based on renewable energy, limiting energy based on hard coal and lignite.
    - RES are associated primarily with the protection of public health, a clean environment, and the country's energy security. Nuclear energy is considered the preferred direction of energy policy development in Poland—one-half of the respondents share this opinion, while the other half are against this energy.
2. The adults surveyed believe:
    - They blame the energy sector for the current negative condition of the natural environment, associating it with high-emission energy sources.
    - They are divided (as in the case of young people) into supporters of nuclear power, considering it to be low-emission and not harmful, and opponents of nuclear power, seeing in it a negative impact on the quality of the environment and humanity, which is largely associated with direct memory the accident of the nuclear power plant in Chernobyl in 1986.

The surveyed respondents see the impact of the energy sector on the quality of the natural environment and expect changes to reduce negative pressure. This issue requires further research, as the economic aspect in the form of electricity prices may be of significant importance for the perception of transformations in the energy sector.

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