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Evaluation of the Significance of Agriculture in Renewable Energy Production in the Member States of the EU

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Abstract: The need to contain climate change and improve energy security has increased the interest in agricultural biomass as a renewable energy source (RES). Given the complexity of the issue of energy production and its environmental impact, the main objective of this study was to assess the significance and potential of the agriculture of the European Union Member States in terms of the capability of producing renewable energy. Using the multi-criteria TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method, we designed a synthetic measure based on several diagnostic characteristics for 2010–2021, obtaining a ranking for EU countries reflecting their agriculture's RES potential. The research showed that the agricultural sectors with the highest potential for renewable energy production were in the Netherlands, Lithuania, Latvia, and Hungary during the study period. Bulgaria, Denmark, and Spain joined this group in 2021. A comprehensive assessment was conducted using the TOPSIS method to identify the leaders and areas in need of support in leveraging the potential of agriculture for energy in the EU.

Keywords: potential of agriculture; biomass production; renewable energy sources (RESs); the European Union Member States; the TOPSIS method

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1. Introduction

Due to the growing population, the scale of human economic activity, and the associated exploitation of natural resources, one of the main challenges in the modern world is the need to protect the environment, combat climate change, and use natural resources sustainably. Therefore, the basic elements of the current European energy policy are energy security and climate change mitigation [1]. The European Union emphasises closer links between climate policy and the development of renewable energy sources [2]. Renewable energy is considered to interact with many aspects of sustainable development [3] and the Sustainable Development Goals, specifically Goal 7 (ensure access to affordable, reliable, sustainable, and modern energy), but it also relates to Goal 12 (ensure sustainable consumption and production patterns). In addition, renewable energy sources have a considerably smaller adverse environmental impact than conventional fossil-based technologies [4,5]. Agriculture and the food economy are also objects of climate and energy policies. This stems from the links between the agricultural sector, renewable energy, and sustainable agriculture [6,7]. On the one hand, agriculture is a significant energy consumer, while on the other hand, the relationship between energy and sustainable agriculture goes far beyond the use of renewable sources [8]. In 2022, on average, agriculture utilised approximately 3% of the gross final energy consumption in 21 EU Member States. This percentage varies from country to country, ranging from 7.5% in the Netherlands to 0.9% in Luxembourg [9]. Sustainable agriculture practices that aim to minimise environmental impacts and increase productivity and energy play a key role in achieving these objectives [10]. Therefore, not only does the agricultural sector emit greenhouse gases and consume energy [11], but it simultaneously has the potential to produce renewable energy [12].

Rokicki et al. [4] noted that agriculture is a significant producer of renewable energy that is recognised by decision-makers. At present, in light of the crises that society is now facing, agriculture has gained an increasing role in ensuring not only food security but also energy security [13,14]. According to Bańkowska and Gradziuk [2], the use of biomass in the production of energy and liquid and gaseous fuel is one of the most promising directions for RESs. Janiszewska and Ossowska [15] emphasised that agricultural biomass as a renewable energy source offers multiple benefits. The most important include the disposal of waste and agricultural residues, a reduction in agricultural emissions, various uses for agricultural biomass (production of heat, electricity, fuel for transport), common access to energy resources, and improving regional energy security by decentralising energy production. One of the methods for producing renewable energy in the agricultural sector uses existing harvested crop residues [16]. However, biomass production may involve any type of agricultural product, so agriculture has a very high energy-generating potential [17].

The problem of renewable energy sources has recently been discussed in terms of both the natural environment [18] and the economy [19,20]. The European Green Deal has set strategic directions for national policies in European Union Member States, primarily related to improving energy efficiency, mitigating climate change, and achieving sustainable development. The need to curb climate change and increase energy security has contributed to increased interest in agricultural biomass as a renewable energy source (RES) [14]. However, the role and potential of agriculture in this respect still need to be explored. Studies investigating the relationship between agriculture and renewable energy production are most often limited to analysing selected single indicators, usually production volumes or biomass estimates [12,15], or refer to selected Member States only [14,21–23]. This study attempted to fill this research gap by designing a synthetic measure using the TOPSIS method to assess the significance of agriculture in renewable energy production. The rationale for conducting this research is the surplus agricultural production in the European Union, which creates potential opportunities for energy use. Given the complexity of the issues related to energy generation and its environmental impact, the main objective of this study was to assess the significance and potential of the agriculture of European Union Member States in generating renewable energy.

The paper is organised as follows. Section 2 reviews the scientific literature on the potential of agricultural energy feedstocks. Section 3 discusses the research methods, including the design of a synthetic index to evaluate the significance of agriculture in generating renewable energy. Section 4 presents a comparative analysis of agricultural potential and its actual use in renewable energy production among the EU Member States, while Section 5 discusses the results obtained. The final chapter contains conclusions from the analyses and identifies possible directions for continued research.

2. Literature Review

The consumption of fossil fuels for energy production is one of the biggest drivers of human-caused climate change. However, the demand for energy and food continues to grow due to global population growth and economic development [24]. Renewable energy production is believed to provide a sustainable strategy for replacing fossil fuels, thereby mitigating climate change by continuing to meet the growing global demand for energy [25]. The production and consumption of renewable energy is currently one of the main pillars of the European Union's energy policy [26]. The EU's energy target for 2030 has increased to reach 42.5% RESs in the energy mix, with an ambitious target of 45% [27]. Castillo et al. [5] emphasised that rural areas, including agriculture, are recognised as key players in achieving climate change and energy transition goals, primarily because of their abundance of natural resources (e.g., water and land). The wide variety of renewable energy resources available for processing in agriculture (Table 1) means that the sector can play an important role in bioenergy production while also contributing to the climate policy goals of reducing greenhouse gas emissions and increasing the share of RESs in final energy consumption to the levels set out in the EU's climate and energy policy [28].

Table 1. Renewable energy outputs from agriculture.

Energy Resource Originating in Agriculture	Type of Resource	Competing Non-Energy Demands for Same Resource	Type of Energy Produced	Final Energy Market
Agricultural crops	Grains, sugar crops, edible parts of other starchy commodities Vegetable oils	Food Other non-food non-energy industrial uses	Biofuels (1st generation) - ethanol - biodiesel	Transport fuel
	Grains		Biogas	Electricity, heat, natural gas
Dedicated energy crops	Grasses, short rotation coppice (willow, poplar, etc.) Any other ligno-cellulosic biomass	No competing food demand, but other industrial demands and possible competition for land	Biofuels (2nd generation)	Transport fuel
			(Direct combustion of primary solid biomass)	Electricity, heat
			Biogas	Natural gas
Agricultural residues and wastes	Straw, any kind of ligno-cellulosic waste Animal manure	Can directly use as fertiliser on farm	Biofuels (2nd generation)	Transport fuel
			Biogas	Natural gas
			(Direct combustion of primary solid biomass)	Heat, electricity

Source: On the basis of [29].

Biomass and agricultural by-products and wastes generated in the agricultural sector can, using thermochemical, physico-chemical, and biological conversion technologies, be used in the production of solid fuels, biogas, and liquid biofuels [30]. Solid fuels include organic, non-fossilised substances of biological origin that can be used as fuel for producing heat or generating electricity. Within this group of resources, agriculture is responsible for the production of biomass from food-grade crops, and a separate group comprises fuels from energy crops (fast-growing trees, dicotyledonous perennials, perennial grasses, cereals grown for energy purposes), as well as organic residues from agriculture and horticulture (e.g., horticultural production waste, animal excrement, straw) [28].

Solid biofuels of agricultural origin can also be used for the production of biogas, meaning combustible gas predominantly composed of methane and carbon dioxide, which is obtained through the anaerobic digestion of biomass [31]. Biogas may be derived from the fermentation of waste in landfills (landfill gas), from the anaerobic digestion of sewage sludge, and from agricultural biogas obtained through anaerobic digestion of biomass from energy crops, crop residues, and animal manure [32]. Another source is the anaerobic digestion of waste biomass in slaughterhouses, breweries, and other food industries. The produced biogas can be used to generate electricity, heat, or, following treatment, directly for household needs [33].

Input materials for biogas plants may comprise agricultural raw materials, agricultural by-products, liquid or solid manure, waste or residues from the processing of products of agricultural origin or forest biomass, and agricultural biomass from land other than agricultural land or forest land [34]. Agricultural biogas plants serve many economic, environmental, and social functions that are necessary for the development of a low-carbon and circular economy. Agricultural biogas production may generate extra income for the rural population, not only for feedstock producers but also for those involved in the storage and transportation of biomass [35]. This is particularly important for pig and poultry farms, which, with their very large-scale production, can use the manure generated in the production process to produce bioenergy. Furthermore, Tymińska [34] highlighted the additional benefits of biogas plants. Farms with biogas plants are seen as innovative and technology-friendly. Frequently, a symbiosis also occurs between the biogas plant and the scientific, educational, and tourism communities.

In turn, liquid fuels are all fuels of natural origin, that is, those produced from biomass or from the biodegradable portion of waste, which can be mixed with liquid fuels of fossil origin or can replace such fuels. Liquid biofuels are a set of products, including biobenzene, biodiesel, and other liquid biofuels called bioliquids, that are used for energy purposes other than transportation, including electricity and heat energy generation [36].

Liquid biofuels, such as bioethanol and biodiesel, are mainly consumed in internal combustion engines when blended with fossil fuels (most often in transport or equipment powered by blends of these fuels). These biofuels can also be used directly for road transport without blending with liquid fossil fuels [37]. Today, at the end of the second decade of the 21st century, biofuel production from plant-based products such as maize, oilseed rape, palm oil, soybean oil, sunflower oil, wheat, sugar, and starch is dominant [38]. These are used to produce first-generation (conventional) biofuels, which include bioethanol made mainly from cereals, and biodiesel made mainly from rapeseed, palm, and soybean oils [39,40]. However, changes to EU regulations limiting the production of biofuels from food-grade raw materials contribute to the increasing the amount of cellulose, wood, straw, and organic waste being used as the basic resources for the production of refined, second-generation biofuels [41]. Third G biofuels are mainly derived from algal biomasses [42]. Apart from algal biomass, bacteria, fungi, and yeast can also be used as feedstocks for 3rd G biofuel production [40]. In turn, 4th G biofuels produced from genetically modified organisms are an advanced version of 3rd G biofuels. The widely used sources for its production include microalgae, fungi, yeast, and cyanobacteria [43].

As depicted above, there are extensive opportunities for utilising agricultural feedstock for energy purposes. However, the absence of analyses of the potential of individual EU Member States and the actual involvement of the agricultural sector in meeting EU energy targets prompted us to undertake research in this area. The innovative contribution is the TOPSIS method used to estimate the energy potential of feedstock derived from agriculture. In the course of research, we attempted to answer the following questions: (1) What is the potential for agricultural renewable energy generation in EU Member States? (2) What is the significance of agriculture in renewable energy production within each EU Member State? (3) What is the ranking of European Union Member States based on a synthetic assessment of their agricultural potential and its actual utilisation for renewable energy production?

3. Materials and Methods

A synthetic index created from a set of sub-indices was used to assess the importance and potential of agriculture in EU Member States in terms of renewable energy generation. Synthetic indices facilitate comparisons between countries, which can be used for illustrating complex and sometimes elusive issues in a broad context, e.g., in the area of the environment, sectors of the economy, and society [44]. Furthermore, interpreting complex indices is easier than identifying common trends for multiple separate indicators. A synthetic index was designed using TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution), a multi-criteria decision-making technique that allows objects to be ordered according to their distance from ideal and anti-ideal solutions [45]. There have been several studies using this method to evaluate renewable energy production [46–48] and promote sustainable agriculture [49–51]. This study brings together these two aspects to encompass different dimensions of impact, providing a comprehensive assessment of agriculture's significance in renewable energy production. This is the innovation of our work.

The TOPSIS method is normally based on the Euclidean distance, which implicitly assumes that the indices describing the objects are independent. In reality, however, the indicators are mostly correlated and the Mahalanobis distance solution comes in handy if the relationship between them is to be considered [52]. This solution makes it possible to measure the distance between points in a multidimensional space, taking into account not only the differences in the values of the individual variables but also their mutual relationships. An advantage of this measure of similarity is that its outcomes are independent of the data scale, which is not observed with most measures of similarity [53]. The Mahalanobis distance between two objects $\boldsymbol{x}$ and $\boldsymbol{y}$ (observation vectors) can be defined as

$$d_i(\boldsymbol{x}, \boldsymbol{y}) = \sqrt{(\boldsymbol{x}-\boldsymbol{y})\boldsymbol{\Sigma}^{-1}(\boldsymbol{x}-\boldsymbol{y})^T}, i = 1, \ldots, m \tag{1}$$

where $\boldsymbol{\Sigma}$ is a variance–covariance matrix defined as $\boldsymbol{\Sigma} = \frac{1}{n-1}(\boldsymbol{X_c})^T(\boldsymbol{X_c})$, $\boldsymbol{X_c}$ is the centred matrix, $\boldsymbol{X_c} = (\boldsymbol{X} - \overline{\boldsymbol{x}})$, $\overline{\boldsymbol{x}}$ is the arithmetic mean, and $\mathbf{X}$ is the data matrix for m objects described by n indicators. The object labelled as $\boldsymbol{y}$ is an ideal or anti-ideal solution, so, in our further considerations, the distance of $\boldsymbol{x}$ from the ideal solution is d_i^+, and from the anti-ideal solution it is d_i^-. Since all the considered indicators are stimulants, an ideal solution should be understood as $\boldsymbol{A}^+ = \{x_1^+, \ldots, x_n^+\}$, where $x_j^+ = \max_i x_{ij}$, and the anti-ideal one is $\boldsymbol{A}^- = \{x_1^-, \ldots, x_n^-\}$, where $x_j^- = \min_i x_{ij} i = 1, \ldots, m; j = 1, \ldots, n$.

Finally, the values of the synthetic measure of the significance of agriculture to renewable energy production are determined as follows:

$$R_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{2}$$

On the basis of the R_i synthetic measure, we calculated the mean $\overline{R} = \frac{1}{n}\sum_{i=1}^{n} R_i$ and the standard deviation $SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(R_i - \overline{R})^2}$ and delineated four classes of objects (countries):

I. Best performing countries: $R_i \geq \overline{R} + SD$;
II. Performing above average: $\overline{R} \leq R_i < \overline{R} + SD$;
III. Performing below average: $\overline{R} - SD \leq R_i < \overline{R}$;
IV. Poorly performing countries: $R_i < \overline{R} - SD$.

The choice of diagnostic variables was based on the theory and guidelines available in the literature concerning the role of agriculture in ensuring energy security and access to data. The data used in the study were derived from the EUROSTAT database, and the study period spans from 2010 to 2021. Table 2 shows the set of indicators considered in this study, together with the direction of their impact on the level of agricultural potential for renewable energy production (stimulant S and destimulant D). We assumed that the renewable energy production potential of agriculture is shaped by the food crop area, which is determined by the utilised agricultural area of the specific country per capita. The higher the level of this indicator, the greater the possibility of allocating agricultural production to non-food purposes [54]. In addition, land and labour productivity were among the diagnostic variables, which, on the one hand, testify to the efficient use of production factor resources and, on the other hand, determine food security and allow for the allocation of part of production or land for energy purposes [54], as it is believed that energy crops will play a greater role in future energy scenarios related to agricultural biomass supply. Further sub-indices used by this study reflect the current significance of agriculture in renewable energy production. They express the scale of production per 1000 inhabitants in tonnes of oil equivalent (X1) and the share of agriculture in renewable energy production (X2). It was also recognised that international trade classification is essential for assessing the significance of agriculture in energy production. Three indicators were adopted for the study: the SITC 0 agricultural product trade coverage ratio (TCR%), the volume of bioethanol exports, and the volume of biodiesel exports. Countries achieving a surplus of exports over imports for agri-food products (for which the TCR import-coverage ratio achieves values above 100) can be considered food self-sufficient [55]. The surplus from food production can be used to produce, for example, biofuels. The commitment to biofuel production was confirmed by the significant exports of bioethanol and biodiesel.

Table 2. Set of diagnostic variables used in designing the synthetic index.

Variable	Name of Indicator	Stimulant/Destimulant
X1	Renewable energy production from agriculture in tonnes of oil equivalent per 1000 inhabitants (tonnes of oil equivalent per 1000 inhabitants)	S
X2	Share of agriculture in renewable energy production (%)	S
X3	Cropland (UAA per capita) (ha per capita)	S
X4	Labour productivity of agriculture (gross farm income per agricultural worker) (EUR/AWU)	S
X5	Land productivity (agricultural output value per 1 ha of UAA) (EUR/1 ha)	S
X6	Trade coverage ratio for SITC 0 agricultural products (TCR%)	S
X7	Bioethanol export (thousand tonnes)	S
X8	Biodiesel export (thousand tonnes)	S

Source: authors' elaboration.

We selected the features describing the potential of agriculture to produce renewable energy based on substantive and statistical analyses, that is, we verified whether they were measurable, available, complete, reliable, and interpretable and whether the coefficient of variation (V) was sufficiently high (V > 15%). Table 3 presents descriptive statistics of the diagnostic variables for the extreme years, that is, 2010 and 2021, and for the whole period under review, that is, 2010–2021. Because all the sub-indices are stimulants, the minimum value was not given and only the maximum was provided. Throughout the period under review, biodiesel and bioethanol exports showed the greatest variability (V > 150%). Among the EU countries, Germany scored the highest for the share of agriculture in renewable energy production (X1) and for biodiesel exports (X8), while the Netherlands scored the highest for the share of agriculture in renewable energy production (X2) and land productivity (X5). Lithuania scored the highest for cropland (X3), Denmark showed the highest labour productivity of agriculture (X4), Bulgaria had the highest trade coverage ratio for agricultural products (X6), and France had the highest bio-ethanol export (X7).

Table 3. Descriptive statistics of diagnostic variables.

Descriptive Statistics	X1	X2	X3	X4	X5	X6	X7	X8
				2010				
mean	24.56	8.04%	0.43	17,451.50	2733.18	106.12	25.43	95.23
SD	20.01	6.51%	0.25	15,152.57	2893.01	69.46	64.36	245.30
V [%]	81.47	80.93	57.55	86.83	105.85	65.45	253.12	257.59
max	83.77 Germany	24.07% Belgium	1.00 Ireland	62,711.20 Netherlands	13,103.10 Netherlands	316.91 Hungary	302.35 France	1258.00 Germany
				2021				
mean	49.25	8.71%	0.43	26,547.78	2986.86	121.98	55.30	328.02
SD	36.00	6.43%	0.27	29,843.62	2951.68	80.54	110.76	620.68
V [%]	73.10	73.88	62.51	112.41	98.82	66.03	200.27	189.22
max	136.55 Netherlands	30.07% Netherlands	1.05 Lithuania	141,006.92 Denmark	14,398.07 Netherlands	384.62 Bulgaria	466.00 Hungary	2597.54 Spain
				2010–2021				
mean	37.98	9.40%	0.43	21,895.40	2855.19	116.88	48.37	212.03
SD	28.06	7.52%	0.26	20,626.08	2895.00	77.49	90.80	406.51
V [%]	73.88	79.96	60.75	94.20	101.39	66.30	187.73	191.72
max	116.62 Germany	33.88% Netherlands	1.01 Lithuania	86,172.50 Denmark	13,829.66 Netherlands	349.55 Bulgaria	324.34 France	1568.25 Germany

4. Results

4.1. Presentation of Sub-Indicators Evaluating the Significance and Potential of Agriculture in Renewable Energy Production

To address the initial two research questions, we calculated and interpreted several sub-indices. The method for calculating them is presented sequentially in the demonstration of each individual indicator. The production capacity of agriculture, and thus the ability to compete and produce energy from agricultural biomass (bioenergy), was determined using the production potential of the sector in the specific country. It is shaped by the production factors of resources, that is, land, labour, and capital [56]. Agricultural land resources in the Member States of the European Union are considered to be very diverse, both in terms of quality (terrain, soil quality, climatic conditions, etc.) and quantity [57,58]. The utilised agricultural area (UAA) per capita plays an important role in the context of the potential surplus of agricultural biomass and its possible uses in renewable energy production. Figure 1 shows the values of this indicator for individual EU Member States from 2010 to 2021. The countries with the largest croplands were Lithuania, Latvia, and Ireland (approximately 1 ha per capita). In addition, countries with an indicator value above the EU average (0.43 ha) included Estonia, Bulgaria, Romania, Hungary, Spain, Greece, Denmark, and France.

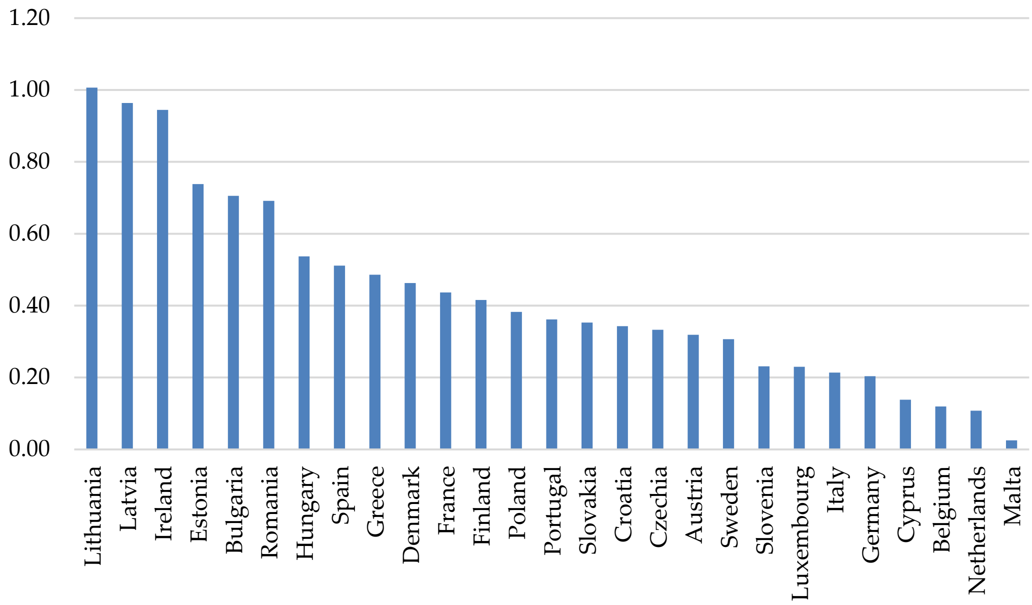

Figure 1. The utilised agricultural area (UAA) per capita in EU Member States from 2010 to 2021 (ha per capita). Source: authors' elaboration.

The efficiency with which land and labour resources are used plays an important role in shaping the country's food security, as well as in the production of agricultural biomass for energy purposes [59]. Figure 2 shows the mean labour and land productivity from 2010 to 2021. The first indicator was calculated as the ratio of the gross farm income to the number of employees in the agricultural sector, while the second was the ratio of the value of agricultural production to utilised agricultural area [60]. Natural and cultural conditions, the different history of the political systems of the countries, the different levels of economic development, the relationship between land and labour factors, the level of fertilisation, mechanisation, innovation, structural change, as well as institutional factors and human capital have been identified as reasons for the differences in factor productivity in agriculture between EU Member States [61–63]. Countries with the highest levels of labour productivity in the agricultural sector included Denmark, the Netherlands, and Belgium, while the land factor was most efficiently managed in the Netherlands, Malta, and Belgium. However, explicit differences still existed between old and new Member States.

Poland, Romania, Bulgaria, Latvia, Slovenia, Hungary, Croatia, Slovakia, and Lithuania are countries in which labour productivity was the lowest from 2010 to 2021. This is a result of several conditions, including structural problems related to farm structure and over-employment in agriculture in some countries. Therefore, there is scope for increasing productivity in agriculture in most of the new Member States. However, this is conditioned by the availability of capital inputs, vehicles for biological, agricultural, and organisational progress, as well as the knowledge and skills of agricultural producers. Increases in labour and land efficiency may also be accompanied by a potential increase in agricultural biomass for non-agricultural purposes, including the production of bioenergy.

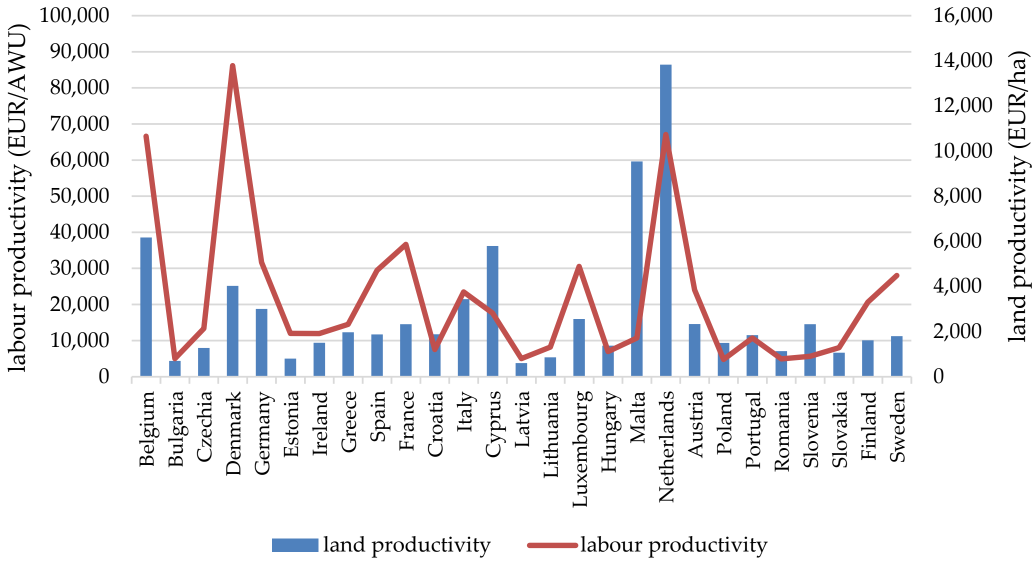

Figure 2. Land and labour productivity in the agriculture of EU Member States from 2010 to 2021. Source: authors' elaboration.

When assessing the potential of agriculture to generate renewable energy in EU Member States using TOPSIS, one of the indicators included in the analysis to illustrate the situation of EU Member States in this aspect was the production of renewable energy from the processing of agricultural biomass and waste from agricultural production per 1000 inhabitants. In this way, the indicator made it possible to compare the situation of individual EU Member States in terms of utilising the potential of agriculture to produce renewable energy by converting agricultural biomass into solid, liquid, and gaseous fuels. Figure 3 shows the average amount of renewable energy production from agriculture per 1000 inhabitants of the country and the share of agriculture in renewable energy production in each EU country from 2010 to 2021. As can be seen from the data presented, the highest levels of renewable energy production expressed in oil equivalents were achieved by countries such as Germany and the Netherlands, which produced 116.6 and 103 tonnes of oil equivalent per inhabitant, respectively. These figures indicate the large-scale exploitation of agriculture's potential for bioenergy production in these countries, as well as to the effectiveness of their climate and energy policies. The specificity of the situation in these countries is that the share of solid biomass in RES production is relatively low, while other sources of agricultural origin such as biogas and biofuels, being a more processed form of biomass, play a significant role [21]. In addition, countries such as Latvia (66.4), Czechia (64.6), Finland (63.5), and Austria (61.9), where energy generation is largely based on converting agricultural and forest biomass into bioenergy, are also countries with a high value for this indicator. The lowest value of this indicator was in countries admitted to the European Union in 2004, such as Estonia (0.37), Lithuania (4.76), Slovenia (5.14), Poland (6.05), and Hungary (7.74), and in 2007, such as Romania (1.31) and Bulgaria (2.23). Most of these countries are former socialist bloc countries, where energy production is still largely based on fossil fuels, and modern bioenergy production technologies have not gained as much popularity as in highly developed countries such as the Netherlands and Germany.

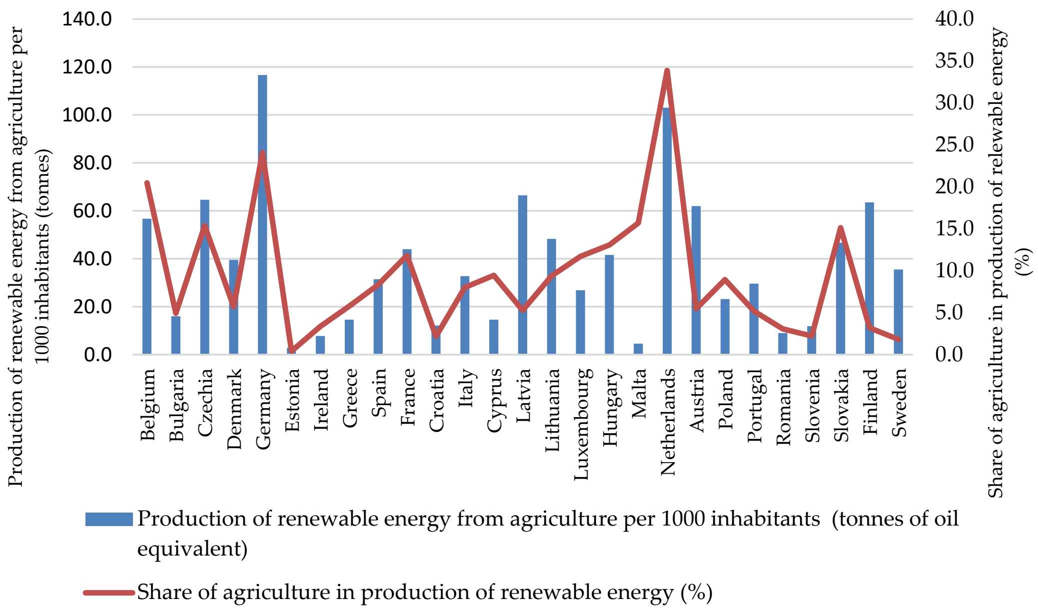

Figure 3. Production of renewable energy from agriculture per 1000 inhabitants (tonnes of oil equivalent) and its share of renewable energy production (%) in EU Member States from 2010 to 2021. Source: authors' elaboration.

These observations were confirmed by data on the average share of agriculture in renewable energy production, where countries such as the Netherlands (33.9%), Germany (24.9%), Belgium (20.5%), Czechia (15.4%), and Slovakia (15.1%) are among the leading countries in this respect. The presence of the latter two in this group indicates that participation in harnessing the potential of agriculture for bioenergy production is not determined by historical heritage, but may result from sound energy, climate, and environmental policies in these countries. It is also worth emphasising that the structure of renewable energy generation from agriculture in individual EU countries is a result of their specific geo-climatic conditions and manageable resources from agriculture and other biomass production sectors. For example, in countries such as Finland and Sweden, which are European leaders in using renewable sources for energy production, the share of agriculture in bioenergy production was relatively low in the years under review, at 1.8% and 3.2%, respectively.

Another sub-indicator used in the construction of the synthetic index was the Trade Coverage Ratio (TCR = (Exports/Imports) $\times$ 100) calculated for food and live animals (SITC 0). The interpretation of this indicator is that countries with a TCR above 100 have a positive agri-food trade balance and are among those with food self-sufficiency [55]. In food-self-sufficient countries, agricultural surpluses that are diverted for export could instead be used locally as feedstock for biofuel production, and the land used for surplus crops could alternatively be used to produce the raw materials from which biodiesel and bioethanol are made. From Figure 4, it can be seen that countries where the average TCR calculated for 2010–2021 exceeded 100 included Bulgaria, Czechia, Denmark, France, Estonia, Latvia, Lithuania, Hungary, Poland, Romania, and Slovakia.

Measures indicating the extent to which agricultural products are used by individual EU Member States to produce RES included biofuel exports. The export volumes of bioethanol and biodiesel were included as stimulants in the TOPSIS synthetic indicators. The main exporters of bioethanol in the EU included France, Hungary, Belgium, Spain, and Sweden, while the largest exporters of biodiesel included Germany, Spain, the Netherlands, Poland, and France (Figure 5). It should be mentioned that some EU Member States are showing considerable interest in the use of biofuels in transport, which is contributing to an increase in biofuel trade within the EU single market. Such countries are Germany, Sweden, and Spain, which, in addition to being major exporters of biofuels, are also significant importers of bioethanol and biodiesel (Germany ranked first in imports of both types of biofuels between 2010 and 2021, followed by Sweden). Regarding biodiesel, in the analysed period, most EU countries and the whole EU had a negative balance of trade—they imported more than they exported. The exceptions were Bulgaria, Germany, Spain, Latvia, Lithuania, Hungary, the Netherlands, and Austria, which noted a positive balance of trade for biodiesel in 2021. The situation was similar for bioethanol, where the whole EU had a negative balance of trade in 2021 (−793 thousand tonnes). In 2021, a positive balance of trade for bioethanol was recorded only in Belgium, Spain, Hungary, and Austria.

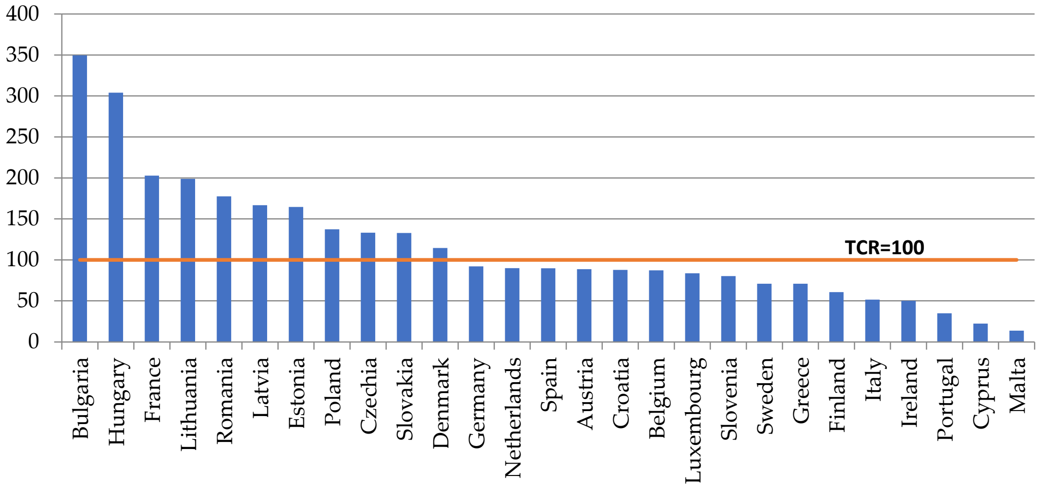

Figure 4. Trade Coverage Ratio (TCR) for food and live animals (SITC 0) in EU Member States in the years 2010–2021 (average value in %). Source: authors' elaboration.

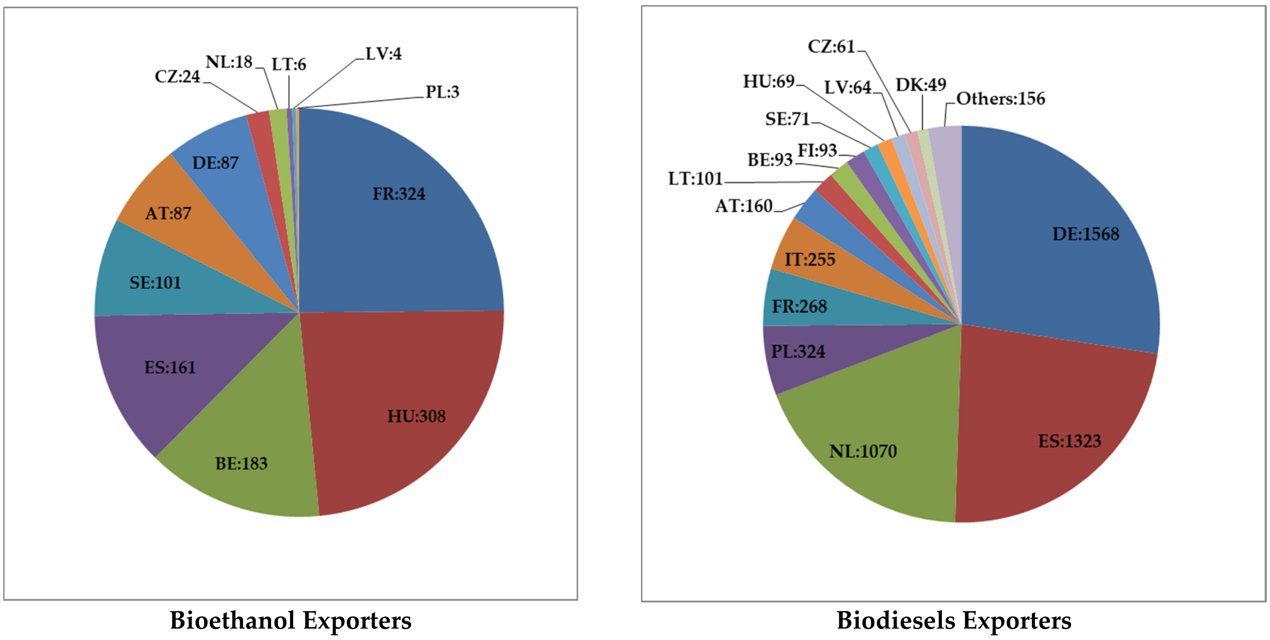

Figure 5. Main exporters of biofuels in the EU in the years 2010–2021 (average value in thousand tonnes). Source: authors' elaboration.

4.2. Synthetic Index of the Importance of Agriculture as a Source for Renewable Energy Production

Based on the synthetic measure obtained using the TOPSIS method, the Member States were ranked (Table 4 and Figure 6) and divided into four typological groups, characterised by the different importance of agriculture for renewable energy generation (Table 5. This allowed us to address the third research question. The synthetic measure averaged 0.169 (Slovenia) and 0.519 (The Netherlands) between 2010 and 2021. It is worth mentioning that in 2021, in the Netherlands, agriculture accounted for 30.1% of renewable energy production, the highest of any Member State. Next to the Netherlands, the top five countries were Latvia, Lithuania, Hungary, and Denmark. In contrast, in Slovenia, Croatia, and Italy, the agricultural sector was the least important for RES generation. Analysing the two extreme years covered by the survey, it can be seen that Denmark (from 13th place to 5th place), Hungary (from 8th place to 3rd place), and Spain (from 14th place to 2nd place) moved up the ranking considerably. In Denmark, this was influenced, among other things, by the fact that the production of renewable energy from agriculture in tonnes of oil equivalent per 1000 inhabitants increased sevenfold between 2010 and 2021. A clear increase was also observed in the share of agriculture in renewable energy production, that is, from 2.5% to 13%. Hungary, on the other hand, increased its export of bioethanol by as much as 111 times in the period under review, markedly increased labour productivity in agriculture (by 95.7%), and increased the production of renewable energy from agriculture per 100 ha UAA by more than two times. The improvement in Spain's position, on the other hand, was due to an almost twofold increase in the production of renewable energy from agriculture per 100 ha UAA, increases in labour (by 40%) and land productivity (27%), and increases in exports of bioethanol (by 32.4%) and biodiesel (by 762%).

Table 4. Classification of EU Member States in terms of the synthetic index of the significance of agriculture to renewable energy production.

Country	R_i 2010	Ranking in 2010	R_i 2021	Ranking in 2021	R_i	Ranking from 2010 to 2021
Austria	0.326	11	0.243	17	0.289	15
Belgium	0.341	9	0.337	8	0.351	10
Bulgaria	0.322	12	0.373	4	0.380	6
Croatia	0.174	27	0.175	24	0.183	26
Cyprus	0.244	19	0.214	19	0.236	21
Czechia	0.247	18	0.215	18	0.275	17
Denmark	0.313	13	0.367	5	0.381	5
Estonia	0.269	16	0.279	13	0.304	13
Finland	0.339	10	0.300	11	0.289	16
France	0.403	2	0.257	15	0.380	8
Germany	0.385	4	0.291	12	0.346	11
Greece	0.240	20	0.200	21	0.242	19
Hungary	0.346	8	0.374	3	0.399	4
Ireland	0.373	5	0.311	9	0.380	7
Italy	0.190	26	0.178	23	0.190	25
Latvia	0.369	6	0.363	6	0.409	2
Lithuania	0.399	3	0.358	7	0.408	3
Luxembourg	0.234	21	0.153	26	0.230	22
Malta	0.349	7	0.300	10	0.335	12
Netherlands	0.446	1	0.441	1	0.519	1
Poland	0.210	24	0.204	20	0.223	23
Portugal	0.233	22	0.171	25	0.204	24
Romania	0.285	15	0.279	14	0.300	14
Slovakia	0.258	17	0.200	22	0.267	18
Slovenia	0.202	25	0.148	27	0.169	27
Spain	0.300	14	0.390	2	0.363	9
Sweden	0.227	23	0.252	16	0.240	20

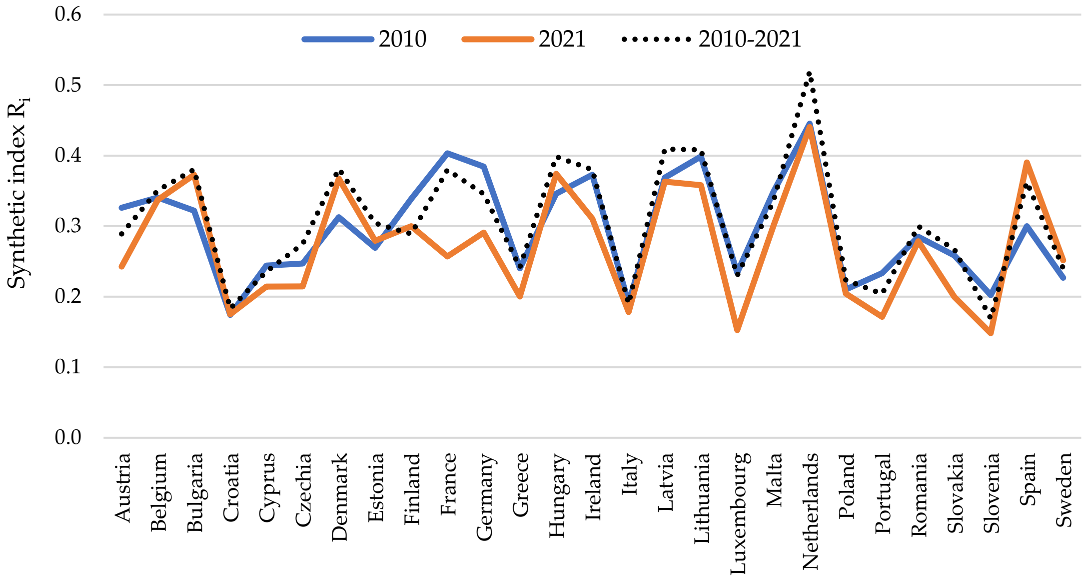

Figure 6. Synthetic measures of the significance of agriculture as a source for renewable energy production in EU Member States from 2010 to 2021.

Table 5. Classes of EU Member States depending on the synthetic index of the significance of agriculture to renewable energy production.

Country	Class in 2010	Class in 2021	Average from 2010 to 2021
Netherlands	I	I	I
France	I	III	II
Lithuania	I	I	I
Germany	I	II	II
Ireland	I	II	II
Latvia	II	I	I
Malta	II	II	II
Hungary	II	I	I
Belgium	II	II	II
Finland	II	II	III
Austria	II	III	III
Bulgaria	II	I	II
Denmark	II	I	II
Spain	II	I	II
Romania	III	II	III
Estonia	III	II	III
Slovakia	III	III	III
Czechia	III	III	III
Cyprus	III	III	III
Greece	III	III	III
Luxembourg	III	IV	III
Portugal	III	IV	IV
Sweden	III	III	III
Poland	IV	III	III
Slovenia	IV	IV	IV
Italy	IV	IV	IV
Croatia	IV	IV	IV

Another step in the analysis was to allocate Member States to four classes according to synthetic measures (Table 5). In 2021, there were seven countries in which agriculture was the most significant source for renewable energy production, which was two more than in 2010. These were The Netherlands, Lithuania, Latvia, Hungary, Bulgaria, Denmark, and Spain. There were seven countries in the second group, eight in the third, and five (Luxembourg, Portugal, Slovenia, Italy, and Croatia) in the fourth, in which agriculture was the least important. Germany, France, and Ireland were not in the Class I in 2021 compared to 2010. However, the new countries in this group were Latvia, Hungary, Bulgaria, Denmark, and Spain.

5. Discussion

There is a general consensus in the literature on the need to redirect EU energy policies towards an increase in renewables, which is in line with a sustainable development pathway [64,65]. The involvement of the agricultural sector for this purpose is mainly justified by increasing the reliability of energy supply, saving non-renewable fuels, supplying energy to local communities, improving the quality of life and employment levels of rural populations, ensuring sustainable growth, and meeting the state's nature conservation obligations [14]. The research carried out has shown that there are clear differences between Member States, both in terms of the value of the synthetic measure of the significance of agriculture to renewable energy production and in terms of individual sub-indicators relating to the significance of agriculture to renewable energy production, the characteristics of the agricultural sector in the context of the possibility of allocating agricultural production to energy purposes, and selected aspects of international trade. Also, Tutak et al. [66] observed that despite the EU's concerted action to protect the environment, Member States vary widely in terms of their energy and environmental conditions. This can be explained by the different levels of economic development, the state of energy systems, their structure, public awareness, and the country's geographical location and surface area. This highlights the necessity of customising EU policy to accommodate the specific circumstances and potential of agriculture in each Member State. In this context, the results of our research can be used to improve the Common Agricultural Policy and energy policy and identify future measures to increase the involvement of the agricultural sector in renewable energy generation. It is difficult to relate the results obtained directly to those of other authors because of the different scopes of their analyses. For instance, Janiszewska and Ossowska [15] demonstrated that European Union Member States feature significant agricultural biomass potential. However, owing to the high demand for this raw material in agriculture, only approximately 15% of the existing potential can be utilised for energy purposes. Their research also identified a large spatial variation in the agricultural biomass potential of the European Union Member States, which they believe may have a negative impact on the economic efficiency of utilising this renewable energy source. These studies show that the highest agricultural biomass potential for energy purposes is in France and Spain, and the lowest is in Malta and Luxembourg. Wieruszewski and Mydlarz [54] demonstrated that in recent years, there has been a significant increase in the potential of both forest and agricultural biomass in the EU. Furthermore, the increase in the demand for energy biomass in EU Member States was offset by partial imports from non-EU countries. These observations, combined with our research findings, have significant implications for utilising the existing agricultural potential more effectively for energy purposes. Simultaneously, it is important to draw the line between the agricultural production volume necessary for food security and the potential surplus of agricultural feedstock that can be utilised for non-food purposes, including for energy production. Sulewski et al. [21] pointed out that in many EU Member States, despite their high production potential, agriculture has a relatively small share in renewable energy production. They stressed that agricultural biogas plants can play a special role in increasing the significance of agriculture in the development of renewable energy. Agricultural biogas production is not only a means of generating renewable energy but also contributes to reducing methane emissions from the storage of organic fertilisers, which is particularly important from the point of view of the EU climate policy. The uneven distribution of biomass potential for energy purposes in EU Member States is also mentioned by Bentsen and Felby [1], who expect specialised energy crops to account for a higher proportion of biomass for energy production in the future. However, promoting this change in energy policy is necessary to speed up the trend of increasing the agricultural sector's role in renewable energy production. An important aspect should be promoting best practices, providing a basis for imitation. Tutak et al. [66], using the TOPSIS method, assessed the energy sustainability of the EU-27 in four dimensions: energy, economic, environmental, and social dimensions. In addition, their study considered economic potential (GDP of a specific country) and demographic potential (population size). Their analysis showed that three EU countries, namely Sweden, Finland, and Austria, have been undisputed leaders in sustainable energy development. However, these studies examined the development of renewable energy in general and did not specifically address the significance of the agricultural sector. It is worth seeking similar leaders in utilising agriculture to ensure energy security and viewing this progress as an opportunity for agricultural producers to earn additional income.

6. Conclusions

The analysis and research of the sub-indicators carried out in this study and the synthetic index designed on their basis made it possible to address the research questions and classify and rank EU Member States according to the significance and potential of agriculture as a renewable energy source. Our research methodology addressed a research gap by comparing Member States in terms of the significance of agriculture for its potential and energy use. The available scientific studies only focused on selected sub-indices that indicate the links between the agricultural sector and renewable energy or express the scale of energy production from agricultural resources. Several studies have used the TOPSIS method to evaluate renewable energy production and promote sustainable agriculture. In our work, these two aspects converged, encompassing various dimensions of impact on the phenomenon under review. This represents the innovative work we have undertaken. It provides a comprehensive assessment of the importance of agriculture in renewable energy production, identifies the leaders, and indicates the EU Member States requiring support in this area. Member States with the highest potential and featuring the highest use of agriculture in renewable energy production were both the so-called old and new EU Member States. In addition to the Netherlands and Denmark (which was promoted from Class II in 2010 to Class I in 2021), Lithuania, Latvia and Hungary ranked highly as the top five. The Netherlands had the highest land productivity among all EU Member States, while Denmark had the highest labour productivity. The remaining three lagged significantly behind the leaders in terms of labour and land productivity, but had the highest cropland per capita in the whole of the EU; Lithuania and Latvia, despite being among the smallest EU countries, nevertheless displayed a favourable ratio of cropland in ha per capita. It can be summarised that the countries in Class I have used their inherent potential in agriculture for RES production, and for the countries that joined the EU in 2004, there are still significant reserves due to the potential for productivity growth in agriculture (these countries also include the remaining V-4 countries classified as Class III).

Countries such as Belgium, France, Germany, Ireland, Bulgaria, and Spain were in Class II based on the calculated average for the period from 2010 to 2021. In these countries, the use of agriculture for renewable energy production was significant, although not as much as in Class I. Class II included Member States that were both significant producers and exporters of agri-food products (such as France), as well as countries that were net importers of the aforementioned products (for example, Germany, Belgium, Ireland, and Spain) and simultaneously had a very high level of production of renewable energy from agriculture per 1000 inhabitants and a share of agriculture in renewable energy production (especially Germany and Belgium). This testifies to the effective promotion of RES development policies in these countries and the major role of agriculture in this respect. Spain's fairly high position is due to the fact that the country was a significant producer and exporter of bioethanol and biodiesel compared to other EU Member States.

The third and most numerous group included both Member States with little potential and prospects for growth in agricultural-based renewable energy production (for example, Cyprus, Luxembourg, and Greece), and those with a significant but under-utilised agricultural potential for renewable energy production (including Austria, Estonia, Finland, Sweden, Romania, Slovakia, Czechia, and Poland). The first group of countries in Class

III and the other countries classified in Class IV (Portugal, Italy, Croatia, and Slovenia) are unlikely to play a significant role in agriculture-based renewable energy production due to the prevailing climate and soil conditions in these countries, the low significance of agriculture to the economy, and the utilisation of other renewable energy sources such as wind, water, and the sun. To conclude, it should be emphasised that countries with significant but under-utilised agricultural potential for renewable energy production should be given special attention and targeted with initiatives and funding to stimulate the development of agricultural-based renewable energy. Thus, it seems reasonable to diversify the instruments and measures at the EU level to better support countries with significant potential for renewable energy production from agriculture. An important course of action should be to subsidise the agriculture advisory system in the area of renewable energy. Furthermore, to properly assess the degree of implementation of energy policy in the EU, including the involvement of agriculture for this purpose, detailed monitoring of the use of agricultural feedstock for energy purposes is necessary. The study was limited, among other reasons, due to the lack of data on agricultural waste.

Agriculture has huge potential for renewable energy production. Therefore, it can not only meet its energy needs but it has also become a more significant supplier of energy to other sectors, thus diversifying the income sources of agricultural holdings. However, increasing the production of renewable energy from agricultural biomass often raises concerns about food security and the environmental impact of production facilities. Hence, further research should focus on assessing the potential of agriculture from the perspective of its role in ensuring energy security when confronted with its role in shaping food security. An assessment of the agricultural sector should also include an evaluation of innovative solutions for renewable energy production.

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