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# Waste as substrates for agricultural biogas plants: A case study from Poland

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**Abstract:** Energy production from renewable sources is one of the main ways to fight against global warming. Anaerobic digestion process can be used to produce biogas containing methane. In the light of the growing demand for substrates, a variety of raw materials are required. These substrates should be suitable for anaerobic digestion, and processing them need to provide the desired amount of energy.

This paper aims to discuss the agricultural biogas market in Poland, its current state, and the possibility of development during energy transformation, in particular in terms of using waste as a substrate for energy production. In February 2022, there were 130 agricultural biogas plants registered in Poland. On the other hand, in 2020, 4,409,054.898 Mg of raw materials were used to produce agricultural biogas in Poland. Among all the substrates used, waste played a special role.

With the right amount of raw materials and proper management of a biogas plant, it is possible to produce electricity and provide stable and predictable heat supply. Bearing in mind the development of the Polish and European biogas markets, attention should be paid to ensure access to raw materials from which chemical energy in the form of biogas can be generated. Due to limited access to farmland and the increasing demand for food production, one should expect that waste will be increasingly often used for biogas production, especially that with high energy potential, such as waste related to animal production and the meat industry.

**Keywords:** biofuels, biogas plant, circular economy, renewable energy, waste management, waste to energy

## INTRODUCTION

Energy is one of the most important areas for the economy of any country, and it is the prerequisite for both the municipal and industrial sectors to function. Access to energy and the energy generation infrastructure are essential [Ferreira *et al.* 2020]. The main sources of energy include fossil fuels, nuclear energy, and increasingly often renewable energy sources. At present, the predominant source of energy in the world is based on fossil fuels. However, renewable energy started to attrac special attention in recent years [Delapedra-Silva *et al.* 2022]. It is mainly due to the need to limit the negative environmental impact of energy production from fossil fuels, primarily $CO_2$ emissions. Of all types of renewable energy sources, the processing of biomass plays a special role [Martino *et al.* 2020]. This is because biomass is available practically all over the world and the technologies for producing energy from all kinds of biodegradable substrates are well known. Moreover, biomass, as the only renewable energy source (apart from geothermal energy which is rarely used), enables energy to be produced in a completely stable and controllable manner. In this way, among various sources of renewable energy, biomass can readily replace fossil fuels.

Biomass is most often used for thermal energy production (combustion in dedicated installations). However, especially in the case of biomass with a low level of total solids, it is also used as a substrate for biogas plants to produce electricity and heat or biomethane of similar parameters to natural gas.

As a result of the anaerobic digestion process in biogas plants, biogas is generated [Kowalczyk-Juśko *et al.* 2020]. It is a gas mixture with a predominant content of methane [Aryal, Kvist 2018]. A wide variety of substrates can be used to produce biogas, which is a source of renewable energy [Mazurkiewicz 2022]. It should be emphasised that these substrates include large quantities of waste and by-products [Czekała 2017]. Their use significantly improves the economic balance of a biogas plant, which may charge fees for waste disposal. An additional benefit is the management of biodegradable waste, which, if not properly managed, may pose a threat to the environment [Alves *et al.* 2020; Czekała 2021]. It is also worth emphasising that electricity produced from manure, for example, will have a negative carbon footprint, which is even more important in EU countries with high GHG emissions from electricity production (in Poland, 1 kWh of electricity equals 760 g $CO_2$e in 2021). The production of agricultural biogas offers numerous benefits. Agricultural biogas has many possible applications, e.g. combustion, cogeneration, convertion to biomethane, or use in transport.

Due to the development of the biogas market, it has become necessary to provide growing quantitie of substrates to produce biogas. Considering that arable land is limited, it is recommended to produce biogas primarily from waste rather than crops. Provided substrates in a biogas plant are managed properly, it is possible to obtain financial benefits not only from the sales of biogas, but also for the sales of electricity, heat, and digestate. Additional income is related to the treatment of biodegradable waste. It is possible to obtain financial benefits while having a positive impact on the natural environment (in particular, avoiding GHG emissions) [Paolini *et al.* 2018]. For this reason, innovations should be applied in the technical and technological aspects of biogas plants.

This paper aims to discuss the agricultural biogas market in Poland, its current state, and its possible development during energy transition in Poland, in particular in terms of using waste as a substrate for energy production.

## RENEWABLE ENERGY AND AGRICULTURAL BIOGAS PLANTS IN POLAND

For several years, slow but methodical development of renewable energy installations has been observed in Poland. This led to the increase in the number of energy-generating units and the total amount of energy produced from renewable sources. In 2020, in Poland, the total primary energy obtained from renewable sources was 524,113 TJ. The share of energy from renewable sources in the gross final energy consumption was 16.10% [GUS 2021]. The exception is the photovoltaic sector, which, thanks to favourable subsidies for customers installing micro-installations (up to 50 kW of power), witnessed a major increase in power generation at the end of 2021.

Solid biofuels are predominant among all renewable sources from which energy is obtained. In 2020, their share in the structure of energy production was 71.61%. It is followed by wind energy (10.85%) and liquid biofuels (7.79%) – see Figure 1. Biogas was classified fourth with its percentage share of 2.58%. However, it should be emphasised that this includes biogas produced not only in agricultural biogas plants. Additionally, biogas produced in sewage treatment plants and landfills has also been taken into account [GUS 2021].

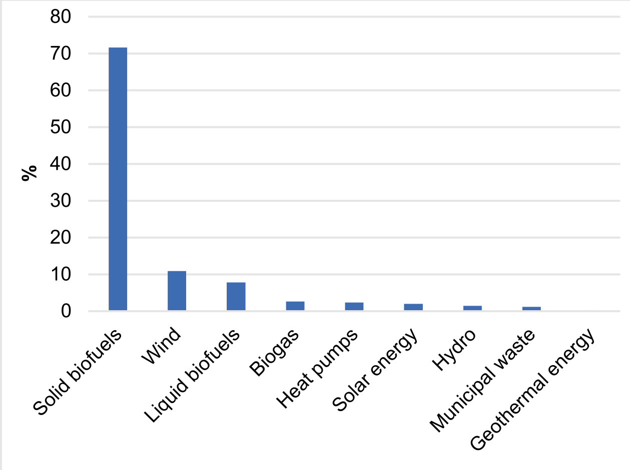


**Fig. 1.** The share of renewable energy sources in the total renewable energy produced in 2020; source: GUS [2021]

Facilities that allow the production of electricity and heat in a sustainable way include biogas plants in general, and agricultural biogas plants in particular [Czekała 2022]. The latter use all kinds of substrates, including biodegradable waste, to produce energy [Al-Wahaibi *et al.* 2020]. As a result of the anaerobic digestion process in fermentation tanks, organic matter is first converted into simple compounds (monosaccharides, amino acids), then into organic acids, and finally into biogas, and at the same time, digestate is produced and can be used as valuable fertiliser. It is worth emphasising that biogas plants operate regardless of weather conditions, and their operation is fully controllable. Due to the possibility of biogas storage under the dome of fermentation tanks, biogas plants can also operate as peak installations, producing electricity on demand, during the largest demand in the power grid. This should be considered a significant advantage over wind energy or photovoltaics.

The main product of the anaerobic digestion process is biogas. It is a mixture of gases with a predominant share of methane which is an energy source [Llano *et al.* 2021]. Depending on substrates and technology, its share in the mixture usually ranges from 50 to 65%. The remaining product is a decomposition residue called digestate [Czekała 2019].

The Poland's support scheme for agricultural biogas plants has been established lately. Initially, it was based on "certificates of origin" for agricultural biogas. It is worth noting that although there were only a dozen agricultural biogas plants in Poland when the system was introduced, the potential for the development of the biogas market in Poland was substantial. This is evidenced by both the amount of land used for agriculture and the country's well-developed agriculture and agri-food sector. In Germany, the electrical capacity of agricultural biogas plants reaches 6 GW generated in almost 9,000 installations. In Poland, the market is not developed, as there are 130 agricultural biogas plants with a total installed electrical capacity of less than

130 MW, i.e., slightly more than 2% of that in Germany. Meanwhile, according to the estimates by specialists from the Poznań University of Life Sciences, the potential for generating electricity from bio-waste and secondary biomass is 3.5 GW, and with the use of special purpose crops as substrate (e.g. silage from maize or energy crops), it can be even twice as high. It is worth emphasising that Poland has over 17 mln ha of agricultural land, which is 1.5 mln ha more than Germany. However, in order to obtain large amount of fuel, the sector should be adequately developed. This, however, is both time-consuming and cost-intensive. Nevertheless, it is inevitable due to the need to replace fossil fuels. It is worth emphasising that in 2021 as much as 76% of energy produced in Poland came from burning hard coal and lignite.

Agricultural biogas plants perfectly fit into the country's energy policy of producing energy in a sustainable and predictable manner. This is extremely important in view of the current problems with energy supply and the recent increase in gas prices. Despite the relatively low share of biogas in the production of primary energy in Poland, the biogas market has been developing rapidly. This has been proved by the increase in the number of biogas installations and their total capacity. Apart from small and micro installations, as of February 10, 2022, Poland has 111 enterprises producing agricultural biogas registered, whereas the total number of installations registered is 130. The annual capacity of the installations for the production of agricultural biogas is 521,428,626 $m^3$, and the total installed electrical capacity of the installations is 127.911 MWe [KOWR 2022].

## SUBSTRATES USED FOR THE AGRICULTURAL BIOGAS PRODUCTION IN POLAND

In order for an agricultural biogas plant to function properly, it is necessary to provide an appropriate mass of substrates of required parameters every day (Photo 1). The demand depends on the cogeneration unit size and the energy potential fed to the biogas plant. There are many substrates from which biogas can be produced in modern biogas plants. These include any raw material rich in organic matter (except wood and its waste) that can be decomposed in anaerobic conditions [Pochwatka *et al.* 2020]. These substrates differ in their origin and properties. The raw materials for the anaerobic digestion process include energy crops intended for energy production, by-products, and waste. While analysing the properties of substrates, such as their aggregation, total solids, organic matter content, methane efficiency, and the presence of pollutants and inhibitors (in particular, nitrogen and chemical compounds such as antibiotics) are most often compared.

**Photo 1.** Agricultural biogas plant for energy production using waste only (phot.: *W. Czekała*)

Key factors directly related to biogas plant input include energy potential, availability, and the possibility of sourcing substrates close to the biogas plant [Marks *et al.* 2020]. The price that the biogas plant owner pays for raw materials can be as much as 30–40% of the total costs related to the operation of the biogas plant. For this reason, substrates with a relatively low price in relation to their methane efficiency, i.e., the amount of methane that can be produced from 1 Mg of fresh mass, are in high demand. Their availability is also important, as the cost of delivery increases with each kilometer, which, considering the need to transport several tons of substrate per day, can significantly affect the profitability of the investment. It should be emphasised that biogas plants with the capacity of 0.999 MWe are most often operated in Poland. For their effective and continuous operation, they require between 35 and 90 Mg of substrate per day, depending on its energy potential. It is important to ensure the continuity of biogas plant operation, and it is also necessary to store the substrates in such a way as to maintain their energy value for several months. This is especially necessary when the biogas plant is fed with a waste stream which may fluctuate depending on the downtime of agri-food factories or their seasonal production.

The basic raw material for biogas production in many countries is maize silage. In combination with slurry, this substrate is still a very popular input in agricultural biogas plants. Considering that land used for agricultural purposes is limited and the demand for food is growing, the preferred use of substrates for biogas production requires to increase the share of waste in the biogas input stream. This will make it possible to use agricultural land for food production, and thus avoid a conflict between the production of food and the production of biofuels.

After maize silage, the second most popular substrate for biogas production is slurry, which is a natural fertiliser [Koryś *et al.* 2019]. Its popularity is mainly due to the possibility of obtaining it practically worldwide. Its advantages include the possibility of hydrating the substrate input with a higher total solids content and the fact that the slurry acts as an inoculum because it contains methane bacteria. The first biogas installations in Poland mainly used maize silage and slurry for energy production. This mixture of substrates is still popular in many countries, including Germany, which is the European leader in the production of agricultural biogas.

Due to insufficient funding available for agricultural biogas production as a renewable energy source, new solutions in the field of biogas production have been examined. This also involvs the search for cheaper substrates as effective as maize silage. According to Act of 20 February 2015 on renewable energy sources [Ustawa … 2015], agricultural biogas is defined as a gas obtained in the process of anaerobic digestion of agricultural raw materials, agricultural by-products, liquid or solid animal excrements, and by-products, waste or residues from the processing of agricultural products or forest biomass, or plant biomass collected from land other than designated for agriculture or forestry, except biogas obtained from raw materials from sewage treatment plants and landfills. While analysing the above definition, it should be stated that numerous types of waste and by-products can be used to produce agricultural biogas. This is also confirmed by the data shown in Table 1 which presents the list of raw materials used in 2020 to produce agricultural biogas in Poland. The list of substrates for biogas plants clearly indicates that Polish biogas plant operators are looking for cheaper alternatives to maize silage (the most popular substrate for agricultural biogas plants in Europe).

**Table 1.** List of substrates used for agricultural biogas production in 2020, compiled based on quarterly reports submitted to the National Support Centre for Agriculture (KOWR) – as of March 19, 2021

| Raw material | Quantity (Mg) |
|---|---|
| Distilling grains | 920,995.247 |
| Slurry | 759,773.954 |
| Fruit and vegetable residues | 706,944.922 |
| Maize silage | 491,869.598 |
| Food processing waste | 344,329.140 |
| Technological sludge from the agri-food industry | 227,148.226 |
| Beet pulp | 209,815.865 |
| Waste from the dairy industry | 132,910.511 |
| Expired food | 117,184.169 |
| Manure | 91,681.445 |
| Slaughterhouse wastes | 85,776.821 |
| Fruits and vegetables | 45,925.628 |
| Green fodder | 43,691.158 |
| Waste plant | 42,247.298 |
| Poultry manure | 27,531.751 |
| Grass and cereal silage | 26,708.233 |
| Fats | 25,580.422 |
| Sludge from the processing of plant products | 21,089.638 |
| Fodder | 20,066.290 |
| Grain, grain waste | 18,970.565 |
| Wastes from the production of vegetable oil | 12,231.831 |
| Gastric contents | 11,347.706 |
| Straw | 7,752.650 |
| Vegetable oils | 3,891.139 |
| Fatty sludge | 3,461.990 |
| Protein and fat waste | 3,035.680 |
| Digestate | 1,600.000 |
| Catering waste | 1,528.372 |
| Slops | 1,214.550 |
| Liquid wheat residues | 1,100.569 |
| Protein and fat slurries | 802.760 |
| Glycerine | 414.590 |
| Fusel oils | 247.840 |
| A mixture of lecithin and soaps | 181.160 |
| Coffee | 3.180 |
| **Total** | **4,409,054.898** |

Source: KOWR [2021].

Based on the data presented in Table 1, in 2020, the most popular substrates for the production of agricultural biogas in Poland were distilling grains, slurry, and fruit and vegetable residues. All together, 2,387,714 Mg of these three substrates were used in 2020, which accounted for over 54% of the total mass of all substrates. Maize silage of 491,869 Mg was the fourth most popular substrate. It was observed that other wastes from the food industry prevailed among other substrates. These included food processing waste, technological sludge from the agri-food industry, beet pulp, waste from the dairy industry, and out-of-date food. Manure, a popular substrate for biogas production in many countries, came only tenth (Tab. 1).

## WASTE MANAGEMENT AND ENERGY PRODUCTION

Due to the limited co-financing for agricultural biogas production, solutions are sought to improve the economic balance of a biogas installation. This phenomenon can be observed in Poland as a result of the crisis on the renewable energy market. In 2013–2015, the price of electricity from biogas plants (with subsidy) was only EUR55–75 per 1 MWh, while in Germany it was EUR240 per 1 MWh. Usually, the purchase and transport of substrates are the highest cost items in the operation of a biogas plant. As mentioned earlier, the daily demand for the raw material in a typical agricultural biogas plant is several tons. Therefore, the largest savings can be made by obtaining and processing waste, which often serves as an excellent raw material for biogas production. The most effective solution is to replace raw materials obtained from crops with waste [Czekała 2018]. For this reason, for almost 10 years, maize has been replaced with various types of waste in Poland. This is confirmed, for example, by data pertaining to the use of raw materials for the production of agricultural biogas. In 2011, 108,876 Mg of maize silage (23.19% of all substrates) was used, which made it the second most popular substrate after slurry. In 2020, it was 491,869 Mg, which placed it in the fourth position (11.16% of all substrates). In particular, this process is accelerated by implementing modern Polish biogas technologies involving the separation of fermentation stages. Separating hydrolysis and acidogenesis into preliminary tanks and enabling these processes to take place under acidic conditions significantly increases the efficiency of the process (by 5–25%) compared to the technology without stage separation, and it enables the use of a wider range of waste substrates. An example of this is the high biogas production in installations with separate fermentation stages (Photos 2 and 3).

Among all types of waste, waste from agri-food production and processing plays a special role. The sector is very well developed in Poland, and its decentralisation is a significant advantage. This translates into the availability of potential raw materials to produce renewable energy practically in every commune. The substrates include the following waste: waste and sludge from food processing, including meat industry, fruit and vegetable residues, distilling grains, brewery pulp, beet pulp,

**Photo 2.** 1.6 MWe biogas plant (ProBioGas linear technology) in Miedzyrzec Podlaski with separated hydrolysis and the possibility of biohydrogen production (phot.: *J. Dach*)

**Photo 3.** 0.5 MWe biogas plant (Dynamic Biogas technology) with separated acid hydrolysis built in PULS experimental farm in Przybroda in 2019 (phot.: *J. Dach*)

as well as many others. The use of slaughterhouse waste is economically advantageous (income from the sales of waste) and energy effective (high methane production). However, so far, there have been few biogas plants using slaughterhouse waste due to social protests during the planning process for such facilities.

In Poland, various production waste and by-products can be used for energy production in agricultural biogas plants [Czekała *et al.* 2016]. This is highly beneficial for owners of agricultural biogas plants, although it requires obtaining appropriate permits. There is no doubt that biodegradable waste is a suitable substrate for biogas production. Bearing in mind the fact that it is possible to generate income from the delivery of waste to a biogas plant, it is expected that substrates will not only support large biogas production but provide additional source of income [Kozłowski *et al.* 2019]. Agricultural biogas plants are therefore the right place to combine waste management with sustainable energy production. Operation of a biogas plant can also bring numerous social benefits. For example, residents of nearby villages may have access to cheap heat from co-generation [Czekała *et al.* 2021]. For this reason, such installations should be given more attention, because currently, most houses in rural areas in Poland use hard coal for heating, the combustion of which is a source of air pollution and smog.

Environmental protection should be among the most urgent topics in the context of global warming. Waste management in agricultural biogas plants brings many benefits. Another important aspect is the production of clean energy, including that from agricultural biogas. Agricultural biogas plants can handle various types of waste, including problematic types, and simultaneously produce energy from renewable sources.

## CONCLUSIONS

With the growing energy demand, alternative energy sources are required. This state of affairs is also influenced by issues related to environmental protection. One of renewable energy sources is biogas produced in the anaerobic decomposition process. The production of biogas allows electricity and heat to be generated in environmentally friendly conditions. The range of substrates from which biogas or biomethane can be produced is extremely wide. Substrates include almost all raw materials that are biodegradable. In agricultural biogas plants, substrates from crops intended for biofuels, by-products, and waste can be used for biogas production. This has an additional positive influence on waste management in public and private sectors.

Installations converting biomass and waste into energy are an important element of the energy policy in each country. It is worth mentioning that the right number of installations may have a positive impact on the energy security in a region. Anaerobic digestion enables to produce electricity and heat, and in consequence it reduces the amount of extracted, processed, or imported fossil fuels. In Poland, increased use of waste in agricultural biogas plants has been observed for several years. This supports waste management in communes and companies generating waste. Since biogas plants perfectly match sustainable development and circular economy trends, the systemic development of the biogas market should be expected.

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