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Changes in feedstocks of rural anaerobic digestion plants: External drivers towards a circular bioeconomy

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ABSTRACT

The aim of this study is to better understand the recent changes in the feedstocks of anaerobic digestion plants, the driving forces behind these changes and consequent opportunities to strengthen closed-cycle energy production and promote the circular bioeconomy approaches. The study analyses Poland – a country with a highly diversified agrarian structures and with various levels of the development and focus of regional agricultural sectors which belong to the main sources of biosubstrates to be energetically processed in anaerobic digestion (AD) plants. Biowaste, including biowastes originating in agri-food production and in households, is indicated as one of the key sources for a more sustainable biogas generation. Our findings indicate and prove a gradual shift in the mix of substrates, including the growing role of energy processing of biowaste from households and municipalities. It was also ascertained that in the initial phase of the development of Polish biogas market in early 2010s, the AD substrates in most important position were agricultural raw materials (energy crops) and agricultural waste. On the other hand, during the course of time and due to developing legal requirements as well as financial and market conditions, the biowastes from the food industry and of municipal origin have gradually gained significance. An unintentional shift towards the energy processing of the more sustainable AD substrates in Poland is visible despite a rather low environmental awareness of AD operators.

1. Introduction

Existing energy systems are under scrutiny and pressure to change as environmental policies are becoming stronger and more integrated, seeking to simultaneously address multiple and diverse societal challenges related to environmental degradation, and paying more attention to human health, well-being, equity and the need to fundamentally change the ways in which our 'business as usual' economic models have been producing negative externalities. Resource efficiency and circular economy are cornerstones of such environmental policies, found for example in the European Green Deal, ratified in 2019 [1] and the long-term climate strategy adopted by the European Commission in 2018 [2].

The idea of circular economy implies an economic system that is principally restorative or regenerative by intention and design; it replaces the epistemological concept of waste that is discarded (e.g. in landfill sites) with crucial emphasis on restoration, recycling, shift towards sustainable energy and food systems, reduction of the usage of toxic chemicals that impair the reuse and harm biosphere. The Circular economy aims to turn waste into a useful resource by applying the superior design of materials, products, systems, services and business models [3]; this is becoming a focal component of environmental policy and environmental management.

Bioeconomy is a concept that is closely related to the circular economy approach [4] and is understood as sustainable utilisation of bioresources as well as the conversion of resources and waste generated during their processing into added-value products, i.e. food, animal feeding stuffs, bioproducts, bioenergy [5]. As a concept, the bioeconomy is inherently circular with the use of biomaterials (as opposed to finite and non-renewable resources) serving as key elements of circular setting

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of the economy. The circular bioeconomy is a cornerstone of and a prerequisite for the further evolution of circular economy approaches [6].

Bioenergy (i.e. biomass utilised to produce useful heat, electricity, locomotion etc.) is a key aspect of the circular bioeconomy, as appropriate deployment and utilisation of bioenergy can yield benefits such as greenhouse gas emission reduction, the provision of affordable and locally sourced energy services, the removal of pathogens and even the use of residues – e.g. as organic fertiliser [7].

Given the radical extent to which humanity has altered natural ecosystems whilst we are still fundamentally dependent on provisioning ecosystem services for our livelihoods, the sustainable utilisation of biomass plays an important role in a zero-greenhouse gas economy [8]. Different forms of biomass can be processed into biogas, liquid and solid biofuels which can be utilised in engines and stoves to produce heat, locomotion or electricity. In particular methane which is clean burning and is produced through the anaerobic digestion of wet biomass waste, holds a particular promise for building a local, more resilient and sustainable economy [9]. Other important aspects of the utilisation of biogas are its use as an alternative to natural gas. Moreover, biogas can be transported by means of existing gas pipeline network, and it provides opportunities to reduce greenhouse gas emissions from agricultural production through organic waste management [10] while connecting the final products (electricity, heat, fertiliser) for local sustainable development. A key question arises, what types of feedstock should be used for the generation of biogas energy so that the principles of the circular economy and sustainability are best served? The 'in principle' answer can be provided through life cycle analysis (LCA), but equally important is the 'in practice' answer, i.e. to what extent are existing biogas operators shifting towards the use of more sustainable practices in terms of feedstock.[1] Whilst there is good 'in principle' understanding of feedstock sustainability from existing LCA studies, there is a lack of existing academic studies on the empirical question of how biogas plants operate in practice.

We address this 'in practice' question through a case study of existing AD plants in Poland. For the empirical study of the sustainability of biogas feedstock or substrate (these words are used interchangeably), a Polish case study is particularly suitable for three reasons; Poland's biogas sector is quite new, i.e. plants are technologically up to date and fully operational, with some 100 AD plants and a total installed capacity of 120 MW [11]. Secondly, it is a mature market were feedstock has become a constraining factor; the building of new AD plants has stalled as operators of existing biogas plants find themselves competing for affordable and regionally available feedstocks of sufficient quantity and quality in order to keep their plants running. As a consequence, actual electricity production has fluctuated between 600 and 700 GWh annually [12].

With regards to the agricultural sector, a Polish case study is of interest because of significant geographical differences in farming structure (large agri-businesses in the west of the country; small family farms in the east), and because of the systemic changes the agricultural economy has been exposed to in the last 30 years. The fall of communism created strong economic disruptions. Joining the European Union (EU) and transitioning to a market economy brought in many new policies (esp. environmental regulations), incentives (e.g. agricultural subsidies; renewable energy subsidies) and (global market) opportunities and exposures.

The aim of this study is to better understand the recent changes in the feedstocks of anaerobic digestion plants, the driving forces behind these changes and consequent opportunities to strengthen closed-cycle energy production and promote the circular bioeconomy approaches. As we know that regional varieties in agricultural structures heavily affect the possibilities for the development of sustainable rural bioeconomies, we are focusing on understanding of regional specifics and regional trajectories in the usage of feedstocks or substrates for AD. The analysis was carried out on two scales; national and regional, for the time period of 2014–2018 (the period for which we have feedstock data).

The article consists of two main parts. In the first part, theoretical and conceptual framework of the study highlighting the circular economy approach in understanding of agricultural biogas energy cycle is discussed. The second part present our findings based on the analysis of changes in the mixture of biogas feedstock.

2. Theoretical and conceptual framework

2.1. Circular bioeconomy

Scholarly literature provides us with multiple definitions of circular bioeconomy. The circular economy shifts from the linear economy model to the recycle economy mode [13]. The circular economy provides a solution to re-using and re-consumption resources, inlcuding waste. The objective is to develop a recycle-production-use mode so that the waste can be utilised as products [14]. Hence, it ensures not only economic growth, but also socio-environment well-being [15]. As can be seen above, the reference points that connect all the definitions are the circularity of the use of wastes and resources and the conversion of these resources and wastes into value added bio-based products. A strong voice among researchers also point to circular bioeconomy as an opportunity to implement circular economy with respect to the use of bioresources.

The concept of the bioeconomy is well-grounded in the idea of reuse through reduction, recycling, and recovery of materials during the production, distribution, and consumption [16–19]. Other authors point to the need for a more broad view on circular bioeconomy that goes beyond technical and economic issues. As suggested by Szymańska et al. [19], circular bioeconomy focuses on the sustainable and resource-efficient use of bioresources. This approach enables taking into account the social aspects of the economy thus shaped.

However, irrespective of whether we consider circular bioeconomy in a narrow or a broad sense, the basis for its development lies in bioresources, which are distinguished by a permanent production process. Their sustainable use for energy purposes positions biogas plants as leading the way for the future of the circular bioeconomy.

An amount of biosubstrates available to be energetically processed in biogas plants are increasingly generated in both urban and rural areas. The global urban population alone provides about 2 billion tonnes of waste per year, of which 34–53% is the biodegradable organic fraction [20–22]. When considering the suitability of biowaste in terms of energy and economic efficiency, Termansen et al. [23], propose to divide them into several groups, including six main ones differentiated by colour, i.e. green, yellow, blue, brown, black, and grey (Table 1). The green group refers to energy crops. Maize is the most widely used energy crop for AD plants in Central Europe but it is facing relatively high production costs. The use of the blue group for energy purposes, which consists mainly of algae, also requires further research and the experimental phase to continue. The brown group is broadly understood as wood, but given the priorities of nature protection, the role of woodlands as carbon sinks and the LCA logic to use wood for higher value and longer term purposes (e.g. as building materials), the role of this raw material in bioenergy production should be marginalised. At present, three groups are characterised by the highest market maturity, and they comprise agricultural, industrial, and municipal waste. The grey group consisting of livestock breeding waste; the yellow group, refers to crop production waste (e.g. straw); and finally, the black group is composed of municipal and industrial waste, including food processing and catering waste [23,

[1] This paper focuses on the sustainability of the feedstock. We acknowledge that 'whole system' sustainability concerns are wider and include the building, operation and eventual dismantling of the biogas plant, as well as the displacement effects and end use of the outputs – e.g. how the waste heat and digestate are utilised.Highlights.

Table 1
The main AD feedstock categories with key benefits and concerns reported in the literature. In brackets are the 'Danish' colour categories [23,24].

Source of bioenergy	Benefits	Concerns
Energy crops (green)	Easy to harvest, economic security for farmers [25, 26].	Crowding-out the food production, food insecurity issues, environmental concerns (monoculture fields, overuse of fertilizers), space requirements, storage needs [27, 28].
Algae (blue)	Carbon neutral, rapid growth of algae, cultivable throughout the year [29].	High use of water and fertilizers, high costs, complicated harvesting [30, 31].
Livestock faeces and manure (grey)	Availability throughout the year, killing pathogens, upgrades for the on-farm waste management, fluent supplies, reduces risk of pollution [32].	Storage needs, possible odour leakages [33, 34].
Crop waste (yellow)	Usage of waste that would stay unused, doesn't compete with land [35].	Removal from fields results in the loss of soil fertility, high risk of soil erosion, seasonal feedstock (needs to be stored) [36].
Municipal and industrial biowaste (black)	Wide availability throughout the year, killing pathogens, avoiding landfilling, usage of waste that would stay unused [37, 38].	Pre-treatment is needed, location of the large-scale plants in densely populated areas causes conflicts, possible odour leakages [39].

Source: own elaboration

24].

Taking into account the amount of biowaste generated as a potential source for biogas production, and its energy and economic efficiency, it should be noted that biogas production emerges as a priority strategy for the management and processing of municipal, industrial, and agricultural organic waste. AD plants play an important role here as they digest and recover energy from both agricultural and food-processing waste. These facilities operate on the basis of combined heat and power generation (CHP), enabling them to reach an efficient of up to 90% (35% for electricity plus 65% for heat) [40]. Biogas plants enhance energy security not only in relation to the generation of more sustainable electricity, but also in terms of heat that can be distributed to surrounding buildings and thus, inclusively support local social development. The combination of energy recovery (i.e. biogas for energy services) and nutrient recovery (i.e. residual effluent used as organic fertiliser) is essential for the proper functioning of the bioeconomy [41]. Apart from the above-mentioned aspects of AD plants' operation, it is worth noting one more feature – they advance the decentralisation of energy and the dissemination of the prosumer model of energy production, implemented by individuals, entrepreneurs, farmers, as well as local associations and organisations [42].

2.2. Circular bioeconomy and AD plants

The current environmental crisis puts significant pressures on AD plant owners, farmers, policymakers and technology providers to focus on as much sustainable operation of the AD plants as possible [43,44]. At the same time, the application of approaches of circular economy in the AD sector creates plenty of opportunities to do things differently, in a more environmentally friendly way and more sustainably. The use of products (substrates in the case of AD) beyond the end of their service life conceptually brings new horizons for thinking about the benefits of AD [45]. As has already been proved by many studies [46], improving the operation of ADs might, in the end, make the bioenergy sector more beneficial for future settings of our green economy and society. Indeed, accommodation of principles of circular economy in the AD sector shifts the limits of distribution of benefits exclusively from AD operators to wider communities [47].

Let us focus first on the perspective of the origin and the mixture of substrates to be supplied to AD and on the position of ADs in sustainable waste management. It is important to note that an optimal (or ideal) AD system is a myth. AD plant operation cannot be ramped up and down on short notice. Farming anaerobic bacteria is a dynamic process with significant temporal inertia. Ensuring stable growing conditions for methane producing bacteria requires a careful balancing of feedstocks that arrive in variable quality e.g. in terms of nutrient concentration, acidity, temperature. Large-scale local storage is required for these unstable materials in order to deal with the seasonal dimensions of feedstock production and ensure reliable food supplies for the bacteria. Electricity production might be most profitable during daily peak consumption times, but the demand for heat and for fertiliser is seasonal. AD trade-offs also need to be considered geographically as these are linked to the social, economic and environmental relations in the community where AD is located [48]. On the other hand, we are able to consider key hints that might help us to be knowledgeable about this problem and drive ADs towards sustainability.

It has already been proved that energy processing of biowaste in AD really matters when talking about environmental benefits of the AD operation [49]. We also know that sizes of AD facilities should be aligned with a quantity of substrates available in reasonable distances from particular AD plant [50] which certainly indicates where AD plants should be ideally located; near farms, food industries or cities, towns and villages where sufficient amount of bio-waste is generated and its transport is logistically and economically viable). . This 'feedstock hinterland' is also a key determinant for the scale of each AD plant and it also illustrates why AD plants cannot be geographically concentrated. A circular economy approach fundamentally urges to fully implement AD into waste management [51,52]. This might include energy processing of sewage sludge, biowaste, catering waste, organic leftovers from the food and beverage industry, agricultural by-products from farms like manure and straw [53]. Recycling of organic waste and its processing for energy in AD contributes to the reduction of greenhouse gas emissions that would be otherwise generated if organic waste is not processed but just dumped in landfills. Moreover, the usage of locally produced renewable energy contributes to reducing our dependency on fossil fuels and supports energy decentralisation [54]. Another point that deserves to be mentioned here is a digestate (organic fertilizer) as the co-product of anaerobic digestion that can displace environmentally damaging chemical fertilizers (synthetic nitrogen production is highly energy intensive; phosphorous comes from large-scale mining and is non-renewable).

Products from energy processing of locally produced organic waste (such as biogas, heat) can also serve to reduce rural poverty and inequality. The distribution of locally generated heat is especially important for neighbouring communities that are experiencing negative local impacts (e.g. smell, traffic noise, spillage) [55], and where heat could serve as a form of compensation and benefit sharing. Heat as a co-product of AD is surprisingly still rarely used for local needs, despite it being a waste product that has great potential to reduce carbon emissions (replacing the use of fossil fuels for heating – in rural Poland this includes coal), provide social benefits and increase local support.

Considering that the idea of the circular economy can be explained as a system regenerative by intention and design, shifting towards the use of renewable energy and sustainability, we propose to use a circular bioeconomy, for the purposes of our research. We theorize this suggestion as a concept for managing biowaste, which is certainly in the heart of the circular bioeconomy, to produce energy (green energy) and other products that remain within the circular system that primarily serve to cover the energy needs of the local community. The presented construct allows for a holistic approach to the examined matters, taking into account a broad definition of circular bioeconomy as an idea of sustainable use of bioresources that also includes social issues, and at the same time the concept of circular economy, i.e. a model of continuous production and consumption based on raw materials existing in the system. In this study, we are dealing with the production of a set of products based on biowaste, such as energy, heat, and organic fertiliser (digestate), and their consumption by local communities (please see Fig. 1).

2.2.1. AD plants and sustainability

Transposing activities related to biogas production (being an expression of the development of the bioeconomy) from the global to the local level requires the local communities to develop the local energy market on the one hand and calls for the stimulation of technological development and local public support on the other. Indisputable role of grassroots energy initiatives that manifest themselves through their influence on the formation of the attitudes and behaviours towards energy in the community, stems from the principles of sustainable production and consumption, or even apply the idea of corporate social responsibility [56]. In turn, the coincidence of legislative solutions and economic factors constitutes an external stimulus. If we look at both waste treatment and management through the lens of the circular economy approaches, a shift towards sustainability and understanding of waste as resource, is obvious. Waste management based on landfilling needs to be minimised, due to environmental regulations it is becoming increasingly expensive; some of waste products are harmful and dangerous to human health and environment [57]. Therefore, the increasing importance of biowaste as a bioenergy resource, originating from agricultural production and food industry processing, as well as from sewage sludge is incorporated in legal regulations of numerous countries. On the one hand, we clearly see the tendency when the use of energy not so efficient and environmentally questionable use of green biomass is being gradually restricted, while on the other hand, the use of biowaste in biogas production is encouraged. For example, in Germany as one of the European leaders in the production of biogas energy, the share of maize and maize silage (i.e. green bioresources) in the substrate mixture has been restricted to a maximum of 50% since 2017. Similarly, in Finland, the share of energy crops (green biomass), mainly grasses, is systematically marginalised [58]. In turn, the Czech Republic introduced financial incentives (approximately 32 Euro/GJ) for the distribution of heat generated from biogas in 2016 that support the use of organic and biodegradable waste in biogas production [59].

Following the three basic types of the bioeconomy as defined by Bugge et al. [60], i.e. (1) the biotechnological type focusing on research and innovation, (2) the bioresource type aiming at sustainable economic development through the conversion of biological resources, and (3) the bioecological type, related to biodiversity activities, it should be underlined that biogas production fits within each of these three types. This means that the development of the circular economy is strengthened in all its dimensions.

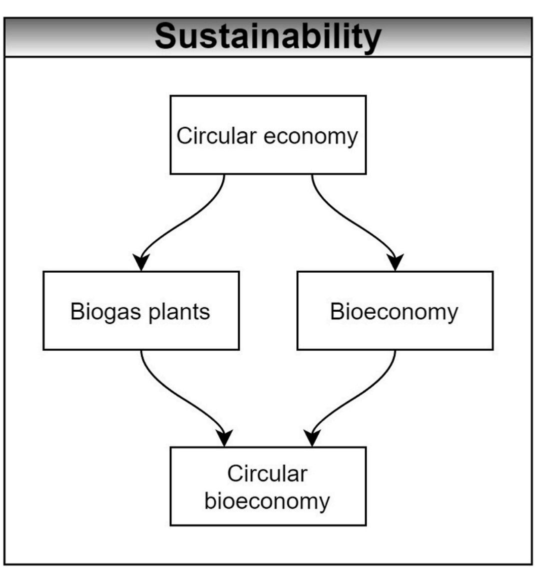

Fig. 1. The conceptual framework of the study.
Source: own elaboration

This multi-faceted energy production based on biowaste is also associated with numerous challenges. On the one hand, it is crucially important to ensure the long-term fluency and stability of the substrate supply and, on the other hand, to stimulate further research and development to better understand possibilities for a more efficient conversion of biowaste into biogas and other products [16]. It is clear that research and innovation projects in the field of bioeconomy require *trans*-sectoral cooperation, taking into account economic, social, and environmental priorities. Ensuring a closed production loop must be crucially based on the principles of economically efficient to ensure the continued viability of the AD business, with regard to the multifunctional use of space and the application of the resultant products [61,62]. It should not therefore, take place without the consent and a high level of acceptance of the population living nearby ADs [63,64].

3. Research area, materials and methods

3.1. Research area

Our empirical study on the changes in the mixture of substrates for biogas production as an opportunity to strengthen closed-cycle production and its relevance to dissemination of the circular bioeconomy approach, we chose Poland as case study. We worked on two spatial scales, on a national level, and a regional level. Poland has a highly diverse regional agrarian structures and varied regional types of agriculture, providing biosubstrates used for the biogas production. These agricultural disparities are the result of, on the one hand, natural conditions for agricultural activity and, on the other hand, historical consequences and application of different agricultural systems in various part of the country. An existing indicator of natural conditions of agricultural suitability, including the quality of soils and climate characteristics, gives the whole of Poland an average of 66.6 points out of 120 possible. The highest values, exceeding 80 points, are recorded mainly in south-eastern and south-western Poland, partly also in its central part [65]. In turn, historical factors manifest themselves in the presence of large-scale farms (mainly in northern and western Poland). In the 18th century, Poland was undergoing the three 'Partitions', which involved the loss of rule to Russia, Prussia, and Austria. Large farms mainly cover the areas that used to be under Prussian rule (northern and western Poland). Their agriculture has been modernised, in contrast to that in the areas of the other two Partitions [66]. The divides between the eastern, western and southern parts of the Polish territory were so deep that they are still visible today in the agricultural landscape and agricultural practices [67,68]. After the WWII, agriculture in northern and western Poland was nationalised. The State Agricultural Farms (SAF) from the Communist era were privatised after the fall of the regime in 1989. The smallest farms, i.e. with up to 5 ha of agricultural land, typically mainly located in southern and eastern Poland, make up more than half of the total number of farms in the country. At the same time, many of these farms are characteristic by a low economic potential and a low production efficiency. Nearly 37% of farms operate on 5–20 ha, while share of the largest farms with over 50 ha (the most economically efficient) amounts just slightly over 2% of the overall number of farms in Poland (please see Fig. 4).

3.2. Materials and methods

3.2.1. Materials

Diverse natural conditions and historical factors still affecting Polish agriculture has enormously contributed to the development of various types AD plants in terms of their size and the mixture of substrates they process. Today, more than 100 agricultural AD plants with total installed capacity of 120 MW can be found in Poland [11] (Fig. 2).

The detailed analysis of ADs in Poland was carried out on the basis of data obtained from the National Support Centre for Agriculture (NSCA) [12] which is a Polish governmental agency, supervised by the Minister of Agriculture and Rural Development. The analyses were conducted for Poland as a total (on a national scale) and for individual regions (on the NUTS 2 level), in our case the voivodships (on a regional scale). We were enabled to get the data for our in-depth analyses in accordance with the principle of using public sector information in Poland under the Act on Access to Public Information [69].

In order to trace the operation of individual AD plants, the study covered the years 2014–2018 when the biogas sector has already been formed and stabilised. Due to the institutional factors, lack of support and the most recently the COVID-19 pandemic situation, the biogas industry in Poland has already reached a certain level of saturation and thus, has not been subject to further significant modifications. The selection of the time period for the study (between the years 2014–2018) was determined by a thorough analysis of the development biogas market in Poland. A diagnosis of the driving forces of the biogas market in Poland showed that its shape had been significantly determined by the European Union's financial instruments that were available in previous funding period (2007–2013). In this period, the number of biogas plants in Poland recorded peak growth rates (in 2014 the number of AD plants was 42, while in 2018–96). After the period of years 2007–2013, further growth of biogas sector in Poland has been stopped [11,70]. Hence, the decision was made to select the year 2014 following the end of previous EU funding period as the starting point for the study. At the same time, we believe that the selection of a 5-year study period (2014, 2015, 2016, 2017, and 2018) is sufficient to trace and analyse the dynamics of changes and to identify the mechanisms and driving forces that determine the trajectories of the development of biogas market in Poland.

Furthermore, we also made use of the materials and data available by public data operators, including the Agency for Restructuring and Modernisation of Agriculture (ARMA) and the Institute of Soil Science and Plant Cultivation (ISSPC).

3.2.2. Methodology

Our methodology is based on four mutually interlinked phases: **i)** Understanding the main narrative and driving forces concerning the usage of the substrates for AD (qualitative research) **ii)** Defining the categories of substrates for ADs (desk research); **iii)** Analysing regional diversity of the substrates that feed ADs (quantitative analysis on national level); **iv)** A case study analysis (quantitative analysis on regional level).

During **the first phase**, we focused on better understanding, what are the main driving forces, obstacles and influences covering the changes in the usage of diverse types of biomaterials as the substrates for ADs. This phase was based on the study of media coverage of the issue.

In **the second phase** of the study, based on the multiple materials and results of literature studies [12,23,24], all the substrates for ADs available were assigned into the five basic categories: (1) crops; (2) biodegradable agricultural waste, such as slurry; (3) biodegradable industrial waste, e.g. waste from food processing; (4) sludge from wastewater treatment plants; (5) animal by-products as the substrates of animal origin which are not intended for human consumption; they are the result of, for example, the slaughter of animals in slaughterhouses, cutting plants, processing plants, and other food sector plants.

In **the thirds phase** of our research, a comparative analysis concerning changes in the mixture of substrates and electricity production was performed. Correlation coefficients were determined linking individual categories with the average farm size and the volume of electricity produced. A classification of regions (voivodships) was carried out according to the mixture of substrates for agricultural biogas production in 2018. The authors used the Ward's method as the most appropriate for the purposes of this study. The analysis was conducted using the Statistica software.

In **the fourth phase**, a detailed analysis was carried out utilizing the case study method. The Kujawsko-Pomorskie Voivodship was selected as the region in Poland where the greatest changes in the mixture of substrates were observed. A detailed analysis of the substrates for biogas plants located in the voivodship was conducted. As it is obvious that this region went through a dynamic transformation in the biogas sector, this situation provided us a unique opportunity to grasp and better understand the defining features, causes, driving forces, effects and consequences that might be further theorized. The selection of the case study region for in-depth analysis needed to meet two essential criteria. On the one hand, it should be a region with extremely high rates of changes in the mixture of AD substrates that is clearly visible throughout all the study period (2014–2018) and thus has transformational potential. On the other hand, the region has to have biogas plants of varying size of ADs. Both criteria are met by the above-mentioned Kujawsko-Pomorskie Voivodship.

The case study region houses six biogas plants, both large AD units with an installed capacity of more than 1.5 MW and relatively smaller ones with an installed capacity not exceeding 1 MW. In order to anonymise the AD plants we worked with, these plants were marked with

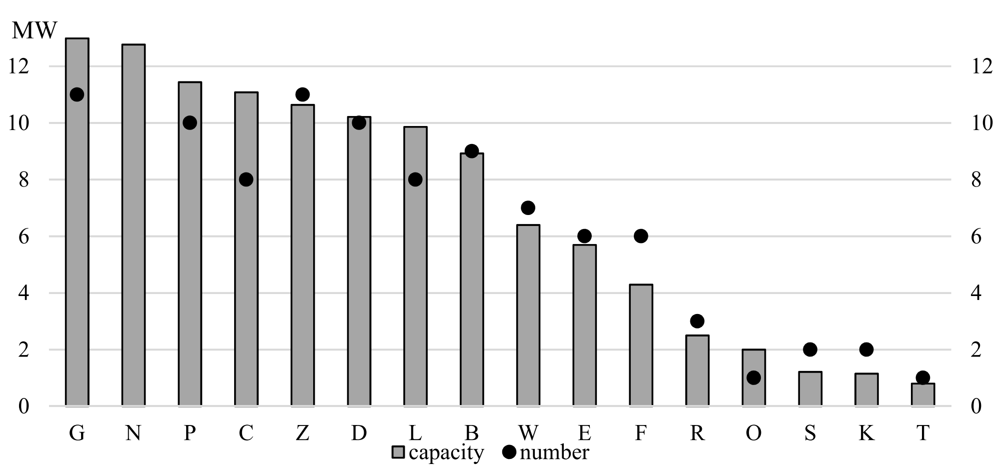

Fig. 2. The capacity and the number of AD plants in Polish regions, 2020. Voivodships, NUTS 2: B – Podlaskie; C – Kujawsko-Pomorskie; D – Dolnośląskie; E – Łódzkie; F – Lubuskie; G – Pomorskie; K – Małopolskie; L – Lubelskie; N – Warmińsko-Mazurskie; O – Opolskie; P – Wielkopolskie; R – Podkarpackie; S – Śląskie; T – Świętokrzyskie; W – Mazowieckie; Z – Zachodniopomorskie.
Source: Own study based on data from [12].

the numbers from I to VI. Finally, based on in-depth research, the main directions of the transformation of the substrate mix for biogas plants were defined.

4. Research results

4.1. The key narrative and driving forces of the usage of the AD substrates in Poland

One of the most important underpinnings and challenges of the biogas sector is the endeavour to ensure the continuity of the fluent supply of the stable mix of substrates from a long-term perspective. At the same time, it is also crucial to dispose of a right amount of the mix of substrates to be energetically processed available anytime (the just-in-time principle). To promote bioeconomically sound activities, the structuring of substrates should be principally based on the re-use or recycling of existing raw materials, while limiting the use of purposely produced feedstock such as energy crops. This scenario of biogas plant operation is not only necessary to be consistent with resource-efficient management, but also has significant economic connotations. The efficient acquisition of energy crops for the production of biogas requires either the use of own resources or the purchase of these from agricultural producers. That means the AD plant must be operated within a large farm, or it operates as a separate business that is purchasing its feedstock and is thus dependent on an external supply chain. The difficulties in obtaining adequate quantities (and qualities) of green raw material (like maize) are clearly apparent due to the limited production capacity of Polish farms that are amongst the smallest in the EU. Environmentally motivated behaviour of AD operators to reduce energy processing of purpose grown maize in favour of biowaste processing is rather rare; profit generation considerations are much more frequent.

A big issue is the cost associated with the purchase of maize which increases the total cost of operating a biogas business. In recent years the price of maize, a staple agricultural commodity, has been significantly rising in Poland. This is a consequence of the generally rising prices of cereals on one hand [71], and on the other hand, a result of the growing importance of maize production for both biogas production and export generated by demand from China [72].

As a response, biogas entrepreneurs are searching for new market niches and reorienting the mix of substrates they are feeding their ADs with, towards the usage of biowaste. There is no doubt that growing unaffordability of maize and a wide availability of biowaste belong to the key driving forces. Waste is becoming an increasingly valued and sought-after substrate for the biogas energy production. Another important driving force of the usage of biowaste for biogas production in Poland is that it is perceived as an additional and/or equivalent source of income.

4.2. Substrates for AD plants from a national perspective

As the number of biogas enterprises and the scale of biogas production in Poland increases, the diversification in considerations about the mixture of substrates for agricultural ADs is becoming more and more visible. While in the year 2011, 16 substrates were distinguished around the country, three years later it was already 49. We can say that during the years 2011–2012, energy processing of agricultural biodegradable waste (from animal production) gradually prevailed. To be more exact, in 2011, slurry as the AD substrate represented almost 60% of all substrates used. Starting from the year 2013, biodegradable industrial wastes, mainly from agri-food processing, began to gain its importance in the mixture of AD substrates [70]. The shift in the mixture of the substrates becomes visible; from the usage of raw materials of agricultural origin like energy crops and animal organic waste (the share dropped by 10 p.p. in the period 2014–2018), towards the usage of biowastes of industrial and municipal origin (their share in the period 2014–2018 increased by more than 12 p.p. (please see Fig. 3).

When considering the mixture of substrates and the production of electricity from biogas in relation to agricultural potential measured by the value of the agricultural production space index and the average farm area, it should be noted that visible changes took place in the period of years 2014–2018 (see Table 2; Fig. 4). On the one hand, the dependence of the volume of biogas electricity produced on the average farm area and the share of energy crops in the substrate mixture was reduced. On the other hand, the relationship between the share of energy crops in the substrate mixture and the average farm area was strengthened. We also calculated that the quality of agricultural production was correlated neither to the mixture of substrates nor to the amount of electricity produced, which indicates a lack of connection between the substrates used (agricultural, including energy crops) and the quality of natural conditions, including soils, for agricultural activity.

4.3. AD plants from a regional perspective

4.3.1. Mixture of the substrates for AD in 2014

In 2014, when more than a half of the substrates for biogas production originated from agricultural production (energy crops and animal organic waste), the dependence of the substrate mixture on the average size of an agricultural holding was apparent. The largest share of the usage of energy crops (exceeding 40% and consisting mainly of maize) was recorded in two regions characterised by the largest average size of agricultural holdings. These regions can be found in northern Poland, namely the Zachodniopomorskie Voivodship with the average farm size of more than 30 ha and the Warmińsko-Mazurskie Voivodship with the average farm size of 23 ha. In these two regions, the largest share of the land managed by post-State Agricultural Farms is to be detected. Until the end of the Communist era in Poland in 1989, up to over 70% of the agricultural land in the above-mentioned voivodships

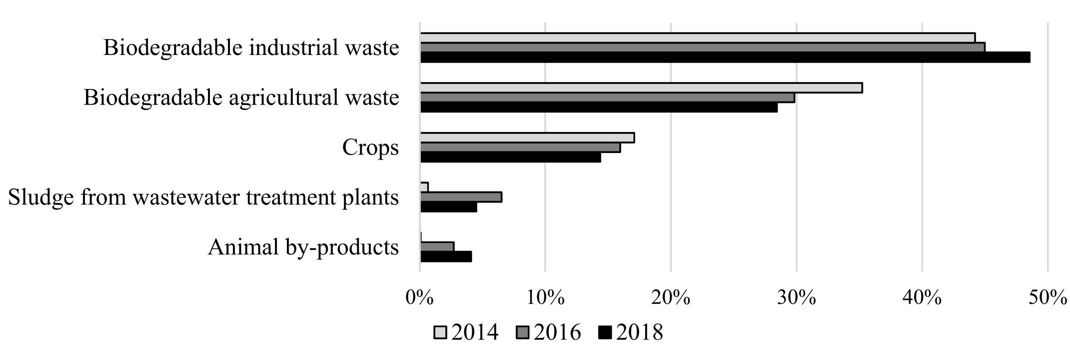

Fig. 3. Change in the mixture of substrates for agricultural biogas production in Poland in the period 2014–2018.
Source: Own study based on data from [73].

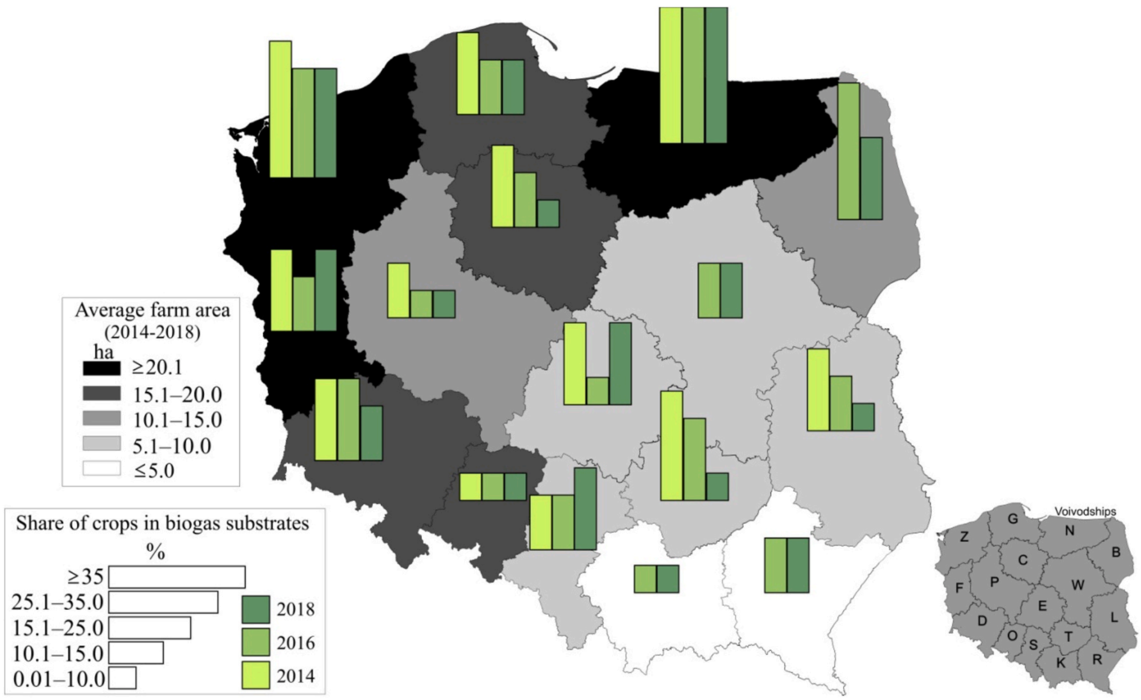

Fig. 4. The average farm area and share of crops in biogas substrates in Poland 2014–2018. Voivodships, NUTS 2: B – Podlaskie; C – Kujawsko-Pomorskie; D – Dolnośląskie; E – Łódzkie; F – Lubuskie; G – Pomorskie; K – Małopolskie; L – Lubelskie; N – Warmińsko-Mazurskie; O – Opolskie; P – Wielkopolskie; R – Podkarpackie; S – Śląskie; T – Świętokrzyskie; W – Mazowieckie; Z – Zachodniopomorskie.
Source: Own study based on data from [12,73].

Table 2
The correlation coefficient between the average farm area and crops and energy production in Polish Voivodships.

	Average farm area vs. crops	Average farm area vs. energy production	Energy production vs. crops
2014	0.531	0.690	0.539
2016	–	0.685	0.571
2018	0.603	0.608	0.521

Source: Own study based on data from Refs. [12,73]; N = 15 (2014), N = 16 (2016, 2018)

was within the boundaries of State Agricultural Farms. It is in this part of Poland where the first biogas plants were built (in the early 2000s), constituting the largest concentration of AD plants in the country and producing the most electricity from biogas in 2014 (Fig. 5). AD plants located in three voivodships (Pomorskie, Warmińsko-Mazurskie, and Zachodniopomorskie) provided 44% of the country's biogas electricity and 45% of biogas heat. In turn, the smallest amount of green energy came from the voivodships where only single AD plant was situated. In this case, the AD operation is also strongly linked to the agricultural production despite a relatively small average size of farms in these regions (Świętokrzyskie, Śląskie, Mazowieckie, and Podkarpackie voivodships).

4.3.2. Mixture of the substrates for AD in 2016

In the period between the year of 2014 and 2018, the number of agricultural biogas plants in Poland increased by 130% (from 42 in 2014 to 96 in 2018). During the same period, the amount of agricultural biogas and electricity produced from AD almost doubled. From spatial perspective it can be added that as a result of the new biogas investments in this period, spatial concentration of AD plants in Poland decreased. After the year 2014, Poland experienced the largest increase in the number of new biogas investments. The vast majority of these newly created AD facilities are the result of the co-funding of the European Union's funds in the period 2007–2013. This EU budget included the most substantial funding for the investments in renewable energy implemented in Poland [12]. With the emergence of the new AD plants, the importance of energy crops and biodegradable agricultural waste decreased, although the voivodships with a relatively large average farm area, including Zachodniopomorskie and Warmińsko-Mazurskie, remained leaders in the use of these raw materials for biogas generation (Fig. 6). It should be noted here that the highest number of the new biogas plants emerged in the Podlaskie Voivodship, where the average farm area oscillates around 12.2 ha. It was this region that joined the regions specialising on the use of crops and organic agricultural waste. In 2016, the most profound change in the structure of AD substrates concerned the growing role of biodegradable industrial waste, whose share between the year 2014 and 2016 increased by 3.7 p.p. The emergence of these substrates can be seen in almost all regions of Poland. Similarly, sludge from wastewater treatment plants is becoming increasingly important. Its share increased from less than 0.7% in 2014 to 3.6% in 2016. Sludge was used in twelve of the sixteen voivodships in 2016 (compare to just eight voivodships in 2014). A third, increasingly important category of biowaste are animal organic by-products. In the year 2014, these played a marginal role as their share did not exceed 1%. On the contrary, in 2016, the increase in both share in the substrate mix and the number of regions is clearly visible.

In 2016, the most energy from biogas was generated (similarly as in 2014) in three voivodships in northern Poland (a total of 39.8% of the national energy from agricultural biogas). With the increasing number of biogas plants established all around Poland, the growing production of energy from biogas was also widely recorded. For instance, in 2016, the regions in eastern Poland (Podlaskie, Lubelskie, Świętokrzyskie, and Podkarpackie voivodships) provided 18.3% of the total Polish energy from agricultural biogas.

4.3.3. Mixture of the substrates for AD in 2018

Further but much less intense increase in the number of biogas plants, reaching almost 100 ADs in 2018, was associated with a further

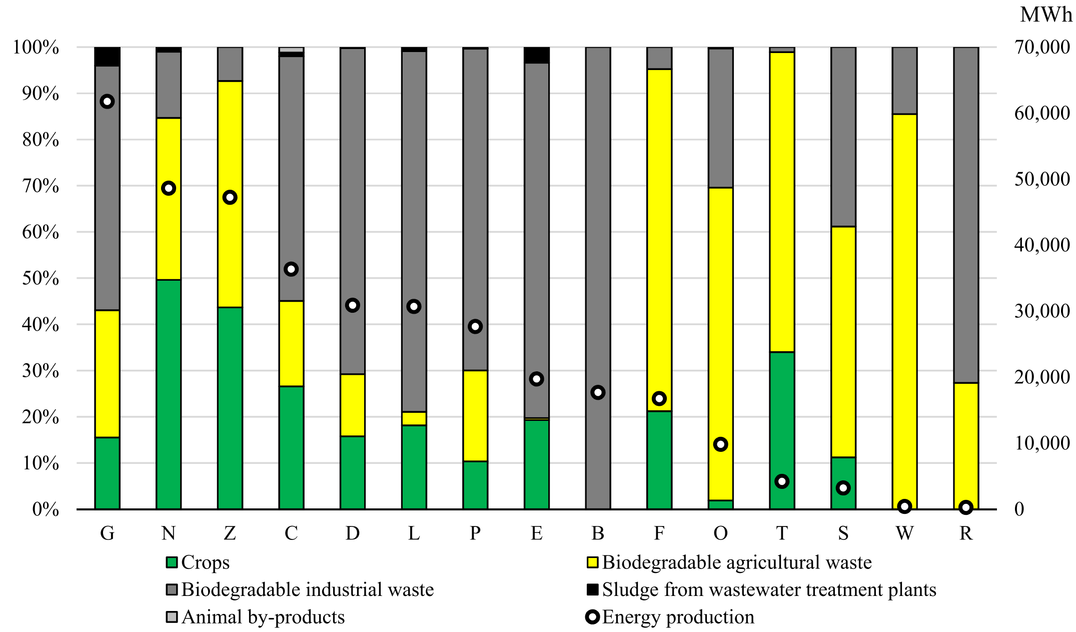

Fig. 5. Mixture of the substrates for agricultural biogas production and energy production from agricultural biogas in Polish voivodships in 2014. Voivodships, NUTS 2: B – Podlaskie; C – Kujawsko-Pomorskie; D – Dolnośląskie; E – Łódzkie; F – Lubuskie; G – Pomorskie; K – Małopolskie; L – Lubelskie; N – Warmińsko-Mazurskie; O – Opolskie; P – Wielkopolskie; R – Podkarpackie; S – Śląskie; T – Świętokrzyskie; W – Mazowieckie; Z – Zachodniopomorskie.
Source: Own study based on data from [12]

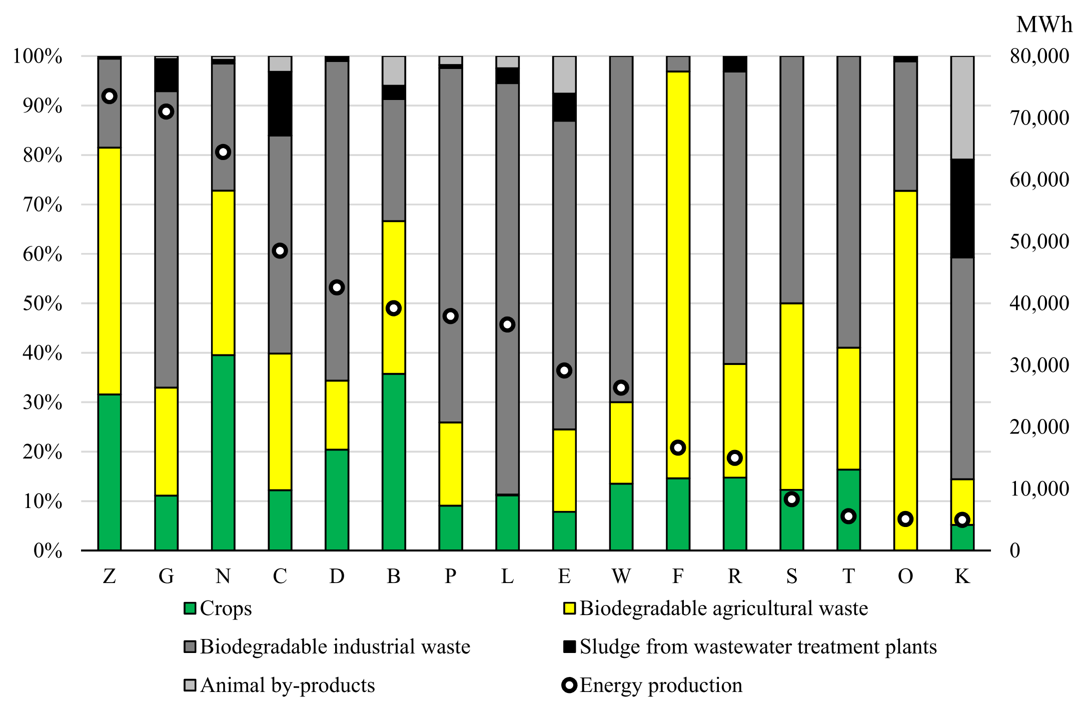

Fig. 6. Mixture of substrates for agricultural biogas production and energy production from agricultural biogas in Polish voivodships in 2016. Voivodships, NUTS 2: B – Podlaskie; C – Kujawsko-Pomorskie; D – Dolnośląskie; E – Łódzkie; F – Lubuskie; G – Pomorskie; K – Małopolskie; L – Lubelskie; N – Warmińsko-Mazurskie; O – Opolskie; P – Wielkopolskie; R – Podkarpackie; S – Śląskie; T – Świętokrzyskie; W – Mazowieckie; Z – Zachodniopomorskie.
Source: Own study based on data from [12]

diversification and polarisation in the usage of substrates for biogas production. Despite systematic decrease of the importance of agricultural production in the biogas generation, agriculture was still important in the regions with a higher than average farm size (including Zachodniopomorskie and Warmińsko-Mazurskie, but also Podlaskie voivodships). In the voivodships where the supply of substrates was carried out by biogas entrepreneurs from their own sources (mainly from agricultural crops grown on their own farms, primarily former State Agricultural Farms), no rigorous re-structuring of the substrate structure took place. In the remaining regions, the key role in biogas production substrates was played by biodegradable waste from food processing, with a share even at 80%–86% in Lubelskie and Wielkopolskie voivodships. Sludge and animal by-products were also gaining importance until 2018, with their share sometimes exceeding even 30% (the

Kujawsko-Pomorskie Voivodship) (please see Fig. 7). The treatment of animal organic by-products appears to be an attractive way for biogas plants to generate additional income by processing this type of waste. Therefore, companies are investing in biogas plants with rendering facilities in order to increasingly process animal by-products.

In terms of the substrate mixture, Polish regions can be divided into two main groups: (1) the regions with a dominance of industrial and municipal raw materials in the AD substrates, and (2) the regions with a dominance of agricultural raw materials in the AD substrates. In 7 out of 16 voivodships, biodegradable industrial waste is the main source of the AD substrates, with a share of at least 60%. This largest group (the 1a type; please see Fig. 8 where the types are shown in the map) is made up of the regions located throughout Poland, including those with a relatively small average farm size (south-eastern Poland). Similar features (a domination of raw materials from the industrial sector in the substrate mix) are also found in these two voivodships: Kujawsko-Pomorskie and Małopolskie (the 1b type). However, these regions are distinguishable by a much smaller share of energy crops and waste from the agricultural sector in the substrates mix. The second group is made up of the regions with a dominant share of agricultural raw materials (agricultural waste and energy crops). These are, on the one hand, the voivodships with the largest share of large farms (former state-owned farms) in northern Poland, where biogas plants operate as integral elements of agricultural enterprises, and on the other hand, the voivodships where small biogas plants operate (the 2a type). Raw materials of agricultural origin also predominate in Lubuskie and Opolskie voivodships (the 2b type), but with a definite prevalence of biodegradable agricultural waste in the AD substrate mix (see Fig. 8).

4.4. *The case study of Kujawsko-Pomorskie Voivodship*

We chose this region for a more detailed analysis because it has a relatively large AD sector (4th largest installed capacity; see Fig. 2) and it has seen some of the biggest changes in the mixture of the AD substrates. In 2014, 45% of the substrate mix originated from agriculture (energy crops and organic waste), and more than a half was based on the biodegradable industrial waste in this region. In the following years, municipal waste (from wastewater treatment plants) and animal organic by-products gained more importance and the standing of agriculture in the AD substrate mix was reduced (please see Figs. 5–7).

In 2018, six agricultural biogas plants (we are coding them as BP I–BP VI, please see Fig. 9) were operating in the Kujawsko-Pomorskie Voivodship. These were primarily AD plants operating as off-farm separate economic entities, whose operations were based on external supplies of raw materials. In the years 2014–2018, all the analysed biogas entities recorded an increase in electricity production or maintained production at an almost unchanged level. The highest increase in electricity generation (over 4.6 times) was documented in the biogas plant no. 2 (BP II): from 3.1 GWh in 2014 to 14.5 GWh in 2018.

The re-structuring of the substrate mixes began in the years 2015–2016. The reorientation was caused by the ongoing financial and legal changes in the domestic market for renewable energy sources, including fluctuations in the price of electricity generated in agricultural biogas plants (sale of green energy is the primary source of income for the operators of biogas plants). In particular, the tenfold(!) reduction of guaranteed purchase prices of energy produced was pivotal for the functioning of biogas plants, including their need to reduce operational costs and search for the new market niches [70]. Cost reductions translated into limiting the purchase of the raw materials (maize), and effectively using technological potential through the treatment of organic waste. In turn, market niches were exploited to create additional sources of income in the waste treatment sector.

The changes run along two axes. The first one concerns the reduction of the importance of raw materials from agricultural production, while the second one deals with the diversification of the substrate mixture. Regarding the first axis: in 2014, energy crops provided more than 30% of all the substrates for biogas production in the case of biogas plant no. 2 (BP II), and from 2016 onwards this share did not exceed 1%. The role of biodegradable agricultural waste was also limited. In the case of biogas plant 1 (BP I), they accounted for 13.5% percent in 2014 and 3.6% in 2018. Biodegradable agricultural waste was the basis for the operations of the biogas plant no. 2 (BP II) in 2014, and in subsequent years its share systematically dropped to below 10% in 2018. The biogas plant no. 4 (BP IV) went along the same route – in 2014 agricultural production waste accounted for 30%, and four years later for 19%. Taking into account the second axis of transformation, the growing importance of biodegradable industrial waste should be emphasised, as it rose to over 96% in the case of biogas plant no. 1 (BP I), 70% in biogas

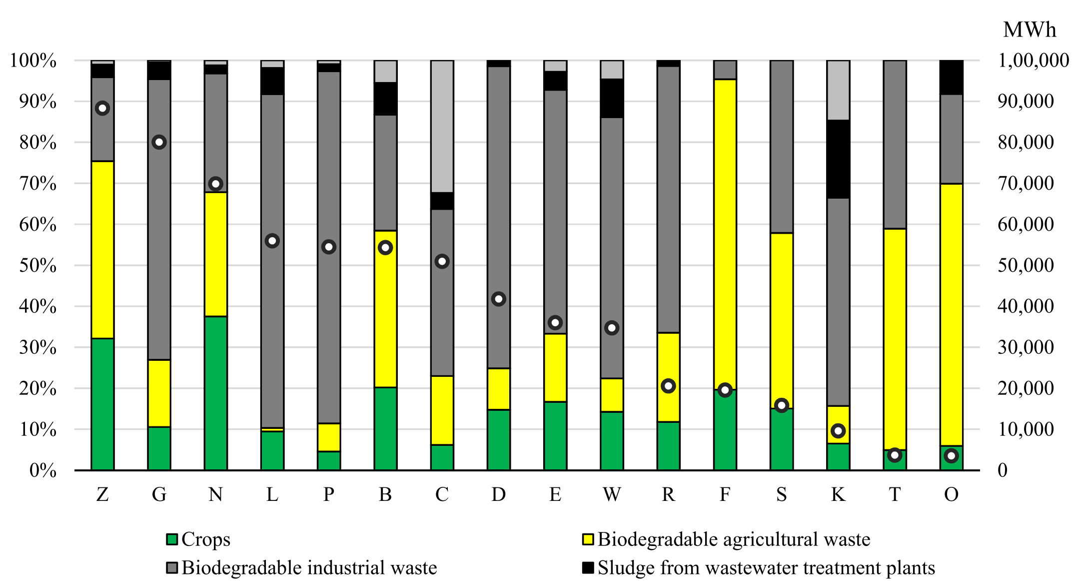

Fig. 7. Mixture of substrates for agricultural biogas production and energy production from agricultural biogas in Polish voivodships in 2018. Voivodships, NUTS 2: B – Podlaskie; C – Kujawsko-Pomorskie; D – Dolnośląskie; E – Łódzkie; F – Lubuskie; G – Pomorskie; K – Małopolskie; L – Lubelskie; N – Warmińsko-Mazurskie; O – Opolskie; P – Wielkopolskie; R – Podkarpackie; S – Śląskie; T – Świętokrzyskie; W – Mazowieckie; Z – Zachodniopomorskie.
Source: Own study based on data from [12]

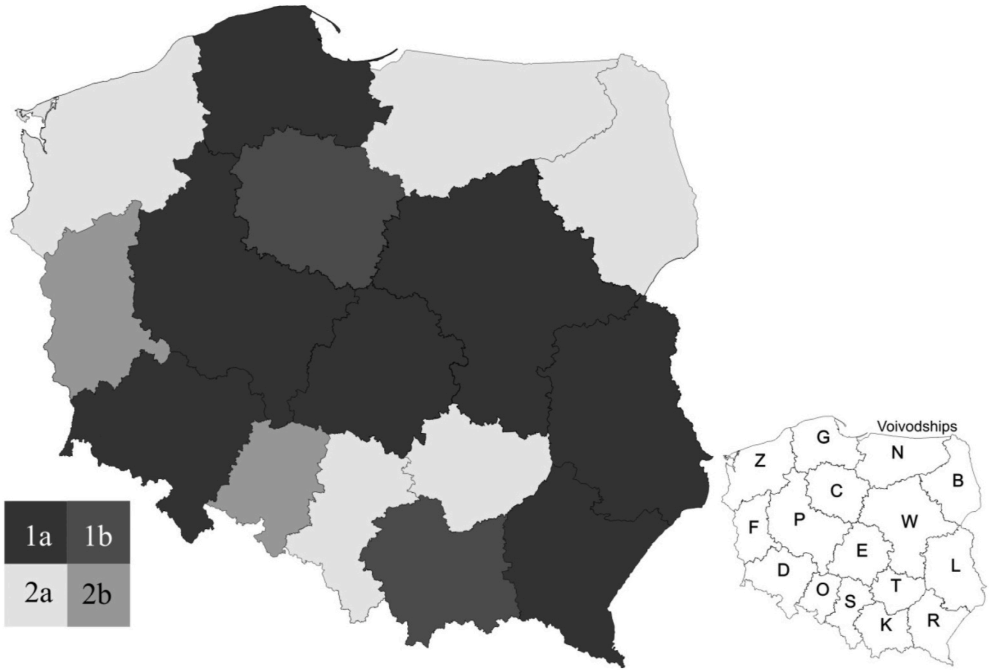

Fig. 8. Classification of Polish voivodships according to the mixture of substrates for agricultural biogas production in 2018. Spatial distribution of Ward's agglomeration method results Explanation: 1a – predominance of biodegradable industrial waste with a share of agricultural substrates; 1b – predominance of biodegradable industrial waste. 2a – predominance of agricultural waste with a share of biodegradable industrial waste; 2b – predominance of agricultural waste. Voivodships, NUTS 2: B – Podlaskie; C – Kujawsko-Pomorskie; D – Dolnośląskie; E – Łódzkie; F – Lubuskie; G – Pomorskie; K – Małopolskie; L – Lubelskie; N – Warmińsko-Mazurskie; O – Opolskie; P – Wielkopolskie; R – Podkarpackie; S – Śląskie; T – Świętokrzyskie; W – Mazowieckie; Z – Zachodniopomorskie.
Source: Own study based on data from [12]

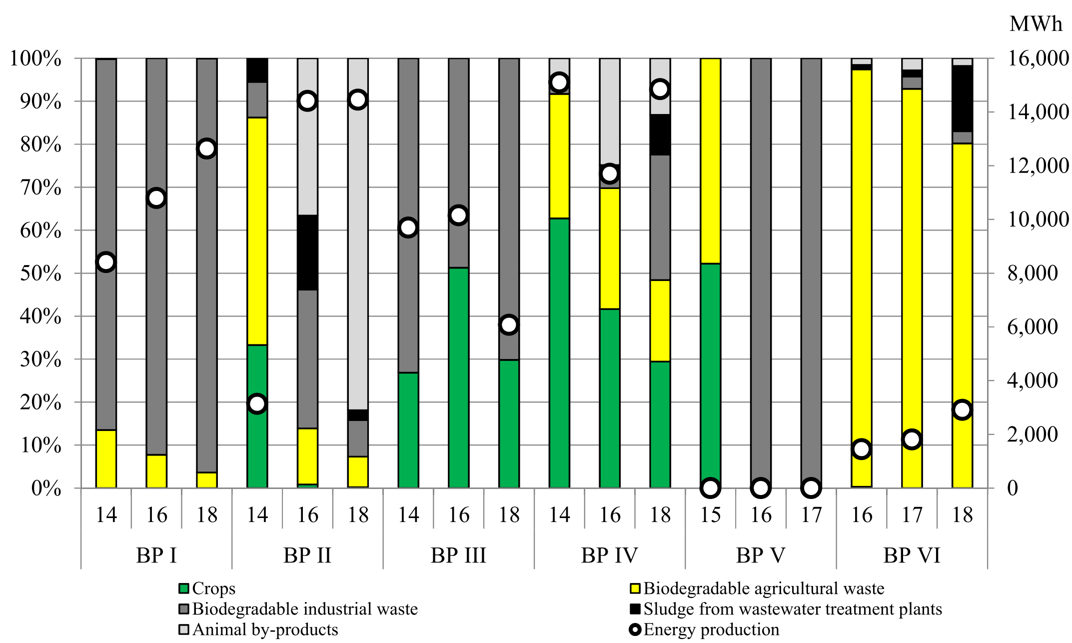

Fig. 9. Mixture of substrates for and electricity production from AD plants in the Kujawsko-Pomorskie Voivodship in 2014–2018.
Source: Own study based on data from [12]

plant no. 3 (BP III), and 30% in biogas plant no. 4 (BP IV).

Another group of raw materials that was gaining the ground is sludge from wastewater treatment plants. The mix of raw materials for agricultural biogas production also comprised animal-by products. They played the largest role in the substrate mixture in the case of biogas plant no. 2 (BP II - over 80% in 2018). They were also used in case of the biogas plant no. 4 (BP IV, 13%) and the biogas plant no. 6 (BP VI, 1.8%). It is worth stressing here that the diversification of the substrate mixture creates a chance for growth, but also for the stabilisation of electricity production. A model example of this finding is the situation in the biogas plant no. 2 (BP II), where since the year 2016 (which is the year when the changes were implemented), the amount of electricity produced has not changed much. This is all the more important as it enables plants to make production forecasts and has an impact on the companies' efficiency. We observe similar developments in other biogas plants with diversified substrate mixtures, including those with a growing weight of industrial and municipal waste. The reuse of this type of waste – which has to be treated – guarantees the operation of AD plants also because waste treatment provides a new, additional source of income (Fig. 9).

5. Discussion

5.1. AD plants in the heart of circular bioeconomy

According to the circular economy roadmap for Poland, the priority action in the energy sphere should be the focus on biogas production. This will embody the development of the circular bioeconomy – a pillar of economy transformation towards the circular economy [74]. The importance of biogas for sustainable and resource-efficient development is well confirmed by the recent studies [42,75–77]. Biogas energy, especially generated from the agricultural substrates, seems to be one of the types of renewable energy with a great potential for the future development due to: a) availability of input materials (like agricultural or household biowaste), b) electricity supplies to the grid, c) provision of jobs for the community, d) waste heat from biogas plants that could be utilised for community purposes (such as heating of public buildings as schools, offices, administrations or even business companies, or residential homes), e) the digestate as one of the co-products of anaerobic digestion being used as fertiliser on the local fields [42,78].

Biowaste, including the waste from agricultural and food production, is indicated as one of the key sources of biogas production [74]. Our study has found clear evidence of a re-structuring of the substrate mix, including the growing utilisation of non-agricultural biowaste. Changes in the mixture of the substrates for agricultural biogas production can be defined with a reference to the division of bioresources into the five basic groups, colour labelled according to Danish studies [23,24]: green, yellow, blue, black, and grey. Four of the above-mentioned groups, i.e. green, yellow, grey, and black, are used for agricultural biogas production in Poland. Their importance in the biogas production has been changing over time. In the initial phase of the biogas market, the most important role was played by agricultural raw materials of energy crops and waste, but during the course of time and changing legal and financial conditions, the substrates of industrial and municipal origin have gained a higher significance. Green biomass*,* i.e. energy crops, and waste from agricultural production (yellow biomass*),* are being reduced in favour of waste from agri-food processing (grey biomass), and municipal and other industrial waste (black biomass) (Fig. 10).

5.2. Mechanisms of transformation of AD plants

The axes of the transformation of the substrate mixture are: i) the reduction of the role of agricultural raw materials, including energy crops, and ii) the diversification of raw materials used in biogas production. The reduction in the importance of agricultural substrates and diversification of raw materials used are caused by the reactions to changing legal and economic factors. On the one hand, legislative decisions at the central level have significantly reduced the profits from green energy production. On the other hand, increasing costs resulting from the necessity to purchase agricultural raw materials, mainly energy crops, have forced biogas businesses to search for the new solutions. AD plants operating within agricultural enterprises were designed and scaled to run on raw materials produced on the same farm, i.e. 'in-house' from a business perspective. Even with changes to subsidies and market prices, the efficient running of the AD plant remains integrated part of the overall farming operation and a key aspect of a generic strategy to diversify farm income streams and adopt value-added activities on the farm. And since farms always produce crop residues and/or livestock slurry, these plants continue to operate on the basis of agricultural raw materials. These AD are mainly situated in northern and north-western Poland, where larger post-socialist farms can be found.

Other AD plants operate as separate businesses (located off-farm, often on industrial sites of small towns) which means that the operators have to purchase all their feedstock externally. These AD businesses are strongly focused on minimising the cost of securing and delivering sufficient feedstock to their plant and this has resulted in the re-structuring of the substrate structure towards industrial and municipal waste. The economic factors behind the observed change in substrate mixture also include the possibility of obtaining an additional source of income from waste treatment as the AD operator is being paid by the waste producer to take their waste and dispose of it safely, in accordance with waste management regulations. Such 'gate fees' may be of vital importance for AD operators who are trying to survive the loss of green subsidies for their electricity sales.

The transition from green feedstock to yellow, grey and black feedstock means that the operation of the AD plant becomes more environmentally sustainable, but we must acknowledge that farming, industry and municipal waste policies are but it should also be considered within a wider societal context of public support plays a leading role in the development of the renewable energy market [79,80]. External actions should take into account all the aspects of the production of biogas and energy from biogas. The research findings from Germany shows that the introduction of the legislation to promote smaller biogas facilities based on agricultural waste may even lead to a slowdown in the development of the biogas market [81,82]. Considering the basic definition of sustainable development as based on three pillars: environmental care, economic efficiency, and equitable social

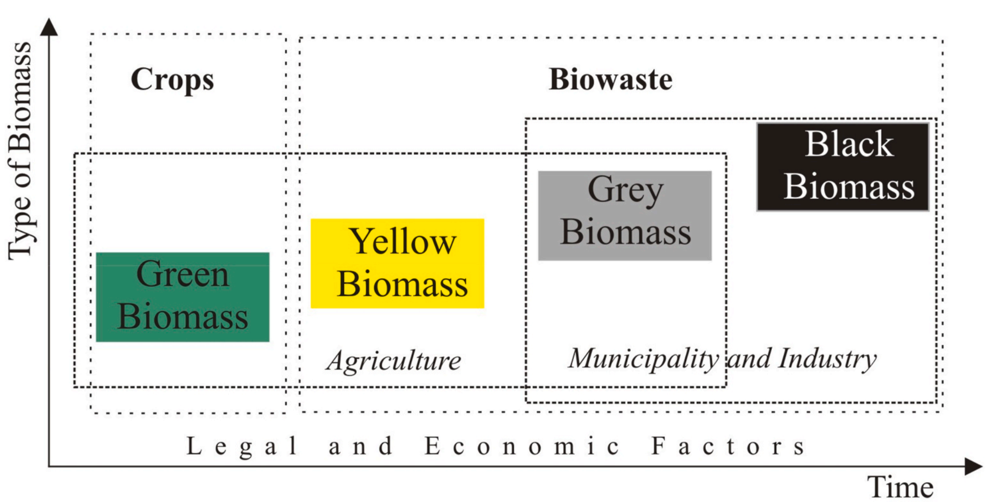

Fig. 10. From green to black biomass – gradual re-structuring of the AD substrates. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Own study based on data from Refs. [12,23,24].

transformation, it is important to emphasise the need to democratise the operations around ADs and to increase the role of local communities in the operation, profit-sharing and the decision-making in local biogas plants [52,79].

The increase in the use of biowaste for biogas production may certainly also arouse multiple controversies and consequently disapproval of local communities for entities operating on the biogas market [80,83]. This is caused by indisputable fact that biogas plants have a significant impact on the experience of local communities of how such enterprises operate and affect their immediate surroundings. An inadequately functioning biogas plant may even make a community less attractive to visitors [84] despite the environmental, economic, and social benefits. Therefore, the main challenge is to develop relations with the local environment and local entities and to enable residents to participate in the profits resulting from the emergence of new energy players in the area, e.g. to use electricity and other products.

6. Conclusions

The increase in the number of agricultural biogas plants in Poland in the years 2014–2018 is not only a manifestation of the ongoing energy transition but also an opportunity to achieve the objectives related to the implementation of the circular economy. Through the reuse of biowaste, AD plants provide valuable inputs into the dissemination of the circular bioeconomy as a pillar of the circular economy. The growing share of industrial and municipal waste in biogas production is a specific response of biogas investors to the current market needs related to the reduction of the profits from the sale of green energy and the growing costs of obtaining agricultural raw materials (purchasing energy crops).

AD plants are a relatively new component of the rural environment and local social structures that were primarily developed as a result of external support. One of the starkest challenges facing AD plants today is to take into account the expectations and needs of local communities in the re-structuring of the substrate mixture and to enable them to participate in the benefits that the AD facilities generate. The cooperation and mutual communication with the local stakeholders allows biogas entrepreneurs to gain acceptance for their businesses, which in turn determines the success of each such company.

Credit author statement

Chodkowska-Miszczuk, Justyna: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization, Investigation, Software, Validation, Writing- Reviewing and Editing, Martinát, Stanislav: Conceptualization, Data curation, Writing- Original draft preparation, Methodology, Writing- Reviewing and Editing, Visualization, Validation. van der Horst, Dan: Conceptualization, Supervision, Methodology, Writing- Reviewing and Editing, Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111344.

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