




Article

The Role of Agriculture and Rural Areas in the Development of Autonomous Energy Regions in Poland

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Abstract: In many countries, energy security is treated as a priority for the coming decades, and at the same time energy production from the vast majority conventional energy sources does not meet environmental protection criteria. Hence, the need to use renewable energy sources (RES), which can largely satisfy energy needs. The aim of the study was to identify possibilities of creating autonomous energy regions (ARE) in Poland, based on renewable energy sources. Attention was paid to the role and significance of the potential of rural areas in this respect, taking into account the possibilities of increasing energy production from these sources in individual regions of Poland. The research was conducted on a regional level (division into voivodships) and on a local level (division into powiats, which form voivodships). When assessing the potential for constructing ARE based on RES, the following energy sources were taken into account: water, wind, sun, biogas and biomass. It was found that the highest RES potential versus energy consumption can be obtained in powiats where the share of arable land and forests exceeds 80%. The research showed that in most regions of Poland (powiats, voivodships), there is a large potential for obtaining additional energy from RES, which would cover over 73% of the country's demand for electricity. This could be the basis for building energy independence on a local scale. The results of the study indicated that as many as seven regions would become self-sufficient in terms of electricity demand.

Keywords: regional potential; rural areas; renewable energy sources; autonomous energy regions



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1. Introduction

Energy production, like food production, is of strategic importance to every country. At the current stage of development, there is an increasing demand for energy, which affects the socioeconomic development and quality of life of the population [1,2]. In the report *International Energy Outlook*, released by the Energy Information Administration (EIA), it was assumed that by the middle of this century energy consumption will increase by about 50% [3], and only from 2000 to 2018 global energy consumption increased by 48.2% [4]. At the same time, it was emphasized that energy production, in its vast majority, is based on conventional energy carriers [5,6], which poses an increasing threat to the environment [7] and human health, especially children's health [8]. Increased energy consumption determines the competitiveness and growth opportunities of businesses and the well-being of households [9], and as Gielen et al. [10] state, renewable energy can meet two-thirds of total global energy demand, but this will require new technologies and innovations.

Herrington et al. [11] indicate that billions of people worldwide remain without access to modern energy services, most of whom live in rural areas [1,12]. To support the

deployment of such services, local energy solutions must be taken into account [13]. Hence, there is a need to look for innovative solutions to meet growing energy demands [14–16], improving energy security while reducing the negative effects of its production on the environment [17–20], and thus on the health (quality of life) of people. A solution to this search is the development of Autonomous Energy Regions (ARE) based on RES, seen as the construction of energy self-sufficient regions (local development of RES potential, also sometimes referred to as Municipal Energy Centres) that fit into the socio-economic conditions of the development of a given area and their sustainable development [21,22]. As energy production based on RES has a spatial character, a special role in the creation of ARE is played by rural areas, which constitute the dominant part of Poland's area (93%) [23] and endogenous potential related to agriculture and the development of nonagricultural functions of these areas [24,25].

The idea of ARE is in line with the latest global trends of energy distribution based on locally available energy sources that contribute to increased efficiency of the energy system [4,7,26]. Undoubtedly, RES-related technologies are a part of smart technologies and, at the same time, part of the Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. The directive highlights the coupling of the particular importance of rural areas in the development of RES and, vice versa, the development of RES for rural development [27,28].

The need for RES development is widely recognised. The possibility of transmitting energy from remote areas is even indicated to move towards a sustainable, resource-efficient and low-carbon energy system [29]. Müller et al. [30] report that the use of renewable energy sources (RES) in small autonomous (decentralised) power systems can reduce emissions and increase the cost-effectiveness of energy supply. This is confirmed in a study by Marchenko and Solonim [31], which indicates the use of renewable energy sources in autonomous energy supply systems proves to be economically efficient. However, it also highlights that deployment of renewable energy sources is cost-intensive [32,33].

For some renewable sources, electricity production depends on environmental factors such as water resources (hydroelectric power plants) or weather (wind and solar power plants), and, as studies indicate, these resources vary regionally [34–36]. RES, in contrast to conventional power plants, are characterized by a much wider range of net efficiency: from 9% for photovoltaic panels to about 80% for hydroelectric power plants [37]. This lower efficiency (except for hydroelectric power plants) translates into higher costs of energy production in the micro account, which, in the case of RES, should be considered on a macro scale taking into account the theory of public goods. A special feature of public goods related to agriculture and rural areas is the fact that they may be an external effect of agricultural production [38,39], an intentional effect or a common resource held by society [40]. This is particularly important in relation to the creation of autonomous energy regions based on energy from RES.

It is worth emphasizing that in recent years there have been many studies focusing on the description of the renewable energy potential [41] or the dynamics of electricity production from renewable sources in Poland [42]. Some of the works usually focused on one of the renewable sources, such as the description of hydropower resources made by Kowalczyk and Cieśliński at the voivodship level [43] or the energy potential of straw and hay estimated by Jarosz [44] at the municipal level. Therefore, due to different levels of spatial aggregation and selective presentation of particular issues, a need arose to describe the entire potential of renewable energy in the era of the upcoming energy transformation. Research in this field is an important contribution to work on improving the energy policy supporting the development of renewable energy sources as an important factor in improving the quality of the environment and limiting the causes and effects of greenhouse effects.

The aim of the paper is to identify potential possibilities of constructing autonomous energy regions (ARE) in Poland based on renewable energy sources on the basis of diverse

endogenous potential of regions. The main research problem relates to finding an answer to the fundamental question of what role do and can rural areas play in the construction of ARE and in the production of energy from renewable sources in Poland. In particular, we seek to find out:

- The current role of RES in balancing the total energy production in the regions;
- The possibilities for increasing energy production from these sources in individual regions of Poland;
- The current balance of energy production and consumption in each region;
- The status and potential for development of energy production: wind, hydro, biogas, biomass and photovoltaic;
- The potential for energy generation (energy density) from RES per hectare of nonurbanised land (including agricultural land and forests) and per capita.

The opportunities for the ARE development resulting from varied endogenous potential at regional and local levels are still poorly recognised in Poland. Such recognition is important from the point of view of the need to build the ARE development strategy, taking into account the specificity of regions resulting from their endogenous potential as well as from the point of view of the necessary measures supporting the ARE development.

2. Materials and Methods

The research was carried out on a regional basis in Poland. The spatial scope of the research covered all voivodships (regional level) of the country and their powiats (local level). In the projection of the assessment of potential for constructing RES-based ARE, the study was limited to the main sources, namely energy from: water, wind, sun, biogas and biomass. The potential of electricity production from these sources was calculated for each powiat. In the case of biogas and biomass, it was assumed that these raw materials are burned in cogeneration devices with an overall efficiency factor of 65% (this is the lower efficiency limit of devices currently available on the market) [45]. Thus, the obtained values of electricity production from the considered RES were compared with the data included in the balance report of energy carriers and heating infrastructure (G-02b) prepared by Statistics Poland in 2018 [46]. The choice of electricity for the assessment of RES potential and the construction of ARE relates to the fact that it is a form of energy that is significantly more difficult to produce than heat. Therefore, comparing the potential of electricity production from renewable sources against its consumption allows for a more detailed picture of RES potential for individual powiats.

Bearing in mind that some powiats, due to the location of large power plants, may have a considerable surplus of electricity, in further calculations only the consumption of electricity was taken into account excluding the energy industry and lignite mining (lignite-fired power plants and lignite mines are in fact the same complex). The above assumption made it possible to calculate the demand for energy in each of the powiats, disregarding the so-called parasite power from conventional utility power plants. The calculation of electricity production potential was carried out for each renewable energy source separately. Subsequently, their total potential was compared with the current electricity consumption.

2.1. Calculation of Small Hydropower Potential

In Poland, as in the rest of Europe, the construction of large hydropower plants (with a capacity of several hundred MW) is impossible, mainly due to the geographical and ecological conditions. Therefore, the study focuses on the possibility of hydropower development based on the expansion of MEW, which, according to the terminology used in Poland are facilities with an installed capacity of less than 5 MW. In contrast to large hydropower plants, small hydropower plants can be built on existing water stages and the electricity produced in these installations could be used primarily to meet local needs. Most MEW can operate on the basis of an Archimedes turbine using a low water drop of 1–10 m and low flow, so it can be easily seen that they fit perfectly into the hydrological conditions of the country. The potential of MEW was calculated based on Renewable

Energy Sources Transforming Our Regions (RESTOR) Hydro database, which shows that there are more than 6000 sites in Poland suitable for MEW construction [47]. In order to calculate the so-called technical potential, it was assumed that the installations operate with a net efficiency of 80% for 70% of hours in a year [48]. The calculations of the potential of small hydropower plants (MEW) were carried out based on the RESTOR Hydro database taking into account facilities for which the size of the minimum drop exceeds 1.6 m and the annual average flow is not less than $0.1 \text{ m}^3/\text{s}$ [49]. The facilities that were found in the inventory materials as dams that once existed and were decommissioned were not taken into account. In this way, the potential of MEW power was achieved, which was feasible for economic reasons.

2.2. Calculation of Wind Energy Potential

An analysis of the wind energy zone map prepared by the Institute of Meteorology and Water Management—National Research Institute shows that about 60% of Polish territory has favourable conditions for wind energy development [50]. Wind has the largest share in energy production from renewable sources. Onshore wind power is currently the cheapest new energy generation technology in Poland [51]. The installed capacity of wind farms was over 6.7 GW in March 2021 [52]. However, it should be remembered that a large part of such areas is excluded from the possibility of their use by various forms of nature protection, e.g., national parks and their buffer zones, landscape parks and Natura 2000 areas [53]. Buildings or inaccessibility of the terrain (mountainous areas, swampy areas or dense forest complexes) are also a limitation. The factor of the so-called roughness of the terrain, which is determined mainly by the proximity of forest complexes and buildings, is indicated as very important [54]. In practice, the introduction of the so-called 10H rule [55], under which the permissible distance of a windmill from residential buildings is to be equal to or greater than ten times the height of the wind turbine measured from ground level to the highest point of the windmill, including the rotor with blades, has limited the possibility of building new wind turbines in Poland.

Furthermore, an important aspect recently raised in public discussion is the impact on human health. Negative factors include the stroboscopic effect [56] and noise caused by rotor blades in operation [57–59]. The above-mentioned factors make it necessary to locate wind turbines at a distance of at least 500 m from the nearest buildings or terrain obstacles. In our calculations, the condition of roughness of the terrain was taken into account, among other things, by eliminating all cities with powiat rights. An important limitation is also the accessibility to the energy network and the possibilities of connecting the power.

Applying the above restrictions, a list of 257 powiats with areas convenient from the point of view of wind energy was obtained, then only powiats where the wind power exceeds $750 \text{ kWh}/\text{m}^2/\text{year}$ were taken into account (i.e., areas ranging from extremely favourable to favourable wind energy zones in Poland). As a result, a list of 102 powiats was obtained in which the construction of wind turbines with the use of current technologies would be profitable (marked with a windmill symbol in Figure 1). Taking into account the average power of wind turbines built in Poland so far, $\sim 2.2 \text{ MW}$, and an average effective onshore working time of up to 22% hours per year (according to PSE—Polish Power Grid Company), it was calculated that the total value of electricity production would reach 17,498 GWh, which would cover more than 10.3% of electricity production in 2018. Subsequently, the potential of wind electricity production was divided by electricity consumption (G-02b report, Statistics Poland), which allowed for a more accurate assessment of the importance of wind energy at the powiat level.

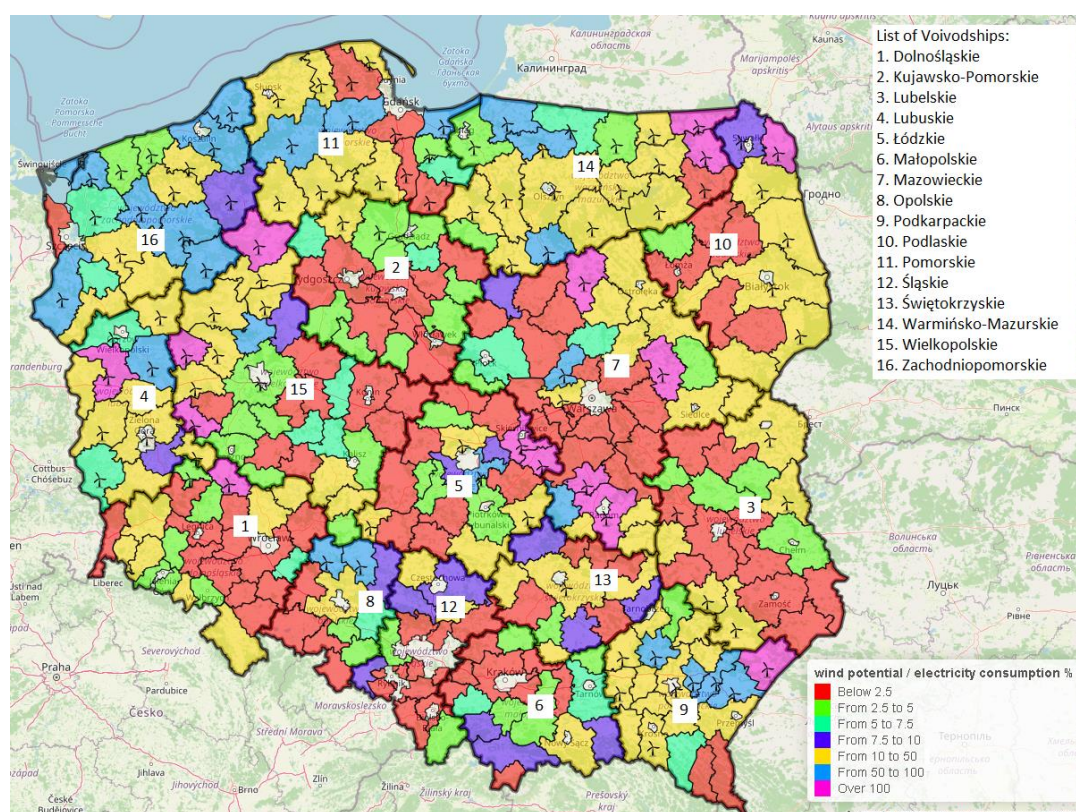


Figure 1. Wind energy potential relative to electricity consumption in 2018, powiats meeting the criteria necessary for wind energy development are marked with a windmill symbol. Source: own study.

2.3. Methods for Calculating Solar Energy Potential

In the case of our country, 80% of the total annual amount of insolation falls on the spring and summer term, from the beginning of April to the end of September. This means that the energy obtained from this source will not be evenly distributed over time, and the highest yield is achieved in the period from spring to autumn. This study focuses on the possibility of using solar energy to generate electricity (using photovoltaic cells). The most important value for the potential energy yield is insolation. Monthly sums of insolation for particular voivodships were used in the calculations, obtained with the help of the solar radiation potential distribution taken from the Atlas of the Republic of Poland [60]. On average, in Poland, each square meter of land (horizontal area) receives annually from 950 kWh to 1160 kWh in the form of solar radiation. In the case of direct radiation reaching directly from the solar disk, the optimal use of the absorbing surface would require that such surface be oriented perpendicular to the direction of the radiation. In practice, it is unrealistic in the latitudes of Poland. Therefore, it is necessary to select the installation inclination in the optimal angle to the incident radiation, which would allow for the highest energy yields and proper operation of the installation. For the purposes of the calculations, it was assumed that the inclination of the installation at an optimal angle in relation to the incident radiation is in the range of 25 to 40 degrees for the southern regions of the country and from 30 to 50 degrees in the north of Poland, such an arrangement ensures the most effective use of solar energy [61]. Next, the average cycle of the length of the day in the following months of the year was taken into account, based on the data of the Central Office of Measures [62] and the changes in insolation, which are influenced by meteorological conditions (Institute of Meteorology and Water Management). Moreover, the calculations take into account the influence of the orientation of photovoltaic modules in relation to the directions of the world (for the southern orientation, the average energy production reaches 3300 kWh/year, while for the northern orientation it is only 1900 kWh/year) [63]. When

calculating the technical potential, it was assumed that electricity would be produced by monocrystalline silicon cells with an average standard efficiency of 15%. In real conditions, with the panels facing south at the optimal all-year angle, the average annual efficiency is in the range from 55% to 60% of the normative efficiency. For a monocrystalline silicon cell with a normative efficiency of 15%, this means an average annual efficiency of about 9%.

When calculating the potential of solar energy, the focus was on the possibility of generating solar energy on the premises of photovoltaic farms and investigating the potential related to the use of this type of installation in the case of single-family buildings (so-called microinstallations). Pursuant to the legal requirements, solar farms may be built only in areas with IV or lower valuation class, as well as on wastelands. In this study, it was assumed that farms may be located on wasteland, but excluding meadows and pastures, and in order not to compete with agricultural crops, they should not occupy more than one tenth of the wasteland [64]. Due to the terrain (e.g., slope inclination, shading, exposure direction) and the possibility of connecting to the electric network, the area of wastelands that could be used in each of the powiats was a subject to further restrictions. In the case of home photovoltaic installations it was assumed that the most frequently used place for investment is the roof of a building with an area of approx. 25 m², a slope of 35 degrees and southern exposure [63].

2.4. Calculation of Biogas Potential

The basis for the calculation of biogas potential was statistical data from Statistics Poland concerning agriculture and waste management [65]. When calculating the biogas potential, the possibility of its production from organic waste in landfills, animal and plant waste in farms and sludge in sewage treatment plants was taken into account. Under optimal conditions, about 400–500 m³ of biogas can be produced from one tonne of municipal waste. However, in reality not all organic waste is fully decomposed and the fermentation process depends on many factors. Therefore, in calculations it is assumed that a maximum of 200 m³ of biogas can be obtained from one tonne of waste [66].

Livestock farms generate significant amounts of waste that can be used for biogas production. The potential of agricultural biogas production is determined mainly by the amount of agricultural waste available [67]. In conducted calculations it was assumed that from 1 m³ of liquid faeces it is possible to obtain 20 m³ of biogas on average, and from 1 m³ of manure, 30 m³ of biogas [49]. The analysed data included the livestock by species (cattle, pigs, horses, sheep, poultry, goats) and performance groups and the average annual production volumes, natural fertilisers depending on the animal species, its age and performance and the housing system. In order to calculate biogas emission from manure originating from individual animal species, a study prepared by the Zootechnics Institute was used [68].

Sludge from sewage treatment plants is also used for biogas production. In order to calculate biogas emissions from the treatment plant, it was assumed that 100 m³ of biogas can be obtained from 1000 m³ of incoming sewage [69].

Another source that can be used for biogas production is agricultural crops [70,71]. In the calculations, only losses and wastage of agricultural crops were taken into account, such as: basic cereals with mixtures, potatoes, vegetables, fruit, maize, legumes and oil plants. Data on losses and wastage of these crops were taken from the Agricultural Statistical Yearbooks of Statistics Poland [72]. On the other hand, data taken from [73,74] were used to estimate the amount of biogas obtainable from plant biomass.

2.5. Calculation of Biomass Potential

For the estimation of biomass potential, it was assumed that it would come from crop production; including straw surpluses, hay surpluses, energy crops, orchards, forestry production as well as annual prefelling and tending cuts. In calculating the potential offered by the wood industry, the methodology proposed by Bujakowski [49] was used:

- One hectare of forest may yield 45 tonnes of wood, this amount is assumed for 1% of the forest area, furthermore it is assumed that 12 tonnes of wood may be harvested from one hectare of forest from pre-cutting and tending cuts, and this amount refers to 5% of the forest area.
- For every 100 m³ of wood mass harvested in the forest, after deducting 36 m³ of sawn wood for finished wood products, it is assumed that the remaining 64 m³ of wood mass can be used for energy purposes.

The formula [75,76] was used to assess the surplus straw available for energy use:

$$N = P - (Z_s + Z_p + Z_n) \quad (1)$$

where: N—surplus straw for nonagricultural use (tonnes), P—volume of cereal straw production (tonnes), Z_s—straw demand for bedding (tonnes), Z_p—straw demand for fodder (tonnes), Z_n—straw demand for ploughing (tonnes).

In calculating the volume of straw production, demand for fodder, litter and ploughing, the methodology used in Hryniewicz's work [77] was used. In the case of straw shortages in individual powiats, it was assumed that they are supplemented by "imports" from neighbouring powiats having surpluses of this raw material. Then, the estimated straw surplus was converted into energy, assuming that 1 ton of straw with 15% moisture content has a calorific value of 13.1 GJ [44].

Despite being less popular, as indicated by Pudełko [78], surplus hay is also a significant biomass resource, which counts in potential use for energy purposes. In order to calculate the hay surplus, the statistical data of Statistics Poland covering the harvest of permanent meadows and permanent pastures, the population of ruminants (cattle, horses, sheep, goats) and their annual demand for fodder were used [79]. The problem of hay shortages in individual powiats was solved using the same assumption as for straw. The estimated hay surplus was converted into energy by assuming that 1 tonne of hay with 15% moisture content has a calorific value of 13.4 GJ [44].

An important role among the potential resources of solid biomass is also played by energy crops (willow, miscanthus, sida hermaphrodita, poplar). The analysis of the potential from energy plantations was carried out on the basis of statistical data from Statistics Poland and information obtained from the Agency for Restructuring and Modernisation of Agriculture (ARiMR) [80]. The potential of energy crops was calculated using the equation [44]:

$$P_w = [P_e + (P_g \cdot w_e)] \cdot Y_e, \quad (2)$$

where: P_w—potential of perennial energy crops (tonne), P_e—area of existing plantations of perennial energy crops (ha), P_g—sum of land of the soil quality class V, VI and VIz bonitation class (ha), w_e—land use coefficient for perennial energy crops (%), Y_e—average perennial yield (tonne/ha).

In the calculations, the w_e value equal to 1/10 was assumed as a safe limit eliminating competition between the production of raw materials and production for food purposes [81]. For the purpose of calculations, it was also assumed that in the case of marginal soils, the average yield will be at the level of 7.5 tonnes/ha [82], while the energy value was assumed at the average level of 17 MJ/kg [83]. When calculating the biomass potential, the biomass obtainable from orchard stand maintenance and replacement was also taken into account; for the purpose of the calculations, it was assumed that 3 tonnes of dry matter could be obtained from one hectare of orchard per year [84].

2.6. Ranking of Voivodships

At a further stage of the work, the level of utilisation of renewable energy sources was assessed using the TOPSIS method (Technique for Order Preference by Similarity to an Ideal Solution) in positional terms with the application of Weber's spatial median [85,86]. The TOPSIS method is based on the idea of constructing a synthetic pattern and antipattern of

values of diagnostic features and enables synthetic evaluation of a phenomenon described by many features.

3. Results

3.1. Small Hydropower Potential

Water is essential in the production of electricity. According to Statistics Poland data, generation and supply of electricity, gas, steam and hot water consumed 6284.4 hm³ of water in 2018, which accounted for more than 66.5% of the total water withdrawal in Poland. For comparison, the EU average in 2018 was 13.7% [87]. According to the Energy Regulatory Office, in 2018, in Poland there were 586 small hydropower plants (SHP) with an installed capacity of up to 300 kW, 96 hydropower plants with an installed capacity of up to 1 MW, 68 hydropower plants with an installed capacity of up to 5 MW, and 20 with a capacity greater than 5 MW. In 2018, the total electricity production of hydroelectric power stations was 2.387 TWh, which accounted for more than 1.4% of the total electricity production in Poland. According to some studies, this is only 20% of the energy potential of Polish rivers. Thus, the maximum use of the energy of falling water would cover about 7% of current electricity consumption [88]. Thus, hydropower in Poland can only play a supporting role, offering a stable (compared to, e.g., wind or sun) power source.

The results of calculations show that the activation of the SHP potential consisting of more than 6000 facilities would allow the production of 584 GWh of electricity, which would account for only 0.34% of energy production in 2018. On the other hand, the potential of SHP in covering electricity consumption for most powiats in Poland would be at the level of <1%. The situation was more favourable in the eastern and northern parts of the country. This was mainly due to low energy consumption in areas where there are no energy-intensive industries. Thus, as can be seen, the potential of small hydropower cannot solve Poland's energy problems, but the development of SHP and construction of small water reservoirs would have a beneficial effect on increasing water retention. This is especially important in the central part of Poland threatened by desertification/stagnation, as pointed out by Kowalczak [89] and Kudlicki [90]. The construction of MEW would allow, first of all, to rebuild the country's water resources (the so-called small retention), greatly needed both by agriculture and the "traditional" coal-burning power industry.

3.2. Wind Energy Potential

In the calculations of wind potential the most important factors limiting the development of onshore wind energy were taken into account. Figure 1 presents the differentiation of Poland's areas (broken down into powiats) with respect to wind energy production possibilities by establishing the wind potential in relation to electricity consumption. The largest wind energy potential is found in the powiats located in the western, north-western and north-eastern parts of the country. Powiats in Świętokrzyskie and Podkarpackie voivodships also belong to the group of areas with significant wind energy potential. It should be noted that the high share of wind energy in meeting the demand for electricity in individual powiats results not only from favourable natural conditions (high average annual wind power and low roughness coefficient), but primarily from low electricity consumption in these powiats.

When broken down by voivodships, the largest wind energy potential is found in Pomorskie voivodship (2258 GWh/year), while the smallest in Śląskie voivodship. It is worth noting that, according to PSE data, in the same year wind energy covered over 7.6% of the electricity demand, while in 2019 it was over 9.2%. Summing up, the results of our calculations show that the developmental potential of this branch of renewable energy in the inland part of the country is close to exhaustion, while taking into account the good wind conditions, it can be seen that the decisions on the location of this type of investment in the Baltic Sea are perfectly justified. Due to the emergence of new technologies allowing the storage of energy from renewable sources, the sense of building wind power plants acquires new importance, as indicated by Watson et al. [91]. A good example is the CO₂ methanation

system for storing electricity through SNG (substitute natural gas) production [92]. It is indicated that this kind of solution would stabilise the operation of wind turbines through energy storage [93].

3.3. Solar Energy Potential

The obtained results indicate that, on a national scale, large-scale PV farms could produce 10,592 GWh of electricity per year, while the potential of domestic PV micro-installations reached 430.9 GWh per year. The total potential of Polish photovoltaic installations is estimated at 11,022.9 GWh per year, which corresponds to 6.48% of the electricity production in 2018 [23]. The results of the calculation by powiats are presented in Figure 2.

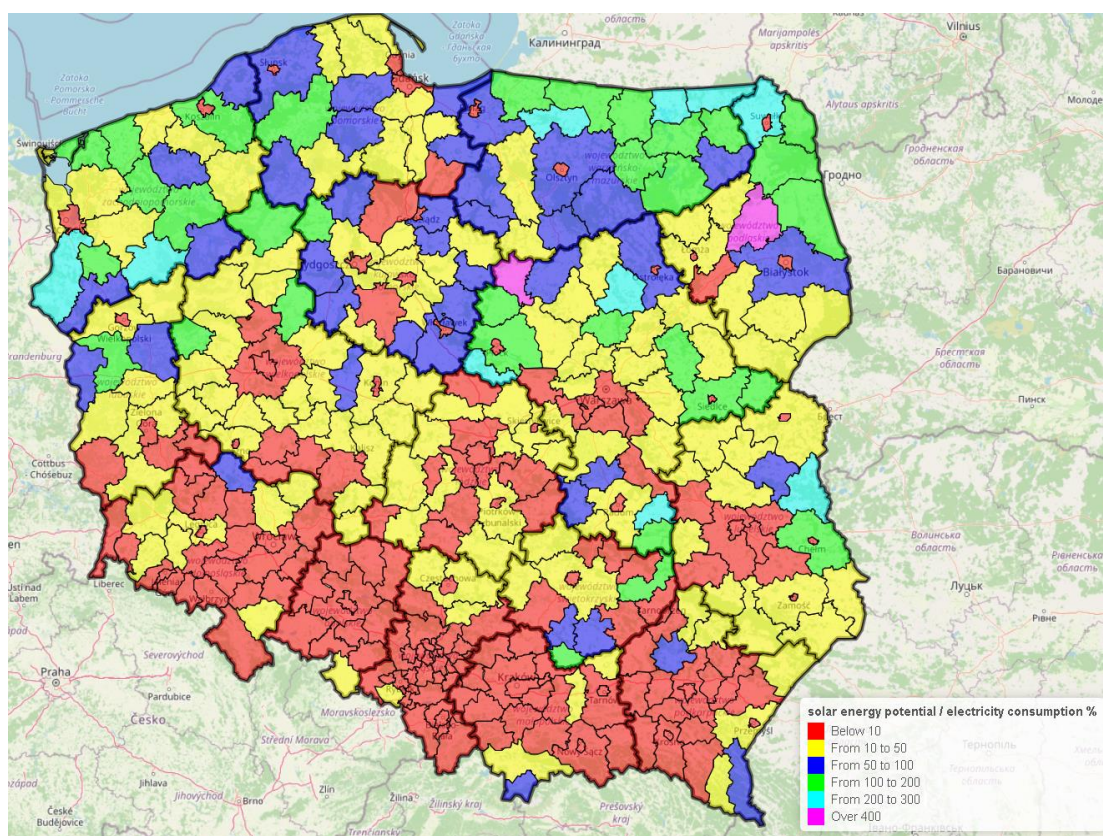


Figure 2. Solar energy potential relative to electricity consumption in 2018. Source: own study.

As can be seen in Figure 2 for most powiats the calculated solar energy potential did not exceed 10% of electricity consumption. In the scale of voivodships the leader in solar energy potential is still Zachodniopomorskie voivodship (1682 GWh/year), while the smallest potential is in Opolskie voivodship (101 GWh/year). However, the potential of solar energy is more significant in the northern and northeastern parts of Poland. This is partly due to the fact that, with the exception of urban centres, energy-intensive industries are mainly located in the central and southern parts of the country.

3.4. Biogas Potential

The biogas production potential was calculated according to the methodology presented in subchapter 2. Further, in order to calculate electricity production, it was assumed that 2.1 kWh of electricity can be produced in cogeneration from 1 m³ of biogas [94]. The obtained results were compared with the data of Statistics Poland for 2018 included in the balance report on energy carriers and heating infrastructure (G-02b). They were further presented in graphical form in Figure 3.

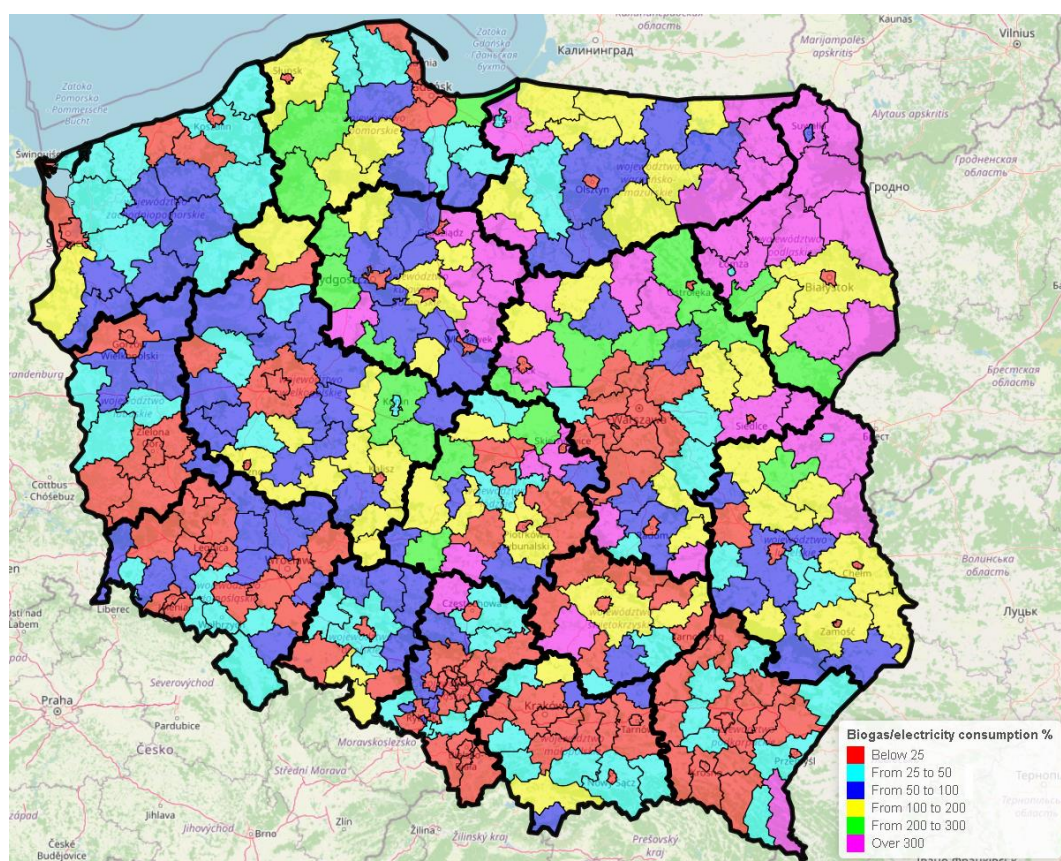


Figure 3. Electricity demand coverage through biogas electricity generation in 2018. Source: own study.

The results of Table 1 (Chapter 3.6) indicate that on a national scale biogas energy production could cover more than 11% of electricity consumption, while in the case of the voivodships, Podlaskie voivodship remains the leader, where biogas energy production could cover almost 53% of electricity consumption. This is mainly connected with intensive cattle breeding in that region, but also with the lack of energy-intensive industries. Warmińsko-Mazurskie (27.8%) and Wielkopolskie (21.4%) voivodships also have a high potential of biogas energy production, which is also connected with intensive agricultural production in those areas.

The smallest potential in terms of biogas production is shown by Śląskie voivodship (3.6%), whose biogas production potential is more than double that of Podlaskie voivodship, but the consumption of natural gas due to the heavy industry located there is more than 11 times higher. When analysing the structure of biogas production sources it can be seen that natural fertilisers, especially cattle manure, have the greatest potential in its creation, as also indicated by Sefeedpari et al. [95]. According to our calculations, on a national scale cattle manure can cover more than 81% of biogas production from natural fertilizers. In the case of Podlaskie voivodship even 96%, which results from the highest cattle density in the country: 93.9 heads/ha [23]. The results of our calculations indicate that in the case of using biogas for electricity production, only 42 powiats with a developed agricultural economy could achieve energy independence.

Table 1. Relative potential to electricity consumption in 2018.

Voivodships	RES Potential [GWh/Year]				Share of RES Potential in Total Consumption [%]			
	WWS (Water + Wind + Sun)	Bg (Biogas)	Bm (Biomass)	WWSBgBm (Water + Wind + Sun + Biogas + Biomass)	WWS/Total Consumption	Bg/Total Consumption	Bm/Total Consumption	WWSBgBm Total Consumption
Dolnośląskie	358.75	660.31	3656.89	4675.94	3.45	6.35	35.16	44.95
Kujawsko-Pomorskie	1012.58	1011.20	2758.11	4781.89	15.78	15.76	42.98	74.52
Lubelskie	1412.84	705.21	3398.27	5516.32	26.67	13.31	64.16	104.15
Lubuskie	1373.73	295.40	2694.20	4363.33	46.63	10.03	91.44	148.10
Łódzkie	2027.25	1000.05	2126.65	5153.95	24.82	12.24	26.04	63.10
Małopolskie	340.43	745.80	1828.58	2914.80	3.41	7.46	18.29	29.16
Mazowieckie	2015.53	2298.34	5157.81	9471.68	8.01	9.14	20.51	37.66
Opolskie	405.93	362.03	1833.81	2601.76	11.65	10.39	52.62	74.65
Podkarpackie	4969.47	351.82	3585.95	8907.23	123.66	8.75	89.23	221.65
Podlaskie	2140.90	1328.49	2145.55	5614.95	85.37	52.97	85.55	223.90
Pomorskie	3259.70	642.14	5198.66	9100.50	48.79	9.61	77.80	136.20
Śląskie	389.06	711.06	1774.33	2874.45	1.99	3.64	9.07	14.70
Świętokrzyskie	240.87	335.64	1536.30	2112.81	5.90	8.22	37.63	51.75
Warmińsko-Mazurskie	3238.66	797.55	3405.22	7441.43	113.00	27.83	118.81	259.64
Wielkopolskie	2542.59	2147.49	4006.33	8696.40	25.40	21.45	40.01	86.86
Zachodniopomorskie	3353.21	493.99	4053.75	7900.95	80.61	11.88	97.45	189.93
Poland	29,081.50	13,886.49	49,160.41	92,128.40	23.12	11.04	39.10	73.27

Source: own study.

3.5. Solid Biomass Potential

The solid biomass potential was determined according to the methodology presented in Chapter 2. The results obtained by powiats are presented in graphic form in Figure 4.

As in the case of the renewable sources mentioned above, also in the case of solid biomass there is a clear tendency for powiats with the highest potential to be located in the eastern and northern parts of the country, i.e., regions where energy-intensive industries are found mainly in large urban centres. At the voivodship level, Pomorskie voivodship remains the leader in terms of solid biomass potential (5198 GWh/year), while Świętokrzyskie voivodship is characterised by the lowest potential (1536 GWh/year). More than 63% of solid biomass potential in the country is based on wood that is post-production waste, the result of cultivation operations or cutting for energy purposes. The second source, reaching 15% in the scale of the country, are energy crops (e.g., willow, miscanthus). In this case, according to the methodology used, their potential is related to the area of the weakest land—the soil quality class V, VI and VIz. The third source on the national scale is straw (~13.6%), in the case of Opolskie voivodship its share can reach over 45%, while for Podlaskie voivodship it is only 0.5%, which is due to, inter alia, differences in the intensity of keeping animals (mainly cattle) in these regions.

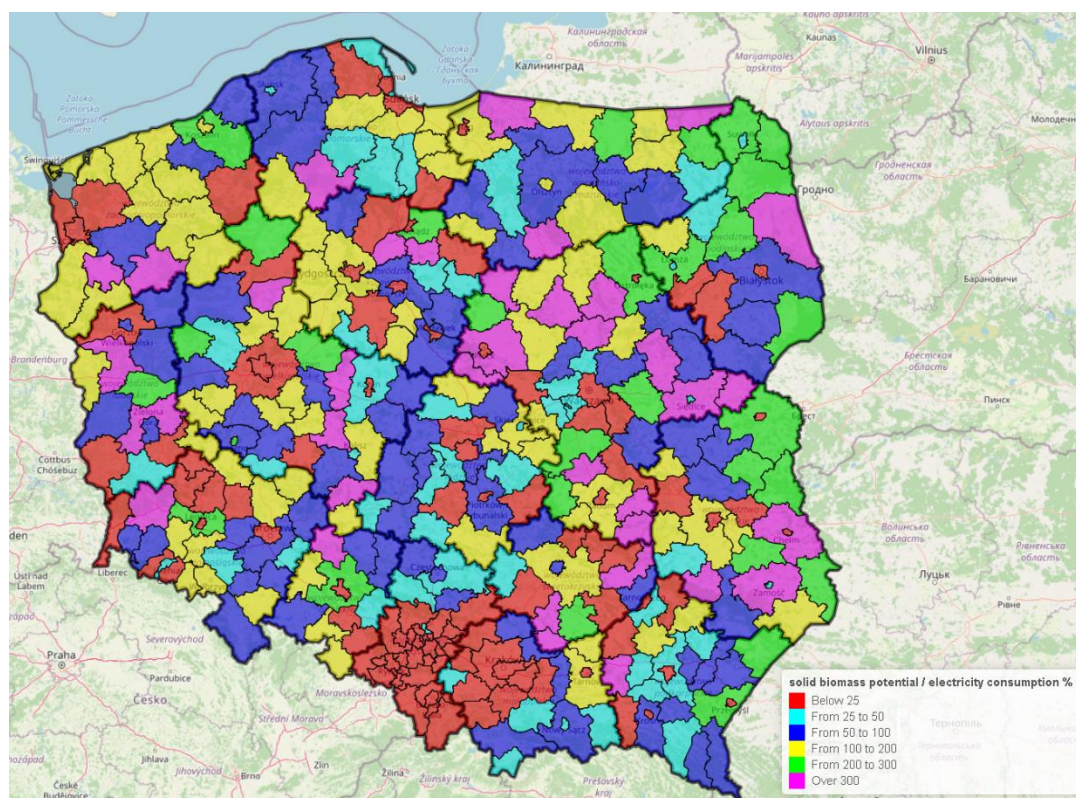


Figure 4. Electricity demand coverage through solid biomass electricity generation. Source: own study.

3.6. Total Potential of Renewable Sources

Our calculations showed that mobilising the potentials of wind, sun and water would cover over 23% of electricity demand, biogas combustion would cover over 11% of demand, while the use of solid biomass alone could cover over 39% of electricity consumption nationwide. In total, the renewable sources considered would cover more than 73% of electricity demand (Table 1).

The results presented in Table 1 indicate that, on a national scale, electricity production based on biomass resources could cover nearly 50% of demand. The importance of agriculture and forestry in building RES potential becomes more visible at the level of powiats. The data presented in Figure 5 imply that the biggest RES potential was found in powiats where the percentage share of agricultural land and forests in the total area of the powiat exceeded 80%. Out of the total number of 380 studied powiats, as many as 220 (57.9%) had RES potential exceeding their own demand for electricity. From this group as many as 214 powiats (56.3%) had a percentage share of agricultural land and forests exceeding 80%. It is worth noting that in the case of 25 powiats RES potential exceeded the demand for electricity more than 10 times. In Figure 5, powiats from Śląskie voivodship, characterized by the lowest RES potential (14.7%), are marked with green colour, while powiats from Warmińsko-Mazurskie voivodship, possessing a high surplus of RES potential (259.64%), are marked with blue colour.

Powiats from other voivodships are marked in red. As can be seen in Figure 5, only one powiat (city of Elbląg) from Warmińsko-Mazurskie voivodship would not be able to cover its total demand for electricity on the basis of RES potential. The situation is different in the case of Śląskie voivodship, where only one of the powiats shows RES potential exceeding the electricity consumption. It is worth noting that in the case of most of the powiats in Śląskie voivodship the share of arable land and forest land did not exceed 80%, which negatively influences the building of RES potential.

Spatial diversification of RES potential is also presented in Figure 6, where it can be seen that most of the powiats with low RES potential (<100%) are located in the southern

and central part of the country (mainly Śląskie, Małopolskie and Opolskie voivodships). Moreover, the majority of cities with powiats status, regardless of the size of area, number of inhabitants or type of prevailing economic activity show RES potential below 50%. The powiats with the highest RES potential are mostly located in the northern and eastern part of the country.

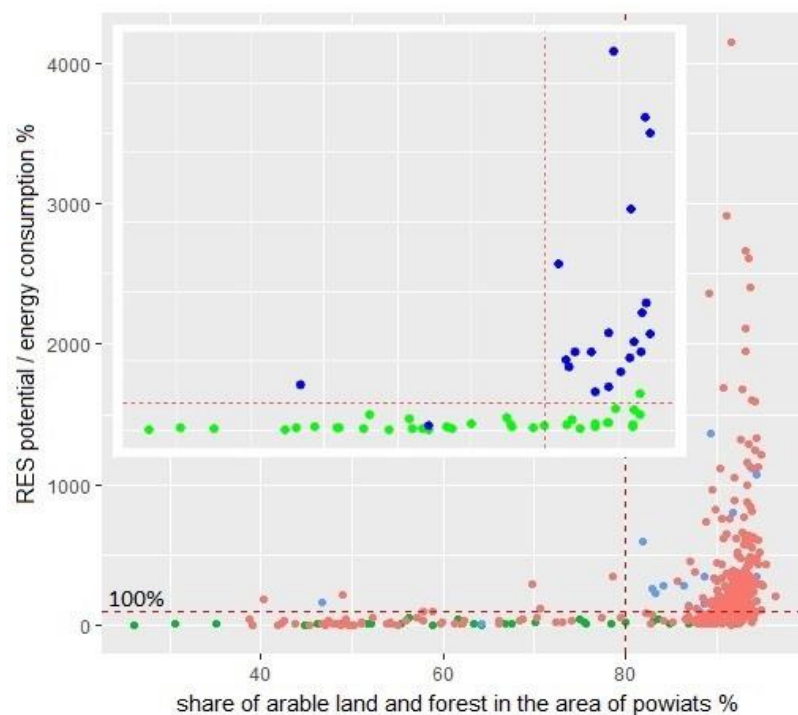


Figure 5. Dependence of RES potential on forest and agricultural land area at powiat level. In the upper left corner only powiats from the Warmińsko-Mazurskie and Śląskie voivodships. Source: own study.

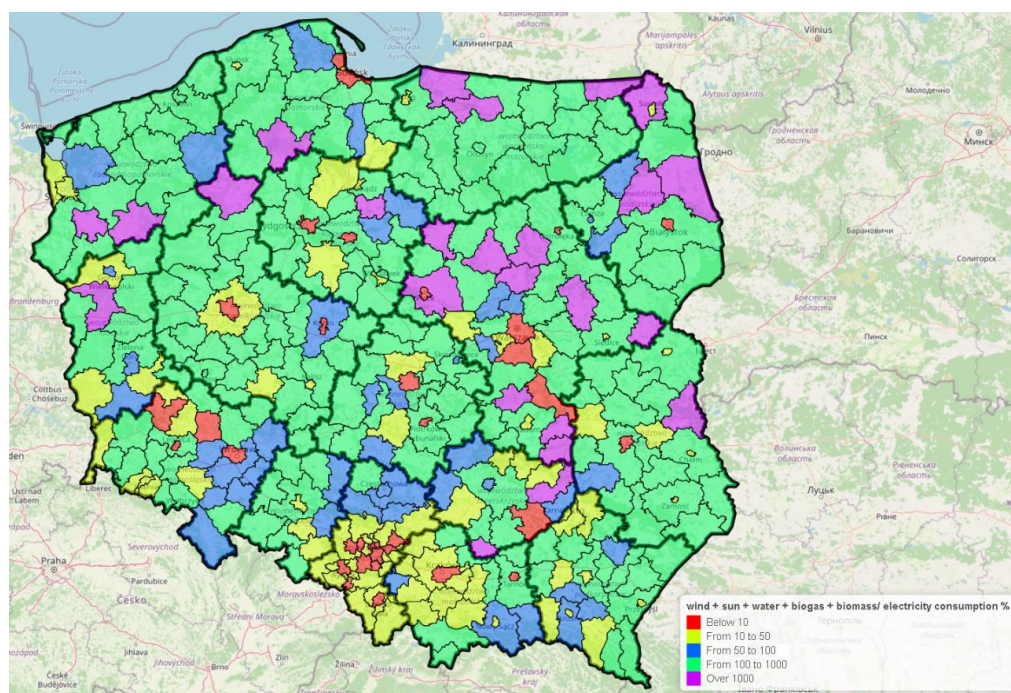


Figure 6. Total RES potential relative to electricity consumption in 2018. Source: own study.

Subsequently, a ranking of voivodships was prepared using the TOPSIS method. The results of the calculations allowed not only to establish the ranking of voivodships using renewable energy sources in 2018, but also allowed to compare them with RES potential available for use. When preparing the ranking of voivodships, the following indicators were taken into account: RES potential in relation to electricity consumption, RES potential in relation to arable land and forest area, and RES potential in relation to population. The obtained results are presented in Table 2.

Table 2. Ranking of voivodships according to TOPSIS with renewable energy production and production potential.

Voivodships	Year 2018			Unleashing the Full Potential			Current Utilisation of RES Potential [%]
	Energy Production from Renewable Energy Sources [GWh]	Topsis	Share of Renewable Energy in Electricity Consumption [%]	Sun, Wind, Water, Biogas, Biomass [GWh]	Topsis	Share of Renewable Energy in Electricity Consumption [%]	
Dolnośląskie	644.3	14	6.02	4675.9	13	44.9	13.8
Kujawsko-Pomorskie	3311.2	2	39.74	4781.9	11	74.5	69.2
Lubelskie	473.3	16	8.29	5516.3	9	104.2	8.6
Lubuskie	655.1	7	17.53	4363.3	5	148.1	15.0
Łódzkie	1466.1	6	17.91	5153.9	10	63.1	28.5
Małopolskie	413.1	15	3.25	2914.8	16	29.2	14.2
Mazowieckie	1450.2	10	5.87	9471.7	8	37.7	15.3
Opolskie	521.6	12	11.03	2601.8	12	74.7	20.1
Podkarpackie	568.8	13	10.43	8907.2	1	221.7	6.4
Podlaskie	717.5	11	23.49	5614.9	6	223.9	12.8
Pomorskie	2104.2	4	27.44	9100.5	2	136.2	23.1
Śląskie	803.1	9	3.96	2874.5	15	14.7	27.9
Świętokrzyskie	1822.1	3	41.32	2112.8	14	51.8	86.2
Warmińsko-Mazurskie	969.2	8	24.79	7441.4	4	259.6	13.0
Wielkopolskie	2092.6	5	18.57	8696.4	7	86.9	24.1
Zachodniopomorskie	3604.8	1	64.27	7900.9	3	189.9	45.6
Poland	21,617.2	x	15.39	92,128.4	x	73.3	23.5

Source: own study.

In 2018, the leaders in terms of electricity production from renewable sources were the following voivodships: Zachodniopomorskie, Kujawsko-Pomorskie, Świętokrzyskie and Pomorskie, respectively. On the other hand, in the case of “unleashing” RES potential, the following voivodships would become the leaders: Podkarpackie, Pomorskie, Zachodniopomorskie and Warmińsko-Mazurskie. In this situation, Świętokrzyskie and Kujawsko-Pomorskie voivodships would record the largest drops, from third to 14th place and from second to 11th place, respectively. Thus, the regions that in 2018 were characterised by the best use of RES potential would record the largest decrease, respectively: 86.24% (Świętokrzyskie voivodship) and 69.2% (Kujawsko-Pomorskie voivodship).

According to the ranking of voivodships, which takes into account the activation of the total RES potential, Podkarpackie voivodship would be the biggest beneficiary (promotion from 13th place to first place). In the case of this voivodship, RES could jointly cover over 221%, of which energy from wind, solar radiation and falling water could cover over 123% of electricity consumption. A further 98% of the surplus could come from biomass and biogas combustion. The situation is similar in the case of Warmińsko-Mazurskie voivodship, where wind, sun and water could cover more than 113% of electricity demand. In the case of the remaining voivodships: Lubelskie, Lubuskie, Podlaskie, Pomorskie and Zachodniopomorskie, achieving self-sufficiency would be possible only through the activation of all discussed RES.

3.7. Discussion

The issue of ARE development in Poland at the regional and local level is relatively poorly recognised. This was pointed out by Maśloch et al. [2] in their publications, that indicate the lack of proposals for regional development directions in terms of autonomous energy regions, but their research referred to only one region—Mazowieckie voivodship. A comprehensive assessment at the level of voivodships was made by a team of experts led by Wiśniewski [96], drawing the conclusion already in 2011 that regions in Poland have a huge, only slightly used technical and economic potential of renewable energy resources. The authors predicted that even taking into account environmental and spatial constraints, the existing potential makes it possible to cover at least 20% of the country's energy needs by 2020, and will ultimately make it possible to ensure 100% of the energy supply comes from renewable energy resources available in the country. Our research for 2018 indicates that the existing RES potential would cover more than 73% of the country's electricity needs, significantly more than the projections.

The spatial variation of RES potential has also been studied in other countries. In Romania, research in this area was conducted by Benedek et al. [27]. The results referred to the potential of three main renewable energy sources—solar, wind and biomass. The authors mapped the renewable energy potential indicating that the use of local RES resources is a development opportunity for farmers, wood producers, technology providers and small and medium-sized enterprises. The great importance of wood waste is indicated by Borzęcki et al. [97] taking into account its spatial distribution and determining the potential in the NUTS-2 regions of the EU-28. The total potential of this waste is about 7.85% of the estimated waste biomass and by-products of the European Union, which represents a significant fraction suitable for recycling or use in biofuel production.

On the other hand, Hartmann and coworkers [98] analysed the issue of wind energy in Hungary noting the need to find ways to maximise the use of locally available resources. The authors point out the great importance of local resources due to the emergence of more and more energy saving buildings and renewable energy resources. The use of local resources would enable the potential to be used more efficiently, but, as they point out, geospatial potential for wind energy is not an easy task to accomplish in the absence of accurate data in remote and extensive areas. The results of this research also show this problem.

Research on identifying the most favourable locations for wind generators was conducted by Potić et al. [99] in Serbia. The researchers considered the issue of how to select the best locations for renewable energy investments and minimise environmental impacts. Similar to our study, they showed that alternative energy sources represent a great potential as a solution to the energy crisis and their advantage over other energy sources is their wide availability.

As shown by Godlewska-Majkowska and Komor [100], access to energy and energy management, especially in rural areas, increase the locational advantages and reduce the economic risk of farming, which contributes to increasing the sustainability of agricultural production. This is of particular importance in rural areas in Poland, which in the past were dominated by state-owned agricultural and cooperative enterprises. The authors showed the significant influence of the energy factor on investment attractiveness at the local level.

An interesting study was conducted by Scaramuzzino and team [101] grouping the EU-28 regions and Switzerland into 17 clusters in terms of renewable energy potential. The results show a heterogeneous distribution of potential across countries, but there are cross-border similarities in the distribution of renewable energy potential. Poland, the Czech Republic and the Baltic States were included in cluster 2 forming the East European plain, with low renewable energy potential. However, our research indicates that the importance of renewable energy in the Polish economy is growing and the potential is significant, only the share of RES in energy production is still low. This is important because the use of renewable resources as energy sources is a factor that improves the security of energy supply, as indicated by Zhu et al. [102]. This is pointed out by Islam et al. [103] stating

that renewable energy sources are becoming more common as more electricity generation is needed and renewable energy sources could provide half of the total energy demand by 2050.

In recent years, in Western Europe, mainly in Germany, a very rapid development of biogas plants has been observed (annual production reached 10 billion m³). This is due to the consistently conducted energy transformation and the need to diversify supplies (the German economy consumes over 87 billion m³ of natural gas annually) [104]. Poland, with an annual production of ~0.48 billion m³ in 2018, is at the beginning of this road [105]. According to calculations, the use of such sources as natural fertilizers, plant production waste, landfills and sewage treatment plants could provide over 6.6 billion m³ of biogas (i.e., approximately 4.3 billion m³ of methane) annually. This would cover about 25% of the demand for natural gas (according to the Statistics Poland in 2018, natural gas consumption was 17.2 billion m³). Therefore, it would be a very important support for the national economy in the era of energy transformation. The results of our calculations show that this type of energy production would cover over 11% of the electricity demand in the country (Table 1). According to Statistics Poland, in 2018 for Podlaskie voivodship, the share of renewable energy in energy production reached 68%, while for Warmińsko-Mazurskie voivodship, it was over 82%. These voivodships have become leaders in the development of renewable energy sources in the country, mainly due to the intensive development of wind energy and solid biomass combustion (Białystok power plant). Such a large share of renewable energy sources may suggest that they are close to achieving full energy transformation, however, taking into account the fact that biogas potential has not been released so far, one can risk a statement that they are only at the initial stage of transformation leading not only to energy independence (ARE on a voivodship scale), but also to become exporters of energy/gas. While investigating the potential of solid biomass, it was noticed that large power plants with units specialized in biomass combustion can exert a significant influence on the local energy policy aimed at the use of local resources of solid biomass. A good example is the Połaniec power plant (Świętokrzyskie voivodship), which burns ~1.4 million tonnes of biomass annually in its “green unit”, of which 57% in 2016 was imported [106]. However, the remaining 43% of biomass came from the surrounding powiats. Taking into account the biomass resources we calculated for Świętokrzyskie voivodship (~0.53 million tonnes), it can be seen that such a large consumption by one entity may significantly affect local RES development plans, limiting the possibility of building local biomass-fired cogeneration installations in favour of the use of other renewable resources. A similar situation occurs in the case of the Białystok power plant (Podlaskie voivodship), which consumes over 0.4 million tonnes of biomass annually, while the potential of this energy carrier in the entire region is estimated at about 0.8 million tonnes.

The results presented in Table 1 indicate the dominant share of biomass in building RES potential. Both biogas and solid biomass are energy carriers strongly dependent on the broadly understood condition of agriculture and the condition of forest management. The amount of polonium depends not only on the degree of mechanization of agriculture, soil quality or the amount of mineral fertilizers used, but also on the water resources in a given area. Therefore, in the era of climate change, it would be worth following the changes that have occurred in the biomass potential in recent decades, with particular emphasis on drought (2015) and floods (2010) in Poland.

4. Conclusions

Autonomous energy regions (ARE) based on renewable energy sources appear to be one of the solutions which can ensure coverage of the growing energy needs while at the same time taking into account measures respecting the environment. In contrast to the traditional energy industry, RES can be distributed throughout the country. This is due not only to the “dispersed” character of renewable energies (wind, sun, water), but also to the fact that almost every powiat has an intensive agricultural and forestry economy. Therefore,

each examined administrative unit in Poland (voivodship, powiat) may be treated as a source of biomass, which, supplemented with energy obtained from wind, water and sun, may constitute the basis for construction of ARE, which may improve not only local energy security but also reduce energy costs for local consumers, improve utilisation of endogenous potential of regions and, above all, reduce negative environmental impact caused by traditional methods of energy production.

The research showed that in Poland, on the one hand, the share of RES in energy production is still small, but at the same time, in the majority of regions (powiats, voivodships) there is a great potential to obtain additional energy from RES, which may constitute the basis for development of ARE. In this respect, there is a large spatial diversification both in relation to the status of RES energy production and its share in energy balance of particular regions and their constituent powiats as well as potential possibilities to increase the volume and structure of production from particular RES.

Activation of RES potential would make it possible to cover over 73% of the country's demand for electricity. Activation of RES potential could provide a basis for building energy independence on a local scale, where only large industrial and urban centres would require "support" from the traditional energy sector covering at least 30% of the national demand for electricity. In the proposed "scenario", as many as seven regions would become self-sufficient in terms of electricity demand. Such a large potential present in the powiats is a premise for the construction of ARE, but one should be aware that its launch is connected to the necessity of incurring huge costs. Obtaining significant financial assistance is a necessary condition for launching RES potential located in rural areas to boost their development.

The results of our calculations presented in Figure 5 indicate that the development of ARE could start first in the group of 220 powiats (57.9% of the total 380) with RES potential exceeding their own electricity consumption. Therefore, in addition to covering their own demand, these powiats could also "export" their surplus energy, thus making the whole project more economically stable.

The creation of RES-based ARE is an important undertaking related to the improvement of energy security, but at the same time it favours the improvement of environmental quality. Such regions may contribute to counteracting marginalisation of areas where undesirable socioeconomic phenomena intensify.

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References

1. Owusu, P.A.; Asumadu-Sarkodie, S.A. review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng.* **2016**, *3*. [CrossRef]
2. Maśloch, P.; Maśloch, G.; Kuźmiński, Ł.; Wojtaszek, H.; Miciuła, I. Autonomous energy regions as a proposed choice of selecting selected EU regions—Aspects of their creation and management. *Energies* **2020**, *13*, 6444. [CrossRef]

3. IEO. U.S. Energy Information Administration's International Energy Outlook 2020. Center for Strategic and International Studies. Independent Statistics & Analysis, U.S. Energy Information Administration. 2020. Available online: www.iea.gov (accessed on 12 March 2021).
4. Gradziuk, P.; Gradziuk, B. Renewable energy sources as a development opportunity for peripheral areas. *Econ. Reg. Stud.* **2020**, *13*, 184–196.
5. Zou, C.; Zhao, Q.; Zhang, G.; Xiong, B. Energy revolution: From a fossil energy era to a new energy era. *Nat. Gas Ind. B* **2016**, *3*, 1–11. [\[CrossRef\]](#)
6. Sonter, L.J.; Dade, M.C.; Watson, J.E.M.; Valenta, R.K. Renewable energy production will exacerbate mining threats to biodiversity. *Nat. Commun.* **2020**, *11*, 4174. [\[CrossRef\]](#)
7. Johnsson, F.; Kjärstad, J.; Rootzén, J. The threat to climate change mitigation posed by the abundance of fossil fuels. *Clim. Policy* **2019**, *19*, 258–274. [\[CrossRef\]](#)
8. Perera, F. Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: Solutions exist. *Int. J. Environ. Res. Public Health* **2017**, *15*, 16. [\[CrossRef\]](#)
9. Greenstone, M.; Reguant, M.; Ryan, N.; Dobermann, T. *Energy and Environment*; Evidence Paper; International Growth Centre, University of Oxford: Oxford, UK, 2019.
10. Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [\[CrossRef\]](#)
11. Herington, M.J.; van de Fliert, E.; Smart, S.; Greig, C.; Lant, P.A. Rural energy planning remains out-of-step with contemporary paradigms of energy access and development. *Renew. Sustain. Energy Rev.* **2017**, *67*, 1412–1419. [\[CrossRef\]](#)
12. Akhtar, S.; Zahedi, K.; Liu, H. *Regional Cooperation for Sustainable Energy in Asia and the Pacific*; ESCAP, United Nations: Bangkok, Thailand, 2017.
13. Ford, R.; Maidment, C.; Fell, M.; Vigurs, C.; Morris, R. *A Framework for Understanding and Conceptualising Smart Local Energy Systems*. Energy REV; University of Strathclyde Publishing: Strathclyde, UK, 2019; pp. 1–18.
14. Omer, A.M. Energy use and environmental impacts: A general review. *J. Renew. Sustain. Energy* **2009**, *1*, 053101. [\[CrossRef\]](#)
15. IRENA. *Innovation Landscape for a Renewable-Powered Future: Solutions to Integrate Variable Renewables*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019.
16. Plich, M.; Skrzypek, J. Trendy Energochłonności Polskiej Gospodarki. *Wiadomości Stat. Pol. Stat.* **2016**, *16*–38. [\[CrossRef\]](#)
17. Clinch, P. Cost-benefit analysis applied to energy. *Encycl. Energy* **2004**, *1*, 715–725. [\[CrossRef\]](#)
18. Sharma, B.; Ingalls, R.G.; Jones, C.L.; Khanchi, A. Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future. *Renew. Sustain. Energy Rev.* **2013**, *24*, 608–627. [\[CrossRef\]](#)
19. Dampier, J.E.E.; Lemelin, R.H.; Shahi, C.; Luckai, N. Small town identity and history's contribution to a response in policy change: A case study of transition from coal to biomass energy conversion. *Energy Sustain. Societ.* **2014**, *4*, 1–14. [\[CrossRef\]](#)
20. Famielec, J.; Kijanka, A.; Żaba-Nieroda, R. Economic growth and carbon dioxide emissions. *Pol. Stat. Stat. Pract.* **2019**, *64*, 5–21. [\[CrossRef\]](#)
21. Gradziuk, P. Innowacje organizacyjne w bioenergetyce. In *Bioenergetyka Podkarpacka. Innowacje Technologiczne i Organizacyjne w Podkarpackiej Bioenergetyce*; Kościuk, B., Ed.; Wydawnictwo Naukowe Państwowej Wyższej Szkoły Zawodowej im. ks. Bronisława Markiewicza w Jarosławiu: Jarosław, Poland, 2007; pp. 215–233.
22. Maśloch, G. Budowa autonomicznych regionów energetycznych w Polsce—Utopia czy konieczność? *Studia Prawno Ekon.* **2018**, *CVI*, 251–256.
23. Statistics Poland. *Rural Areas in Poland in 2018. Statistical Analyses*; Statistics Poland: Warszawa, Olsztyn, 2020.
24. Wójcik, M. Non-agricultural economic functions of rural areas in the Łódzkie Voivodship (1999–2009). *Reg. Barom. Anal. Progn.* **2013**, *2*, 43–50.
25. Sima, E. Non-agricultural activities in the economic development of the Romanian rural area. In *Proceedings of the Agrarian Economy and Rural Development—Realities and Perspectives for Romania*. In *Proceedings of the 6th Edition of the International Symposium, ICEADR, Bucharest, Romania, 19 November 2015*; pp. 390–395.
26. Kiciński, J. Autonomiczne Regiony Energetyczne (ARE)—Szansa Dla Polskiej Wsi, Instytut Maszyn Przepływowych PAN w Gdańsku, Uniwersytet Warmińsko-Mazurski w Olsztynie. Available online: <https://docplayer.pl/13433401-Autonomiczne-regiony-energetyczne-are-szansa-dla-polskiej-wsi.html> (accessed on 19 April 2021).
27. Benedek, J.; Sebestyén, T.-T.; Bartók, B. Evaluation of renewable energy sources in peripheral areas and renewable energy-based rural development. *Renew. Sustain. Energy Rev.* **2018**, *90*, 516–535. [\[CrossRef\]](#)
28. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources. *Off. J. Eur. Union* **2018**, *L 328/82*, 1–128. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN> (accessed on 20 March 2021).
29. Benasla, M.; Hess, D.; Allaoui, T.; Brahimi, M.; Denai, M. The transition towards a sustainable energy system in Europe: What role can North Africa's solar resources play? *Energy Strategy Rev.* **2019**, *24*, 1–13. [\[CrossRef\]](#)
30. Müller, S.; Brown, A.; Ölz, S. *Renewable Energy Policy Considerations for Deploying Renewables*; Information Paper; OECD/IEA: Paris, France, 2011.
31. Marchenko, O.; Solomin, S. Economic efficiency of renewable energy sources in autonomous energy systems in Russia. *Int. J. Renew. Energy Res.* **2014**, *4*, 548–554.

32. Blazquez, J.; Fuentes-Bracamontes, R.; Bollino, C.A.; Nezamuddin, N. The renewable energy policy Paradox. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1–5. [\[CrossRef\]](#)
33. Marks-Bielska, R.; Bielski, S.; Pik, K.; Kurowska, K. The Importance of renewable energy sources in Poland's energy mix. *Energies* **2020**, *13*, 4624. [\[CrossRef\]](#)
34. Matyka, M. *Rolnictwo a Odnawialne Źródła Energii—Szanse i Zagrożenia*; Zegar, J.S., Ed.; Z Badań Nad Rolnictwem Społecznie Zrównoważonym. No 11; Instytut Ekonomiki Rolnictwa i Gospodarki Żywnościowej: Warsaw, Poland, 2011; pp. 95–120.
35. Wang, Y.; Zhang, D.; Ji, Q.; Shi, X. Regional renewable energy development in China: A multidimensional assessment. *Renew. Sustain. Energy Rev.* **2020**, *124*, 109797. [\[CrossRef\]](#)
36. Ślusarz, G.; Gołębiewska, B.; Cierpiał-Wolan, M.; Gołębiewski, J.; Twaróg, D.; Wójcik, S. Regional diversification of potential, production and efficiency of use of biogas and biomass in Poland. *Energies* **2021**, *14*, 742. [\[CrossRef\]](#)
37. Jezierski, G. Elektrownia Jądrowa a Konwencjonalna. *Energetyka Ciepł. Zawodowa* **2009**, *10*, 1–12. Available online: https://www.cire.pl/pliki/2/jadrowa_a_konwencjonalna.pdf (accessed on 25 April 2021).
38. Maciejczak, M.; Zakharov, K. Public goods as a source of rural development. In Proceedings of the International Conference Development Prospects of Rural Areas Lagging Behind in the CEE Region, Szent Istvan University, Godollo, Hungary, 24–26 May 2011.
39. Santos, J.L.; Madureirab, L.; Ferreira, A.C.; Espinosac, M.; Gomez y Paloma, S. Building an empirically-based framework to value multiple public-goods of agriculture at broad supranational scales. *Land Use Policy* **2016**, *53*, 56–70. [\[CrossRef\]](#)
40. Plantinga, A.J.; Miller, D. Agricultural land values and future development. *Land Econ.* **2001**, *77*, 56–67. [\[CrossRef\]](#)
41. Koryś, K.A.; Latawiec, A.E.; Grotkiewicz, K.; Kuboń, M. The review of biomass potential for agricultural biogas production in Poland. *Sustainability* **2019**, *11*, 6515. [\[CrossRef\]](#)
42. Kukuła, K. Dynamika produkcji energii elektrycznej wykorzystującej źródła energii odnawialnej. *Wiadomości Stat. Pol. Stat.* **2015**, *12*, 58–69.
43. Kowalczyk, K.; Cieśliński, R. Analiza potencjału hydroenergetycznego oraz możliwości jego wykorzystania w województwie pomorskim. *Woda Śr. Obsz. Wiej.* **2018**, *18*, 69–86.
44. Jarosz, Z. Potencjał energetyczny biomasy roślinnej i możliwości wykorzystania do celów energetycznych. *Probl. Rol. Świat. Probl. World Agric.* **2017**, *17*, 81–92. [\[CrossRef\]](#)
45. Cogeneration, European Biomass Industry Association. 2021. Available online: <https://www.eubia.org/cms/wiki-biomass/cogeneration> (accessed on 16 May 2021).
46. Sprawozdanie Bilansowe Nośników Energii i Infrastruktury Ciepłowniczej. Available online: <http://form.stat.gov.pl/formularze/2018/passive/G-02b.pdf> (accessed on 25 April 2021).
47. Available online: <https://eref-europe.org/restor-hydro-database/> (accessed on 25 April 2021).
48. Blok, M.; Tomaszewska, B. Ocena potencjału technicznego wybranej MEW w powiecie rzeszowskim (Evaluation of the Technical Potential of a Selected Small Hydropower Plant in The Rzeszów District). *Geol. Explor. Technol. Geotherm. Energy Sustain. Dev.* **2015**, *2*, 61–78.
49. Bujakowski, W.; Barbacki, A.; Grzybek, A.; Hołojuch, G.; Pajak, L.; Skoczek, A.; Skrzypczak, M.; Skrzypczak, S. *Opracowanie Metody Programowania i Modelowania Systemów Wykorzystania Odnawialnych Źródeł Energii na Terenach Nieprzemysłowych Województwa Śląskiego, wraz z Programem Wykonawczym dla Wybranych Obszarów Województwa*; Część I: Metodyka Opracowania; Instytut Gospodarki Surowcami Mineralnymi i Energią PAN: Kraków, Poland; Katowice, Poland, 2005.
50. Filipowicz, M.; Żołądek, M.; Ochalik, J. Potencjał Rozwoju i Problemy Energetyki Wiatrowej (Growth Potential and Problems in Development of Wind Energy). *Rynek Instal.* **2020**, *1–2*. Available online: <http://www.rynekinstalacyjny.pl/arttykul/id4944> (accessed on 25 April 2021).
51. PSEW. Analiza Krajowego Planu na Rzecz Energii i Klimatu na Lata 2021–2030 z Dnia 30 Grudnia 2019 r. Polskie Stowarzyszenie Energetyki Wiatrowej. 2019. Available online: http://psew.pl/wp-content/uploads/2020/06/Analiza-KPEiK_PSEW.pdf (accessed on 25 April 2021).
52. Energetyka Wiatrowa. 2021. Available online: <https://globenergia.pl/> (accessed on 20 May 2021).
53. Stolińska, B. The factors of wind turbines location. *World Real Estate J.* **2014**, *88*, 27–31.
54. Dragusha, B.; Hoxha, B. Impact of field roughness and power losses, turbulence intensity on electricity production for an onshore wind farm. *Int. J. Power Electron. Drive Syst.* **2020**, *11*, 1519–1526. [\[CrossRef\]](#)
55. Dz.U. 2016 Poz. 961, Ustawa z Dnia 20 Maja 2016 r. o Inwestycjach w Zakresie Elektrowni Wiatrowych. Available online: <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20160000961/U/D20160961Lj.pdf> (accessed on 27 March 2021).
56. Voicescu, S.A.; Michaud, D.S.; Feder, K.; Marro, L.; Than, J.; Guay, M.; Denning, A.; Bower, T.; van den Berg, F.; Broner, N.; et al. Estimating annoyance to calculated wind turbine shadow flicker is improved when variables associated with wind turbine noise exposure are considered. *J. Acoust. Soc. Am.* **2016**, *139*, 1480–1492. [\[CrossRef\]](#)
57. Pantazopoulou, P. Wind turbine noise measurements and abatement methods. *WIT Trans. State Art Sci. Eng.* **2010**, *44*, 621–659. [\[CrossRef\]](#)
58. Botelho, A.; Arezes, P.; Bernardo, C.; Dias, H.; Pinto, L.M.C. Effect of wind farm noise on local residents' decision to adopt mitigation measures. *Int. J. Environ. Res Public Health* **2017**, *14*, 753. [\[CrossRef\]](#)
59. Díaz, K.M.A.; Velarde-Suárez, S.; Oro, J.M.F.; Perez, J.G. Simplified assessment on the wind farm noise impact of the E2O experimental offshore station in the Asturian coast. *Energies* **2020**, *13*, 5788. [\[CrossRef\]](#)

60. Kozłowska-Szczęśna, T. Promieniowanie, Temperatura Powietrza, Główny Geodeta Kraju, Warszawa 1994. In Atlas Rzeczypospolitej Polskiej. Cz.2. Warszawa: Główny Geodeta Kraju. 1994. Available online: <https://www.igipz.pan.pl/mapy-all.html> (accessed on 3 April 2021).
61. Tytko, R. *Urządzenia i Systemy Energetyki Odnawialnej*, Wyd; Towarzystwo Słowaków w Polsce: Krakow, Poland, 2013.
62. Available online: <https://www.gum.gov.pl/pl/transfer-wiedzy/inne/mapy-godzin-wschodu-i-z/2652,Mapy-godzin-wschodu-i-zachodu-slonca-w-Polsce.html> (accessed on 1 April 2021).
63. Mirowski, T.; Sornek, K. Potencjał energetyki prosumenckiej w Polsce na przykładzie mikroinstalacji fotowoltaicznych w budownictwie indywidualnym. *Energy Policy J.* **2015**, *18*, 73–85.
64. Thompson, E.P.; Bombelli, E.L.; Shubham, S.; Watson, H.; Everard, A.; D'Ardes, V.; Schievano, A.; Bocchi, S.; Zand, N.; Howe, C.J.; et al. Tinted semi-transparent solar panels allow concurrent production of crops and electricity on the same cropland. *Adv. Energy Mater.* **2020**, *10*, 1–9.
65. Available online: <https://bdl.stat.gov.pl/BDL/start> (accessed on 19 April 2021).
66. Wiśniewski, G. (Ed.) *Odnawialne Źródła Energii Jako Element Rozwoju Lokalnego*; Europejskie Centrum Energii Odnawialnej; EC BREC: Warszawa, Poland, 2003.
67. Wąs, A.; Sulewski, P.; Krupin, V.; Popadynets, N.; Malak-Rawlikowska, A.; Szymańska, M.; Wysokiński, M. The potential of agricultural biogas production in Ukraine—Impact on GHG emissions and energy production. *Energies* **2020**, *13*, 5755. [CrossRef]
68. Walczak, J.; Krawczyk, W.; Szewczyk, A.; Mazur, D.; Pająk, T.; Radecki, P. *Oszacowanie Wielkości Produkcji Oraz Jednostkowej Zawartości Azotu Nawozów Naturalnych, Powstałych w Różnych Systemach Utrzymania Zwierząt Gospodarskich w Polsce*; Instytut Zootechniki Państwowy Instytut Badawczy: Kraków, Poland, 2012; p. 17.
69. Kołodziejak, G. Możliwości wykorzystania potencjału energetycznego biogazu powstającego w trakcie procesu oczyszczania ścieków. Analiza opłacalności proponowanych rozwiązań. *Naft. Gaz* **2012**, *12*, 1036–1043.
70. Cherevko, G. Rapeseed growing for energy purposes in Ukraine. *Rocz. Nauk. Stowarzyszenia Ekon. Rol. Agrobiz.* **2016**, *18*, 29–34.
71. Gradziuk, P. Potencjał i prognozy wykorzystania biogazu rolniczego w Polsce. Potential and forecast for use of agricultural biogas in Poland. *Rocz. Nauk. Stowarzyszenia Ekon. Rol. Agrobiz.* **2017**, *19*, 64–70. [CrossRef]
72. Available online: <https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/uprawy-rolne-i-ogrodnicze/produkcja-upraw-rolnych-i-ogrodniczych-w-2018-roku,9,17.html> (accessed on 18 April 2021).
73. Martinát, S.; Dvořák, P.; Frantál, B.; Klusáček, P.; Kunc, J.; Kulla, M.; Mintálová, T.; Navrátil, J.; van der Horst, D. Spatial consequences of biogas production and agricultural changes in the Czech Republic after EU accession: Mutual symbiosis, coexistence or parasitism? *AUPO Geogr.* **2013**, *44*, 75–92.
74. Bharathirajaa, B.; Sudharsanaa, T.; Jayamuthunagaib, J.; Praveenkumarc, R.; Chozhavendhand, S.; Iyyappan, J. Biogas production—A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renew. Sustain. Energy Rev.* **2018**, *90*, 570–582. [CrossRef]
75. Ludwicka, A.; Grzybek, A. Bilans masy rolnej (słomy) na potrzeby energetyki (Balance of the agricultural biomass (straw) for energy purposes). *Probl. Inż. Rol. Probl. Agric. Eng.* **2010**, *2*, 101–110.
76. Gradziuk, P. *Gospodarcze Znaczenie i Możliwości Wykorzystania słomy na Cele Energetyczne w Polsce*; Monografie i Rozprawy naukowe nr. 45, Wyd; Instytutu Uprawy, Nawożenia i Gleboznawstwa—Państwowy Instytut Badawczy w Puławach/Institute of Soil Science and Plant Cultivation State Research Institute: Puławy, Poland, 2015; p. 176.
77. Hryniewicz, M.; Grzybek, A. Nadwyżka słomy dostępnej do wykorzystania na potrzeby energetyczne w 2016 r. *Probl. Inżynierii Rol.* **2017**, *3*, VII–IX.
78. Pudełko, R. Ocena potencjału biomasy ubocznej z rolnictwa w UE. *Nowa Energ.* **2013**, *4*, 44–47.
79. Koprowicz, A. *Planowanie Bilansu Paszowego w Gospodarstwach Mlecznych*; MPODR: Karniowice, Poland, 2016.
80. ARiMR-Agencja Restrukturyzacji i Modernizacji Rolnictwa. Available online: <https://www.arimr.gov.pl/> (accessed on 4 April 2021).
81. Kuś, J.; Faber, A. Alternatywne kierunki produkcji rolniczej. *Studia Rap. IUNG-PIB Puławy* **2007**, *7*, 138–158.
82. Kołodziej, A.; Matyka, M. *Odnawialne Źródła Energii. Rolnicze Surowce Energetyczne*; PWRiL: Poznan, Poland, 2012; p. 594.
83. Han, S.H.; Shin, S.J.; Kim, B.R.; Aggangan, N.S.; Yun, C.W. Growth chemical composition and energy contents of seven clones of one-year-old *Salix caprea* L. as short rotation coppice. *Asia Life Sci.* **2013**, *22*, 413–426.
84. Lach, A.; Dyjakon, A.; Noszczyk, T. Sady jabłoniowe jako lokalne źródło biomasy do ogrzewania gospodarstw domowych w Województwie Mazowieckim (Apple orchards as a source of local biomass for households heating in the Mazowieckie Voivodeship). In *Rolnictwo XXI Wieku—Problemy i Wyzwania*; Łuczycyca, D., Ed.; Idea Knowledge Future: Wrocław, Poland, 2018; pp. 528–539.
85. Pavić, Z.; Novoselac, V. Notes on TOPSIS Method. *Int. J. Res. Eng. Sci.* **2013**, *1*, 5–12.
86. Wysocki, F. *Metody Taksonomiczne w Rozpoznawaniu Typów Ekonomicznych Rolnictwa i Obszarów Wiejskich*; Wydawnictwo Uniwersytetu Przyrodniczego w Poznaniu: Poznań, Poland, 2010.
87. EC 2021. Eurostat. Available online: <https://ec.europa.eu/eurostat/data/database> (accessed on 18 April 2021).
88. Igliński, B. Hydro energy in Poland: The history, current state, potential, SWOT analysis, environmental aspects. *Int. J. Energy Water Resour.* **2019**, *3*, 61–72. [CrossRef]
89. Kowalczak, P. *Hierarchia Potrzeb Obszarowych Małej Retencji w Dorzeczu Warty*; Instytut Meteorologii i Gospodarki Wodnej: Warsaw, Poland, 2001.

-
90. Kudlicki, Ł. Zagrożenie Pustynnieniem w Polsce. *Bezpieczeństwo Nar.* **2006**, *1*, 201–211. Available online: <https://www.bbn.gov.pl> (accessed on 21 April 2021).
 91. Watson, S.; Moro, A.; Reis, V.; Baniotopoulos, C.; Barth, S.; Bartoli, G.; Wiser, R. Future emerging technologies in the wind power sector: A European perspective. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109270. [[CrossRef](#)]
 92. Available online: <https://www.tauron-wytwarzanie.pl/innowacje/co2-sng> (accessed on 23 April 2021).
 93. Leahy, M.J.; Connolly, D.; Buckley, D.N. Wind energy storage technologies. *WIT Trans. State Art Sci. Eng.* **2010**, *44*, 621–714. [[CrossRef](#)]
 94. Nsair, A.; Cinar, S.O.; Alassali, A.; Abu Qdais, H.; Kuchta, K. Operational parameters of biogas plants: A review and evaluation study. *Energies* **2020**, *13*, 3761. [[CrossRef](#)]
 95. Sefeedpari, P.; Pudełko, R.; Jędrejek, A.; Kozak, M.; Borzęcka, M. To what extent is manure produced, distributed, and potentially available for bioenergy? A step toward stimulating circular bio-economy in Poland. *Energies* **2020**, *13*, 6266. [[CrossRef](#)]
 96. Wiśniewski, G. (Ed.) *Określenie Potencjału Energetycznego Regionów Polski w Zakresie Odnawialnych Źródeł Energii—Wnioski dla Regionalnych Programów Operacyjnych na Okres Programowania 2014–2020*; Ministerstwo Rozwoju Regionalnego: Warsaw, Poland, 2011.
 97. Borzęcki, K.; Pudełko, R.; Kozak, M.; Borzęcka, M.; Faber, A. Spatial distribution of wood waste in Europe. *Sylvan* **2018**, *162*, 563–571.
 98. Hartmann, B.; Talamon, A.; Sugár, V. Renewable energy potentials in the administrative regions of Hungary. *Strateg. Plan. Energy Environ.* **2017**, *37*, 33–57. [[CrossRef](#)]
 99. Potić, I.; Joksimović, T.; Milinčić, U.; Kićović, D.; Milinčić, M. Wind energy potential for the electricity production—Knjaževac Municipality case study (Serbia). *Energy Strategy Rev.* **2021**, *33*, 100589. [[CrossRef](#)]
 100. Godlewska-Majkowska, H.; Komor, A. Energy as a factor of investment attractiveness of regions for agricultural enterprises. *Energies* **2021**, *14*, 2731. [[CrossRef](#)]
 101. Scaramuzzino, C.; Garegnani, G.; Zambelli, P. Integrated approach for the identification of spatial patterns related to renewable energy potential in European territories. *Renew. Sustain. Energy Rev.* **2019**, *101*, 1–13. [[CrossRef](#)]
 102. Zhu, D.; Mortazavi, S.M.; Maleki, A.; Aslani, A.; Yousefi, H. Analysis of the robustness of energy supply in Japan: Role of renewable energy. *Energy Rep.* **2020**, *6*, 378–391. [[CrossRef](#)]
 103. Islam, M.A.; Hasanuzzaman, M.; Rahim, N.A.; Nahar, A.; Hosenuzzaman, M. Global renewable energy-based electricity generation and smart grid system for energy security. *Sci. World J.* **2014**, 1–13. [[CrossRef](#)] [[PubMed](#)]
 104. Mardani, A.; Streimikiene, D.; Balezentis, T.; Saman, M.; Nor, K.M.; Khoshnava, S. Data envelopment analysis in energy and environmental economics: An overview of the state-of-the-art and recent development trends. *Energies* **2018**, *11*, 2002. [[CrossRef](#)]
 105. Available online: file:///C:/Users/p138602/AppData/Local/Temp/2020-EurObserv_ER-biogas-barometer-GB-20201215.pdf (accessed on 16 April 2021).
 106. Available online: <https://powermeetings.eu/konferencja/forum-biomasy/wp-content/uploads/sites/19/2017/04/06-Rafal-Domaszewski-Enea.pdf> (accessed on 8 April 2021).