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Assessment of the Prospects of Polish Non-Food Energy Agriculture in the Context of a Renewable Energy Source

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Abstract: This paper describes examples of energy crops that are profitable to burn, and whose cultivation is not complicated or expensive. Rapid growth of biomass, especially the green mass of energy crops, is indicated, which means that, in relation to fossil fuels, energy crops are considered renewable raw materials. An assessment of Polish non-food energy agriculture was conducted in the context of the prospects of a renewable energy source, namely, biomass. Recommendations for crop cultivation, the size of possible yields and the most important parameters of the obtained biomass, which have the greatest impact on the suitability of energy use, are presented. Materials of biological origin for combustion are divided into three groups: wood waste, by-products and plant products for the energy industry. It is indicated that 2 tons (Mg) of dry wood or straw is energetically equivalent to 1 Mg of coal, and 1 m^3 of biogas is energetically equivalent to 1 kg of Polish coal. A novelty of this article is the interpretation of obtaining primary energy, including energy from renewable sources, in the European Union and Poland, taking into account the production of wood waste, straw, cereals and energy crops. The mechanism of the impact of the production parameters of energy crops was revealed during the prepared analysis of the prospects of Polish energy agriculture. Additionally, we conducted an analysis of the potential of biomass as a source of energy in the context of: obtaining primary energy, including energy from renewable sources, in the European Union and Poland; the number of biogas plants in Poland; and the area of agricultural land that is potentially useful for the cultivation of energy crops.

Keywords: energy agriculture; waste wood; straw; cereals; energy crops

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1. Introduction

Plants, as the main producers of oxygen (O_2) and decomposers of carbon dioxide (CO_2) into O_2 and organic compounds, are essential for the existence of all types of flora on Earth. They create natural habitats for most animals, both on land and in aquatic environments. The important role of vegetation is to protect the soil surface against direct exposure to rain and hail, which break up soil aggregates and wash away and lift soil particles (water erosion), and against wind (wind erosion). Moreover, plant roots take up nutrients and transfer them from deeper layers to the upper soil layers [1].

One of the remarkable aspects of the present day is the return to technology related to the primitive era. This is related to the use of plants as energy sources. The current situation in the fossil fuel market has led to serious environmental problems resulting from air pollution. Additional elements drawing attention to alternative energy sources are the decreasing reserves of these fuels available for human activity and the associated increasing cost of their operation. The big advantage of plants as energy sources is their development associated with the use of CO_2 for growth and the release of O_2. It follows that plants can not only be a source of energy materials, but can also use the CO_2 released during energy production. The problem is the selection of plants that show rapid production of biomass used in the later stages of processing for energy production.

These plants can be grown in areas where the soil is severely degraded for two main reasons: firstly, because they are not bred for consumption, and secondly, because they show faster biomass growth and have low soil requirements.

Biomass is the oldest and most widely used renewable energy source, which includes all existing organic matter on Earth, such as all substances of plant or animal origin—biodegradable. Biomass is also leftovers from agricultural production, forestry residues, and industrial and municipal waste [2].

Biomass is the third largest natural source of energy in the world. According to the European Union's definition, biomass is the biodegradable fractions of products, waste and residues of the agricultural (including plant and animal substances), forestry and related industries, as well as the biodegradable fractions of industrial and municipal waste [3].

Each plant can be dried and burned, but not every plant belongs to the group of energy plants. Energy crops are those that are profitable to burn. Growing these plants should not be complicated or expensive, as the energy produced afterwards would be too expensive. Energy crop plantations must obtain high yields at low cost [4].

Energy plants are characterized by similar features. They are distinguished by rapid growth and high biomass yield, including annual and perennial species [5]. Energy plants are processed mainly into solid biofuels and biocomponents, and the high calorific value makes them a very attractive raw material for the production of electricity and heat [6]. Energy crops have a number of requirements for soil conditions. One of the most important things to check before investing in a plantation is the pH of the soil. The pH value should be in the range of 5.5–7.5. In addition, energy plants also require proper soil irrigation. Both of these factors significantly affect the efficiency and general condition of the plantation. The discussed group of plants is also recommended for soil contaminated with heavy metals. By accumulating impurities in the root system, they clean the soil of undesirable elements. The collected harmful compounds do not infiltrate the green part of the plant; thus, during the combustion process, pollutants do not escape into the natural environment [7]. Biomass of energy plant origin is commonly regarded as an alternative source of energy [8]. Its use for energy purposes is perceived to impose a much lower burden on the environment in relation to fossil fuels. Although energy is required for its production and processing into biofuel, it is estimated that the negative impact is much smaller than that from the extraction and subsequent refining of crude oil or the exploitation of hard coal deposits. This is mainly due to the absorption of CO_2 by plants during their growth. This eliminates the overall balance of the impact of its later use on the ecosystem. The rapid growth of biomass, especially the green mass of energy plants, makes it a renewable resource in relation to fossil fuels [9,10].

Pointing to the research gap (assessment criteria), it was suggested to present the current situation, problems and perspectives of non-food energy agriculture.

This problem was taken up by the Institute of Technology and Life Sciences—National Research Institute in Falenty, the University of Life Sciences in Lublin in Poland and Opole University of Technology. For this purpose, plants that show rapid production of biomass used in the later stages of processing to produce energy were selected. An analysis was conducted on materials of biological origin intended for combustion, representing potential sources of energy from the perspective of Polish energy agriculture in the context of renewable energy production under the BIOGAS & EE project financed by the National Center for Research and Development, implemented as part of the BIOSTRATEG 1 program.

The aim of the research presented in this article was to assess the prospects of Polish non-food energy agriculture in the context of renewable energy sources. An attempt was made to establish the production conditions and profitability of materials of biological origin for combustion according to three groups:

I. Waste materials;
II. Materials that are by-products;
III. Plant products deliberately cultivated for the purposes of energy.

The structure of this article corresponds to the characteristics of the materials:

- Waste wood;
- Straw;
- Cereals (maize, sorghum, oats, rye);
- Energy crops (Jerusalem artichoke, Sakhalin knotweed, Pennsylvanian mallow, miscanthus, prairie spartina, reed canary seed, rotary millet, elongated couch grass).

These characteristics allowed us to estimate the prospects of Polish energy agriculture. The following criteria were adopted to assess the prospects of Polish energy agriculture:

- Biological origin;
- Physicochemical properties of the materials (ash, humidity, flammable substances, volatile matter);
- Resource balance (yield, fertilizing variants);
- Energy characteristics of raw materials (energy content, energy production, energy value, heat of combustion, calorific value, fuel consumption);
- Territorial dependence affecting the production of biomass.

2. Materials and Methods

A characteristic feature of practically all substrates of plant origin is the considerable variability in their properties [11]. First of all, the water content, i.e., humidity, is variable. This is due to both the different stages of maturity and the influence of weather conditions.

Materials of plant origin are materials with a low degree of compaction; therefore, they require a large area (volume) for storage. Often, the storage of substrates requires a roofed surface or the use of a foil cover. In some cases, exposure to atmospheric agents improves the ability to bond and compact, and it is advisable to store these materials without protection. In many cases, atmospheric factors significantly affect the content of impurities, especially sandiness. The variability in the chemical composition, and thus energy efficiency, should also be taken into account. One-year crops (e.g., cereals) are an example of such a substrate. Particularly problematic is the volatile supply, caused, among other things, by the instability of the crops. In addition to variable availability, differentiated yields result in the instability of raw material prices. When material costs constitute a significant item in the production costs, this may cause changes in profitability.

Materials of biological origin for combustion can be divided into three groups, as shown in Table 1.

According to the proposal of the European Union [12], biomass includes materials of biological origin (mainly of plant origin) that are either produced on special plantations or generated as waste materials in the forestry and wood industry. Historically, biomass has been used in the rural economy for centuries as firewood and as organic waste.

Usually, 2 tons (Mg) of dry wood or straw is energetically equivalent to 1 Mg of coal, and 1 m^3 of biogas is energetically equivalent to 1 kg of coal. Polish coal generally has parameters of 25/22/0.8 (heat of combustion, 25 $MJ \cdot kg^{-1}$; 22% ash; 0.8% sulfur), while plant biomass, such as wood or straw, has parameters of 13/3/0.03. In dry sewage sludge, parameters of 14/45/0.8 are found, somewhat resembling the parameters of waste sludge generated during coal washing or the parameters of lignite fines [13].

Table 1. Materials of biological origin for combustion (own elaboration).

Group I	Group II	Group III	
		Plant products deliberately grown for energy purposes	
Waste	By-products	Plants used in human and animal nutrition but with a changed use	Plants grown specifically for energy purposes
- Leaves, needles of trees and shrubs, branches remaining after cleaning and maintenance works in orchards, gardens and parks, grass cut on lawns and areas located by roads; - Pits, cuttings and nut shells.	- Straw, for which the demand in livestock production has significantly decreased; most farms (especially when the share of cereals in the production structure increases) struggle with the problem of its management.	- Cereals; - Grass.	- *Helianthus tuberosus* L. (Jerusalem artichoke); - *Reynoutria sachalinensis Nakai* (Sakhalin knotweed); - *Sida hermaphrodita* L. *Rusby* (Pennsylvanian mallow); - *Miscanthus x gianteus*.
They are often treated as troublesome waste, and their disposal is troublesome and costly.	Straw briquetting and pelleting are attractive forms of straw compaction that can be used as solid fuel that can be incinerated or co-incinerated.	Cereals intended for combustion as whole plants or part of the crop (grain—especially low-quality chaff, husks and straw with an admixture of collected weeds). Burning grasses requires similar requirements to burning straw; the advantage is the high yield, and there is no risk in the event of changes in the law limiting the use of plants that can be a source of food for energy purposes.	There are plant varieties bred specifically for energy purposes; the most advantageous use of cereal and rapeseed straw is as a material for the production of pellets and briquettes.

Biomass can be used as a direct fuel, and in the case of dry biomass, its heat of combustion is 18 MJ·kg^{-1}. In Poland, solar radiation is estimated at 3600 MJ·m^{-2}·year^{-1}. In the case of a photosynthesis efficiency of 0.5%—the average is 1%, and the maximum is 3.2%—this gives chemical energy in biomass of 18 MJ·m^{-2}·year^{-1}. When 18 MJ·m^{-2}·year^{-1} per biomass is divided by 18 MJ·kg^{-1}, we obtain 1 kg·m^{-2}·year^{-1}. The production of biomass will then amount to 1 kg·m^{-2}·year^{-1}, that is, 10,000 kg·ha^{-1}·year^{-1}, which is equal to 10 Mg·ha^{-1}·year^{-1}, that is, 1000 Mg·km^{-2}·year^{-1}. The area of agricultural land in Poland is 200,000 km^2, so production of 1000 t·km^{-2}·year^{-1}·200,000 km^2 is equal to 200 million Mg·year^{-1}, i.e., at least 100 million Mg·year^{-1}. Thus, Polish agriculture produces approximately as much coal as Polish mining. Instead of food agriculture, there is a new alternative, i.e., non-food energy agriculture.

The methodology focuses on the use of materials of biological origin intended for combustion, representing potential sources of energy in Poland, and forecasting the use of energy carriers, in addition to demonstrating the relationship between biomass and renewable energy.

Forecasting of wood harvesting for energy purposes in the State Forests and in private forests is presented. The costs of straw combustion in relation to coal are compared. Heating fuels are also compared. Exemplary possibilities of using maize as an energy resource are presented, in addition to the chemical composition of biomass of sorghum varieties for the production of bioethanol.

The use of energy carriers in selected farms for heating purposes is developed on the basis of energy parameters. For example, the content of biomass on fallow land, biomass calorific value and biomass characteristics in relation to the calorific value, energy value and net energy production are indicated.

The acquisition of primary energy, including energy from renewable sources, is presented, and the share of energy from renewable sources in the European Union and in Poland is indicated.

In Poland:

- The area of agricultural land that is potentially useful for the cultivation of energy crops is interpreted;
- The relationship between the installed biogas capacity and the amount of electricity produced from biogas is demonstrated;
- The relationship between the installed power coming from biomass and the amount of electricity produced from it is demonstrated;
- The relationship between the area of agricultural land that is potentially useful for the cultivation of energy crops and the regional approach to the installation of energy from biogas and to the capacity installed from biomass is demonstrated.

Biomass Potential in Poland

According to the definition contained in the Act on Renewable Energy Sources [14], biomass of agricultural origin is biomass from energy crops, as well as waste or residues from agricultural production and industry processing. At the same time, the act defines agricultural biogas as gas obtained in the process of methane fermentation of agricultural raw materials, agricultural by-products, liquid or solid animal excrements, by-products, waste or residues from the processing of agricultural products or forest biomass, or plant biomass collected from areas other than those recorded as agricultural or forestry, excluding biogas obtained from raw materials from landfills, as well as wastewater treatment plants, including on-site wastewater treatment plants from agri-food processing, where industrial wastewater is not separated from other types of sludge and wastewater.

Therefore, the substrates constituting the basis for the production of agricultural biogas can be divided into the following groups:

(A). Natural fertilizers, including manure and non-mineralized guano, classified as category 2 materials according to the EU regulation on animal by-products [15].

(B). Waste of plant origin from agricultural production (e.g., cereals that do not meet quality standards), classified according to the waste catalog [16] as subgroup 02 01 waste from agriculture, horticulture, hydroponics, forestry, hunting and fishing.

(C). Slaughterhouse waste, classified as category 2 and 3 materials according to the EU regulation on animal by-products.

(D). Food processing waste, classified according to the waste catalog into the following subgroups:

- 02 02 waste from the preparation and processing of food products of animal origin;
- 02 03 waste from the preparation and processing of food products and stimulants, waste of plant origin, including waste from fruit, vegetables, cereal products, edible oils, cocoa, coffee and tea, waste from the preparation and processing of tobacco and yeast, waste from the production of yeast extracts, and waste from the preparation and fermentation of molasses (except 02 07);
- 02 04 waste from the sugar industry;
- 02 05 waste from the dairy industry;
- 02 06 waste from the baking and confectionery industry;
- 02 07 waste from the production of alcoholic and non-alcoholic beverages (except for coffee, tea and cocoa).

(E). Crops dedicated to the organic recycling process through biogasification.

Literature reports [17–20] show that in Polish conditions, natural fertilizers are most often used, i.e., manure, slurry, liquid manure and chicken manure. Most often, however, the main substrate for biogas plants is slurry in the form of a mixture of water, feces and urine from farm animals. Slurry is a substrate with a relatively low biogas yield because it contains a large amount of water. The data in Table 2 show that the production of biogas from 1 Mg of dry organic matter of slurry ranges from 200 to 700 m^3, with pig slurry being more efficient than cattle slurry.

Table 2. The potential of biomass as a source of energy in Poland (own elaboration).

Substrate Name	**Dry Matter Content per Ton of Substrate**					**Organic Matter Content**					**Biogas Production**				
	[%]					**[% Dry Weight]**					**[m^3/Mg Dry Organic Matter]**				
acc.	**[21]**	**[19]**	**[17]**	**[20]**	**[22]**	**[21]**	**[19]**	**[17]**	**[20]**	**[22]**	**[21]**	**[19]**	**[17]**	**[20]**	**[22]**
Natural fertilizers															
Cattle slurry	9.5	8.0	10.0	8.0–11.0	8–11	77.4	86.0	93.0	77.4	75–82	222.5	280.0	225.0	200.0–500.0	200.0–500.0
Pig slurry	6.6	6.0	6.0	ok.7.0	ok 7.0	76.1	80.0	96.0	76.1	75–86	301.0	400.0	300.0	300.0–700.0	300.0–700.0
Poultry droppings wet with litter	15.1	-	15.0	ok. 32.0	ok.32	75.6	-	77.0	63–80	63–80	320.0	-	560.0	250.0–450.0	250.0–450.0
Dried poultry droppings	30.0	-	-	-	-	72.7	-	-	-	-	230.0	-	-	-	-
Turkey droppings	15.1	-	-	-	-	75.6	-	-	-	-	320.0	-	-	-	-
Liquid manure	8.5	-	-	-	-	85.5	-	-			154.0			-	-
Dairy cow slurry	2.1	-		-	-	60.0	-	-	-	-	222.5	-	-	-	-
Manure	-	25.0	-	-	-	-	80.0	-	-	-	-	450.00	-	-	-
Animal feces (manure) cattle	-	-	8.0	ok.25.0	ok. 25.0	-	-	80.0	68.0–76.0	68.0–76.0	-	-	410.0	210.0–300.0	210.0–300.0
Animal feces (manure) pigs	-	-	8.0	20.0–25.0	20.0–25.0	-	-	70.0	75.0–80.0	75.0–80.0	-	-	420.0	270.0–450.0	270.0–450.0
Slaughterhouse waste															
Flotation sludge from slaughterhouses	14.6	-	-	5–24	-	90.6	-	-	80.0–95.0	-	680.0	-	-	900.0–1200.0	-
Bovine stomach contents	15.0	-	-	11.0–19.0	-	84.0	-	-	80.0–90.0	-	264.0	-	-	200.0–400.0	-
Stomach contents	-	-	-	-	12.0–15.0	-	-	-	-	75.0–86.0	-	-	-	-	250.0–450.0
Separated adipose tissue	34.3	-	-	-	-	49.1	-	-	-	-	700.0	-	-	-	-
Food processing															
Fruit waste and scraps	45.0	-	-	-	-	61.5	-	-	-	-	400.0	-	-	-	-
Fruit pomace	-	-	-	-	25.0–45.0	-	-	-	-	90.0–95.0		-	-	-	590.0–660.0
Waste and leftovers of vegetables	13.6	-	-	-	-	80.2	-	-	-	-	370.0	-	-	-	-
Molasses	81.7	-	73.0	-	-	92.5	-	78.0	-	-	301.6	-	510.0	-	
Brewer's grains	20.5	-	-	-	20.0–25.0	81.2	-	-	-	70.0–80.0	545.1	-	-	-	580.0–750.0
Distillery potato broth	13.6	-	-	-	6.0–7.0	89.5	-	-	-	85.0–95.0	387.7	-	-	-	400.0–700.0
Grain decoction	-	-	-	-	6.0–8.0	-	-	-	-	83.0–88.0	-	-	-	-	430.0–700.0
Waste from oil production	78.8	-	-	-	-	97.0	-	-	-	-	600.0	-	-	-	-
Whey (serwatka)	5.4	-	-	-	-	86.0	-	-	-	-	383.3	-	-	-	-
Cheese production waste	79.3	-	-	-	-	94.0	-	-	-	-	610.2	-	-	-	-
Bakery waste	87.7	-	-	-	-	97.1	-	-	-	-	403.4	-	-	-	-
Agricultural production and dedicated crops															
Corn silage	-	32.0	35.0	20.0–35.0	20.0–35.0		95.0	97.0	85.0–95.0	85.0–95.0		600.0	730.0	450.0–700.0	450.0–700.0
Whole grain silage	-	40.0	-	-	-	-	95.0	-	-	-	-	520.0	-	-	-
Rye silage	-	-	33.0	-	-	-	-	93.0	-	-	-	-	730.0	-	-
Potato pulp	-	-	14.0	-	-	-	-	93.0	-	-	-	-	-	-	-
Grass silage	-	-	35.0	25.0–50.0	25.0–50.0	-	-	91.0	70.0–95.0	70.0–95.0	-	720.0	540.0	550.0–620.0	550.0–620.0
Shredded corn cobs	-	65.0	-	-	-	-	98.0	-	-	-	-	680.0	-	-	-
A grain of grain	-	86.0	-	-	-		98.0	-	-	-	-	700.0	-	-	-
Rye	-	-	-	30.0–35.0	30.0–35.0	-	-	-	92.0–98.0	92.0–98.0	-	-	-	550.0–680.0	550.0–680.0
Fodder beet	-	-	-	12.0	-	-	-	-	75.0–85.0	-	-	-	-	620.0–850.0	-
Sugar beet root	-	-	22.0	23.0	-	-	-	90.0	90.0–95.0	-	-	-	840.0	170.0–180.0	-
Beet leaves	-	-	-	16.0	-	-	-	-	75.0–80.0	-	-	-	-	550.0–600.0	-
Mown grass	-	-	-	-	ok 12.0	-	-	-	-	83.0–92.0	-	-	-	-	550.0–680.0

According to Kowalczyk-Juśko (2009) [23], the efficiency of biogas production using a slurry substrate can be increased by adding co-substrates, e.g., maize silage, fruit pomace or manure. The diversification of substrates is conducive to obtaining better parameters of biogas production [24].

Processed substrates in the form of slaughterhouse and meat processing waste are characterized by high biogas production efficiency (Table 2). According to Regulation (EC) No 1069/2009 of the European Parliament and of the Council, category 2 and 3 materials of animal by-products may be used for the biogasification process. However, when using these types of substrates, it is necessary to meet the process and process monitoring requirements in accordance with the regulation of the EU Commission [25]. The processing of animal by-products also represents waste management in the recycling process, taking into account the waste management hierarchy. An example is the biogas plant in Sokółka, where the feedstocks for the biogas production process are floatants from in-house treatment plants, feathers and stomach contents characterized by high biomethane efficiency [26].

Substrates for the production of biogas can also be of plant origin, being both crops that do not meet the quality standards for the food industry, and targeted crops. The plant species most often used for biogas production is maize [7]. According to Gołaszewski (2014) [27], the most efficient substrate in the process of anaerobic decomposition through the biogasification process is maize silage. Maize silage ensures a stable chemical composition of the raw material supplied to the fermentation chamber, because the polysaccharides biodegrade during the silage process, and the acetic acid produced can be directly used in the production of methane. Therefore, other plants are also used for pickling, including cereals, grass and alfalfa. Sugar beet silage is also a good substrate [28].

Substrates for the production of biogas can also be waste from food processing, including beet pulp, potato pulp and fruit pomace (formed in the production of juices and wine); from distilleries and breweries, such as distillery stillage; from the dairy industry, such as whey and hammer (strawgrass) brewing; and from the production of sugar from sugar beets, such as pulp and molasses [7].

The potential of organic substances that will undergo anaerobic decomposition and biogas production in Polish conditions is high. The diversified chemical composition, and thus the different process efficiencies of individual substrates, means that the selection of a substrate, preferably several substrates, should be conditioned by the potential location of the biogas plant and the availability of substrates on site. The selection of substrates for the process, on the one hand, should guarantee the highest efficiency in obtaining biogas, including methane; on the other hand, it is necessary to ensure the continuity of supplies of substrates to the biogas plant and, if possible, their constant composition.

3. Results and Discussion

Lignocellulose, a building material for plant cell walls, is a rich source of polysaccharides [29]. Raw materials rich in lignocelluloses, including wood biomass or agricultural waste, are valuable renewable energy sources of particular importance in the production of bioethanol. Bioethanol is considered an environmentally friendly substitute or biocomponent of petroleum-derived propellants, the use of which in transport is an important element of sustainable development.

3.1. Waste Wood

In Poland, about 19 million m^3 of wood was produced in 1993, and about 3.5 million m^3 of firewood was obtained from forests in 1997. About 4/5 of the sawn timber becomes waste wood in the form of sawdust, cuttings, shavings, etc., and 1/5 hits the market as end products: furniture, windows, doors, floors, etc. Various forms of waste wood can be used for energy purposes [13].

In forestry, for example, we can distinguish either heavy wood or pieces of wood, i.e., brushwood, such as sticks and branches. In Poland, in 2002, it was estimated that approximately 2 million m^3 of fuel wood and 1.5 million m^3 of small-sized wood were obtained, i.e., 3.5 million m^3 of wood in total. Heavy wood consists of trunks cut to a length of 1 m and divided into logs when the diameter of the trunk exceeds 25 cm. Brushwood is less than 8 cm in diameter and is also cut to a length of 1 m for storage in the forest before being transported to the user. The highest amount of fuel wood is obtained by the Regional

Directorates of State Forests in Wrocław, Szczecin, Białystok and Olsztyn, and the lowest amount is obtained in Warsaw, Radom, Kraków and Piła [13]. Firewood is sold by foresters as "loco forest". The recipients of firewood are either small thermal energy or chipboard factories competing for wood.

A separate item in the balance of resources is waste wood in the economy. It should be taken into account that out of every 100 m^3 of wood mass harvested in the forest, 10 m^3 is used for bark, 15 m^3 is used for brushwood, 20 m^3 is used for fuel roughage, 19 m^3 is used for sawdust and edgings, 36 m^3 is used for sawn timber and 20–25 m^3 is used for finished wood products from the "sawn timber" item [30]. Analyses have shown that there is no possibility of a greater increase in the amount of waste wood in Poland, unless there is a wider introduction of fast-growing tree plantations: poplar and shrub willow [31,32]. If 4/5 is deducted from the harvested 20 million m^3 of wood per year for waste, then 16 million m^3 of wood will be obtained annually for possible disposal. Thus, the wood resources for energy use amount to approximately 16 million m^3. The average density of firewood is 450 kg in 1 m^3 [33], so the resources amount to 7.2 million Mg of wood per year, which is the equivalent of about 4 million Mg of hard coal [34]. The use of wood for energy purposes in Poland was estimated at over 1.5 million Mg in 2000 [35].

In Poland, in 2017, the supply of waste wood biomass for energy purposes was estimated at about 20 million m^3 [36]. It consists of forest biomass at 7 million m^3, road plantings and bushes at 1 million m^3 and waste from the wood industry at 7 million m^3, as well as materials from municipal management at 4.5 million m^3 and agriculture at 0.5 million m^3. According to the opinion of the Bureau of Forest Management and Forest Geodesy [37], the demand for biomass for energy purposes significantly exceeds the amount of this raw material in Poland that can be supplied by the State Forests [38], which are the main suppliers of wood in Poland. The research conducted thus far has estimated the level of demand for this product to be in the range of 24–30 million m^3 for system energy and 13 million m^3 for local heat generation. With such assumptions, the demand is more than 7 times higher than the capacity of the forests managed by State Forests [38]. The basic raw material base of energy wood can be supplemented with felling residues and stumps. Acquiring carp as an energy resource is currently associated with significant logistical difficulties or unprofitability. However, it can be estimated that in the event of favorable economic conditions, these reserves could increase the level of forest biomass use. On the other hand, the acquisition of logging waste is limited by environmental policy conditions. The current regulations and requirements of sustainable forest management assume shredding, spreading and leaving some of the waste in the forest [36].

Such a significant demand of the power sector for biomass is the result of the Tradable Green Certificates (TGC) system, which has been in force since 2005. It is widely criticized because it prefers co-firing of biomass in condensing power plants, which raises a lot of ecological, technical, market and strategic controversy. In 2005–2014, such power plants generated electricity from renewable energy sources (RES) ranging from 49.8% in 2009 to 22.4% in 2013. Assuming that 1 MWh of chemical energy contained in biomass produces 0.2 MWh of electricity, and the calorific value of 1 Mg of biomass is 3.4 MWh, in 2014, over 13 million m^3 of this fuel was used to produce electricity. If we also include the 4256.7 GWh of energy from dedicated units (only biomass was used to power them), characterized by a higher efficiency of 0.35, the total consumption amounted to over 20 million m^3. A significant part was imported, increasing almost eightfold since 2008, i.e., 0.423–3.591 million Mg, and its value exceeded PLN 1.2 billion. Imports of agricultural biomass were characterized by higher dynamics, including mainly sunflower husks and sunflower and palm cakes. This was the result of the introduction of restrictions on the energy use of wood. Most of the imported biomass came from neighboring countries, mainly Ukraine (44.8%) and Belarus (23.1%), but it was also supplied by Indonesia and Malaysia (16.5%). As a result of such a significant increase in imports, from 2012, the supply of biomass in Poland began to exceed the demand, which led to a drop in prices and a wave of bankruptcies in the new, laboriously created market [36].

In the current support system, even after the enactment of the RES Act and its amendment [39], it is preferable to generate electricity according to the current rules. Once again, the legislator did not take into account the postulates regarding the provision of similar aids to heat energy in the proportion (1)

$$1\ \mathrm{MWh_e} = 3\ \mathrm{MWh_c} \tag{1}$$

where:

MWh_e—megawatt hours of electricity;
MWh_c—megawatt hours of thermal energy.

Under the current regulations, biomass will be transported to power plants, and coal will remain the basic fuel for heating in rural areas and small towns. Meanwhile, there are already many examples of proven solutions and good practices in Poland. In Nowa Dęba, since 2003, the fuel has been wood chips with a heat energy of 8 MW_c [36]. As for Polish conditions, the completed investment is an innovative undertaking, both in terms of the technology used and the organization of the fuel supply system. After many years of experience, it can be concluded that all the assumed goals have been achieved, including the most important one, i.e., stopping the growth of heat energy prices. Moreover, the purchased biomass came from local suppliers, and the waste produced as a result of its incineration was neutral to the environment. The implementation of investments in 2016–2017 was primarily the result of courage, activity and creativity, and was sometimes even a hobby approach of municipal authorities or entrepreneurs, not a system solution. This example shows the key role of local governments in creating a local energy policy based on renewable energy sources [36].

On average, wood contains 39.5% cellulose (12.4–65.5%), 34.5% hemicellulose (6.7–65.6%) and 23.1% lignin (26.0–44.5%) [40]. The content of basic elements in individual species of deciduous and coniferous trees is similar. The average contents in wood are as follows: 52.1% C (48.7–57.0%); 41.2% O_2 (32.0–45.3%); 6.2% H_2 (5.4–10.2%); 0.4% N_2 (0.1–0.4%); 0.08% S (0.1–0.42%). It is assumed that dried wood contains the following: 49.5% C; 6.3% H_2; 44.2% O_2; 0.04–0.26% N_2; 0.2–2.3% mineral compounds [40].

Table 3 presents the potential amounts of wood that can be harvested for energy purposes in the State Forests (managed by the State Forests National Forest Holding) and private forests [41]. It can be seen that the theoretical (forecasted) wood base for energy purposes will increase both in the State Forests and private forests.

Table 3. Forecast of timber harvesting in 2031 for energy purposes in the State Forests and private forests: 40.7 million m^3 and 6.0 million m3 of net merchantable timber [41].

Assortment	National Forests	Private Forests	Together
		mln m^3	
Thickness of fuel	3.05	0.78	3.83
Small-sized wood:	2.44	0.30	2.74
including general heating material	1.63	0.24	1.87
Framework residues	2.04	0.30	2.34
Together	7.53	1.38	8.91
Together without industrial groupage	6.72	1.32	8.04

The moisture content of wood depends on its type and may be subject to changes. The moisture content of freshly cut wood is 50% for conifers and 60% for deciduous trees. After about 2 years of storage in a sunny, dry place, the wood achieves the best quality, and its humidity is reduced to 15%.

The wood is characterized by high porosity, amounting to 20–45%, depending on the type of wood. Porosity has a significant influence on the mechanical and physical properties of wood.

The average value of the density of wood used in the Polish climatic zone is 500–600 kg·m^{-3}, while the actual density of wood (the ratio of the mass of wood in a dry state to its volume, excluding pores) is usually 1500–1600 kg·m^{-3} [42]. The bulk density and total moisture content of various types of wood waste are presented in Table 4.

Table 4. Total moisture content and bulk density of wood waste [42].

Wood Waste Assortment	Total Moisture Content—Virgin Material without Drying and Storage	Bulk Density
	%	kg·m^{-3}
Wood chips	40–60	250–400
Chips from wood waste	10–50	150–300
Bark	50–60	250–350
Scobs	45–60	250–350
Shavings	5–15	80–120
Sawdust from grinding waste	5–15	100–150
Unpainted demolition wood	15–30	150–250

The calorific value of wood from different tree species is similar. Different types of biomass have a calorific value of 15.5–16.5 MJ·kg^{-1}, with a moisture content of 15%. The conducted research on the dependence of the calorific value of wood on its moisture shows that it is beneficial to dry the fuel before burning. Moisture contained in wood constitutes a thermal ballast, which reduces the value of the heat from the combustion of wood and the efficiency of the entire combustion process [42].

3.2. Straw

One of the most important waste materials from agriculture that can be used for energy purposes is straw [36]. In practice, only its surplus may be taken into account, as the management of this raw material must comply with the provisions of the Code of Good Agricultural Practice [43]. When determining its size, it was assumed that straw should primarily cover the demand generated by animal production, i.e., litter and fodder, and for fertilization purposes, such as plowing, in order to maintain a good balance of soil organic matter. From 1983, the straw harvest began to exceed the needs resulting from agricultural production. In the years 1983–1990, the average annual agricultural surplus amounted to 5.119 million Mg, and in the years 2007–2015, it amounted to 17.909 million Mg. The growing disproportion is caused by a decrease in the number of livestock and a change in the technology of their keeping—resignation from barn farming in the production of cattle and pigs in favor of grate production [36].

The analysis carried out in the regional system showed that the possibilities of alternative uses of straw are much smaller than it would appear from the assessment of the potential for the entire country. In some voivodships, a part of the surplus should be allocated to incorporation in order to maintain a good balance of organic matter in the soil. Such a necessity did not arise from the straw balance prepared for Poland. For example, for 1999, according to the assessment carried out for the regions, the surplus was 3.201 million Mg, and in 2009, it was 5.439 million Mg. This means that the macroscale estimates are subject to averaging errors. Therefore, decisions regarding the possibility of alternative management of this raw material should be preceded by the preparation of a local straw balance. In this study, the balance sheet was prepared in the voivodship system. This was mainly due to the possibility of obtaining reliable data. The size of the surpluses varies greatly from region to region, as it depends on the structure of land use, the structure of crops, the size of farms, and the stocking density and method of animal rearing. The following voivodeships were characterized by the greatest possibilities of using straw for energy purposes: Greater Poland (Wielkopolskie), Lubelskie, West Pomeranian (Zachodniopomorskie), Kuyavian-Pomeranian (Kujawsko-Pomorskie), Masovian (Mazowieckie), Warmia and Mazury (Warmińsko-Mazurskie), Pomeranian (Pomorskie), Lodzkie and Silesian. On the other hand, there is little possibility of using straw for energy purposes in Podlaskie and Podkarpackie Voivodeships. In some years, there was even a deficit in them, which does not mean that, on a local, commune or powiat scale, straw could not be used for energy purposes in these regions as well. However, this requires keeping a microscale calculation, which would allow for a more precise determination of the demand for straw for agricultural purposes, taking into account various ways of keeping animals, including litter or litter-free systems, and methods of feeding, such as concentrated or bulky feed [36].

The largest recipient of straw is the electricity sector, which consumes about 1 million Mg of this fuel annually in the form of pellets or briquettes. Composting plants are also a significant recipient of straw, including producers of mushroom substrates. According to the estimates of the Cultivated Mushroom Industry Association, about 0.6 million Mg of straw, mainly wheat straw, is used annually in Poland for this purpose. About 0.3 million Mg of straw is also used in local heating plants. Undeveloped straw surplus is plowed and constitutes an organic fertilizer. It is also a source of minerals, such as nitrogen, phosphorus, potassium, magnesium and calcium. The main problem, however, is the real availability of surplus straw. From this point of view, the area structure of farms in Poland is very unfavorable, because small farms dominate. This significantly limits the possibility of using high-performance, large-size balers for straw harvesting. The effectiveness of biofuel supply depends on the organization of an efficient collection, storage and transport system [36].

It is suggested that potential straw suppliers should be looked for in regions that meet the following conditions:

- A significant surplus of straw exceeding the needs arising from agricultural production, until at least 2030;
- A favorable area structure of farms, i.e., a significant number of large-area farms over 50 ha.
- Currently, these conditions are met by three regions of Poland [36]:
- South-east, eastern part of Lublin and Podkarpacie Voivodeships;
- South-west, Lower Silesia Voivodeship;
- North-west, Pomeranian and West Pomeranian Voivodeships.

The practical possibilities of using renewable fuels are decisively influenced by the prices of raw materials and the incurred capital expenditure for the production of power. Table 5 compares the costs of burning straw and coal, using calculations by the Polish National Energy Conservation Agency (KAPE) [44].

Table 5. A summary of the costs of burning straw and coal—KAPE calculations [44].

Device Power	Fuel Consumption		Expense	
	Straw	Coal	Straw	Coal
kW	$kg \cdot h^{-1}$		$PLN \cdot kg^{-1}$	
70	19.4	14.6	0.06	0.162
100	27.6	20.8		
200	55.4	41.6		
300	83.0	62.4		
400	110.7	83.2		
500	138.3	104.0		
600	166.1	124.8		
700	193.7	145.6		
800	221.4	166.4		
900	249.1	187.2		
1000	276.7	208.0		
2000	528.9	416.0		
5000	1322.2	1040.0		

The heating season lasts 4000 h, which corresponds to 0.5 years. The straw consumption is calculated at 100% full load, with a straw combustion value of 4.2 MWh·Mg^{-1} at 15% humidity and 86% efficiency for devices up to 1200 kW and 90% efficiency for devices above 1200 kW. Coal consumption is calculated at 100% full load, with a coal combustion value of 6.4 MWh·Mg^{-1} and 75% efficiency [44].

According to Table 6, the cheapest energy carrier is straw (assuming 1 Mg of straw is equal to PLN 150). Table 6 compares the costs of using heating fuels to heat a building with the following assumptions [29]:

- Heat load of 70 kW;
- Hourly load of 2968 h·year^{-1};
- Energy demand of 207,786 kWh·year^{-1}.

Table 6. Comparison of heating fuels [44].

Type of Fuel		Straw	Coal	Wood Chips	Pellets	Natural Gas	Heating Oil
Unit		PLN·kg^{-1}				PLN·m^{-3}	PLN·l^{-1}
Value		0.15	0.75	0.40	0.675	3.56	3.84
Characteristic	Unit						
Unit costs of fuels	PLN·m^{-3}	7.50	525.00	60.00	607.50	3.56	3840.00
Annual fuel costs	PLN·year^{-1}	8506.52	15,577.72	34,922.02	37,302.01	67,369.60	78,882.67
Fuel costs	PLN·MWh^{-1}	32.80	61.50	117.60	143.60	291.80	322.70
	PLN·GJ^{-1}	9.10	17.10	32.70	39.90	81.10	89.60
Fuel demand	m^3·year^{-1}	11,434.00	26,673.00	404.00	84.00	24,302.00	24.00
	kg·year^{-1}	56,710.00	20,770.00	8305.00	55,262.00	18,924.00	20,542.00
Boiler efficiency	%	80.00	82.00	70.00	80.00	90.00	85.00
Final energy requirement	kWh·year^{-1}	207,786.00	207,786.00	207,786.00	207,786.00	207,786.00	207,786.00
Fuel moisture	% wag.	20.00	23.00	30.00	8.00	0.00	0.00
Calorific value	MJ·kg^{-1}	16.50	30.00	12.30	17.00	44.00	42.70
	kWh·kg^{-1}	4.58	12.20	3.40	4.70	12.20	11.90
	MJ·m^{-3}	825.00	34.30	2644.00	11,079.00	34.30	36,078.00
	kWh·m^{-3}	229.00	9.50	735.00	3077.00	9.50	10,022.00

Straw is a fuel that is often overlooked when designing new biomass installations due to the difficulties with combustion and transportation. The combustion of straw is accompanied by trace SO_2 emissions, and the value of NO_x emissions is comparable to the emissions from coal-fired boiler houses. The calorific value of straw is approx. 16.5 MJ·kg^{-1}, so it is an average calorific fuel. The most common heat carrier in Poland is hard coal. Until 2022, the average price for one tonne was approx. PLN 700 (from 2022, on average, PLN 3800). However, when fossil fuels are burned, NO_x, SiO_x and CO_2 gases are produced, which have a negative impact on the environment. Despite the constantly increasing efficiency of coal-fired boilers, a large amount of heat is irretrievably lost in the flue gases when using a standard installation. The calorific value of hard coal is approx. 30 MJ·kg^{-1}.

Wood chips and pellets are less common fuels. The price for 1 kg of wood chips is slightly lower than that of pelleted fuel; however, wood chips are more popular due to the ease of processing wood and branches into chips. The difference in the calorific value of wood from different types of trees is small. Additionally, the proportions of different components in the fuel, the different parts of the tree, the bark, etc., do not have a marked effect on the calorific value. Dry wood has the highest calorific value. At a humidity of 0%, it is assumed that the calorific value of wood fuel is 19.2 GJ·Mg^{-1} dry weight (d.w.), i.e., 5.3 MWh·Mg^{-1} (d.w.). The calorific value decreases with increasing water content [44].

3.3. Cereals and Energy Plants

Cereals are a group of plants that occupy the largest acreage of arable land in the world. They are the staple food source for most people. The term "cereal" is used to describe species belonging to the *Poaceae* family. Their seeds are characterized by a high starch content. The most popular products from the processing of cereal grains are flours, groats, oils and syrups. They are also used in various industries, such as brewing, distilling, pharmaceuticals and feed production [45].

Common corn *Zea mays* L. is a plant originating in Central America [30]. Corn remains the dominant food source in many parts of the world. It provides food for 1.2 billion people, mainly from Latin American and African countries. In other places, e.g., in the USA, only about 2–3% of the production of this plant is intended for direct human consumption.

Worldwide, about 116 million Mg of maize is used for direct human consumption, with 30% in Africa and 21% in sub-Saharan countries. The highest per capita consumption is in Lesotho (Southern African country) and amounts to 174 kg·year^{-1} per person. Corn constitutes 15–20% of the total daily calories in the diets of 20 developing countries, located mainly in Latin America and Africa.

As the primary source of starch, edible oil and gluten, corn is used in many dishes by cooking or frying it, and in all sorts of food production processes. Corn provides 90% of the starch demand in the USA [46].

The flasks are harvested in a state of so-called milk maturity, when the seeds are soft and contain more sugars. The harvest period is from August to September. The flasks break off easily from the stem, and the leaves should not be removed from the flasks. Only the Puławska, Ryżowa and Bąkowska varieties, which are types of cracking maize, are harvested when fully ripe (so-called wax). Then, they are dried, and the seeds are peeled from the cob.

Corn is best grown in sandy loams or clay sands. It fails in heavy soils, wetlands and sands. Soils below pH 6 require liming [47].

The varieties that have been bred over the centuries are most often classified according to the shape of the grain. Due to the predominance of hybrid forms in cultivation, they often do not represent the pure original form, but are intermediate types. For energy purposes, mainly hybrids of vitreous maize, i.e., flint and horse's tooth, i.e., dent, are used [48].

All varieties of this species are dioecious and monoecious. They develop strong, thick stalks up to 3 m high. They are topped with a panicle, which is a male inflorescence. The female inflorescence is a flask. It develops more or less in the middle of the stem, at the end of a shortened side branching, known as the dobot. Maize usually does not propagate because this is an undesirable trait in cultivation, which makes it difficult to carry out agrotechnical treatments [49]. As a plant with C4 photosynthesis [45], it manages water quite sparingly. However, due to the large production of biomass, it has high water needs. The flowering period of plants is a particularly critical moment in this respect [50].

In Poland, the main factor influencing the efficiency of maize cultivation is the humidity conditions. They are shaped only by the amount of rainfall and its distribution during the growing season, as plantations are not irrigated. While this is a variable beyond the farmer's control, the high thermal demands of maize can be easily minimized by selecting the appropriate varieties. Varieties with greater tolerance to cold and with a short growing season deserve attention [48,51,52].

Due to the various environmental conditions prevailing in Poland, there is a region of maize cultivation. The large number of available varieties means that, in order to obtain optimal yields for a given place and purpose of cultivation, varieties are matched on the basis of their FAO number, i.e., their earliness class [49].

The number of FAOs is in the range of 100–1000. The lower this number, the earlier the given variety, i.e., its growing period from sowing to harvesting for grain is shorter [53]. In Lower Silesia, Greater Poland, Mazovia and the Lublin region, early, mid-early and mid-late (250–290) FAO varieties reach full grain maturity. In the southern part of the country, FAO late varieties (300–350) can also be cultivated for the needs of biogas plants [54].

On the basis of the experiments carried out in the vicinity of Rawicz in the Stary Sielec Experimental Station of the Institute of Natural Fibers and Medicinal Plants, it was found that maize of the mid-early variety 'Opoka', grown in secondary yield for ordinary life, is also efficient and profitable. Several years of field research have shown that, in this way, it is possible to obtain 26 Mg·ha^{-1} dry matter (d.m.) of maize with a biogas efficiency of about 11,000 m^3·ha^{-1} [50]. Two technologies of maize cultivation are used for energy purposes: silage or grain technology. Whole plant silage is obtained using silage technology. Therefore, maize is usually harvested in one step, and the biomass is chopped into small pieces. After ensiling, it becomes a substrate for biogas production. On the other hand, using grain technology, several products can be obtained: dry or silage grain, grain silage with the addition of cob cores (CCM, corn cob mix), silage from crushed proper cobs, silage from cobs collected with leaf ground cover (LKS, from the German *Lieschkolben Schrott*) [55,56]. The possibilities of using maize as a raw energy material are presented in Table 7.

Table 7. Possibilities of using maize as an energy resource [48].

Grain (5–10) Mg·ha^{-1}		**Biomass (8–20) Mg d.m.·ha^{-1}**	**Straw (3–6) Mg d.m.·ha^{-1}**		**Cores (1–2) Mg d.m.·ha^{-1}**
Fermentation industry	Burning, energy and domestic installations	Whole plants or pickled	By-product after harvesting grain or CCM		By-product after harvesting whole flasks
		Biogas plants	Biogas plants	Combustion—energetics	Combustion—energetics
		Production volume from 1 Mg of raw material			
370–410 L of ethanol, 400 L of stock	Around 19 GJ	600–700 m^3 of biogas including 350–450 m^3 of methane	250–300 m^3 of biogas including around 150 m^3 of methane	Around 15 GJ	Around 15 GJ

As can be seen in Table 7, maize has a variety of uses. An amount of 1 Mg of corn can produce about 400 L of ethanol on average. Moreover, the same amount of straw is a substrate for the production of up to 700 m^3 of biogas, including up to 450 m^3 of methane. Cores can also be used for energy purposes because their calorific value is similar to the parameters of straw. For this reason, maize is a good raw material for the conversion of its energy [57].

Corn has one of the highest gas extraction values per Mg. Cultivars with a high dry matter content can yield 60 Mg of fresh weight per hectare and 6000 m^3 of methane per hectare, mainly used for energy production [10].

The genus *Sorghum* L. includes short-day spring plants of the C4 photosynthesis type [45]. Around the world, *Sorghum bicolor* L. and *Sudanese grass Sorghum bicolor* L. *Moench nothosubsp. drummondii*, as well as their hybrids, are grown on a larger scale. In Europe, they are used as feed or for energy purposes [54]. In Poland, mainly subspecies and various forms of bicolor sorghum are used. They form stalks that are 0.5–4 m high. The leaves, on the other hand, are 0.2–0.8 m long and covered with a layer of wax. This protects them from excessive transpiration. Moreover, sorghum has a strongly developed bundle root system, which reaches up to 2 m deep into the ground [48,52]. Thanks to this root system, sorghum has less soil requirements than maize, can be grown in very light, sandy soils and can better withstand periodic droughts. Sorghum, especially its sugar variety 'Sucrosorgo 506', is very sparing in the management of water [58]. This is an important feature, especially in the case of shortages of atmospheric precipitation often occurring in the area of central Poland [10].

Sorghum leaves can be used for the production of cattle feed, and the grain can be processed into groats and flours, which are used to make cakes, pasta or bread. Alcoholic drinks are made from sorghum (just like potatoes).

It is best to sow after May 20, when the soil temperature is around 14–15 °C, because rapid germination occurs in warm soil [59].

The long period of vegetation makes it necessary to harvest in late autumn. Sorghum should be grown in light, dry but fertile soils. It likes warm soils that heat up quickly, and dislikes moist soils. It is perfectly adapted to longer periods of drought. It has a well-developed root system, by means of which it draws water from the deeper parts of the soil.

Field tests carried out at the Stary Sielec Experimental Station and Pętkowo Institute of Natural Fibers and Medicinal Plants have proven that sugar sorghum of this variety effectively tolerates low rainfall and allows for obtaining a higher biomass yield—on average, 23.4 Mg d.m.$\cdot$ha^{-1}—in comparison to other plants grown for energy purposes [50]. Sorghum is characterized by very high thermal requirements. For this reason, its yield depends mainly on the temperature distribution during the growing season. Very late or early autumn frosts, to which the plant is not resistant, can also cause significant damage. Due to late sowing, i.e., recommended after May 15, sugar sorghum can be cultivated in secondary crops, after winter catch crops and even after early potatoes [54,60]. Biomass is usually harvested from the end of September to mid-October, before the first frosts occur. This is because they inhibit vegetation and reduce the sugar content of green mass, which significantly reduces its quality [48]. According to Lewandowski and Ryms [58], sugar sorghum does not bear fruit in the Polish climate. However, according to Michalski and Burczyk [50,54], some cultivars reach threshing maturity in favorable weather conditions, i.e., hot and long summers. On the other hand, typical tropical varieties of sorghum in a temperate climate extend the vegetative period to frost and do not produce inflorescences [50,54]. Due to the continuous, dynamic development of breeding works, new varieties of sorghum species are appearing on the market in great numbers. Their economic potential is estimated to be very high. Initial experience shows that the new hybrids can be successfully grown for grain in the climatic conditions of Poland. Hence, the country has adopted a colloquial term for this group of varieties: grain sorghum [45].

The most important advantages of grain sorghum include the following:

- High yield potential (based on information from Polish farmers, up to 9 Mg of grain per ha can be obtained in Poland);
- Wide range of uses (consumption, feed, industrial grain);
- Belongs to the group of gluten-free cereals (important for the production of gluten-free food);
- Low water requirements and high resistance to drought [61];
- Lower costs of seeds and tending treatments than in maize cultivation;
- High energy value and content of minerals (nutritional value similar to that of maize);
- High content of antioxidants, in relation to other cereals;
- Very good water management, helping sorghum to survive drought.

The disadvantages, however, are as follows:

- Long growing season, necessitating harvesting in late autumn;
- The possibility of strong infestation of the grain by fungi, especially in unfavorable weather conditions and under improper handling after harvesting (in wet grain, fungi develop very quickly);
- The possibility of birds destroying the ripening grain and the decrease in the amount and quality of the grain yield;
- High (too high in the case of a monodiet) content of some amino acids: valine, methionine, cysteine, isoleucine, phenylalanine, tyrosine and especially leucine (excess leucine may cause pellagra-Lombard erythema) [62].

Sorghum grown in light soil is characterized by greater agricultural and physiological nitrogen efficiency than maize. Diversified nitrogen fertilization as well as the course of the weather during the growing season affects the content of this element in plants of both species. The assessed species are characterized by a very similar average fat content in dry matter. However, they react differently to an increase in the nitrogen dose: in maize, there is a slight reduction in the amount of fat, and sorghum fertilized with higher doses of nitrogen shows a higher content of this component. Sorghum has a higher ash content than maize. Increasing the dose of nitrogen fertilization in sorghum was found to result in an increase in the ash content, while maize contained the highest amount of ash when fertilized with a dose of 120 kg·ha^{-1} [63].

Its extensive, bundled root system and economical water management make grain sorghum suitable for cultivation in light and dry soils, just like the green sorghum varieties. Moreover, it is not sensitive to the soil pH, as it can be successfully grown in soils with a wide pH range, ranging from 5 to 8.5. It also tolerates soil salinity and periodic flooding in summer after heavy rainfall relatively well. Spring floods are dangerous, especially if they take place in the early stages of plant development. In combination with the low temperature, they reduce the seed germination capacity, which implies a lower yield [64].

Grain sorghum is characterized by a large increase in biomass. Therefore, it requires intensive fertilization; however, it makes good use of the nutrients contained in fertilizers, including organic ones. For grain sorghum, plant feeding is similar to that of maize and should amount to approximately 80–150 kg N_2, 30–60 kg P_2O_5, 60–120 K_2O and 30 MgO per hectare of crops. Despite the fact that grain sorghum requires weeding in the initial phase of growth, similarly to green sorghum, it does not require spraying against pathogens, which reduces the cost of cultivation [64].

Experiments conducted in various European countries show that the yield of sorghum seeds from 2 to 8 Mg·ha^{-1} of crops varies. In addition, from the same acreage, the fresh weight yield of grain sorghum is about 45 Mg, and the new varieties are even more fertile [64].

Sorghum biomass, composed mainly of lignocellulosic structures, is a good raw material to be used for energy purposes [10]. The conversion of the energy contained in the biomass can be carried out using thermochemical and biochemical methods. In the process of combustion, gasification, carbonization and pyrolysis or in the production of biogas or bioethanol, especially from sorghum straw, it is possible to obtain significant amounts of bioenergy at a low cost, i.e., about 10 PLN·GJ^{-1} [50,58].

As climate warming increases and the water level in the soil decreases, it can be expected that the cultivation of sorghum in Poland will find more and more supporters. Moreover, it should be noted that sorghum biomass is a worse roughage than maize due to its hard and woody stalks, especially when harvested at the end of the growing season, but it is a good substrate for commercial energy [65]. It is possible to use sorghum biomass for the production of both biogas [66] and bioethanol [67–69]. Table 8 shows the chemical compositions of sorghum biomass grown in primary and secondary crops for individual cultivars.

Table 8. Chemical composition of biomass of sorghum cultivars grown in primary and secondary crops for the production of bioethanol [70].

Variety of Sorghum	Primary Yield			
	Cellulose	**Hemicellulose**	**Holocellulose**	**Lignin**
	%	%	%	%
Sucrosorgo 506	32.8	32.9	65.7	19.4
Santos	34.7	32.8	67.5	20.2
Rona 1	34.6	29.4	64.0	19.2
	Secondary Yield			
Sucrosorgo 506	27.0	38.5	65.5	17.9
Santos	32.1	31.2	63.3	20.8
Rona 1	25.8	35.6	61.4	18.3

It is found that the Sucrosorgo 506 biomass has similar holocellulose contents, i.e., total cellulose and hemicelluloses, components constituting potential substrates for enzymatic hydrolysis and the fermentation process, in the main and secondary crops, and a lower lignin content, a component that is an obstacle to the production of bioethanol from plant biomass, in the secondary crop than in the main crop. For the other two cultivars, Santos and Rona 1, the secondary crop yields lower holocellulose values than the main crop, and the lignin values are at similar levels [70].

Common oat *Avena sativa* L. (a phytosanitary plant) diseases occur sporadically in oat crops, the "perpetrators" of which winter in the soil or colonize plant remains in the field. Threatening diseases of the stalk base are rare, contributing to the lodging of cereals. Part of the soil directly surrounding the outer part of the oat root is colonized by non-pathogenic fungi, which constitute a type of barrier preventing the invasion of unwanted organisms. Moreover, oat root secretions have a fungicidal effect [71].

Oats came to Europe along with wheat from Asia, and as the crops moved from the south to the north of the continent, where the soil and climatic conditions worsened, they began to gain in importance [72].

Oat is self-pollinating and blooms quite early, and its flowering and pollination are not affected by weather conditions. Moreover, it is relatively insensitive to excessive moisture, which causes the grain to become drained. The plant is resistant to lodging, i.e., excessive bending, breaking and falling over. It tolerates harrowing well, as it spreads quite deeply, and this treatment even improves its tillering [72].

Oats are grown mainly for the production of fodder (mainly in mixtures for horses), but also for consumption purposes, for the production of groats, flakes and flours. They are also increasingly used as biomass. When grown for fodder, oats must be characterized by a high grain yield, while for food purposes, they must have a low husk content and a higher fat and protein content.

Common oats probably come from deaf oats and barren oats, which were found naturally in the Mediterranean regions. Interestingly, oat is the only grain that does not have a winter form [73].

Oats have low soil and climatic requirements and can be grown on mountains and in light, lowland soils [72].

For years, Poland has been at the forefront of the global production of the common oat *Avena sativa* L. [74]. Although it is primarily a food source for humans and a substrate for the production of fodder, due to its properties, i.e., high calorific value and low ash content, its straw and grain are sometimes mentioned as substrates for bioenergy production.

Oats have many benefits. They are characterized by low soil requirements, have phytosanitary properties and are also a good forecrop for cereals. For energy purposes, the grain can be used for the production of bioethanol or for direct combustion in specially adapted boilers with burners for burning seeds as an add-on. However, the reluctance of society towards its use as a fuel—because it could be a potential source of food—means that it is not used in the energy sector. It is recommended that only low-quality oat kernels that are unfit for consumption, e.g., those infected by fungi, should be used in heating installations [10].

Around the world, including Poland more recently, cereal grains, mainly oats and maize, are used for energy purposes. Grain, due to its small size, is easier to transport and store than straw and wood. Moreover, this feature provides great technical possibilities for full automation of the process of feeding fuel to the boiler [75]. The process of grain combustion is carried out in special burners that require the supply of an appropriate amount of air and a different combustion temperature than that commonly used for biomass [76]. The calorific value of oats is 18.5 $MJ \cdot kg^{-1}$ under their average humidity conditions (10–13%), and their bulk density is 0.75 $kg \cdot dm^{-3}$. Reasons to consider using oats as an energy source are as follows:

- Oats have low soil requirements, which means they can be grown almost anywhere;
- There is a long tradition of growing this grain in Poland;
- Machines for growing and harvesting cereal grains are widely available;
- Energy grain is easy to store and transport [77].

The concept of oat grain combustion is widely known and used in Sweden. This is a novelty in Poland, but farmers show great interest, although there is a certain mental barrier resulting from the high respect for the grain.

The advent of oat burners and the spread of renewable energy sources have resulted in an increasing use of oat grain for heating purposes.

In the researched farms reported in [75], most of the houses were equipped with old central heating furnaces, installed in the years 1980–1995. In these installations, major or minor modifications were made, and oat burners were installed. For the purpose of comparison and better characterization, the researched farms were divided into three groups:

- A (13 farms)—oat grain used for heating purposes came from own production and was additionally purchased at the end of the 2007/2008 heating season; the oat cultivation area per farm was 1.68 ha on average.
- B (8 farms)—oats from own production were used for heating, and, additionally, barley grain was added at the end of the heating season; the oat cultivation area per farm was 3.13 ha on average.
- C (5 farms)—oat grain from own production was used for heating, and, additionally, sour cherry stones were purchased; the oat cultivation area was, on average, 2.18 ha per farm.

The use of conventional energy carriers in the researched farms (hard coal, fine coal and wood) before installing the burner for energy grain is presented in Table 9. The annual consumption of hard coal on the farms was, on average, 4.2 Mg, along with 3.0 Mg of fine coal and 3.8 m^3 of fuel wood. For comparison, the consumption of oats as an unconventional source of energy is also shown.

Table 9. Utilization of energy carriers in surveyed farms for heating purposes [75].

Group of Farms	Surface of the Dwelling House to Be Heated	Hard Coal	Coal Dust	Fuel Timber	Oat Grains
	m^2	$Mg\cdot year^{-1}$		$m^3\cdot year^{-1}$	$Mg\cdot year^{-1}$
A	168.1	3.6	2.5	4.1	5.5
B	191.3	5.2	3.3	3.9	5.3
C	174.0	4.4	4.0	2.8	5.7
In total	176.3	4.2	3.0	3.8	5.5

The production of common rye *Secale cereale* L. in Poland is the largest among the member states of the European Union. In terms of the mass of the produced grain, it is very similar to that of the world leader, Russia [74]. For the production of bioenergy, as in the case of oats, one can use poor grain and straw [10].

In addition, rye is grown as a catch crop, and as a substrate source for biogas plants. The research carried out at the Stary Sielec and Pętkowo Experimental Plants, belonging to the Institute of Natural Fibers and Medicinal Plants, showed the usefulness of rye grown as a catch crop, as well as common maize and sorghum in the main crop, as an effective method of biomass production for the needs of agricultural biogas plants. Several years of field experiments have proved that rye, harvested at the stage of milk-waxy grain maturity, and maize, grown for silage, are efficient energy resources. The total amount of biomass obtained in this way amounted to approx. 40 $Mg\cdot ha^{-1}$ d.m. over a year. It was also characterized by high biogas efficiency, amounting to 17,900 $m^3\cdot ha^{-1}$. As a result, low costs of biomass production for energy purposes per unit area of the field were achieved, amounting to less than PLN 10 for 1 GJ of generated energy [50,57].

An alternative direction of winter rye management is the production of biomass for energy purposes [78]. Hybrid winter rye cultivars harvested for biogas production achieved higher yields of both fresh and dry matter [79]. Biogas obtained from rye does not compete with biogas from winter oilseed rape due to the higher energy efficiency of rape—on the order of 43.1 $GJ\cdot ha^{-1}$ [80]. However, research [81] shows that it is rye that is of the greatest importance among cereals as a raw material for the production of bioethanol. From the Poaceae family, a more advantageous alternative is giant miscanthus or common maize [82].

Due to their morphology, the division of energy plants is as follows [83]:

- Annual plants;
- Fast-rotation woody plants;
- Perennial, fast-growing, annual-yielding grasses;
- Fast-growing, annual-yielding perennials.

The yield of energy crops varies considerably and ranges from several to several dozen Mg of dry matter per hectare per year [32]. It is estimated that in Polish conditions, it is possible to obtain about 10 Mg of energy crops per hectare of arable land. According to Stankiewicz [84], the energy value from such an amount of biomass is comparable to the value of 5 Mg of hard coal. Before investing in a plantation, it is important to choose the right selection of plant species that will be grown. Faber et al. [85] suggest finding out about the optimal soil and climate conditions, the technology for cultivating a given plant and the current requirements of power plants regarding the quality of biomass.

Exemplary energy plants that can be recommended for cultivation for energy purposes have been characterized. Recommendations for their cultivation, the possible yields and the most important parameters of the obtained biomass, which have the greatest impact on the usefulness of these plant species, have been presented.

The artichoke *Helianthus tuberosus* L., commonly known as the Jerusalem artichoke, belongs to the *Asteraceae* family. This plant stands out from other energy plants with properties that allow for more efficient use of solar radiation energy, thus transforming it into an organic substance [86]. During its growth, it reaches a height of about 4 m. This plant has a wide range of applications. Jerusalem artichoke tubers are used, among others, for the production of bioethanol. It is estimated that 100 kg of tubers can produce about 10 L of spirit [5]. However, it is mostly used in the food industry due to the high content of inulin. This ingredient is a good substrate for the production of sweets and syrups. The Jerusalem artichoke was one of the first sources of food for humans and animals. This plant, during cultivation, also positively influences the environment. It has properties that enable the rehabilitation of degraded areas. It is also used as a substrate for the production of solid biofuels. The Jerusalem artichoke is often a plant of choice due to its very low climatic requirements. It is characterized by high yields: for stems, the yield is 10–20 Mg d.m.$\cdot$ha^{-1}, and for tubers, the yield is up to 40 Mg d.m.$\cdot$ha^{-1} [87]. The best time to establish a plantation is in the fall or early spring. Due to its high content of inulin, the Jerusalem artichoke tolerates low temperatures well [88]. Tubers should be placed deep (5–10 cm) depending on the season—deeper in autumn, keeping the required row spacing at a distance of 0.7–1.0 m. The distance between seed potatoes in a given row should be 0.5–0.6 m [89].

Perennials, the aboveground parts of which dry up after the end of the growing season, have a high dry matter content without the need to dry them. This feature also applies to the Jerusalem artichoke and is one of its advantages. Samples of the aboveground parts collected after the end of vegetation and drying in their natural state were characterized by a humidity of 20–25%, with a humidity of 9.6% in their analytical state, as shown in Table 10. This humidity, referred to as air-dry, characterizes biomass stored in a room, intended for combustion or initial processing to form granules: briquettes or pellets [90].

Table 10. Energy parameters of tuber sunflower straw, 'Albik' variety [91].

Parameter	Symbol	Unit	State		
			Analytical	Dry	Dry and Ashless
Analytical moisture	W_a	%	9.6	-	-
Ash	A	%	4.9	5.4	-
Combustible substance	-	%	85.5	94.6	
Volatile parts	V	%	67.2	74.4	78.6
Heat of combustion	Q_s	kcal$\cdot$kg^{-1}	3736	4134	4371
		MJ$\cdot$kg^{-1}	15.64	17.31	18.30
Calorific value	Q_i	kcal$\cdot$kg^{-1}	3419	3846	4066
		MJ$\cdot$kg^{-1}	14.32	16.10	17.02

The heat of combustion of topinambour biomass in the analytical state was 15.64 MJ·kg^{-1} (Table 10). The calorific value and heat of combustion depend primarily on the chemical composition and moisture of the material. The calorific value of dry straw is in a relatively narrow range (14–15 MJ·kg^{-1}) and depends primarily on the type of plant. For comparison, the calorific value of coal ranges from 18.8 MJ·kg^{-1} to 29.3 MJ·kg^{-1} [92]. In the study by Sawicka [93], the average value of the heat of combustion of the Jerusalem artichoke was 15.6 MJ·kg^{-1}, with fluctuations from 14.8 MJ·kg^{-1} to 16.4 MJ·kg^{-1}. On the other hand, Majtkowski [94] determined the heat of combustion of the biomass of tuberous sunflower with a moisture content of 20% to be approx. 15 MJ·kg^{-1}, while Kościk [95] obtained a value of 14.9 MJ·kg^{-1} (in a wet state), and 18.0 MJ·kg^{-1} in the dry state. The calorific value of topinambour biomass with a moisture content of 15% determined by Piskier [96] was 15.9 MJ·kg^{-1}.

Sakhalin knotweed *Reynoutria sachalinensis Nakai* is a very fast growing plant. At the end of the growing season, the perennial grows to a height of about 5 m. It stands out from other species of the genus Reynoutria by the size of its oblong-ovoid leaves. They are over 40 cm long, and their width is about 25 cm. In terms of weather conditions, knotweed is not as resistant to low temperatures and a lack of rainfall as the Jerusalem artichoke [97].

Sakhalin knotweed is an invasive plant; therefore, it requires agrotechnical treatments during cultivation to prevent its spontaneous and uncontrolled spreading. It reproduces via seeds and runners. Plantations of this plant should not be located in protected areas due to the very fast regrowth of cut shoots and its lush growth. For this reason, it may displace native species from a given area. This plant has the assimilation properties of heavy metals, thanks to which it has a positive effect on soil contaminated with these elements. Moreover, it has a high calorific value of 15.56 MJ·kg^{-1} [97].

In the conditions of Lower Silesia, three species of knotweed (Reynoutria Houtt.) occur [98]. These are Japanese knotweed (Reynoutria japonica Houtt.), Sakhalin knotweed (Reynoutria sachalinensis) and Czech knotweed (Reynoutria × bohemica Chrtek & Chrtkova) [99].

The total biomass of shoots and rhizomes produced by plants may even exceed 100 Mg·ha^{-1}. For Sakhalin knotweed, the fresh weight of aboveground shoots was, on average, 101.5 Mg·ha^{-1}, while the weight of the rhizomes was 129.3 Mg·ha^{-1}. In the case of knotweed, these values were 79.5 Mg·ha^{-1} and 107.5 Mg·ha^{-1}, respectively (Table 11).

Table 11. Fresh mass of knotweeds occurring on fallow lands [98].

Part of Plant	Fresh Mass Mg·ha^{-1}	
	Giant Knotweed	**Japanese Knotweed**
Aboveground parts	101.5	79.5
Underground parts	129.3	107.5

The variant entailing the double harvesting of plants allowed for the collection of a greater yield of air-dry mass of knotweed (statistically significant differences) than the one-time harvest variant [100]. A much higher dry matter yield was obtained from objects mown once in the fall. This may indicate that the yield potential of knotweed is exhausted as the number of cuts increases. The applied doses of single nitrogen fertilization did not have a statistically significant effect on the final yields of the dry matter of Japanese knotweed. No statistically significant differences were found in the calorific values of knotweed biomass depending on the number of cuts and fertilization variant (Table 12).

Sida hermaphrodita L. *Rusby* belongs to the *Polygonaceae* family. It is a perennial that can be cultivated for 15–20 years. Colloquially, it is called sida or Pennsylvanian mallow. It comes in two forms: the first is mallow, which is intended mainly for the production of fodder and as a substrate for agricultural biogas plants; the second is stalks, which are grown for seeds and are used as a substrate for the production of solid biofuels.

Table 12. Calorific value of Japanese knotweed depending on the number of harvests and the nitrogen fertilization variant [100].

Number of Harvests	Fertilization Variant kg N_2·ha^{-1} 25	50	75	100	Mean
	Calorific Value MJ·kg^{-1}				
One	16.84	16.99	16.96	16.93	16.93
Two	16.24	15.63	15.91	16.41	16.05
Mean	16.54	16.31	16.43	16.67	16.49

In terms of climate and soil requirements, sida adapts to both sandy and poor soils. For this reason, this species can be successfully grown even in class V soils. It is a plant resistant to unfavorable climatic conditions: frosts and droughts. During growth, it shapes a very strong root system and stems that are over 3.5 m high and have a diameter of 5–35 mm. The mallow crops are harvested annually in the form of woody and dry stems. Currently, this plant is used in many ways. It also belongs to the group of ornamental and honey plants [101]. Virginia mallow often obtains high yields of biomass, exceeding 11 Mg d.m.·ha^{-1}. Investment in plantations of this species brings a positive economic balance, assuming a high price for the sale of the obtained crops of approximately 320 PLN·d.m.$^{-1}$ [9]. Due to the high content of protein compounds, mallow is used as food in animal nutrition. The chemical composition of the stems of the plant in question is advantageously distinguished in terms of the quantity of components such as cellulose, resin and wax. These substances determine the possibility of using mallow in the pulp and paper industry. This species, compared to other energy crops, is distinguished by a low content of heavy metals, ash and minerals: nitrogen, chlorine and potassium. It is also used in the pharmaceutical industry. It can be cultivated in chemically degraded soils, which are reclaimed by their properties [102]. There are two routes of mallow reproduction: generative and vegetative [103]. One of the disadvantages of Virginia mallow is its poor resistance to diseases of a fungal origin, e.g., *Phoma* and *Borytis*, which negatively affect the root system and the base of the stems [104].

Biomass of Virginia mallow contains, on average, about 2.5% of ash [105]. A slightly higher ash content was found in the shoots of plants grown from seeds than in plants from other objects (Table 13). The authors of [106] determined an ash content of 2.63% in the biomass of Virginia mallow. In other studies [107], the ash content in mallow biomass was, on average, 3.36% and was significantly higher than that of willow (2.29%) and miscanthus (2.39%). The average heat of combustion was 19.0 MJ·kg^{-1} of dry weight, and the calorific value was 14.0 MJ·kg^{-1}. The energy value of the biomass yield (the product of the yield of fresh mass and the calorific value) in the experiment was, on average, in the range of 173–225 GJ·ha^{-1}. For comparison, the energy value of the willow yield in the studies [108] fluctuated in the range of 100–400 GJ·ha^{-1}·year^{-1}. The content of C and H_2 determined in the biomass of mallow, determining the energy value, was, respectively, 47.3% and 6.25%, while the content of undesirable sulfur (S) was only 0.03% [105].

Table 13. Characteristics of Virginia fanpetal biomass as a fuel [105].

Specification	Unit	Type of Propagules and Seeding/Planting Density					
		Seeds		Rooted Cuttings		Seedlings	
		kg·ha^{-1}		thous.·psc ha^{-1}			
		1.5	4.5	20	60	20	60
Ash content	%	2.65	2.65	2.47	2.30	2.53	2.35
Higher heating value	MJ·kg^{-1} d.m.	19.0	19.1	19.0	19.1	19.0	19.0
Lower heating value	MJ·kg^{-1}	14.0	13.9	14.0	14.0	14.0	14.1
Calorific value of the yield	GJ·kg^{-1}	173	191	175	214	190	225

The conducted laboratory tests [109] confirmed that the carbonization in the temperature range of 300–350 °C for the torrefaction of Pennsylvanian mallow has a positive effect on the improvement of its properties as a potential fuel that can replace coal, e.g., in domestic coal-fired central heating boilers. The calorific value in the sample calcined at 300 °C for 30 min was, on average, about 23.5 MJ·kg^{-1}, and in the sample calcined for 60 min at 350 °C, it was about 26.5 MJ·kg^{-1}. Compared to the calorific value of the raw sample, equal to 16.2 MJ·kg^{-1}, it is clearly visible that the torrefaction of Virginia mallow contributed to a significant improvement in its energetic properties. Taking into account that hard coal has a calorific value of 21–30 MJ·kg^{-1}, it can be concluded that the mallow's torrefaction could compete with hard coal in this respect. The torrefaction significantly contributed to the increase in the heat of combustion and the calorific value of the torrefied samples by significantly reducing the moisture content in relation to the raw sample. As observed, a longer roasting time led to an increase in the calorific value and a reduction in the moisture content (apparently) of the char by removing O_2 from the disintegrating molecules of lignin and cellulose. However, a longer roasting time means that a much greater amount of energy is required for the process, which increases the cost of producing the char. As a result of the research, it turned out that the roasting time can be shortened even to 20–30 min at the temperature of 300 °C without any significant deterioration in the calorific value of the resulting fuel. A separate and very important problem is the process of joining the char. As a result of long-term roasting at a high temperature above 350 °C, it may turn out that the obtained material does not have enough lignin, which is the main bonding component, to form briquettes [109]. In the case of energy grasses, it is possible to obtain large amounts of biomass without the need to incur large financial outlays [8]. The highest costs must be taken into account when establishing a plantation in the first year, as the planting material and plant protection products necessary to protect young crops against diseases and weeds are relatively expensive.

Energy grasses are primarily perennial species; therefore, in the following years, fighting weeds is not necessary due to the abundant growth of plants. Most of the species grown in Poland develop well in the soil and climatic conditions prevailing in the country. It is equally important to get acquainted with their characteristics, because the selection of the right energy grass has a significant impact on the success of a plantation.

Currently, the interest in introduced species of perennial grasses is growing. For energy purposes, growers place their hope, above all, in new hybrids of the genus *Miscanthus*. The sugar miscanthus *Miscanthus sacchariflorus* and the *Chinese Miscanthus sinnensis*, which are of Asian origin, have been cultivated for many years. The giant miscanthus *Miscanthus x giganteus J. M. Greef & M. Deuter* [110] is the result of crossing the above two species. It is a sterile triploid bred in Denmark in the 1980s [96]. It belongs to the group of plants that utilize the C4 photosynthetic pathway. As a result, it uses water, nutrients and solar radiation more efficiently. Its other advantage is its high yield potential. In the Polish climatic conditions, it is possible to obtain up to 20 Mg d.m.·ha^{-1}. Research carried out in many research units throughout Europe has shown that the yields of Miscanthus can be very diversified. Experimental results show that the biomass yield ranges from 4 Mg d.m.·ha^{-1}

in Germany to as much as 44 Mg d.m.$\cdot$ha^{-1} in Greece. On this basis, it can be concluded that giant miscanthus yields better in countries with warmer climates [8].

The service life of miscanthus giganteus is about 15–20 years. The cultivation of the soil, prior to plantation, as with other perennial crops, is a key factor in the subsequent success of the project. The most important procedure before establishing a plantation is the destruction of perennial weeds. In addition, it is advisable to perform deep winter plowing and additional soil tillage in spring before planting. Additionally, when the pH of the soil is below 5.5, liming is recommended [9,111].

It is estimated that the most economically justified and effective route of Miscanthus giganteus reproduction is to divide the underground parts of the plant. In this case, the reproductive material should consist of rhizomes that are at least 0.1 m long and weigh 25–35 g, with at least 2–3 buds. They are characterized by the best growth dynamics. They should be taken from relatively young (three- or four-year-old) mother plants. It is very important not to dry the rhizomes during their storage. This results in a reduced ability of emergence and, in extreme cases, even complete failure to accept the planting material. For this reason, the rhizomes should be obtained just before the planned planting, that is, at the beginning of April, or stored in a moist substrate [112].

A characteristic feature of all species of the genus *Miscanthus* is their high water needs. A particularly critical moment is the period just after the plantation has been established, when the plants are just developing a root system. If the spring is dry, it becomes necessary to irrigate the plantations. In the subsequent years, the yield of biomass in the main measure is determined by the soil moisture during the growing season, but due to the extensive underground part of the plants, they are better able to survive periods of drought [58]. Nevertheless, to obtain satisfactory cultivation results, a total rainfall of more than 700 mm during the growing season (April–October) is necessary. This accounts for over 100% of the average total annual rainfall for most of Poland [97,98]. For this reason, lower yields than those found in the source data should be expected, the results of which are based on experiments conducted in Western Europe [8].

Miscanthus x giganteus, compared to sugar or *Chinese miscanthus*, is characterized by relatively low frost resistance in young plants. This is especially true of plants obtained using the in vitro method. In this case, it is recommended to protect the plantation against freezing, especially in the first year of cultivation. For this purpose, leaf or straw mulch is used, or plants are optionally covered with agrotextiles. This is undoubtedly a very expensive procedure, but a necessary procedure, because in the case of frosty and snowless winters, most rhizomes can be damaged. For example, due to the cost of one seedling amounting to PLN 1–1.5, with the desired planting density of PLN 10,000 pcs$\cdot$ha^{-1}, the outlays incurred to establish a plantation constitute up to 70% of the costs of growing and harvesting *Miscanthus giganteus* [9,111]. This is why it is so important to properly protect the plantation over the winter.

Keeping a monoculture for many years can lead to soil depletion. To avoid this, fertilization is essential. According to researchers Wiśniewski and Podlaski [112], it is possible to abandon the use of mineral fertilizers in favor of organic ones: slurry or sewage sludge. Such fertilizers, in the case of miscanthus, should be applied in the amount of about 30 m$^3\cdot$ha^{-1}. This is estimated to be a good way to reduce biomass production costs. It is important, however, to be particularly careful when distributing them in the interests of the natural environment and good agricultural practice.

The maintenance of miscanthus plantations is not very laborious. However, it may be necessary to destroy weeds in the first years of cultivation. Segetal species are fought mechanically using inter-row combinations. The use of herbicides is also possible, but usually not economically viable. As far as pathogens are concerned, their mass occurrence in miscanthus giganteus plantations in Poland has not been found thus far. As a result, the use of expensive plant protection products against diseases and pests is not necessary.

Harvesting of Miscanthus biomass is carried out after its vegetation has ended. The optimal date for cutting shoots is from November to early March. Early cutting of miscanthus prevents lodging, which occasionally occurs after heavy snowfall in the pre-winter period, before the plants become woody [9]. The autumn harvest allows for obtaining a large amount of biomass, but it is characterized by high humidity. After harvesting, it requires drying in a covered place. This increases the workload and requires the creation of an appropriate warehouse, which generates additional costs. Early harvesting also makes it necessary to cover young carp for the winter [112]. Harvesting in early spring allows for obtaining biomass with the lowest humidity, thus removing the requirement for additional drying. It is important to carry out activities on a frosty and sunny day. During the thaw, it may be very difficult to enter the field with the equipment. However, it should be borne in mind that after winter, the miscanthus biomass yield is about 25% lower than in autumn [9]. This is related to the falling of leaves during strong winds and large diurnal temperature fluctuations [111].

Miscanthus giganteus is harvested in one or two stages. One-stage harvesting is possible in the early spring, when the biomass humidity drops and amounts to about 20%. For this purpose, specially adapted harvesters are used, which mow and compact the straw during one pass. Another recommended solution is the use of forage harvesters cooperating with tractors or a self-propelled forage harvester. During the two-stage harvest, the plants are first cut with a rotary mower with a conditioner. The straw laid in even swaths is then dried naturally in the field. After the humidity reaches a dozen or so percent, it is pressed using presses with a high degree of compression. In this way, formed solid biofuels with a density of 120–180 kg·m^{-3} are obtained. Biomass prepared in this way can be a source of fuel for a combined heat and power plant; however, dried miscanthus is often characterized by a large amount of chlorine. The content of this element can sometimes be over 10 times higher than in the willow shoots. For this reason, miscanthus is not as popular as short-rotation trees, because its combustion may cause the corrosion of boilers [9,111].

Most biomasses from *Miscanthus giganteus* plantations can be obtained from the third to the eighth or ninth year of cultivation. In the following years, the productivity of plants systematically decreases. As the amount of obtained biomass is strongly correlated with the course of the weather in a given season, it is difficult to estimate the expected yield. Nevertheless, the annual low precipitation in central Poland, below 400 mm during the growing season, means that plantations located in this part of the country may be less productive [113].

It is estimated that the cultivation of *Miscanthus x giganteus* may be unprofitable in Wielkopolska, Kujawy and the central part of Mazovia. This species can be successfully grown in Pomerania and Żuławy. These areas have favorable water conditions for miscanthus, caused, inter alia, by a greater amount of precipitation [112].

The calorific value of the fuel is determined not only on the basis of experimental tests using a calorimeter, but also on the basis of the knowledge of the fuel composition. As such studies have been conducted [114], Table 14 presents the computational values of the heat of combustion, using various dependencies presented in the literature and the fuel composition determined for whole miscanthus plants.

Table 14. Caloric value of Miscanthus, calculated on the basis of the elementary composition, according to various sources, for selected humidities [114].

No.	Sources Used for Calculations	Combustion Heat	Heating Value for Moisture	
			% 10	% 30
		s. m. kJ·kg^{-1}	kJ·kg^{-1}	kJ·kg^{-1}
1	Kozaczka [115]	18,317	15,051	11,163
2	Ebeling and Jenkins [116]	18,998	15,664	11,640
3	Demirbas [117]	17,890	14,666	10,864
4	Gaur and Reed [118]	20,259	16,799	12,523
6	Mean	18,759	15,448	11,472

Chinese miscanthus is characterized by high biomass productivity, low habitat requirements [119] and resistance to unfavorable conditions. Due to its features, it is more and more often used for energy purposes [120]. Biomass obtained from Miscanthus crops can be used both for the production of eco-energy in direct combustion processes, and for the production of biogas [121] and biofuel for combustion engines—bioethanol [122]. Prairie spartina, similar to giant miscanthus, is a species of perennial grass with the C4 photosynthesis type [8], originating in North America. In its natural environment, it grows mainly in poorly drained ditches and wetlands. There, it reaches 1–2.5 m in height. In addition, it occurs in wet meadows, but also in overgrown dunes. It is also used to strengthen sandy dikes as an anti-erosion plant. It is highly adaptive and tolerates soil salinity well [123].

For energy purposes, spartina is grown to obtain a substrate for biogas production. It can be harvested several times during the growing season. Nevertheless, frequent harvesting increases the costs of running a plantation, which may make it unprofitable. Spartina is recommended for soils that are poor in nutrients [87].

The chemical composition of prairie spartina biomass and its energy parameters, i.e., combustion heat and calorific value, determine its suitability for combustion [124]. A lower ash content and a higher proportion of volatile parts, combustible substances and C were determined in the biomass of prairie spartina collected after the end of the third growing season than in the raw material obtained after the end of the first year of vegetation (Table 15). These differences resulted in the heat of combustion being higher by 0.59 MJ·kg^{-1} d.m. for the biomass of prairie spartina plants obtained after the end of the third growing season compared to that found in the biomass of plants obtained after the end of the first growing season.

Table 15. Energetic parameters of cordgrass biomass [124].

Parameter	Symbol	Unit	Condition					
			Analytical		Dry		Dry and Ash-Free	
			I Year	III Year	I Year	III Year	I Year	III Year
Analytical moisture content	W_a	%	13.4	13.5				
Ash	A	%	5.1	3.6	5.9	4.1		
Combustible matter		%	81.5	83.0	94.1	95.9		
Volatile matter	V	%	65.1	69.1	75.2	79.8	80.0	83.3
Gross calorific value	Q_s	kcal·kg^{-1}	3811	3932	4402	4544	4679	4740
		MJ·kg^{-1}	15.96	16.46	18.43	19.02	19.59	19.85
Net calorific value	Q_i	kcal·kg^{-1}	3486	3609	4118	4261	4377	4446
		MJ·kg^{-1}	14.59	15.11	17.24	17.84	18.32	18.61

The reed canary grass *Phalaris arundinacea* is a perennial grass that is very resistant to low temperatures. For this reason, it is popular in Scandinavia and is one of the main species grown for energy purposes [8]. The Finnish Ministry of Agriculture and Forests, as a priority until 2016, set the achievement of 100 thousand ha of cultivated area of the reed canary grass [125]. The advantage of the reed canary grass is the low cost of establishing a square of antennas. This consists of the direct sowing of seeds into the ground in the amount of 15–18 kg·ha^{-1}. Moreover, it is possible to fully mechanize the production of biomass with agricultural machines for the cultivation of cereals. It yields the best in wet but also sandy areas, giving 4–7 Mg·ha^{-1} d.m. The reed canary grass plantations can be used for up to 15 years [126].

In order to obtain straw, the blades should be cut in early spring, right after the snow has melted, because the canopy starts vegetation very early. Its biomass in early spring is characterized by a very low humidity, amounting to only about 10–15%, so straw can be easily formed into bales. During this time, it also has a lower ash content, although in March, compared to other species, it is still relatively high. Depending on the site where the brain grew, it amounts to 2–10%. Apart from that, the biomass of reed brain contains a lot of nitrogen and chlorine, which, given the relatively low yield, is not an alternative source of solid biomass in Poland compared to giant miscanthus, sorghum or maize [50,125].

In [127], the values are very high (Table 16), comparable with those of [128] and much higher than those obtained in [129] and [130]. Such favorable results are a consequence of the high bulk density resulting from biomass pelleting, which was proved in [131–133].

Table 16. Characteristics of energy values of reed canary grass (own study).

Author of Investigations	Energy Value of Yield	Incinerating Warmth	Ash	Moisture
	$MJ \cdot kg^{-1}$ d.m.	$MJ \cdot kg^{-1}$ d.m.	$g \cdot kg^{-1}$ d.m.	%
Grzelak [112]	18.2	19.4	69	7.7
Dadrach et al. [115]	17.0	17.0	68	6.8
Harkot et al. [113]	18.0	19.1	55	–
Rogalski et al. [114]	15.5	17.6	128	–

The natural environment of rotary millet *Rotshtrahlbush Panicum virgatum* is also North America [8]. Since the 1990s, research has been conducted there on the use of rotary millet for energy purposes. Millet forms clumps up to 3 m high. It produces strong but short stolons. Thanks to this, it is suitable for the turfing of degraded and erosion-endangered soils. It can also be used as a pioneering plant in areas created after mining excavations. The yield of its biomass, however, is lower compared to the yield of miscanthus biomass [48,58].

The rosewood plant has a total lignin content of about 17.6%, along with 31.0% cellulose and 24.4% hemicellulose [134]. The content of cellulose and lignin in biomass is important when it is processed biochemically by methane or alcohol fermentation. The conversion of lignocellulosic biomass into ethanol is a renewable, environmentally friendly alternative to oil [135]. The biodegradability of cellulose is higher than that of lignin, making low-lignin biomass more suitable for fermentation processes. Additionally, the mutual spatial distribution of lignin and cellulose in biomass has a huge impact on the possibility of using cellulose as a raw material for fermentation [136]. Panicum biomass is susceptible to pre-treatment and hydrolysis. Studies [135] have shown over 90% conversion of cell wall carbohydrates to simple sugars. The energy value of cellulose may slightly change depending on the raw material. The average heat of combustion for cellulose is 17.4 MJ kg^{-1}, while for lignin, it is 21.2 MJ kg^{-1}. The lower heat of combustion of cellulose is due to its higher level of oxidation [136].

The generative biomass (straw) of this new energy grass, due to its high fiber and cellulose content, can be a valuable, promising source of energy for direct heating of apartments, public buildings, greenhouses and tunnels. The biomass obtained annually is a valuable raw material for direct combustion in the form of briquettes, pellets or pressed bales. Millet biomass with a moisture content of about 15–20% is well pressed and briquetted. Research [137] has shown that the heat of combustion is about 17–18 $MJ \cdot kg^{-1}$—higher than that of other field energy plants, and similar to willow or miscanthus. The calorific value of dry matter obtained from 1 ha of plantations may be equivalent to about 5 Mg of hard coal. After burning, the pressed straw leaves little ash, about 5%, which can be used to fertilize soils due to the high potassium content.

The ligno-cellulosic biomass of millet can be successfully used for the production of cellulosic ethanol. About 400 L of ethanol can potentially be produced from 1 Mg of millet. This has the potential to produce around 9500 L of ethanol per hectare, compared to around 6200 L per hectare of sugarcane and around 3800 L per hectare of maize. This species is considered to be one of the most energy-efficient plant crops (Table 17). The net energy production (i.e., the difference between the energy put into the production of a product unit and the energy obtained as a result of biomass processing) of this species is 163.8 $GJ \cdot ha^{-1}$ for the yield at the level of 9 Mg dry weight per ha. The same calculation performed for maize returns 89.2 $GJ \cdot ha^{-1}$ (with a grain yield of 5.7 $Mg \cdot ha^{-1}$), and for rye, it returns 34.7 $GJ \cdot ha^{-1}$ (grain yield of 2.3 $Mg \cdot ha^{-1}$) [137].

Table 17. Net energy production from millet [137].

Plant	Yield d.m.	Energy Content	Net Energy Production
	$Mg \cdot ha^{-1}$	$GJ \cdot Mg^{-1}$	$GJ \cdot ha^{-1}$
Rod millet	9.0	19.0	163.8
Rape	3.0	25.0	89.2
Corn for grain	5.7	18.8	64.0

Perz elongated *Agropyron elongatum Beauvois* synonym *Elytrigia elongata* L., also called clump or energy grass, is a perennial grass with C3 photosynthesis [8]. It occurs in dry and saline sites in Europe and Asia. It creates dense clumps up to 3 m in height. This species does not produce runners [48]. In Poland, the national cultivar 'Bamar' is used for cultivation, which was bred at the Plant Breeding and Acclimatization Institute—National Research Institute in Radzików [138]. Its blades are very stiff due to the high content of cellulose. This prevents plants from lodging, and this variety creates a strong, bundled root system that reaches up to 2–3 m deep. 'Bamar' tolerates periodic droughts and frosts down to −20 °C [139]. Due to the low soil requirements, it is possible to plant this plant in fields with a low valuation class. In order to obtain biomass for energy purposes, a plantation is established in spring, preferably in April, by sowing licensed seeds. Their recommended amount is 10–15 $kg \cdot ha^{-1}$. It is very important that the seed is dormant at low temperature, which significantly improves the germination energy [48]. The costs of establishing an elongated couch grass plantation, calculated by Martyniak et al. [138], are even 10 times lower than in the case of Miscanthus giganteus obtained from in vitro cultures [140].

According to practitioners, pre-sowing fertilization in autumn and top dressing with potassium and phosphorus are of particular importance. Admittedly, these practices increase the costs of obtaining biomass, but for this purpose, expenses can be reduced by using municipal sewage sludge. The research by Kołodziej et al. [48] showed that their use can fully replace mineral fertilization. In the year of sowing, special care should be taken to weed the plantations because, thus far, no pathogens reducing the yield of couch grass have been found [48].

Biomass can be harvested in two ways, depending on its later use. For the production of solid biofuels, i.e., briquettes, pellets and bales, couch grass is obtained in the fall, i.e., at the beginning of the yellowing process of the stalks. The plants are therefore in the seed maturation phase. The straw is collected with a swath mower or a combine harvester. If it is to be used for the production of briquettes or pellets, it must first be dried to a moisture content of 12–18%. In practice, this means leaving cut shoots in the swath for several days. The couch grass blades are a good source of fuel, as they contain only about 3–4% of ash. Additionally, they are characterized by a low content of chlorine and sulfur.

In the case of the cultivation of couch grass as a substrate for biogas production, it is cut even four times during the growing season. The last harvest is carried out by the end of September so that the plants begin to grow back slightly before winter and survive better. In order to obtain biomass, a mower is used. Plants are cut to a height of 8–10 cm. In this way, about 15 Mg of dry matter can be obtained per hectare of cultivation. The production of methane in terms of dry matter amounts to about 600 $m^3 \cdot Mg$ $d.m.^{-1}$ [48,138].

Couch grass can be planted for 8–12 years, i.e., shorter than in the case of other perennial grasses grown for energy purposes. It is estimated that it is a useful species in the reclamation of post-industrial areas created as a result of opencast lignite mining. Elongated couch grass can also be used to remove heavy metals from soils [48,139]. Although it may soon become an alternative source of biomass, especially as a co-substrate for biogas plants for nitrogen-rich animal waste, further research is necessary to confirm the profitability of its cultivation in various soil and climatic conditions in Poland [8].

Due to its high fiber and cellulose content, the biomass of couch grass straw can be a promising source of energy for direct combustion and a very convenient way of heating houses, in the form of briquettes, pellets or pressed bales (in larger boiler houses).

Research conducted [141] on the energy value of its biomass in the form of dry straw or briquettes showed its high heat of combustion value of approx. 18 MJ—higher than that of other field energy plants, e.g., cereal straw, and similar to some types of trees and brown coal. Moreover, the biomass, after combustion, has a relatively low ash content (3–4%), which can be used as a fertilizer with a high content of potassium and other minerals for soil fertilization.

On the other hand, green vegetative biomass of the 'Bamar' variety can be used in the fermentation process for ensiling and in biogas production as an ecological fuel with a high calorific value (18–24 MJ·m^{-3}). At the same time, the biogas digestate (organic waste) can be used to rehabilitate poor, contaminated soils in order to increase their fertility and enrich them with organic matter [142].

3.4. Obtaining Primary Energy, including Energy from Renewable Sources, in the European Union and Poland

Renewable energy sources are an alternative to traditional, primary non-renewable energy carriers (fossil fuels). Their resources complement each other in natural processes, which practically allows them to be treated as inexhaustible. In addition, obtaining energy from these sources is, compared to traditional (fossil) sources, more environmentally friendly (Table 18).

Table 18. Obtaining primary energy, including energy from renewable sources, in the European Union and Poland [143].

Itemization	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	Mtoe									
Total primary energy recovery in the EU	804.0	796.8	792.0	772.9	766.6	760.4	758.8	756.6	739.4	573.1
including from renewable sources	165.4	182.2	194.6	197.5	205.0	217.4	226.3	234.4	242.5	233.5
Total primary energy recovery in Poland	68.8	72.6	71.8	68.2	68.5	66.6	64.2	64.6	62.1	58.0
including from renewable sources	7.5	8.5	8.6	8.1	9.0	9.2	9.2	12.1	12.3	12.5
Itemization	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
	%									
Share of energy from renewable sources in total primary energy in the EU	20.6	22.9	24.6	25.5	26.7	28.6	29.8	31.0	32.8	40.7
Share of energy from renewable sources in total primary energy in Poland	10.9	11.7	11.9	11.9	13.1	13.8	14.4	18.7	19.7	21.6

The use of renewable energy sources significantly reduces the harmful impact of the power industry on the natural environment, mainly by reducing the emission of harmful substances, especially greenhouse gases [144]. In the years 2011–2019, a very mild decrease in the amount of energy produced in the EU was observed (Figure 1), which proves the increasing energy efficiency (decrease in the energy intensity of the economy). The low value of energy production in 2020 against the background of the indicated period is associated with Great Britain leaving the European Union. In the same period, there was a slow increase in the share of energy generated from renewable sources. Since the value of this indicator for 2020 does not differ significantly from the long-term trend, a relatively small share of the contribution to the energy balance of the European Union from renewable sources processed in Great Britain can be noticed.

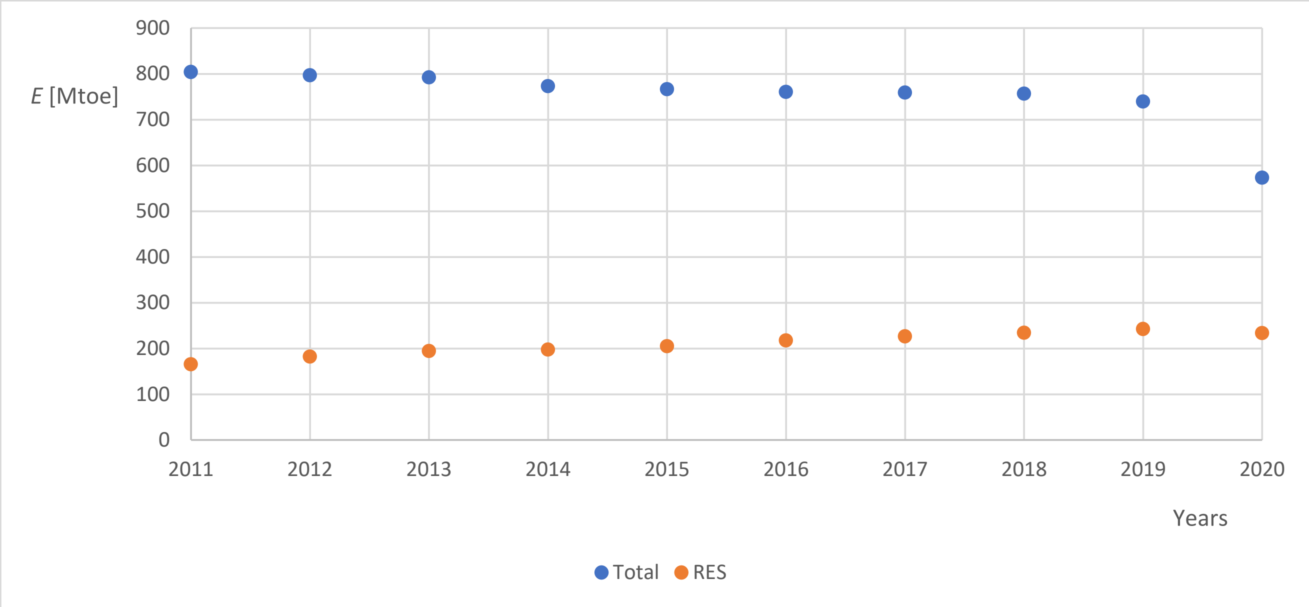

Figure 1. Obtaining primary energy, including energy from renewable sources (RES), in the European Union, according to Table 18 (own elaboration).

In the years 2011–2020, a systematic decrease (14%) in the amount of energy produced in Poland can be observed (Figure 2). This was due not only to the modernization of the industry (implementation of energy-efficient technologies), but also to the deteriorating condition of the national energy infrastructure. The accompanying increase in the production of "green energy", although progressing, should be considered as still inadequate for the needs of the economy.

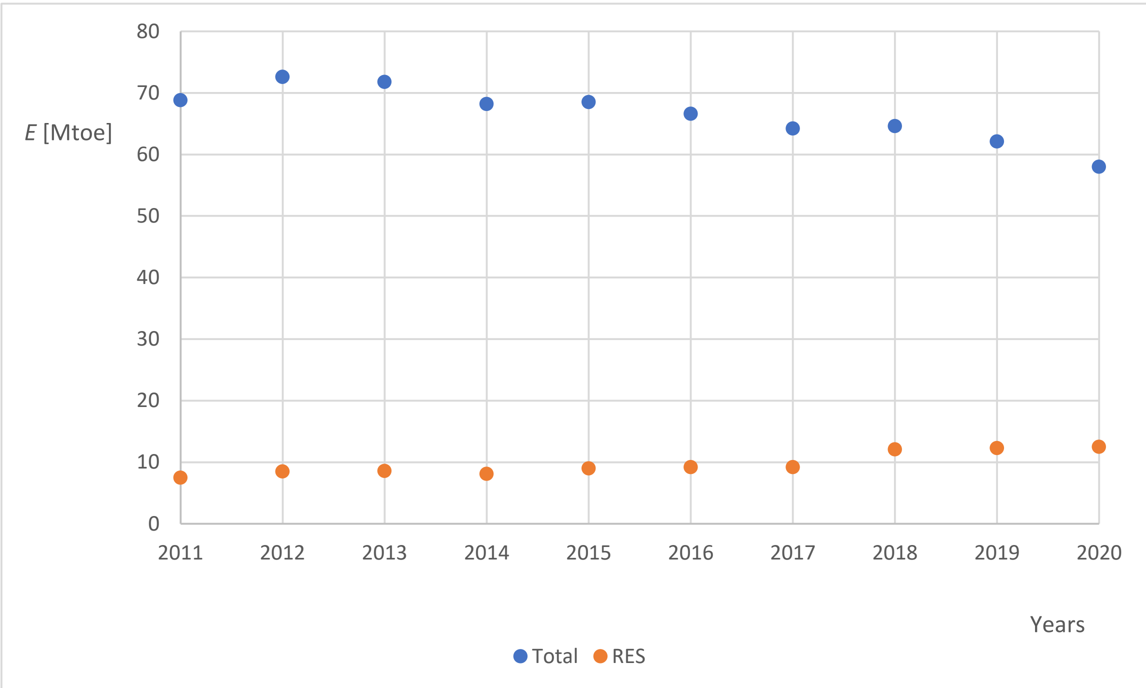

Figure 2. Obtaining primary energy, including energy from renewable sources (RES), in Poland, according to Table 18 (own elaboration).

The comparison of primary (Figure 3) energy generation trends in the EU and Poland is burdened with the fact that Great Britain has left the community. It is noteworthy that there was no increase in production capacity in Poland. This was due to the lack of implementation of investments in the energy sector (conventional and renewable energy).

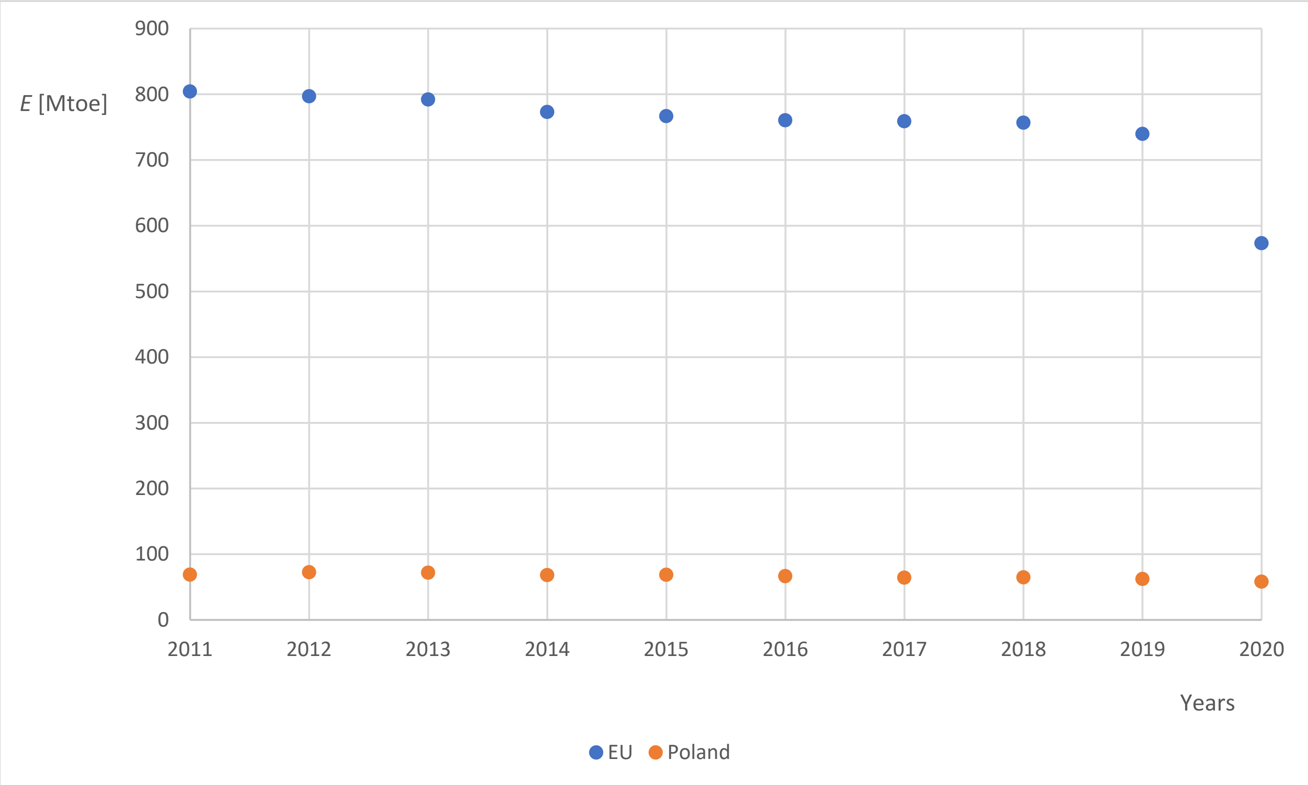

Figure 3. Total primary energy production in the EU and Poland, according to Table 18 (own elaboration).

Taking into account the geographical diversity of the European Union member states, the ease of diversification of renewable energy sources (Figure 4) can be considered natural (a significant share in the production of electricity from the kinetic energy of water in Scandinavia, or the power of wind and tides in coastal countries). It is responsible for the constant increase in the share of renewable sources in the energy balance. The geographical conditions of Poland tend to rely on solar energy and, in regional terms, wind energy. In the context of combustion-based technologies, biogas plants come into play (easy access to cheap substrates). Despite this, a very unfavorable trend (slow growth) is visible.

The parallel increase (Figure 5) in the share of energy from renewable sources in the EU and Poland (stronger in the EU) can be primarily attributed to the progressing social changes (climate catastrophe) taking place on a global scale. The causative factor for the implementation of appropriate environmental standards in this context is undoubtedly the unstable situation in the global energy market, which forces us to become independent of the largest suppliers of fossil carriers.

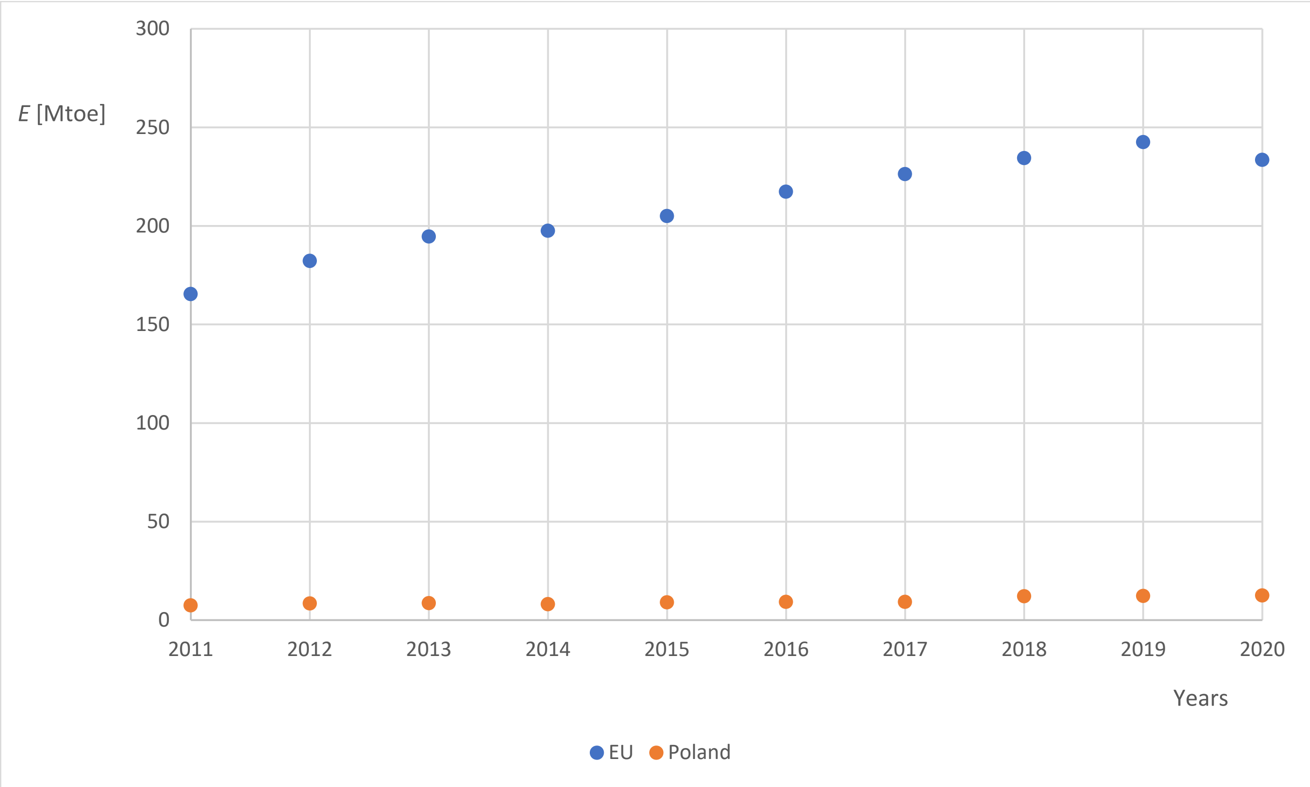

Figure 4. Obtaining primary energy from renewable sources in the EU and Poland, according to Table 18 (own elaboration).

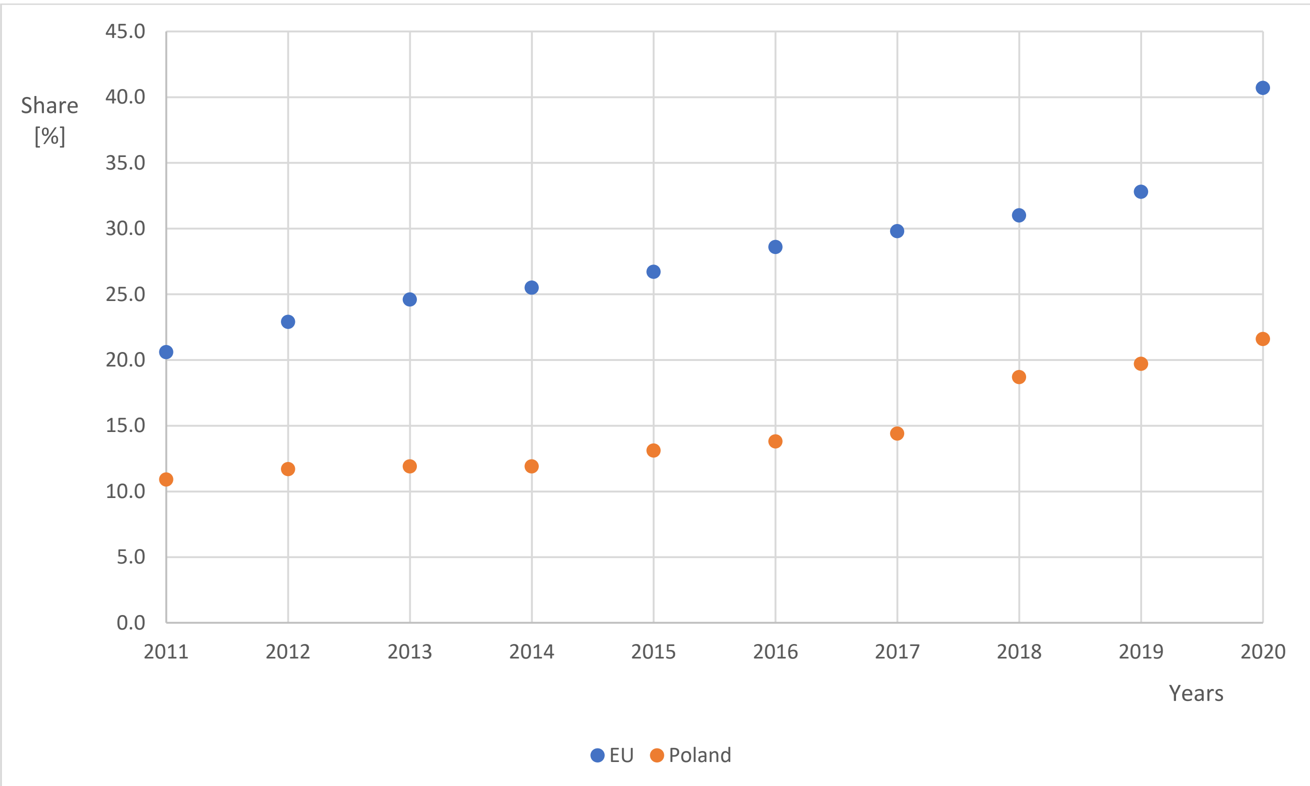

Figure 5. Share of energy from renewable sources in the EU and Poland, according to Table 18 (own elaboration).

3.5. The Area of Agricultural Land Potentially Useful for the Cultivation of Energy Crops in Poland

The land use structure in Poland is as follows [145]: agricultural land covers an area of 18,418 thousand ha, which accounts for 58% of the country's area, of which arable land covers 14,048 thousand ha (76.3% of agricultural land), meadows cover 2350 thousand ha (12.8%), pastures cover 1693 thousand ha (9.2%) and orchards cover 296 thousand ha (1.6%). In the years 1946–2005, the area of agricultural land decreased by over 2 million hectares, while the area of forests increased by over 2.6 million hectares. From the point of view of biodiversity, permanent grasslands—meadows and pastures—are of the greatest importance, accounting for about 10% of the country's area and over 21% of agricultural land. Agricultural land can be defined as follows:

(a) Arable land—part of land and agricultural land subjected to continuous and seasonal cropping.
(b) Cultivation—cereals, 71%; industrial plants, 11%; fodder plants, 10%; potatoes, 3%; legumes, 2%.
(c) Meadows and pastures—agricultural land occupied for the cultivation of grasses or other herbaceous crops (herbs, legumes), both natural and resulting from agricultural activity.
(d) Orchards—an agricultural area or plantation where trees or shrubs providing edible fruit are grown.
(e) Agricultural wasteland, marginal land—these are areas which, as a result of bad agricultural, industrial and forestry activities, do not have or have lost their value in use; wasteland also includes: swamps, dunes, floating sands, ravines, rocks, devastated areas.

The state of biodiversity of agricultural land depends on the type of agricultural activity. Agricultural activity is categorized based on the method of agricultural land development in terms of plant and animal production.

We can distinguish conventional–intensive agriculture and sustainable–ecological–integrated agriculture. Biodiversity in agriculture is perceived in two ways:

- The first is related to the diversity of species and varieties of cultivated plants and species and breeds of farm animals;
- The second is related to the biodiversity of plants and wild animals accompanying agricultural production.

We can also distinguish genetic, intraspecific and interspecific biodiversity and the diversity of ecosystems and landscapes. The biodiversity of a given area is usually characterized using measures such as species richness, species diversity (diversity), taxonomic dispersion of species, and functional and structural diversity.

Agricultural land is a homogeneous and usually poor area within a given crop (single species). In agricultural areas, high biodiversity is characterized by transitional areas between two ecosystems, the so-called ecotones. Considering biodiversity in agricultural use, the most important aspects are the ecosystem and landscape. Based on the appearance of the landscape, we can determine the state of its biodiversity and the type of agricultural activity, especially in terms of the area of agricultural land (Table 19).

The highest cumulative (Figure 6) share and the strongest increase in the share of areas potentially suitable for the cultivation of energy crops are found in Pomeranian Voivodeship, and the Małopolska and Lower Silesia regions.

Table 19. Area of agricultural land potentially useful for the cultivation of energy crops [146].

Voivodeships	2015	2016	2017	2018	2019	2021
	A [ha]					
Lower Silesian	252	404	330	411	373	373
Kuyavian-Pomeranian	48	79	66	59	77	77
Lublin	102	114	113	121	130	130
Lubusz	68	154	95	73	80	80
Łódź	160	157	278	273	283	283
Lesser Poland	266	334	328	317	372	372
Masovian	215	233	228	251	272	272
Opole	21	35	25	43	49	49
Subcarpathian	149	158	192	235	216	216
Podlaskie	34	48	58	75	96	96
Pomeranian	272	348	393	407	440	440
Silesian	181	217	306	226	278	278
Holy Cross	21	25	32	35	44	44
Warmian-Masurian	82	112	124	92	102	102
Greater Poland	174	293	174	205	198	198
West Pomeranian	263	256	264	232	221	221

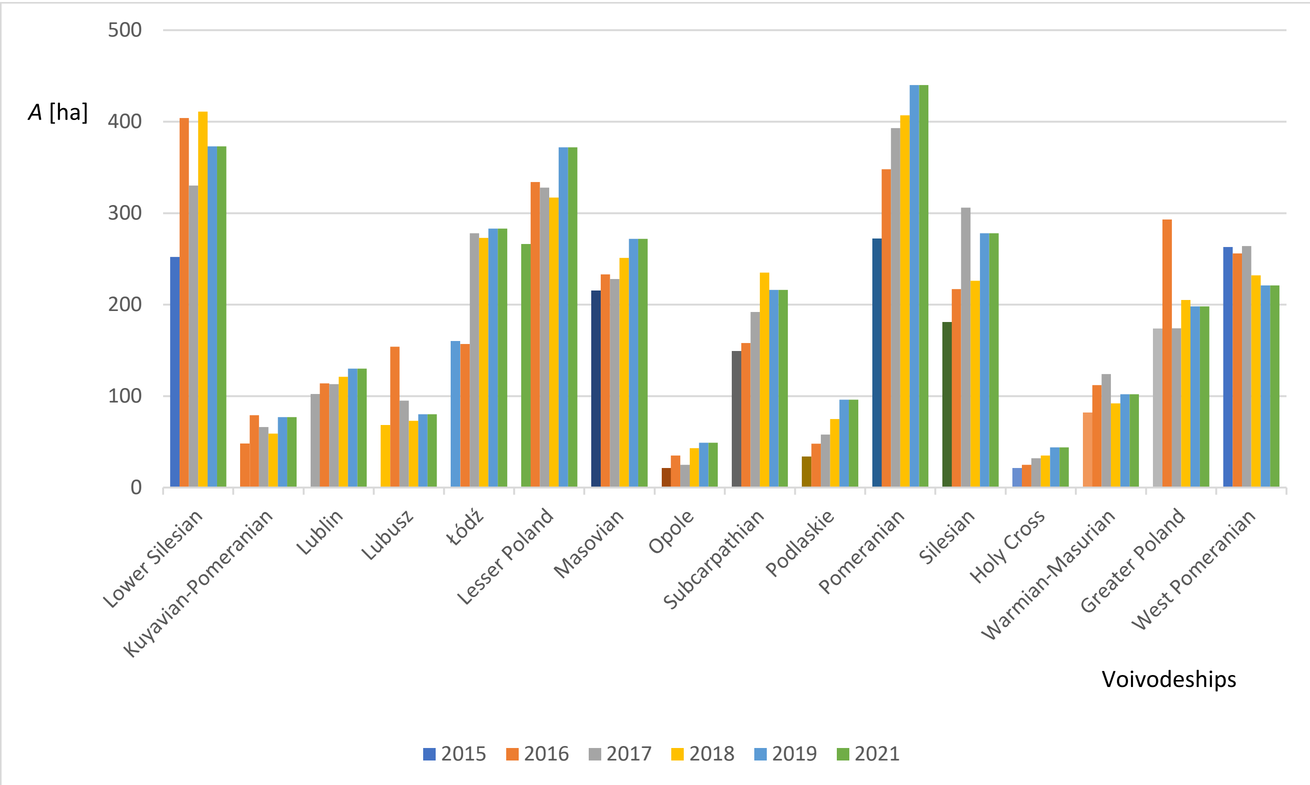

Figure 6. Area of agricultural land potentially useful for the cultivation of energy crops, according to Table 19 (own elaboration).

An increase in the degree of land development of low valuation quality (decrease in the amount of land in these groups since 2017) is only observed in Greater Poland Voivodeship, which can be partly explained by its development of energy crops.

A stable upward trend in the energy efficiency of biogas plants is shown in Figure 7. Large installations are an exception, whose efficiency is not linear in relation to installations with lower power [147,148].

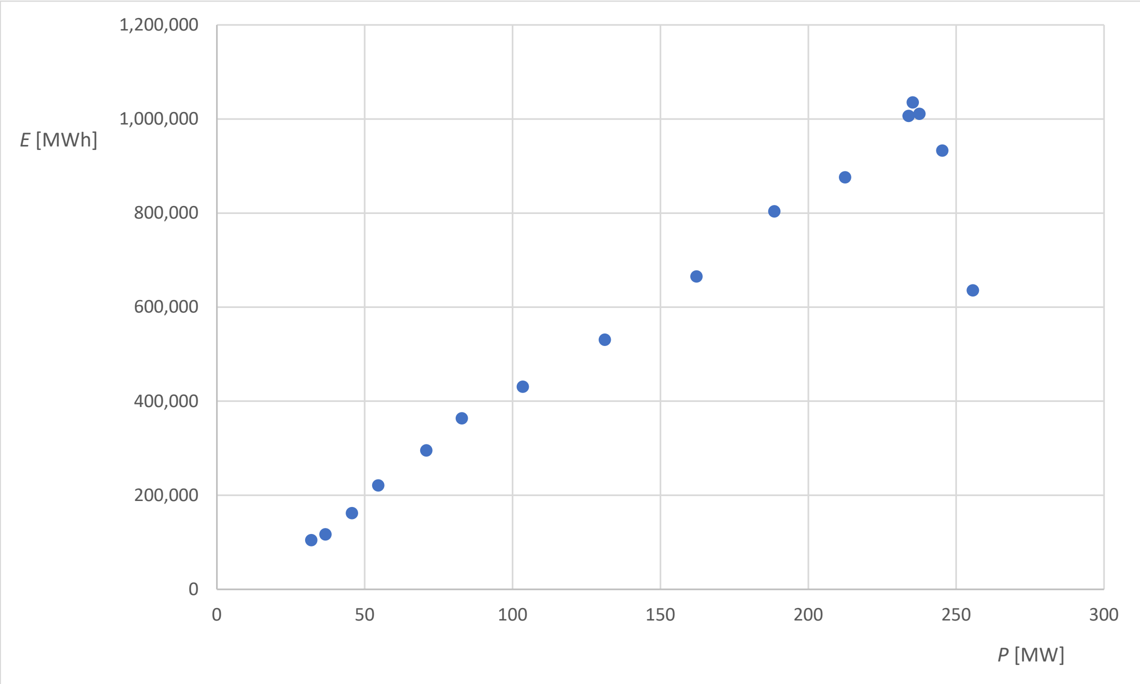

Figure 7. Relationship between biogas power installed in Poland and the amount of electricity generated from biogas in Poland (own elaboration).

The lack of a well-oriented trend in the efficiency of installations based on biomass processing is shown in Figure 8.

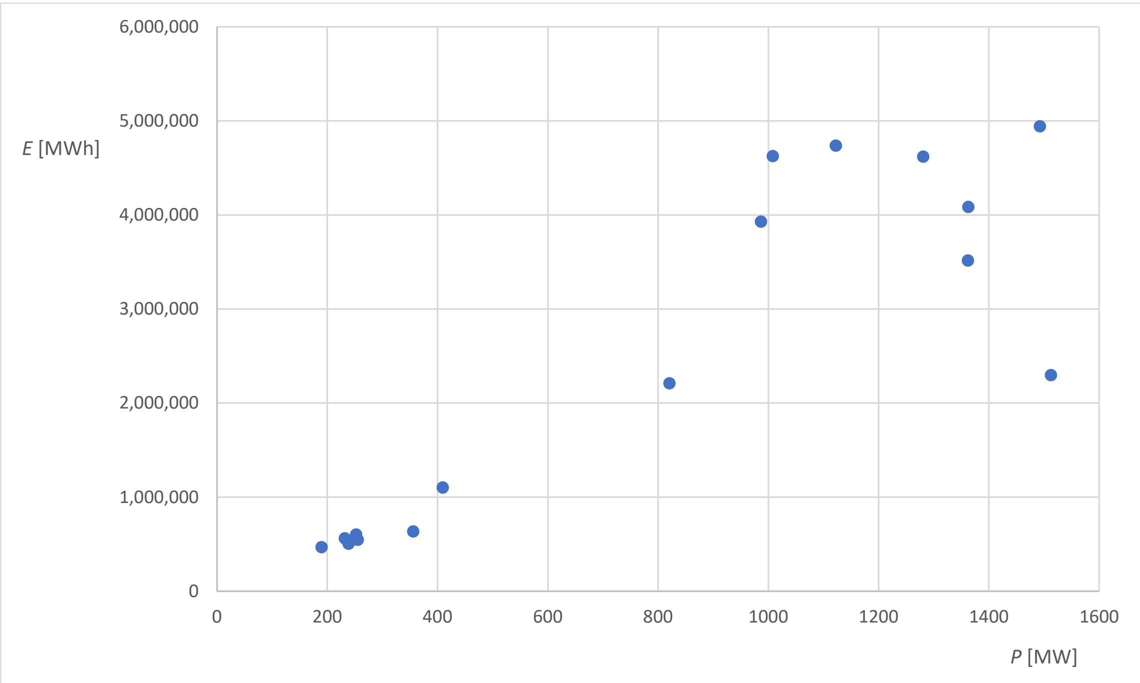

Figure 8. Relationship between the installed capacity derived from biomass and the amount of electricity generated from it in Poland (own elaboration).

The highest ratio of the amount (Figure 9) of power obtained from biogas plants per area unit is found in the Warmian-Masurian, Greater Poland, West Pomeranian and Masovian regions. The Lesser Poland region, Subcarpathian region and, to a lesser extent, Pomeranian Voivodship are unfavorable in this classification. This state of affairs can be attributed to the unfavorable topography (mountainous areas characterized by a more severe climate). The case of Pomeranian Voivodeship can be explained by the intensification of wind energy.

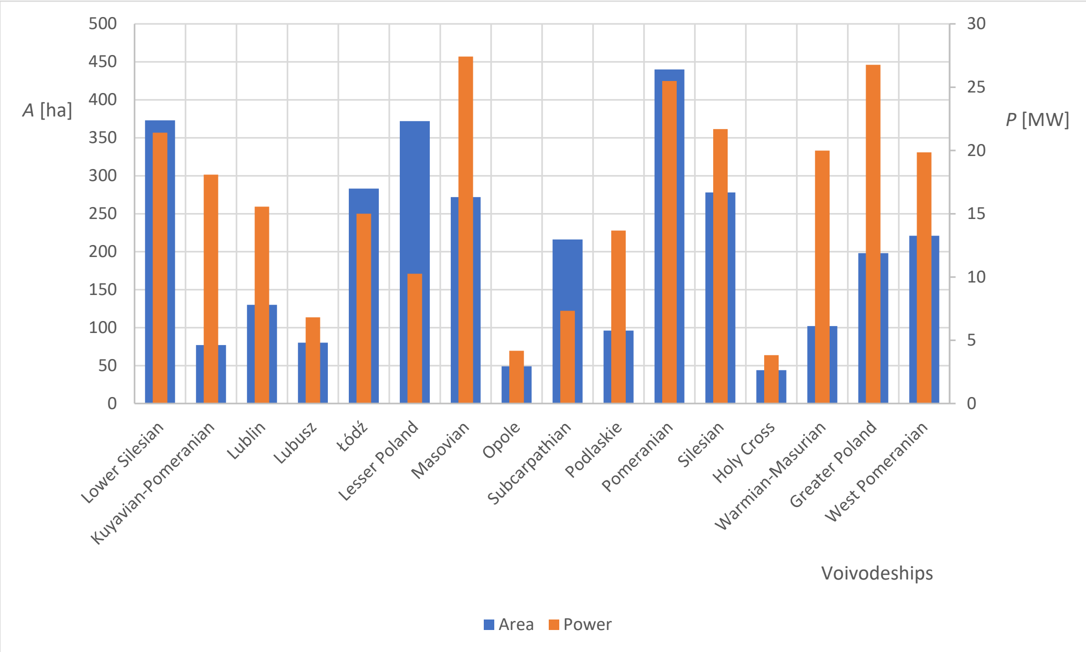

Figure 9. The relationship between the area of agricultural land potentially useful for the cultivation of energy crops (as of 2021) and the regional approach to the installation of power from biogas in Poland (own elaboration).

On a national scale (Figure 10), the problem is the ineffective use of potentially available land for cultivation for the purposes of obtaining biomass.

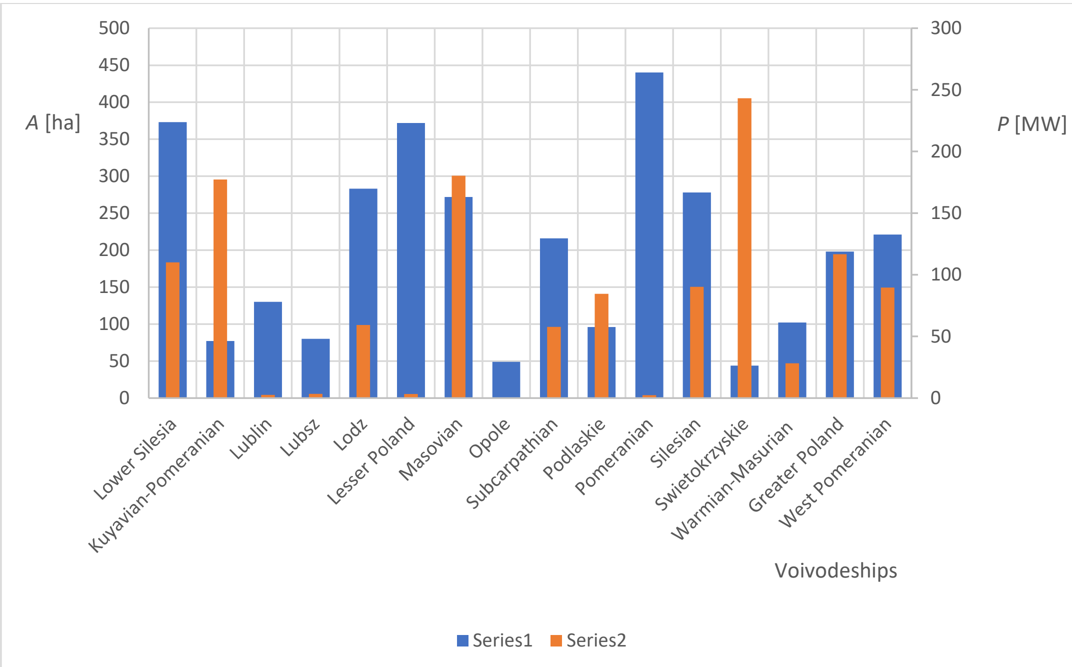

Figure 10. The relationship between the area of agricultural land potentially useful for the cultivation of energy crops (as of 2021) and the regional approach to the installed power from biomass in Poland (own elaboration).

This relationship can be explained by the farmers' competitive offer of material for other needs, which in turn results from the adoption of an unfavorable financing model (subsidies). The highest ratio of the amount of power obtained from biomass per unit area is found in the Holy Cross region.

4. Conclusions

Taking into account biological materials intended for combustion, the following are indicated:

(1) Within the first group of materials, there is large variation in terms of energy usefulness and the degree of difficulty of processing for combustion purposes. Leaves, needles and grass from lawns, while having a relatively high energy value, are often very polluted. Their humidity is also variable, but usually very high. Group I is free from potential concerns related to the limits on their use for energy purposes. However, foresters are trying to increase their share in the biomass inflow to forest soils. The energy value of wood chips after drying is about 17 $MJ \cdot kg^{-1}$ [11]. The cost of obtaining leaves depends on the degree of mechanization of their collection and increases with the involvement of more technical means. The caloric content of the leaves varies depending on the species and the degree of contamination, ranging from 10 to 17 $MJ \cdot kg^{-1}$ [149].

(2) The second group of raw materials is mainly cereal and rapeseed straw. These materials are used both for low-density combustion (cubes from traditional presses), mainly by individual farms, and in the form of cylindrical bales and large-size square bales. The studies conducted and the experiences of producers [11] indicate the deliberate use of simplified, low-cost technologies with limited fertilization and limited use of plant protection products. Thanks to this method of cultivation in light soils, it can be considered beneficial, because the yield of rapeseed straw from 1 ha should be in the range of 2–5 $Mg \cdot ha^{-1}$—it seems realistic to assume a value of 2.5 $Mg \cdot ha^{-1}$. With the assumed capacity and two-shift operation, the capacity of the pelletizing or briquetting line should be about 500 $kg \cdot h^{-1}$. The parameters of pellets and briquettes made of grass straw and sawdust show high stability in properties. Typically, the calorific value oscillates in the range of 15–20 $MJ \cdot kg^{-1}$, and the humidity is in the range of 6–10%. In Polish climatic conditions, it is possible to use these materials for energy purposes, while the remaining maize straw remains after growing maize for grain, the use of which for fodder purposes is ineffective. The large mass of maize straw (10 $Mg\ DM \cdot ha^{-1}$) and its relatively high energy value (approx. 15 $MJ \cdot kg^{-1}$ [143]) make it an attractive energy resource.

(3) The third group of raw materials includes the aforementioned crops, in particular cereals intended for burning in the form of whole plants or parts of the crop, for example, grain alone, chaff, husks and straw with an admixture of harvested weeds. This method is particularly suitable for low-quality grain produced in low-input crops. The cultivation of cereals for energy purposes can be an alternative to fallow land, as well as the cultivation of specialized energy crops. Their cultivation in Poland generally has no tradition, and producers do not have specialized equipment for their harvesting and cultivation, or experience in their cultivation. Often, these plants are also not fully tolerant of the Polish climate. Growing plants for energy purposes can be safe. Burning whole crops is technically problematic because, like straw, they are low-density materials. The exception is grain, the density of which changes relatively little during briquetting or pelleting. Grain can be burned both in small furnaces adapted from eco-pea coal furnaces, and in a condensed form.

(4) The use of renewable energy sources significantly reduces the harmful impact of the power industry on the natural environment, mainly by reducing the emission of harmful substances, especially greenhouse gases [144]. Between 2011 and 2019, there was a very mild decrease in the amount of energy produced in the EU.

(5) The highest indicators of the amount of energy obtained from biogas plants per area unit in Poland were found in Warmian-Masurian, Greater Poland, West Pomeranian and Masovian Voivodeships.
(6) On the scale of Poland, the problem is the ineffective use of potentially available land for cultivation for the purposes of obtaining biomass.

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