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

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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:

$$CEU_i = EU_i \ / \ X_i \tag{1}$$

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:

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

where EU_I denotes the energy use of aggregate I, $i = 1, 2, \ldots, n$ 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:

$$EU_{III} = EU_f - z_{fa} * CEU_f \tag{3}$$

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:

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

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:

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

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

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

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:

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

where I_g represents the set of objects that belong to the g-th group, and $\bar{a}_{gi}$ 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.

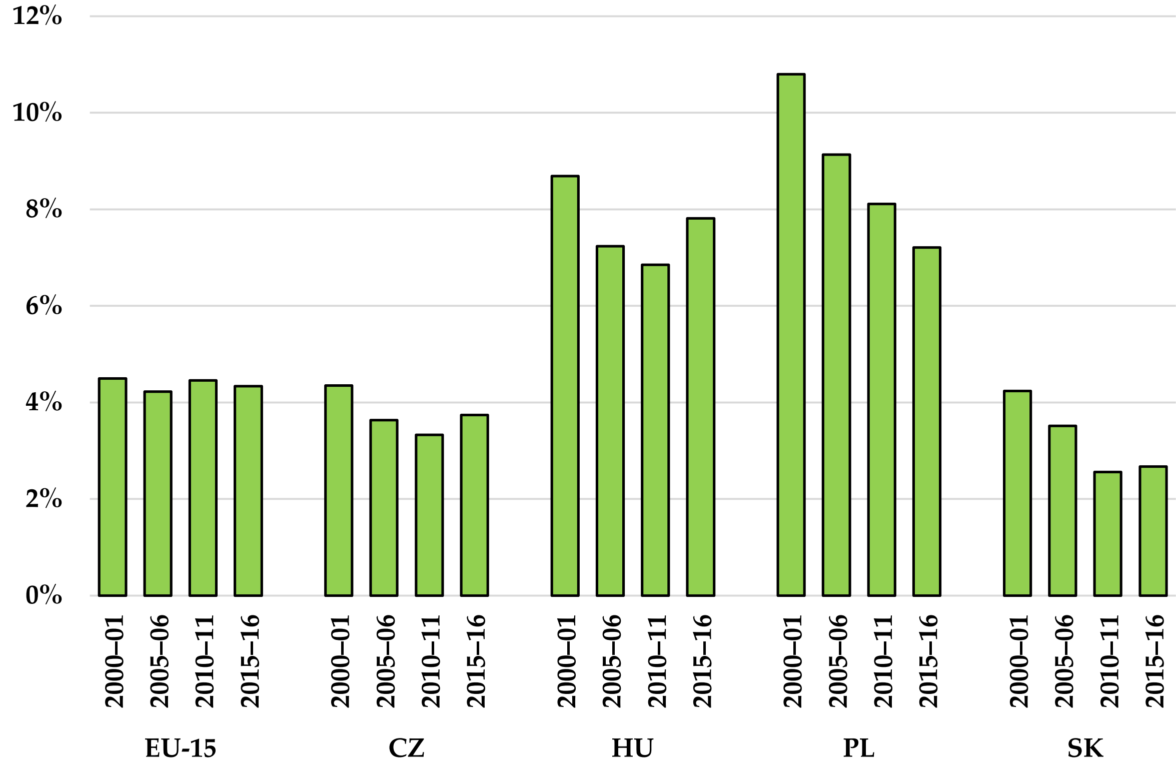

Figure 1. The share of energy consumption in food production systems in total energy consumption by industrial activities. Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

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.

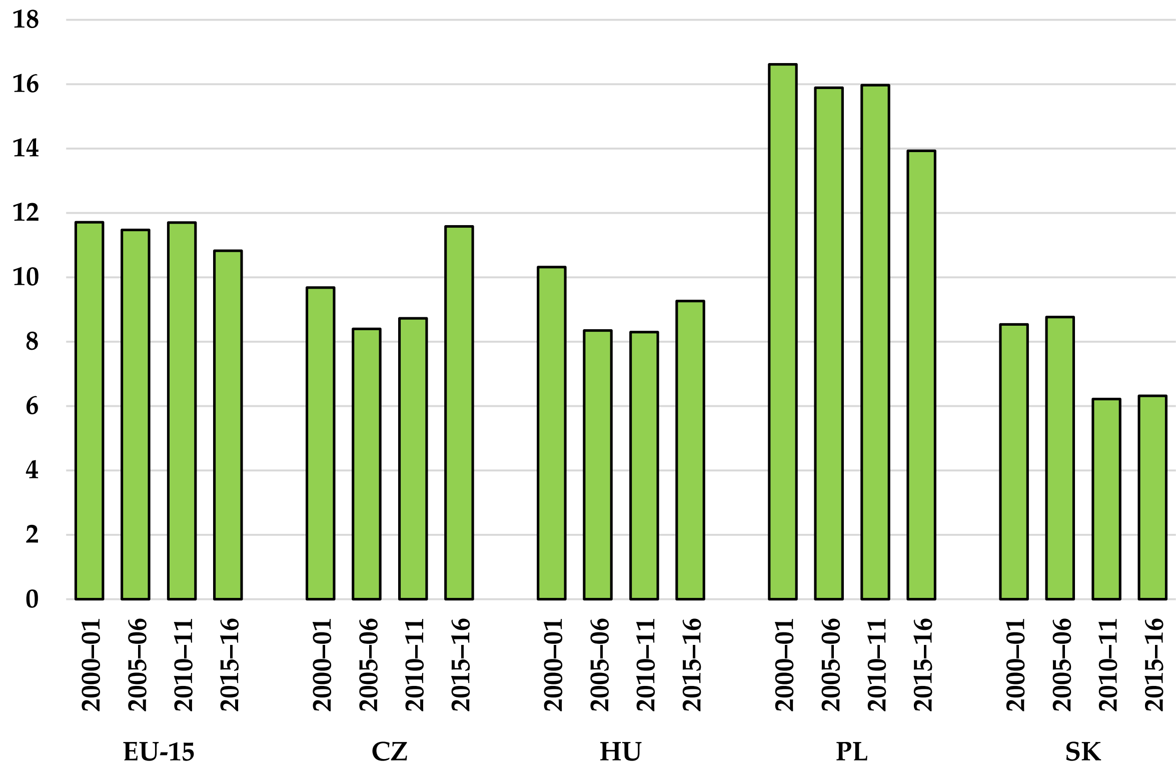

Figure 2. Energy intensity of agricultural land (TJ/1000 ha UR). Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

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.

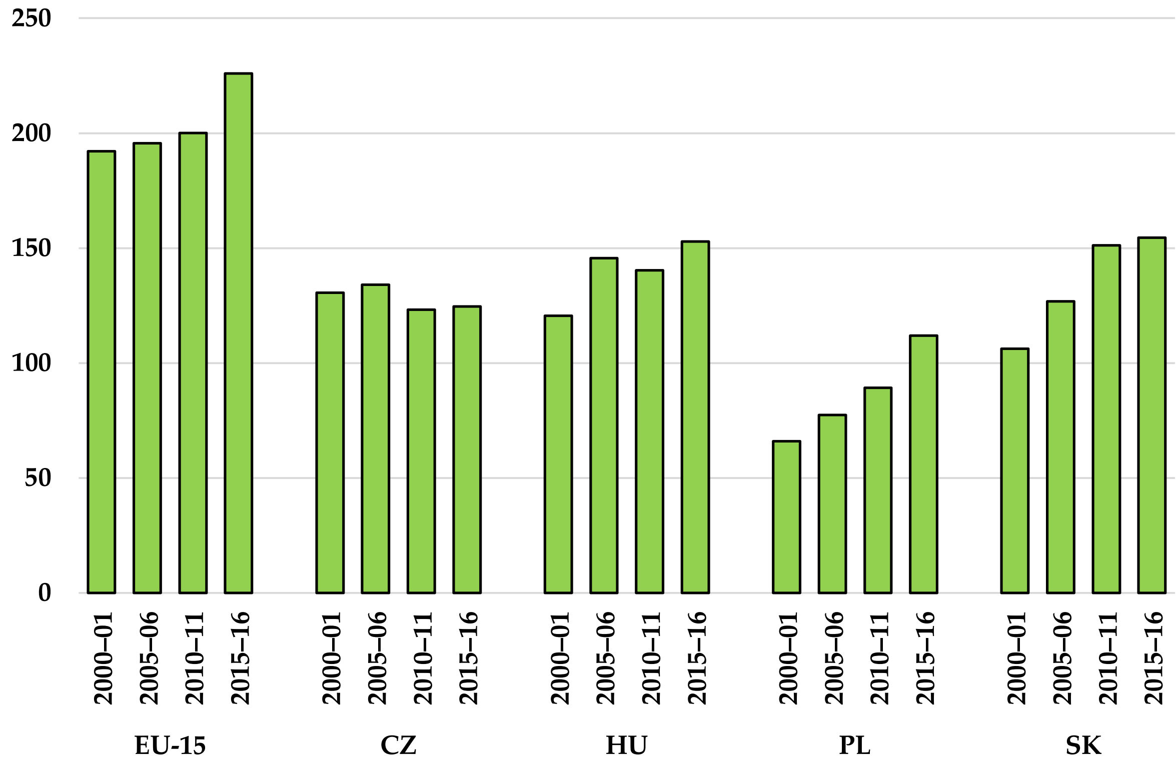

Figure 3. Economic energy efficiency of food production in agriculture (USD in constant prices from 2014-2016/TJ). Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

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].

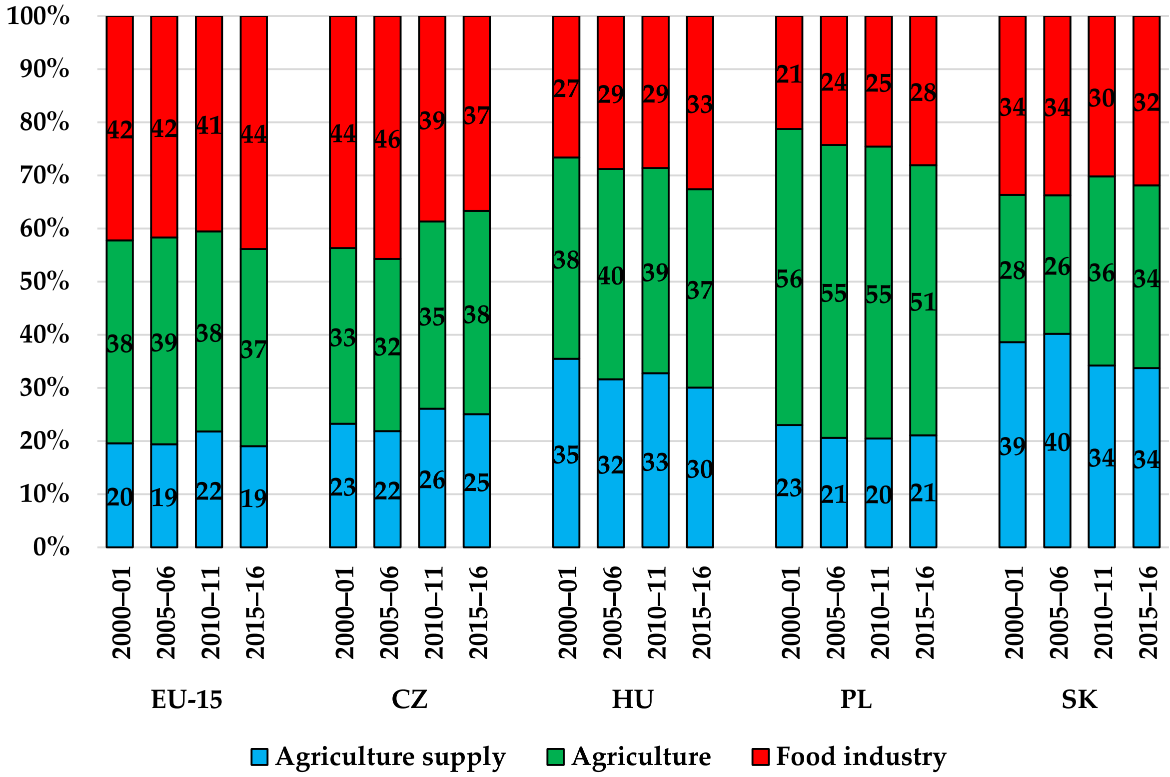

Figure 4. The structure of energy consumption by production sectors. Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

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.

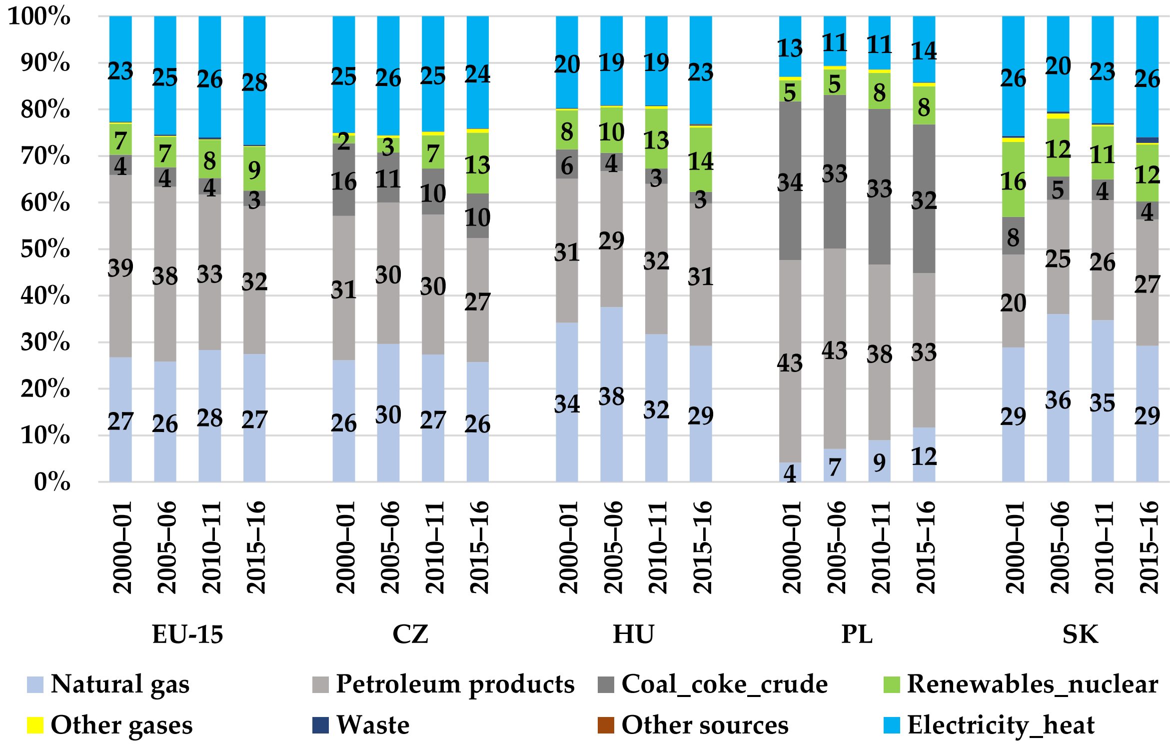

Figure 5. Structure of the sources of energy consumption in food production systems. Source: Own calculations based on WIOD Environmental Accounts and WIOD national input–output tables.

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 ($\gamma = 0.22$).

	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 ($\gamma = 0.18$).

	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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