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Regional differentiation of agricultural biogas, biocomponent and biofuel production in Poland

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Abstract

This article presents an analysis of the producers and the number of biocomponent, biofuel and biogas plants in Poland, taking into account their distribution, efficiency and dominant production regions. The research was based on data collected by Voivodeship, which made it possible to identify regional differences and the key areas dominating certain segments. The largest bioethanol plant is located in the Opolskie Voivodeship and has an annual capacity of 300 million litres, while the smallest, in the Dolnośląskie Voivodeship, produces 5.5 million litres. For methyl ester production, Podkarpackie stands out with a capacity of 475.65 million litres, while the smallest plant is located in Śląskie (124.58 million litres). For liquid bio-carbons and biopropane, Pomorskie is the leader with a capacity of 286 million litres and 32 million litres respectively, while the smallest plants are located in Łódzkie. Biogas production was also analysed, highlighting its importance for the regions' sustainable energy transition. Voivodeships with the greatest potential for the production of biocomponents, biogas and biofuels were identified, including Opolskie, Podkarpackie, Pomorskie and Wielkopolskie, which play a key role in the national production structure. The results of the study highlight the importance of developing regional technological infrastructure and effectively using local resources to strengthen Poland's renewable energy sector.

1. INTRODUCTION

Today's environmental challenges, including progressive climate change, the gradual depletion of fossil fuel resources and increasing ecosystem degradation, pose significant threats to ecosystem stability and long-term economic and social development. In the face of these problems, it is becoming necessary to transform energy systems at global and regional levels, involving changes in production methods and energy consumption patterns. The introduction and development of renewable energy sources are key parts of this transformation, as they make it possible to reduce greenhouse gas emissions, reduce dependence on fossil fuels, and promote a circular economy.

The growing importance of renewable energy sources is reflected in global energy strategies focusing on developing solar, wind, hydro and biomass energy technologies. A particularly important area of this transition is the production of biogas and biofuels, which are renewable alternatives to traditional fuels and can help stabilise national energy systems. Compared to other renewable energy sources, biogas and biofuels are characterised by their independence from atmospheric conditions, making them a stable energy source with a wide range of applications.

In the context of Poland, the growing role of renewable energy sources is closely linked to the European Union's

climate policy and commitments under the 2015 Paris Agreement. Poland's energy economy, traditionally based on coal and other fossil fuels, is facing a gradual transition to more sustainable forms of energy production. In this context, developing agricultural biogas, biofuels, and bio-components plays a key role in the country's energy transition. Biogas produced from the fermentation of organic waste, such as crop residues, manure or other agricultural waste, enables the efficient management of local resources, contributes to reducing methane emissions and minimises agricultural waste disposal problems. In addition, the digestate provides a valuable fertiliser that supports sustainable agricultural practices.

Biofuels such as biodiesel and bioethanol offer an alternative to fossil fuels in the transport sector, reducing carbon emissions and dependence on imported oil. Their use contributes to improved air quality, and their production, especially from agricultural waste, can support rural economic development by creating new jobs and diversifying farmers' incomes.

As additives to conventional fuels, bio-components can reduce greenhouse gas emissions and increase the share of renewable components in the energy sector. Produced from plant-based feedstocks such as rapeseed, maize or sugar cane, they contribute to developing a closed-loop economy and reducing dependence on fossil fuels.

Their use aligns with the European Union's long-term sustainability goals and energy strategies.

The development of the agricultural biogas, biofuels and biocomponents sector in Poland offers numerous opportunities, not only in improving the country's energy balance, but also in activating rural communities through the possibility of producing and selling local energy raw materials. Poland has considerable potential for further development of this sector due to the high availability of agricultural biomass and the growing environmental awareness of the population. However, the effective realisation of this potential requires a detailed analysis of regional differences in the production and distribution of renewable energy sources, which will allow for the optimal design of energy policies at national and local levels.

The development of Poland's agricultural biogas, biofuels and biocomponents industry is characterised by significant regional differences due to different natural conditions, varying political support and uneven technical infrastructure. These differences are crucial for the efficiency and effectiveness of the sector, and their detailed analysis is an important element in the assessment of the national energy potential and the basis for the design of effective policies to support the development of renewable energy sources in Poland.

This publication aims to assess the number of agricultural biogas and biocomponent producers in Poland, taking into account their distribution by voivodeship. The study covers aspects such as the number of plants in operation, their installed capacity, and annual production efficiency. The results will be used to assess individual regions' energy efficiency and identify barriers and opportunities for further development of the biogas and bio-components sector in Poland.

2. RESEARCH METHODOLOGY

To analyse the regional differentiation of agricultural biogas and biocomponent production in Poland, a research approach was adopted that involved assessing and comparing the number of installations, installed capacity, and annual production across individual voivodeships. As part of the adopted methodology, the following analytical criteria were defined:

- 1) Number of installations – the total number of agricultural biogas and biocomponent installations in each voivodeship. This indicator serves as a fundamental measure of sectoral development at the regional level. A higher number of installations may indicate greater regional engagement in renewable energy production, which could stem from the availability of raw materials or favourable regulatory conditions.
- 2) Installed capacity – the assessment of installation capacity (expressed in MW) enables the evaluation of the production potential of individual regions. High values of this indicator signify the ability to generate substantial amounts of energy, which is crucial for assessing energy efficiency and local energy demand.

- 3) Annual productivity – this indicator refers to the total annual energy production (expressed in MWh), allowing for an assessment of the actual contribution of the agricultural biogas and biocomponent sector to the energy mix of each voivodeship. Additionally, it facilitates an evaluation of production efficiency and stability over the long term.

- 4) Regional parameters – to standardise and further refine the regional analysis, additional measures were introduced, including the average productivity per facility and the average productivity per voivodeship. These indicators allow for more precise regional comparisons, irrespective of differences in size or population.

The applied methodology enables a preliminary assessment of regional differentiation within the agricultural biogas and biocomponent sector, considering the specific characteristics of each voivodeship. The use of various analytical tools and metrics allows for the identification of regions with potentially greater development opportunities and those that may require additional support in the field of renewable energy. The results of this analysis may serve as a foundation for further, more in-depth research in this domain.

The data used in the analysis were obtained from two separate registers maintained by the National Agricultural Support Centre (KOWR). The first is the Register of Agricultural Biogas Producers, which contains information on entities engaged in agricultural biogas production. The second is the Register of Biocomponent Producers, which provides data on producers of biocomponents used in the biofuels sector.

The data from both registers were retrieved in November 2024, ensuring their relevance and accuracy during the study. The registers maintained by NEB constitute a reliable source of information due to their mandatory nature and institutional oversight, which minimises the risk of errors in the reported data.

3. THEORETICAL BACKGROUND AND LITERATURE REVIEW

Agricultural biogas, biocomponents and biofuels are important elements of the energy transition aimed at reducing greenhouse gas emissions and increasing the share of renewable energy sources in the national energy mix. In Poland, their production and use are characterised by significant regional differences, resulting from the availability of raw materials, the economic characteristics of individual regions and the level of development of the technological infrastructure [Lubowicz 2022].

Agricultural biogas is produced by anaerobic digestion of agricultural biomass and is mainly used for electricity and heat production [Gruszczyński 2008]. After appropriate purification and enrichment in methane, it can be used

as biomethane in the transport sector [Michał et al. 2023]. On the other hand, biocomponents are organic compounds of plant origin that are added to conventional fuels to partially or completely replace them [Malode et al. 2022]. Biofuels, on the other hand, are a broad group of renewable fuels in liquid, gaseous and solid form used in the transport, energy and industrial sectors [Budzyński, Bielski 2004; Pettka 2007].

The analyses show that the development of these sectors in Poland is strongly dependent on local conditions, energy policy, and the availability of financial support instruments. Comparing the national situation with the experience of other countries makes it possible to identify the main barriers and development prospects for the production of agricultural biogas, biocomponents, and biofuels at the regional level.

3.1. Poland in the context of international experience

Poland has a high potential to produce agricultural biogas, biocomponents and biofuels, but the development of this sector is uneven. Compared to the leading producers in Europe and the world, Poland still faces regulatory, technological and infrastructural challenges that limit the efficient use of biomass resources. This section compares Poland with Germany, France, Italy, the Scandinavian countries and global leaders such as the United States, Canada and Brazil.

Agricultural biogas is a product of the anaerobic digestion of biomass, which mainly includes manure, agricultural waste and crop residues [Biernat 2010]. In Poland, the dominant raw materials for its production are maize silage, manure and slurry, distinguishing the country from other European countries such as Germany or Denmark. In these countries, there is more emphasis on using organic waste and municipal wastewater for biogas production, which results in more diverse raw material sources [Holewa-Rataj, Kukulska-Zajac 2022]. Regarding agricultural biogas production, Poland is far behind Germany, the European leader in this field. Germany has over 9,000 biogas plants, while Poland has less than 176 [Liebetrau et al. 2017]. A key difference is financial support - the German feed-in tariff system (EEG) has provided stable income for biogas producers, leading to the dynamic development of the sector. In Poland, the lack of similar support mechanisms and complicated administrative procedures limits the number of new investments [Pawilonis, Kupczyk 2006, Błażejewska 2010].

France and Italy are developing the biogas sector based on using organic waste and the digestion of municipal wastewater [Levavasseur et al. 2023; Sica et al. 2023]. In France, integrating biomethane into the gas grid is a particularly important factor for development, providing an important source of renewable energy [Bourdin, Chassy 2023]. Despite its potential, Poland does not yet have a well-developed system for feeding biomethane into the

gas grid, limiting its potential for transport use [Pochwatka, Pulka 2020].

Scandinavian countries, such as Sweden and Denmark, emphasise closed cycles and efficient use of waste substrates [Börjesson et al. 2023]. In Denmark, almost 90% of biogas is upgraded to biomethane and injected into the gas grid [Mignogna et al. 2023; Noussan et al. 2023], while in Poland this percentage is marginal [Lindfors, Feiz 2023]. Poland could benefit from the Danish experience, especially in the context of policies to support the use of biogas in transport.

Poland is one of Europe's largest producers of biocomponents, mainly due to its developed production of biodiesel from rapeseed oil and bioethanol from maize and sugar beet [Mystkowski, Wilczewski 2008]. However, in contrast to Germany or France, it still relies on first-generation bio-components, which may pose a problem in the context of the EU's sustainable development strategy [Rutkowski 2018].

In Germany, France, and Italy, second-generation biocomponents produced from agricultural waste, animal fats, and lignocellulose have an increasing market share [Pavičić et al. 2022]. In France, synthetic biocarbon is being developed to replace fossil fuels in aviation [El Akkari et al. 2023]. Poland, despite its large feedstock potential, has not yet developed these technologies on a large scale, which may limit the competitiveness of the domestic biocomponent sector in the coming years.

Poland is among the European leaders in terms of biofuel production, but its market share is still limited compared to global leaders such as the United States or Brazil [Kouhgard et al. 2023].

The United States is developing bioethanol production, mainly from corn, and the biofuels sector is supported by the Renewable Fuel Standard (RFS) programme, which requires the blending of biofuels with conventional fuels [Lark et al. 2022]. Despite significant bioethanol production, Poland has not introduced equally effective regulations to promote its widespread use in the transport sector.

Brazil is the world leader in the production of bioethanol from sugar cane, and its widespread use in transport has contributed to significant reductions in greenhouse gas emissions [Sica et al. 2024; Passos et al. 2020]. Poland has extensive bioethanol production, but does not use such high shares of biofuels in petrol, limiting their impact on decarbonising transport [Majewski 2016].

Scandinavia and Finland are developing hydrotreated vegetable oil (HVO) technologies that can replace diesel without modifying engines. Finland is a leader in producing this type of biofuel through the company Neste, and its exports to other countries are increasing significantly [Gustafsson, Anderberg 2023]. In Poland, HVO production remains very low, although it is considered a future-proof technology for reducing CO₂ emissions in heavy-duty transport.

3.2. Regulatory and financial support

One of the key factors differentiating the development of biogas, biocomponents and biofuels in Poland and Western countries is the regulatory framework and the availability of financial support systems, which play a decisive role in the development of these technologies [Krukowski et al. 2024]. These determinants include the legal framework and financial mechanisms that influence the profitability of investments and incentives for developing innovative technologies in the renewable energy sector [Bużiński et al. 2023; Cai 2021].

In Germany, the development of the biogas sector has been facilitated by the stable EEG feed-in tariff system, which has provided biogas producers with income security through long-term preferential tariffs for many years [De Souza Moraes et al. 2022]. This system, introduced in 2000, is one of the oldest and most comprehensive support mechanisms in Europe, and its stability is seen as a key element in the success of the German energy transition. It has allowed German biogas producers to count on financial predictability, encouraging large investments in new plants and biogas-related technology development [Yang et al. 2021]. German energy policy also supports other renewable energy sources, which, together with an expanded electricity grid, have allowed the biogas sector to develop sustainably [Sobczak et al. 2022].

In Poland, on the other hand, support for the biogas sector is less systematic, which is associated with a higher investment risk [Podkówa, Podkówa 2009]. Although some support mechanisms exist in the country, such as the auctioning system for renewable energy sources, the frequent volatility of regulations and the low stability of long-term support programmes create difficulties for investors [Krukowski et al. 2024]. Changing regulations and inconsistent approaches to financing new installations introduce an element of uncertainty that can discourage long-term investment in biogas technologies [Jordan et al. 2024]. In addition, restrictions on access to agricultural land required for biomass production and difficulties with administrative approval procedures for new installations can also be problematic [Szeptycki 2007].

In France and Italy, the government actively supports developing second-generation biofuels, considered more sustainable than traditional first-generation biofuels [Dale et al. 2020]. In both countries, support for innovative biofuel technologies is provided through tax credit schemes and research and development grants [Popp et al. 2009]. In particular, France has introduced several programmes to support research into second-generation biofuels, increase their large-scale production, and create the conditions for commercialising new technologies [Coll-Martínez et al. 2024]. Italy, on the other hand, has adopted a public-private partnership model in which the private sector has access to EU funds and national subsidies, creating a favourable environment for investment in new technologies and improving the efficiency of biofuel production.

In Poland, the biofuels sector is still largely dependent on support from the European Union, particularly under the Renewable Energy Sources (RES) Development Policy and the Structural Funds [Kupczyk, Piechocki 2010]. In recent years, there has been a significant increase in the number of projects funded by the European Union. However, national support mechanisms are still underdeveloped, hindering biofuels' widespread implementation in the market [Bórawski et al. 2024]. Although Poland has a legal framework related to implementing the Renewable Energy Directive, there is still a lack of integrated solutions to support the development of second-generation biofuels and the transition to more sustainable energy sources [Ślusarz et al. 2023]. In practice, this means that the domestic biofuel sector is not developing as dynamically as in other European Union countries, where, in addition to support from European funds, states are also engaged in creating national policies and support systems for RES technologies [Dragan, Modzelewski 2019]. National incentive mechanisms, such as subsidies, tax breaks or preferential loans for biotechnology companies, are still in the development stage, which may delay the adoption of more advanced technological solutions for biofuels [Sica et al. 2023].

The differences in regulatory conditions and availability of financial support between Poland and Western countries, such as Germany, France or Italy, are a significant barrier to developing the biogas and biofuel sector [Ebadian et al. 2020; Prčík et al. 2022]. For Poland to achieve sustainable development in this area, it is necessary to introduce more stable and predictable support systems that allow investors to plan for the long term and reduce risks. It is also necessary to strengthen national support mechanisms for innovative biofuel technologies, allowing their more effective commercialisation and large-scale adaptation.

3.3. Technological innovations in the production of biocomponents, agricultural biogas and biofuels: a comparative analysis of Poland and selected countries

In the context of global technological trends related to the production of biocomponents, agricultural biogas and biofuels, Poland lags behind many Western and Scandinavian countries, both in terms of technological progress and the scale of implemented solutions [Kirsanovs et al. 2023]. A key aspect differentiating the level of technology development between countries is investment in research and development and government support, both of which influence innovation and the efficiency of the methods used [Przygodzka et al. 2023].

In Scandinavian countries such as Denmark and Sweden, biomethane is an important part of the national energy system, and technologies for biogas purification and its use for electricity, heat and as a transport fuel have reached a very high level of sophistication [Abandes et al. 2022]. In Denmark, one of the European leaders in biogas

technology, systems have been implemented to purify biogas to the level of biomethane so that it can be fed into the gas grid and used as an energy source [Dhir 2024]. These technologies are based on modern purification processes, such as removing carbon dioxide, hydrogen sulphide and moisture, which ensures the production of a high-purity gas suitable for use in the gas grid [Chernysh 2024]. In addition, biogas is increasingly being used in the transport sector in Sweden as part of a broader policy of sustainability and reduction of greenhouse gas emissions [Börjesson et al. 2023]. These technologies result from intensive investment in research and cooperation between the public and private sectors, making them relatively widely available and implemented on a large scale [Gustafsson, Anderberg 2023]. Compared to Poland, where biogas technology is still mainly based on simple digesters with limited efficiency, domestic solutions are still in the development phase and their implementation is hampered by the lack of adequate support systems and high regulatory volatility [Lindfors, Feiz 2023; Rintala et al. 2024].

Also in the context of the production of biocomponents and biofuels, especially bioethanol, the development of ethanol fermentation technology in Brazil is noteworthy [Rodrigues et al. 2024]. This country, one of the world's largest producers of bioethanol, is intensively developing technologies that allow high yields of biofuel from sugar cane [Goldemberg 2007]. The so-called 'advanced fermentation' technology used there allows the efficient conversion of biomass into bioethanol, with significantly higher yields than traditional methods [Bertolino et al. 2023]. Brazil benefits from unique natural conditions, such as a suitable climate and a large area of land dedicated to sugarcane cultivation, making large-scale bioethanol production viable [Khan et al. 2021]. As a result, Brazil has become a leader in biofuel production, and the development of large-scale ethanol fermentation technology allows for significant economic and environmental benefits [Cruz et al. 2021; Vega et al. 2024]. In Poland, in contrast to Brazil, the production of biocomponents, including bioethanol, is still based on less advanced methods, such as the use of maize or wheat as raw materials for bioethanol production [Holewa-Rataj, Kukulska-Zajac 2022]. Although cheaper to implement, these methods do not provide as high productivity or cost-effectiveness as the solutions used in Brazil, which limits the competitiveness of domestic biofuel production on the international market [Passos et al. 2020].

As in the case of biogas, the development of biofuel technologies in countries such as the United States, Brazil and some European Union countries has been driven by both technological innovation [Lark et al. 2022] and strong support from governments [Gustafsson et al. 2024]. In the US, corn- and soy-based biofuels are developed by government policies that include subsidy schemes, tax credits and support programmes for biofuel producers. These schemes, such as the RFS (Renewable Fuel Standard), guarantee the demand for biofuels, which

provides a strong impetus for technology development and increased production efficiency.

On the other hand, new technological solutions for second-generation biofuels are being developed in the European Union, particularly in Germany and France, with the aim of minimising negative environmental impacts and increasing energy efficiency [El Akkari et al. 2023]. Second-generation biofuels, produced from agricultural waste, algae or municipal waste, are a promising alternative in the context of sustainable development and reduced dependence on agricultural raw materials.

In Poland, despite its potential, the biofuel sector still faces challenges in terms of production technologies [Lubowicz 2022]. Most biofuel plants in Poland are based on first-generation technologies that use food crops (such as maize or wheat) to produce bioethanol [Ignatowicz et al. 2023]. Using this type of feedstock raises concerns about food security, making first-generation biofuels potentially an obstacle to developing a sustainable energy sector [Rutkowski 2018]. Poland should therefore invest in research into second-generation biofuels based on agricultural waste and other feedstocks that do not compete with food production. Government support for developing these technologies could be a key element in developing the domestic biofuel sector [Jordan et al. 2024].

In the context of technology development in biogas production, using agricultural biogas for electricity and heat production is also an important direction of innovation [Sadr et al. 2024]. In countries such as Germany and the Netherlands, agricultural biogas plants have become integral to the national energy systems. They are gaining importance as part of the energy transition [Holm Nielsen et al. 2020; Saidakbarovich 2021]. In Germany, the development of biogas plants is supported by long-term feed-in tariffs, which provide financial stability for investments in biogas energy production [Jordan et al. 2024]. In the Netherlands, on the other hand, biogas development is supported by subsidies for innovative technologies for biogas purification and its use in transport, and by the creation of so-called 'green certificates' [Lindfors, Feiz 2023], which promote energy production from renewable sources [Ilves et al. 2024]. In Poland, despite some progress in the development of biogas plants, the sector still faces several challenges, such as insufficient support for investment in new plants and difficulties in accessing suitable raw materials and technology [Jordan et al. 2002]. Furthermore, despite the potential of agricultural biogas, Poland does not fully exploit the available agricultural resources, such as organic waste, that could be used for biogas production.

In summary, the differences in the level of technology and innovation in the production of biocomponents, agricultural biogas, biogas plants and biofuels between Poland and Western countries, Scandinavian countries or Brazil are clear and have a significant impact on the efficiency of biofuel production and the competitiveness of the economy. For Poland to achieve sustainable

development in this area, it is necessary to implement innovative technologies, develop research and international cooperation, and create a stable legal framework and financial support systems that will enable competitive investments in the biofuels, biogas and biocomponents sector.

An analysis of the literature shows that despite its high potential for agricultural biogas, biocomponents and biofuel production, Poland lags behind the leading countries in the European Union and the world. The main obstacles are the lack of a long-term support strategy, limited funding mechanisms and slower adaptation of new technologies. The development of the sector in Poland needs to make better use of the experience of Western countries, especially in the field of biomethane, second-generation biofuels and regulatory systems that encourage investment in renewable energy sources.

4. REGIONAL DIVERSIFICATION OF AGRO-BIOGAS AND BIO-COMPONENT PRODUCTION IN POLAND

The production of energy from renewable sources, including agricultural biogas and biofuels, is characterised by significant regional differences resulting from the availability of local feedstock resources and economic, regulatory and social factors. The analysis shows that voivodeships with a high level of development of the agricultural sector and a significant share of agricultural land, such as Wielkopolskie, Mazowieckie and Pomorskie, have a particularly high potential for the development of agricultural biogas production due to the availability of biomass from agricultural and livestock waste. On the other hand, voivodeships with a well-developed transport infrastructure and a high concentration of industrial plants, especially the Śląskie, Dolnośląskie and Łódzkie voivodeships, are conducive to the intensification of biofuel production due to better access to waste raw materials and favourable logistical conditions for the distribution of energy products.

In the context of regional differences in RES production in Poland, local policies supporting the development of agricultural biogas plants and investments in biofuel production play a key role. In some voivodeships, such as Wielkopolskie and Kujawsko-Pomorskie, the increasing number of biogas plants results from support from national and EU funds and favourable tax regimes. On the other hand, in regions with smaller biomass resources, such as the eastern voivodeships, the sector's development is limited.

Table 1 shows the number of agricultural biogas installations and producers in Poland's voivodeships. The summarised data show significant regional differences in the use of biogas technologies, with the western and northern voivodeships characterised by the highest number of installations and entities engaged in agricultural biogas production. This differentiation is due to several

factors, including specific regional agricultural conditions, availability of raw materials, level of institutional support and economic and political conditions affecting the development of the biogas sector in Poland.

Voivodeships such as Wielkopolskie, Kujawsko-Pomorskie or Mazowieckie are characterised by a high concentration of farms with high animal production (e.g. pig and cattle farming). Animal production generates large amounts of manure, an important substrate for agricultural biogas plants. Regions with intensive agriculture also have more opportunities to use residues from crop production, such as maize silage or cereal waste.

Voivodeships with well-developed agricultural, logistical, and energy infrastructure, such as Wielkopolskie, are more likely to install biogas plants. Voivodeships with less intensive agriculture (e.g., Lubuskie, Opolskie, Świętokrzyskie) have limited availability of suitable raw materials and less developed infrastructure to support the development of biogas plants.

Voivodeships that actively support renewable energy installations have more such investments. An example is Wielkopolska, where investments in biogas plants are often subsidised. Voivodeships with fewer installations do not have adequate support programmes or local initiatives. Agricultural biogas plants are more profitable in regions where larger farms produce significant substrates (e.g. manure, slurry, plant waste). In voivodeships where small farms predominate (e.g. Małopolskie or Świętokrzyskie), the scale of substrate production often does not economically justify the construction of a biogas plant.

In Voivodeships with many installations (e.g. Pomorskie, Warmińsko-Mazurskie), there is greater awareness of the benefits of biogas production, such as improving the energy balance of farms and efficient management of agricultural waste. In voivodeships with fewer installations, awareness of the benefits of biogas plants may be lower and agricultural traditions may be less conducive to innovative technologies. Agricultural biogas plants are most profitable where electricity or heat can be easily sold or used. It is easier to find customers in more urbanised regions with a developed industrial infrastructure (e.g. Wielkopolska Voivodeship).

Regional differentiation results from the synergy of many factors, including the intensity and specificity of agricultural production, availability of raw materials, financial support, and local awareness and tradition. The development of agricultural biogas plants is mainly concentrated in regions with high feedstock potential and favourable economic conditions. In regions with less use of this technology, government policies and greater involvement of local authorities can support the development of biogas plants. Table 2 presents data on the average annual agricultural biogas yield (m³/year) and the average installed electric power (MW) in renewable energy sources (RES) installations producing agricultural biogas in the individual voivodeships of Poland.

The voivodeships with the highest average annual biogas production in Poland are Pomorskie (4,993,862 m³/

Table 1. Distribution of agricultural biogas installations and producers in Poland

No.	Voivodeship	Number of agricultural biogas installations	Number of agricultural biogas producers
1	Zachodniopomorskie	18	14
2	Pomorskie	13	9
3	Warmińsko-Mazurskie	18	12
4	Podlaskie	12	12
5	Lubuskie	10	9
6	Wielkopolskie	29	25
7	Kujawsko-Pomorskie	6	6
8	Mazowieckie	18	15
9	Dolnośląskie	12	11
10	Łódzkie	10	9
11	Opolskie	3	2
12	Śląskie	2	2
14	Świętokrzyskie	2	2
15	Małopolskie	1	1
16	Podkarpackie	7	6

Source: Authors' calculations based on data from the National Agricultural Support Centre

Tabela 2. Average annual capacity (m³/year) and installed capacity (MW) of RES installations producing agricultural biogas - breakdown by Voivodeship

Voivodeship	Average annual yield of renewable energy installations producing biogas for agricultural use (m ³ /year)	Average total installed electric capacity of RES installations producing electricity from agricultural biogas (MW)
Zachodniopomorskie	3 929 380	0.89806
Pomorskie	4 993 862	1.13208
Warmińsko-Mazurskie	3781778	0.88006
Podlaskie	3 481 955	0.88925
Lubuskie	2976000	0.6784
Wielkopolskie	4 178 424	1.04348
Kujawsko-Pomorskie	5 663 517	1.6195
Mazowieckie	3 157 351	0.76461
Dolnośląskie	4 257 462	1.04725
Łódzkie	4 340 661	1.1428
Lubelskie	3 544 533	0.94787
Opolskie	3 387 933	0.88833
Śląskie	3 025 000	0.7475
Świętokrzyskie	3 422 000	0.8995
Małopolskie	864 000	0.15
Podkarpackie	3 078 571	0.71343

Source: Authors' calculations based on data from the National Agricultural Support Centre

year) and Kujawsko-Pomorskie (5,663,517 m³/year). This means these regions have a high agricultural potential and a developed infrastructure for biogas production. The Małopolskie Voivodeship has the lowest biogas production of only 864,000 m³/year, which may indicate a lower agricultural potential or a less developed biogas production technology in this region. The Kujawsko-Pomorskie Voivodeship stands out with the highest installed electrical capacity of 1,6195 MW, which indicates a strong development of the renewable energy sector in this region and an efficient conversion of biogas into electricity. The Małopolska Voivodeship, despite low biogas production, has an installed electrical capacity of 0.15 MW, which may indicate a limited infrastructure for biogas-to-electricity conversion.

The analysed data show large differences between regions in terms of both biogas capacity and installed capacity. Some Voivodeships, such as Wielkopolskie and Lubelskie, have high biogas capacities (more than 4 million m³) and large installed capacities, indicating strong development of this type of renewable energy in these Voivodeships. On the other hand, Voivodeships such as Małopolskie and Podkarpackie have smaller installed capacities than biogas, suggesting that they may have less developed infrastructure for electricity generation from biogas. There are also differences in the efficiency of biogas conversion into electricity. For example, despite its average biogas capacity (3,157,351 m³/year), Mazowieckie has a relatively high installed electricity capacity (0.76461 MW), indicating a higher conversion efficiency. On the other hand, the Podkarpackie Voivodeship has a similar biogas yield but a lower electrical capacity (0.71343 MW), which may indicate a less developed biogas-to-electricity conversion infrastructure.

There is a clear disparity in biogas production and installed capacity across Poland's Voivodeships. Voivodeships such as the Kujawsko-Pomorskie and Wielkopolskie Voivodeships have great biogas production and electricity generation potential. Other regions, especially those with lower capacity, such as Małopolskie, may have limited infrastructure or a less developed biogas market.

Voivodeships with low biogas production and installed capacity (e.g. Małopolskie, Podkarpackie) can benefit from increased investment in infrastructure for biogas production and its conversion into electricity. The development of this sector can contribute to their energy independence.

There is potential to improve the efficiency of biogas conversion in some regions. Optimisation of biogas energy production processes can increase the amount of electricity produced, contributing to the development of renewable energy in Poland.

The development of biogas plants in Poland requires a comprehensive approach that considers legal, financial, technical, and social aspects. Key actions should include, first and foremost, improving the legal and regulatory framework, including the introduction of stable and long-term regulations that provide investors with certainty

about the market's future. It is also important to simplify the administrative procedures for obtaining permits for constructing biogas plants and to introduce a biowaste management obligation to ensure a stable flow of raw materials. Access to national and European funds for constructing and modernising biogas plants, such as EU funds, preferential loans or tax relief, should be improved. Supporting farmers through funding schemes for projects where biogas plants process organic waste is also important.

An important element is the promotion of local initiatives through incentives for municipalities and local governments, support for energy cooperatives and the organisation of information campaigns to raise public awareness of the benefits of biogas plants, such as the reduction of greenhouse gas emissions, the reduction of odours and the production of green energy. The development of the sector requires investment in research into new fermentation technologies, efficient use of substrates, and improvement of the efficiency of biogas plants. It is also important to develop biogas storage technologies, including biomethane, which can be injected into the gas grid as a renewable energy source. Digitalisation and automation of biogas plant management can help increase efficiency and reduce operating costs.

An important step is to integrate biogas plants with other sectors of the economy, for example by promoting the use of biomethane in public transport and trucking, and by deepening cooperation between the energy sector and farmers in the management of agricultural waste. The development of combined heat and power (CHP) can significantly increase the profitability of such investments. Climate and energy policy should consider Poland's commitments within the EU to decarbonise the economy, which can provide an additional impetus for developing biogas plants. Promoting biogas plants as a stable source of renewable energy, which can complement other sources such as photovoltaic or wind energy, should be a key element of the country's energy strategy.

To develop the sector effectively, a monitoring and reporting system on the operation of biogas plants in Poland is needed to analyse their performance and identify barriers to development. An audit of available biomass resources should also be carried out to identify potential locations for new investments. All these activities should be part of a coordinated national strategy, considering cooperation between the public sector, the private sector and local communities.

Table 3 shows the number of bio-component production facilities and the number of bio-component producers in each of the Polish Voivodeships. The Wielkopolskie and Kujawsko-Pomorskie Voivodeships are regions with intensive agriculture, which provide a large number of raw materials for the production of bio-components (e.g. rape, starch raw materials). These raw materials are the main feedstock for biodiesel and bioethanol production. Voivodeships such as Wielkopolskie, Dolnośląskie and

Table 3. Number of installations and producers of bio-components in Poland

No.	Voivodeship	Number of bio-component production facilities	Number of producers of bio-components
1	Pomorskie	3	2
2	Wielkopolskie	7	6
3	Mazowieckie	3	1
4	Dolnośląskie	3	3
5	Łódzkie	2	1
6	Opolskie	1	1
7	Śląskie	2	2
8	Małopolskie	1	1
9	Podkarpackie	2	2
10	Lubelskie	1	1

Source: Authors' calculations based on data from the National Agricultural Support Centre

Śląskie are characterised by access to a well-developed industrial and logistical infrastructure, which favours the location of bio-component production facilities.

Bio-component production is more developed in the western and central Voivodeships due to the proximity of large domestic and foreign markets (e.g., export to Germany or the Czech Republic). Voivodeships such as Wielkopolska often benefit from subsidies or investment support for developing renewable energy installations. The location of plants can also be linked to the presence of refineries and the fuel industry, which is the main consumer of bio-components.

The distribution of biocomponent facilities and producers in Poland results from a synergy of factors such as agricultural intensity, availability of industrial infrastructure, proximity to markets and investment support. The Wielkopolska Voivodeship dominates, underlining its strategic role in the biocomponent sector in Poland, while the eastern and southern regions remain less involved in this production branch.

Table 4 presents the characteristics of biocomponent production facilities in Poland, which show considerable diversity in terms of location and technological efficiency. The analysis of individual Voivodeships shows a concentration of installations in certain regions, reflecting the specific nature of local resources and the development of industrial infrastructure.

The Pomorskie Voivodeship is dominated by installations that produce liquid biohydrocarbons and methyl esters. The capacity of liquid biofuel plants is as high as 286 million litres per year, making the region one of the leaders in this segment. In addition, methyl ester plants have a capacity of 170 million litres per year and biopropane production

is 32 million litres, using diesel hydrodesulphurisation technology.

Wielkopolska is characterised by the diversity and size of its bioethanol plants. These include molecular sieve plants with capacities of 50, 70 and 150 million litres per year and large ethanol dehydration plants with an annual capacity of 204 million litres. Other bioethanol plants in the region have 95 and 80 million litres of capacity. In addition, Wielkopolska has ester production plants with a capacity of 22.65 million litres, which completes the diversification of the regional bio-component industry.

In Mazowieckie Voivodeship, several diesel hydro desulphurisation plants produce liquid hydrocarbons on a large scale. The HON I, HON VI, and HON VII plants have annual capacities of 26, 85, and 118 million litres, respectively, making a significant contribution to the national production of this type of bio-component.

The Dolnośląskie Voivodeship focuses on the production of bioethanol and methyl esters. The alcohol adsorption dehydration plant has a capacity of 35 million litres, and the agricultural distillery with molecular sieve technology supplies 5.5 million litres per year. Meanwhile, the region's methyl ester plant has a significant capacity of 186 million litres annually.

In Łódzkie Voivodeship, there is an ETG plant for producing synthetic fuels with a capacity of 13.88 million litres. Biopropane-butane production here is 3.18 million litres, although infrastructure details are limited.

Lubelskie and Opolskie focus mainly on bioethanol production. Lubelskie has a molecular sieve plant with a capacity of 22 million litres per year. In comparison, Opolskie has the highest capacity in the country at 300 million litres per year, making the region a leader in bioethanol technology.

Methyl ester plants dominate the Silesian region. The largest of these, the ester plant, has a capacity of 268.79 million litres per year, while another plant in the region produces an additional 124.58 million litres of methyl esters.

Małopolskie is one of the most important regions in Poland in terms of methyl ester production, with a plant with a capacity of 353.13 million litres per year.

Podkarpackie is home to Poland's largest ester plant, with a capacity of 475.65 million litres annually. The voivodeship also has an ethanol dehydration plant that produces 68 million litres of bioethanol per year.

The above characteristics show that Poland has a significant production capacity for bio-components and is located in different regions of the country. The plants' production capacity and technological diversity indicate the development of sustainable production of renewable fuels using local resources and infrastructure. Voivodeships such as Wielkopolska, Śląskie, Małopolskie or Podkarpackie play a key role in the national balance of bio-component production, and their development contributes significantly to the energy transition and the increase in the share of renewable energy sources in Poland.

Table 4. Characteristics of biocomponent production facilities in Poland

Voivodeship	Type and scope of activities	Type of installation	Annual production capacity (million litres)
Pomorskie	The production of bio-components (methyl esters) and their subsequent disposal by any legal or de facto act that results in the permanent disposal of these bio-components or their use to produce fuels by oneself	Technical installation for the production of esters	170,00
	Producing bio-components (liquid bio-hydrocarbons) and then using them to produce their fuels	Diesel Hydrodesulphurisation Plants	286,00
	Production of biocomponents (biopropane) and their subsequent use in the production of fuels	Diesel Hydrodesulphurisation Plants	32,00
Wielkopolskie	The production of bio-components (bioethanol) and their subsequent disposal by any legal or de facto act resulting in the final disposal of these bio-components	Molecular sieve systems	50,00
			70,00
		-	150,00
		Ethanol dehydration unit	204,00
		Bioethanol production plant	95,00
			80,00
	The production of bio-components (esters) and their subsequent disposal by any legal or factual act that results in the final disposal of these bio-components	Installation for ester production	22,65
Mazowieckie	Producing bio-components (liquid bio-hydrocarbons) and then using them to produce their own fuels	Diesel hydrodesulphurisation plant (HON I)	26,00
		Diesel hydrodesulphurisation plant (HON VI)	85,00
		Diesel hydrodesulphurisation plant (HON VII)	118,00
Dolnośląskie	The production of bio-components (bioethanol) and their subsequent disposal by any legal or de facto act resulting in the final disposal of these bio-components	Adsorption alcohol dehydration plant	35,00
		Molecular sieve dehydration plant for agricultural distilleries	5,50
	The production of bio-components (methyl esters) and their subsequent disposal by any legal or de facto act resulting in the permanent disposal of these bio-components	Installation for ester production	186,00
Łódzkie	The production of bio-components (liquid bio-hydrocarbons) and their subsequent disposal by any legal or de facto act resulting in the permanent disposal of these bio-components	TG plant for the production of synthetic fuels	13,88
	The production of bio-components (bio-propane-butane) and their subsequent disposal by any legal or de facto act resulting in the final disposal of these bio-components		3,18
Lubelskie	The production of bio-components (bioethanol) and their subsequent disposal by any legal or de facto act resulting in the final disposal of these bio-components	Molecular sieve systems	22,00

Table 4. Characteristics of biocomponent production facilities in Poland

Voivodeship	Type and scope of activities	Type of installation	Annual production capacity (million litres)
Opolskie	Producing bio-components (bioethanol) and then disposing of them by carrying out any legal or de facto act that results in the permanent disposal of these bio-components, or using them to produce its fuels	Molecular sieve systems	300,00
Śląskie	The production of bio-components (methyl esters) and their subsequent disposal by any legal or de facto act that results in the permanent disposal of these bio-components or their use to produce fuels by oneself	Plant for the production of methyl ester	124,58
	The production of bio-components (methyl esters) and their subsequent disposal by any legal or de facto act resulting in the permanent disposal of these bio-components	Estrownia	268,79
Małopolskie	The production of bio-components (methyl esters) and their subsequent disposal by any legal or de facto act that results in the permanent disposal of these bio-components or their use to produce fuels by oneself	Plant for the production of methyl ester	353,13
Podkarpackie	The production of bio-components (esters) and their subsequent disposal by any legal or de facto act that results in the permanent disposal of these bio-components or their use for the production of fuels by oneself	Installation for ester production	475,65
	The production of bio-components (bioethanol) and their subsequent disposal by any legal or de facto act resulting in the final disposal of these bio-components	Ethanol dehydration unit	68,00

Source: Authors' calculations based on data from the National Agricultural Support Centre

Table 5. Total annual yield of bio-components by Voivodeship

Voivodeship	Total annual capacity (million litres)
Pomorskie	488.00
Wielkopolskie	671.65
Mazowieckie	229.00
Dolnośląskie	226.50
Łódzkie	17.06
Lubelskie	22.00
Opolskie	300.00
Śląskie	393.37
Małopolskie	353.13
Podkarpackie	543.65

Source: Authors' calculations based on data from the National Agricultural Support Centre

The highest yield was recorded in Wielkopolska (671.65 million litres), mainly due to the large number of bioethanol plants. The lowest yield was recorded in Łódzkie (17.06 million litres), due to the smaller number and size of plants. The analysis of bio-component production facilities in Poland allows for identifying the largest and smallest facilities in each bio-component category and the dominant regions for their production. In the case of bioethanol, the largest plant is located in the Opole Voivodeship, where molecular sieves reach an annual capacity of 300 million litres, making this region the leader in this segment. By comparison, the smallest bioethanol plant is an agricultural distillery in Lower Silesia, which produces just 5.5 million litres per year. In the case of methyl esters, the largest plant is located in the Podkarpackie Voivodeship, with an impressive capacity of 475.65 million litres, the largest contribution to the national production of this bio-component. The smallest methyl ester plant is located in the Silesia region, producing 124.58 million litres.

Table 6. Share of each Voivodeship in the national total

Voivodeship	Share (%)
Pomorskie	16.3
Wielkopolskie	22.4
Mazowieckie	7.6
Dolnośląskie	7.6
Łódzkie	0.6
Lubelskie	0.7
Opolskie	10.0
Śląskie	13.1
Małopolskie	11.8
Podkarpackie	18.1

Source: Authors' calculations based on data from the National Agricultural Support Centre

A hydrodesulphurisation plant in Pomerania dominates liquid biocarbon production with a capacity of 286 million litres per year, the largest share in this category. In contrast, the smallest liquid biocarbon plant, located in Łódzkie Voivodeship, has a capacity of 13.88 million litres per year. In the case of biopropane and biopropane-butane, the dominant plant is also located in Pomerania, with a capacity of 32 million litres per year. The smallest plant of this type is located in the Łódzkie Voivodeship and produces 3.18 million litres.

Regarding regional dominance in the production of individual bio-components, Opolskie stands out in the bioethanol category, where the largest plant is responsible for 32% of domestic production of this bio-component. Other important voivodeships are Wielkopolska and Podkarpacie, which produce 617 million litres together. In the case of methyl esters, Podkarpacie is dominant, with plants accounting for 39% of national production, with Małopolskie and Śląskie also making significant contributions.

The production of liquid biocarbons is concentrated in the Pomeranian Voivodeship, which accounts for 60% of the national production of this component. Pomerania also dominates in the category of biopropane and biopropane-butane, where production, at 32 million litres, significantly exceeds that of other regions.

Due to differences in raw material availability, infrastructure, and technology development, the distribution of bio-component production in Poland is concentrated in a few key regions. Voivodeships such as Opolskie, Podkarpackie, Pomorskie, and Wielkopolskie play a key role in the domestic production of biocomponents, making them strategic areas for further development of the sector.

Estimating the total national production as the sum of the annual production capacity of the plants in the individual Voivodeships, the total national capacity was 2,997.36 million litres. Table 6 shows the share of each Voivodeship in the annual production of bio-components.

The data presented in Table 6 illustrates the share of each Voivodeship in the domestic production of bio-components and shows significant differences in regional involvement. The dominant position is held by Wielkopolskie and Podkarpackie Voivodeships, which together account for more than 40% of total production. Wielkopolskie, with a share of 22.4%, and Podkarpackie, with a share of 18.1%, owe their results to expanded bioethanol and ester production facilities, which testify to their significant role in the bio-component sector in Poland. The Opolskie Voivodeship, with a share of 10.0%, also stands out from the rest of the country, mainly due to the largest bioethanol plant, which gives it an important role in the national production structure.

The Voivodeships of Śląskie (13.1%) and Małopolskie (11.8%) also play an important role in the national balance, although their share is smaller than that of the leading Voivodeships. The high share of the Pomeranian Voivodeship (16.3%) underlines this region's importance in producing bio-components, which may be due to its favourable logistical location and developed industrial infrastructure. In contrast to these regions, the Mazowieckie and Dolnośląskie Voivodeships, despite their share of 7.6%, have a relatively moderate impact on national production. The marginal share of the Łódzkie (0.6%) and Lubelskie (0.7%) Voivodeships indicates the untapped potential of these regions, which may be due to limited industrial infrastructure or other obstacles to development. These data suggest that there is potential for development in these Voivodeships, especially in the context of the growing demand for bio-components in the country. The percentage analysis shows a clear differentiation between regions, with leaders with a high concentration of production and regions with minimal input, reflecting both the potential and the existing disparities in the development of the biocomponent sector in Poland.

5. CONCLUSIONS

The regional diversity of agricultural biogas and biofuel production in Poland reflects the availability of raw materials in certain regions and the degree of development of policies supporting the energy transition towards renewable energy sources. An analysis of the literature indicates that the key factors determining the development of the biogas and biofuel sector are primarily the local supply of biomass, legal regulations and financial support mechanisms enabling innovative production technologies.

Developing the biogas and biofuel sector brings multi-dimensional benefits, including environmental, economic and social aspects. Agricultural biogas production allows organic waste to be managed and methane emissions to be reduced, while the development of biofuels can help reduce dependence on fossil fuels. Economically, the sector stimulates local economic development by creating jobs in the production, distribution and operation

of biogas plants and plants that convert biomass into fuel bio-components. Socially, developing renewable energy sources increases environmental awareness and promotes circular economy strategies.

The analysis shows that Voivodeships characterised by intensive agricultural production, such as Wielkopolskie, Kujawsko-Pomorskie and Podlaskie, have the highest level of agricultural biogas production, which is directly linked to easy access to organic substrates such as agricultural waste and manure. On the other hand, the production of biocomponents is concentrated in regions with a well-developed processing industry, such as Wielkopolskie, Podkarpackie and Opolskie, where there are technological facilities for the efficient conversion of biomass into renewable fuels. In contrast, the central and eastern Voivodeships, including Mazowieckie and Lubelskie, despite their significant raw material potential, are characterised by a lower level of biogas and biocomponent production, which may be due to limited technological infrastructure, lack of large processing plants and insufficient support mechanisms for investments in the renewable energy sector.

The author draws attention to significant disparities in biogas and biofuel production levels between individual

regions. The dominance of some Voivodeships, such as Wielkopolskie or Podkarpackie, is mainly due to favourable raw material conditions and earlier investments in the technological infrastructure of the bio-components sector. However, the study did not fully consider the impact of regional policies and the level of development of logistics infrastructure, which could significantly determine further opportunities for the sector's expansion in different parts of the country.

The conclusions of the analysis underline the need for a more sustainable development of the biogas and biofuels sector in Poland by intensifying measures to support production in regions with a lower market share. In particular, there is a need to integrate energy, regional and agricultural policies to increase the share of renewable energy sources in the national energy mix and thus meet climate policy and sustainable development objectives. Further research should focus on identifying the barriers limiting the sector's development in regions with lower biogas and biofuel production activity and developing strategies to integrate them more effectively into national energy and industrial policies.

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