Strategy for the use of bioLNG in the area of OMGGS, including the possibility of producing biogas and locating the biogas power plant

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Content

List of symbols and abbreviations

COP26	- 26th "conference of the parties" of the United Nations Convention on Climate Change.
EU	- European Union
RES	- Renewable energy sources
EFRR	- European Regional Development Fund
TFUE	- Treaty on the Functioning of the European Union
ECF	- European Cohesion Fund
EFP	- The European Funds for Pomerania Program
PVDP	- Pomorskie Voivodeship Development Strategy
MW	- Megawatt
kW	- Kilowat t
MWe	- Megawatt of electricity
MWt	- Megawatt of thermal energy
PEFICE	- Program European Funds for Infrastructure, Climate, Environment
OMGGS	- Gdańsk-Gdynia-Sopot Metropolitan Area
bio-LNG	- "liquid natural gas", a natural gas derived from renewable energy sources
Stm^3	- Standard cubic meter, gas volume measured at a temperature of 20^oC and a pressure of 1.01325 bar
kWh/GWh	- Kilowatt hour or gigawatt hour, a unit of work, energy and heat
mln	- Milion
mg	- Miligram
GPZ	- Main power point
t o.d.m.	- Tonne of organic dry matter

Part 1
Introduction, the purpose of the study, legal basis, theoretical issues of biogas plants, bioLNG, basic trends and good global practices in the use of biogas, bioLNG, LNG

Introduction

General information

Since the beginning of the 21st century, the expansion of the global economy has caused a record level of energy demand in the world. Almost 79.7% of the world's energy needs are met by the burning of fossil fuels [1], which are characterized by a lack of long-term stability and limited resources. Most of the electricity and heat used for municipal and industrial purposes is obtained by thermally transforming fossil fuels such as lignite, hard coal, crude oil and natural gas, which consumes these resources and increases pollution of the environment with greenhouse gases, and contributes to change the climate.

Climate is a statistical state of the atmosphere characterized by average values and fluctuations in the values of meteorological variables. To be able to observe climate changes, it is necessary to analyze long time series of weather observations, for at least 30 years. The following mechanisms are responsible for climate change: fluctuations in solar radiation, changes in the parameters of the Earth's orbit around the sun, oscillations in the ocean-atmosphere system, changes in the composition of the Earth's atmosphere and changes in the properties of the Earth's surface. The latter two mechanisms are affected by human activity - a change in the composition of the Earth's atmosphere and a change in the properties of the Earth's surface. The first of the mechanisms are related to the emission of greenhouse gases such as water vapour, carbon dioxide, methane, nitrous oxide, dust and aerosols, and the second is to land use and vegetation [2]. The Earth's climate is warming due to man-made increases in greenhouse gases. Climate change is causing extreme weather events due to rising temperatures causing droughts and fires, and increasing rainfall causing flash floods. Financial losses due to extreme weather and climate events have been estimated to have exceeded EUR 487 billion in the European Union (EU) in the last 40 years [2].

In early 2022, EU foreign ministers approved the conclusions of the COP26 climate conference and set the priorities for the EU's work in the field of climate diplomacy. The increase in climate ambition is linked to the approval of a binding EU target of at least 55% net greenhouse gas emissions reductions by 2030 compared to 1990 levels and changes to the previous 40% reduction target. To mobilize the Member States, a so-called European Climate Law [3] was introduced, making it a legal requirement to reduce greenhouse gas emissions. These actions are in line with previous EU commitments under the Energy Union and global climate action set out in the 2015 Paris Agreement on Climate Change, adopted under the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change, an increase in the mean global temperature below 2 ^{o}C as compared to the pre-industrial level [4].

Transforming the EU economy to meet climate ambitions will boost sustainable economic development, create new jobs, provide health and environmental benefits to EU citizens, and increase the long-term global competitiveness of the EU economy by promoting green technology innovation [5].

Sustainable economic development can be defined as one which, while meeting the needs of modern societies, will not limit the development possibilities of future generations. This means the necessity to simultaneously develop the economy, society and the environment so as not to diminish the chances of future generations for their development. The simultaneous economic development and care for the environment are possible thanks to the departure from fossil fuels and the use of renewable energy sources (RES) to meet the energy needs of society.

EU actions to promote renewable energy sources are included in the Directive of the Parliament and of the Council (EU) 2018/2001 of 11 December 2018 on the promotion of the use of energy from renewable sources (RED II). The directive describes the targets for the consumption of renewable energy in the years 2021-2030 and also promotes the production of biofuels and the share of energy from renewable sources in the energy structures of the energy, heating, cooling and transport sectors. Energy from renewable sources is energy from renewable non-fossil sources such as wind energy, solar radiation energy (thermal and photovoltaic), aerothermal energy, geothermal and hydrothermal energy, ambient heat, tidal energy, wave and other ocean energy, hydropower, the energy obtained from biomass, gas recovered from waste heaps, sewage treatment plants and biological sources (biogas). The RED II Directive also highlights the need to extend the Guarantee of Origin scheme to gas from renewable sources as a consistent way of proving to end-users the origin of a renewable gas such as biomethane, which would also facilitate the development of biogas trade and the integration of biomethane into the natural gas grid. [6].

The provisions of the RED II directive were introduced into Polish legislation in the form of new provisions, including the Act on renewable energy sources [7], which entered into force on April 1, 2022. The changes covered many areas related to renewable energy sources, including energy clusters, modernization of renewable energy installations, hybrid renewable energy installations and offshore wind energy. The Act also includes new provisions related to the launch of the "biomethane market". A definition of biomethane with a calorific value of 34 MJ/m^3 was introduced and its origin was determined as a gas obtained from biogas or agricultural biogas. The Act provides for an improvement in the proceedings related to obtaining a decision on the connection of biomethane generation installations to the natural gas network, which consists of the fact that if the technical and economic conditions do not allow for the issuance of a connection permit to the gas network, the network operator is obliged to indicate the nearest locations where the connection is possible. As a consequence of introducing the provisions of the RED II Directive [6], the Act of 9 December 2021 amending the Act on electromobility and alternative fuels and certain other acts [8] is in force in Poland. In addition, the Act of August 25, 2006, on biocomponents and liquid biofuels [9] is also in force in Poland.

The development of renewable energy sources is associated with the need to finance new energy sources, which was the basis for the development of the European Regional Development Fund (ERDF) program strategy, which, as one of the main instruments for financing the European cohesion policy, serves to alleviate disproportions in the development of European regions. The ERDF activities focused in particular on very sparsely populated regions, which may include OMGGS sites. The legal basis of the ERDF is Articles 174-178 of the Treaty on the Functioning of the European Union (TFEU). Currently, the ERDF programming period is set for the period 2021-2027 and is contained in two acts:

- a regulation on the ERDF and the European Cohesion Fund (ECF),
- a regulation on specific provisions for the European territorial cooperation goal.

The regulations maintain the thematic concentration on the circular green and low-energy economy. It was assumed that after 2020 support for cities will increase and at least 8% of ERDF funds (at the national level) will be allocated to sustainable urban development and the creation of a European Urban Initiative [10].

The ERDF co-finances, together with the ECF, the Program European Funds for Pomerania 2021-2027 (EFP) [11], which is implemented in the area of the Pomeranian Voivodeship classified as less developed and is one of the implementation tools of the Pomorskie Voivodeship Development Strategy 2030 (PVDS) [12]. Based on previous experience, it has been concluded that currently heat production is predominantly derived from coal in distributed energy sources. This causes the so-called low emissions, exceeding air quality standards and carbon dioxide emissions, and also constitutes a barrier to the implementation of the European Green Deal. The program indicates that the Pomeranian region has a significant potential for the development of renewable energy, due to, inter alia, large biomass resources and the potential for the production and use of biogas based on sustainable sources. The need for the development of renewable energy sources in the region is very high despite the activities undertaken in previous years, especially taking into account the expected development of energy clusters, energy cooperatives and energy communities. The document of the PVDS [12] indicates co-financing for renewable energy sources in the field of generating electricity from biogas for installations with an installed capacity of up to 0.5 MWe and for installations generating heat from biogas up to a capacity of 0.5 MWt.

As part of EFP, five Regional Strategic Programs (RSP) have been determined in the field of environmental and energy security, health security and social sensitivity, education and social capital, economy, labour market, tourism and leisure offer as well as mobility and communication, which operationalize the provisions of the PVDS and define the manner of implementation of the development policies of the Pomorskie Voivodeship Self-government until 2030. According to the provisions of the PVDS, due to the coastal location and physiogeographic conditions, the Pomeranian region has very good conditions for the development of renewable energy sources, especially installations using wind and sun energy, and there are great opportunities for obtaining biomass for production biogas and using it for energy purposes [12].

In the field of energy, EFP is complemented by:

- Program European Funds for Infrastructure, Climate, Environment 2021-2027 (FEnIKS), in the scope of: "Priority I Support for the energy and environment sectors from the Cohesion Fund, Specific Objective 2.1 Supporting energy efficiency and reduction of greenhouse gas emissions, and Priority II Support for the energy and environment from ERDF, Specific Objective 2.1. Supporting energy efficiency and reduction of greenhouse gas emissions and Specific Objective 2.2. [13].

- National Plan for Reconstruction and Increasing Immunity Component B “Green energy and reduction of energy consumption” [14].

The scattered development of the Pomeranian Voivodeship and the poorly developed transmission and distribution network, on the one hand, make it difficult to locate centralized heating systems and high-power electricity generation sources, and on the other, create a field for the construction of distributed energy sources based on RES.
Distributed renewable energy sources can work in the on-grid system when they are connected to the power system, or independently off-grid, without connection to the power system, and by using local primary energy sources they increase the energy security of the region.
The development of distributed energy sources, including the production of electricity and heat in a biogas plant, can contribute to the economic growth of rural areas by ensuring energy supplies to areas where there is currently no heating system. Currently, in Pomerania, a large volume of heat is generated in dispersed ineffective coal-fired sources, which is the main source of low-emission air pollution contributing to the formation of smog.

Under the provisions of the Act on Renewable Energy Sources [7], biogas is a gas obtained from biomass, and biomass is called biodegradable parts of products, waste or residues of biological origin. Biogas is obtained in a biogas plant in the process of anaerobic digestion, in which organic biomass is decomposed by bacteria under conditions without oxygen access and in the presence of water. The source of biogas can also be waste treatment plants, in which the gas is obtained in wells drilled into waste heaps. The composition of such biogas is a mixture of methane, carbon dioxide, oxygen and hydrogen sulfide. Both hydrogen and oxygen can be burned or oxidized, which gives off energy and does not interfere with the use of biogas as fuel. Hydrogen sulfide and water vapour will corrode the system and must be removed. The dried and hydrogen sulphide-free (purified) biogas can be used in cogeneration units to produce electricity and heat. The dried and purified biogas after the enrichment process can be used to drive traction motors in heavy commercial vehicles. In this case, the biogas is treated so that the methane content is not less than 96%, such gas is called biomethane.

To reduce the volume of fuel, which is of key importance in the context of the construction of tanks in vehicles and the reduction of the occupied space of storage tanks, biomethane changes the state of matter from gaseous to liquid - bioLNG under the influence of pressure and low temperature (-162^{o}C) [15]. BioLNG can be used in transport as a separate fuel or mixed with LNG fuel. The methods of transporting bioLNG are the same as LNG, using gas networks or tanks. BioLNG is characterized by a high loading speed, comparable to diesel fuel. It is an excellent proposition in the ecological context compared to the supply of energy from the combustion of fossil fuels for trolleybus and tram traction. The use of bioLNG as fuel enables the reduction of greenhouse gas emissions by 90% (by 70% of nitrogen oxides) while completely eliminating the solids content in the exhaust gas.

This Strategy presents the possibilities of producing biogas, biomethane and bioLNG in the area covered by the activity of the local government association called: Gdańsk-Gdynia-Sopot Metropolitan Area (OMGGS). OMGGS covers about 1/3 of the area of the Pomeranian Voivodeship, including 51 communes and 9 poviats, as shown in Figure 1.

Figure 1. Gdańsk-Gdynia-Sopot Metropolitan Area

OMGGS is based on voluntary cooperation, and its activity covers areas such as public transport, labour market and activation of residents, social economy, integration of immigrants, culture and health promotion, development of local enterprises, environmental protection, spatial planning and promotion [12]. The directions of metropolitan cooperation are set out in the strategic document for the development of the metropolis - Strategy of the Gdańsk-Gdynia-Sopot Metropolitan Area until 2030 [16].

In terms of energy, the area of OMGGS lacks large, systemic energy sources, which makes the region dependent on external electricity supplies. As mentioned in the Pomorskie

Voivodeship Development Strategy 2030 [12], the areas including OMGGS are largely coastal areas with very good conditions for the development of renewable energy sources, such as wind farms, photovoltaic plants and biogas plants. In the OMGGS area, agriculture plays a significant role, making it possible to build agricultural biogas plants.

Among the projects implemented by OMGGS is the EU project Liquid Energy, which is co-financed by the European Regional Development Fund, in which 29 partners from 5 countries (Poland, Denmark, Germany, Lithuania and Sweden) participate under the Interreg South Baltic program 2021-2027. As part of the OMGGS project, among others, on analyzes the use of liquefied biogas and natural gas as bio-LNG for the production of clean electricity and fuel for the needs of Żegluga Gdańska, Przedsiębiorstwo Komunikacji Trolejbusowej in Gdynia and Zakład Utylizacyjny in Gdańsk.

To sum up, investments in biogas plants will allow increasing the energy security of the state, while striving for climate neutrality and transforming the Gdańsk Gdynia Sopot Metropolitan Area into the national leader in the production of green energy and eco-efficient technologies, while maintaining the landscape values as the outstanding potential of the region. There are biogas resources available on the premises of OMGGS, which are mainly used locally in cogeneration installations. These resources, once liquefied, can be used in other areas of OMGGS as bioLNG. The unused potential of biogas production can be used by building new biogas plants, the locations of which will be indicated in this study and for which a SWOT analysis will be performed.

Purpose of the study

The study aims to present the biogas production strategy, and the possibility of locating a biogas plant and using bioLNG in the Gdańsk-Gdynia-Sopot Metropolitan Area.

The technology of biogas and bioLNG production

In this section, the production of biogas, biomethane and bioLNG is briefly simplified. A detailed description of the production processes and related technical issues are included in Annex 1.

Biogas is a mixture of methane, carbon monoxide, hydrogen sulfide and water vapour. Depending on the type of substrates, the concentrations of these gases differ [17]. It is possible to obtain substrates from agricultural production (harvest residues (straw, leaves, roots)), agri-food industry (e.g. pulp and sludge, extraction residues, filtration residues, decoctions), animal husbandry (e.g. animal faeces (slurry), feed residues, bedding material) and from slaughterhouse and meat processing waste (e.g. stomach contents, fat, blood, hair, bones). The biogas production technology is based on the anaerobic fermentation of the supplied substrates.

Biogas can arise naturally as a decomposition product of organic substances, or it can be produced on purpose. It is naturally recovered in landfills and is intentionally produced in agricultural or utilization biogas plants.

Depending on the composition of the input material, the biogas production plant has an individual structure. The choice of equipment depends on the availability of substrates, which determines the size of aggregates, tanks and digestion chamber.

The produced biogas should be adapted (treated) according to the technology in which it will be used. When used to generate electricity and/or heat, it is required to be delivered uniformly to the engine, turbine, microturbine or fuel cell.

Biogas treatment includes at least desulphurization and drying. Desulphurization is required due to the presence of hydrogen sulphide in biogas and its unfavourable effect, drying of the biogas is required since the water contained in it increases its volume, reduces the calorific value, and increases the corrosive effect of hydrogen sulphide and carbon dioxide, as well as causes the formation of hydrate blockages.

Purified biogas with a methane content of around 99% is called biomethane and can be injected into gas networks. The cooperation of a biogas plant with the gas network, in addition to registering and controlling the calorific value of gas, requires periodic checking of the content of harmful substances. The amount of biomethane that is introduced into the network is limited by the balance of gas introduced at the supply points and consumed at the consumption points of the distribution network. The problem that arises when introducing biomethane to the gas distribution network is the high expenditure on the construction of an expedition gas pipeline. The unevenness of production and fluctuations in gas demand in the distribution network may additionally contribute to the need to build a gas storage facility.

After cleaning, the biogas can also be liquefied to obtain its bioLNG liquefied form. BioLNG is a liquid renewable fuel, the volume of which is less than that of gaseous biomethane more than 600 times. This makes it easier to transport it, even if it is to be used in gaseous form.

BioLNG is a good solution for transport due to the ratio of the small volume of fuel to its high density of stored energy. It is characterized by a high refuelling speed, comparable to diesel fuel, and the possibility of obtaining considerable ranges by vehicles - up to 1,500-1,600 km on one refuelling. As a result, the transport of bioLNG is cheaper than its gas counterpart and does not require access to the gas pipeline. This allows for the location of the biogas plant without taking into account the access to the gas pipeline.

BioLNG compared to diesel drive reduces greenhouse gas emissions by 90% (by 70% nitrogen oxides) with the complete elimination of solid particles in the exhaust gas, which makes it an excellent proposition in the ecological context.

One of the partners in the Liquid Energy project, Cryo Pur has developed a new integrated technology that combines biogas treatment with liquefaction. Both processes use cryogenic technologies. It should be noted that the same installation can be used to liquefy natural gas, e.g. for transport over longer distances. A by-product of the process is the production of liquid carbon dioxide (bioCO_2), which can have many uses (e.g. in refrigeration or horticulture) and can be sold, which will increase the economic viability of the installation.

Advantages of using the Cryo Pur technology:

- Physical separation of any contaminants - no chemicals required except activated carbon.
- There is also no loss of methane.
- It allows you to maximize the profitability of such a project and reduce its harmful impact on the atmosphere.
- The heat from all processes can be recovered and heated in fermentation chambers where biogas is produced.
- An additional product in this technology is bioCO2 liquefied carbon dioxide, which can be sold to industrial customers, and distributors and can supplement revenues.
- This technology can also be used on a smaller scale of bioLNG production.

Benefits of using bioLNG as fuel

BioLNG is distributed via tankers, cryogenic tanks or via the LNG gas network. It can be used as a fuel for ships, HD Vehicles (HDV) or energy production in a gas cogenerator.

Biomethane as fuel allows for significant reductions in greenhouse gases. In the most recent EU strategy [16], biogas is listed as an important fuel for reducing methane emissions from the agricultural and rendering sectors. These emissions, both anthropogenic and biogenic, come from raw materials that are currently not used for the production of renewable energy.

The benefits of using methane as a bioLNG fuel are, for example, the avoidance of methane emissions to the atmosphere and the use of methane as a replacement fuel for fossil fuels, while allowing CO_2 emissions to the atmosphere. In addition, the biogas sector ensures an increase in soil carbon and soil biodiversity in agriculture. The condition of the soil in Europe described in the report of the EC Joint Research Center (JRC) is threatened, among others, by the decline in biodiversity and organic matter. Sustainable crops, which are later used to generate renewable energy, can significantly improve soil health and reduce nitrogen emissions. In this way, sustainable biomethane is produced, which is embedded in agroecology.

Location conditions for biogas power plant

The location of the biogas power plant is determined by:

- **Availability of substrates.** It is necessary to investigate the possibility of acquiring local resources from a distance of several dozen kilometres, develop a concept of the biomass logistic chain and take into account the monthly or annual variability of its extraction. The use of energy crops as a substrate material for biogas plants requires the determination of the acreage and class of land. It is also important to conclude preliminary agreements for the supply of substrate and the extension or modernization of local roads.
- **Self-assessment and selection of an external location.** The key is the location of neighbouring plots and the size of the land for the biogas plant, which depends on

the power of energy devices and the technologies used, fencing the area following applicable regulations.

- Infrastructure. The most important thing is to determine the connection possibilities to the power system (distance to the nearest GPZ, connection capacity at the connection point), analysis of heat demand and its seasonal variability (heat consumption in the summer season by an industrial recipient or a wood and grain drying room), availability of the gas network for reception biomethane or feeding the cogeneration system in the event of a shortage of biogas, availability of water and sewage network and road infrastructure. If there is no water and sewage system, there is a need to build a dedicated water intake and a sewage intake. Large biogas plants require the ability to transport loads weighing at least 15 tons.
- **Environmental conditions.** Biogas plants with an electric power exceeding 500 kW qualify for projects that may have a significant impact on the environment, which means the investor needs to go through the environmental impact assessment procedure. In particular, it is important for remote clusters of people. Potential negative effects include noise, exhaust fumes, and unpleasant odours. This distance should be at least 300 m. It is also recommended that the post-fermentation waste should be transported outside built-up areas. In addition to the metal fence, a strip of medium-stem and high-growth greenery is required. Significant restrictions are established in areas belonging to Natura 2000, where there may even be a ban on this type of investment. The digest should be used on farmland that is not significantly distant from the biogas plant due to transport costs. For a biogas plant with an installed electrical capacity of 1 MW, the required arable land is in the range of 1,000 to 5,000 ha.
- **Technology options available.** First, the substrates should be analyzed and the biogas production should be calculated based on the biogas productivity index [m^3/t o.d.m.]. More accurate results can be achieved by using fermentation tests, but it is recommended to perform them later in the investment implementation stages. If waste belonging to the sanitary-epidemiological category is used in a biogas plant, then its hygienisation is required and the installations used in the process line should be planned. If the dilution of the substrate mixture is used, the size of the biogas plant equipment may change. It is also very important to assess the volume of digestate and identify its recipients. The construction of lagoons for the storage of fermentation pulp requires a larger area for investment, on average approx. 2-3 ha for a biogas plant with an installed electrical capacity of 1 MW. However, it is a much cheaper solution than the construction of reinforced concrete tanks.
- **Costs.** Assessment of costs, subsidies, investment profitability
- **Social acceptance.** Assessment of the possibility of obtaining permits and social acceptance of the installation.

Basic trends and good global practices in the use of biogas, bioLNG, LNG

According to Eurostat data, in 2022 France is the leader in biogas production in the EU, with 337 installations, and Germany with 242 installations is second [18].

The main trends in biogas production include optimization of the fermentation process and its adaptation to the best available technologies [19], which is ensured by the development of process automation. Another noteworthy trend is the reduction of CO2 emissions by generating green energy from biogas, including fuel for the propulsion of vehicles such as bioLNG. To increase the throughput of existing composting plants, the oxygen phase of the process is shortened, which significantly improves the efficiency of the entire plant. The main trends also include reducing the odour nuisance of the existing composting and stabilization installations [19]. Good global practices, which are also used in Poland, include the production of biogas from substrates from the selective collection of green and kitchen waste. As a result, the capacity of waste treatment plants is improved and the odour load is significantly reduced, as it reduces the amount of stored compost. The future in biogas production is the co-fermentation of waste, which increases the production of biogas, and ensures the continuity of operation of the installation fed with a substrate from food processing, agricultural and municipal waste and fats.

An example of good practice in the use of bioLNG is the biogas plant in Biokraft (Norway), where biogas has been produced since 2018, then dried, cleaned and liquefied to form bioLNG. The biocraft is built adjacent to the paper mill, and bioLNG is produced from biogas obtained from fish waste and residual paper sludge. The manufacturer of the installation is Wartsila. In the first stage of construction, 125 GWh of energy was produced annually, currently, the installation is being expanded and the planned energy production will amount to 250 GWh per year in 2021-2022. BioLNG is used as car fuel in both buses and heavy trucks. Since 2019, Biokraft has been supplying bioLNG to the Hurtigruten passenger ship owner. Biokraft processes residues from bioLNG production into refined bio-fertilizer which are supplied to local farmers [20].

The Greenville Energy plant (Northern Ireland) is the first plant in the world to produce bioLNG from agricultural waste. It was launched in 2018 and produces 300 Nm^3/h of biogas (about 3 tons per day). The company uses organic agricultural waste and waste from the nearby LacPatric dairy. Cryo Pur technology was used in the production of bioLNG. In addition to the production of bioLNG, the plant also produces liquid bioCO_2, which is sold as an industrial gas and, following RED II, directly contributes to the reduction of CO_2 emissions during the production of bioLNG [21].

The European bioLNG market is growing thanks to a combination of government support and private sector demand. Transport connections for bioLNG begin to grow every year, incl. in Norway (Norske Skog Skogn Bio LNG installation, Cryo Pur project and Sunnhordland Naturgass in Stord) and the Netherlands (Nordsol project).

There is already an extensive LNG refuelling network in Europe, which may support the production of bioLNG. As shown in Figure XX, there are 505 LNG refuelling stations and 4111 CNG stations in Europe (Figure 2).

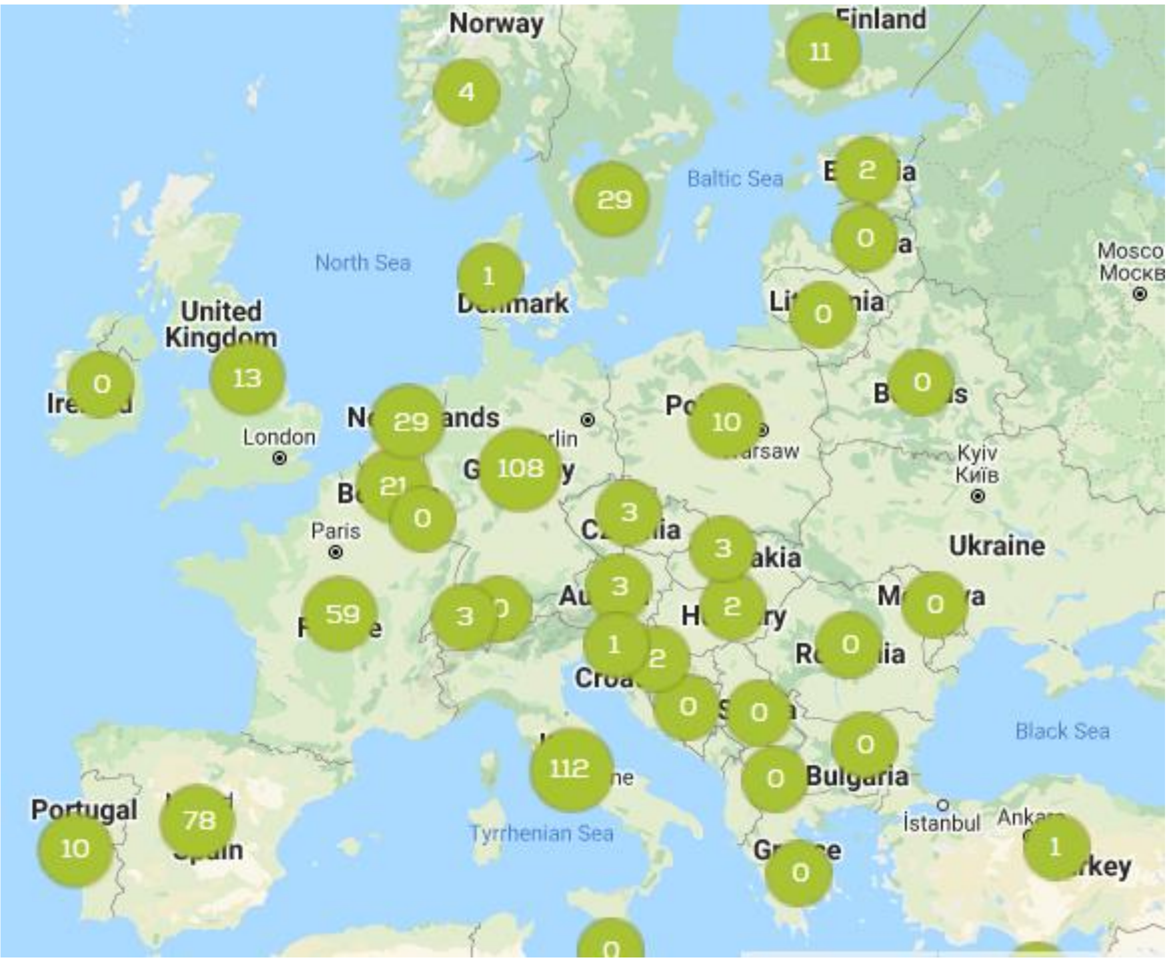

Figure 2. 505 LNG refuelling stations in 2022, NGVA Europe/Gibas

Figure 3. 4111 CNG refuelling stations in 2022, NGVA Europe/Gibas

In Poland, LNG refuelling stations are located in the central and western parts of Poland, as shown in Figure 4.

Figure 4. Locations of LNG stations in Poland [22]

Part 2
Characterization of OMGGS, estimation of bioLNG production potential

Energy characteristics of the OMGGS area

In the area of OMGGS, the heating network is located in cities and highly urbanized areas, while in rural areas and single-family housing estates in small and medium-sized cities it does not exist. For this reason, inhabitants of poorly urbanized areas are forced to generate heat from individual installations. The longest heating networks are located in Gdańsk, Gdynia and Sopot and are operated by Gdańskie Przedsiębiorstwo Energetyki Cieplnej Sp. z o.o. based in Gdańsk and by the Okręgowe Przedsiębiorstwo Energetyki Cieplnej in Gdynia. Apart from the above-mentioned cities, district heating systems operate in 15 municipalities. A detailed description of OMGGS heating systems is presented in the spatial development plan of the Gdańsk-Gdynia-Sopot 2030 Metropolitan Area [23], and the main features include:

- the persistently high share of coal in the balance of energy carriers, contributing to the formation of the so-called "Low emission",
- insufficient use of low-emission energy carriers such as gas and renewable energy,
- the need to invest in the development of heating networks to better use heating systems, due to the large share of individual heat sources,
- low level of utilization of the energy potential of municipal waste (the so-called energy fraction).

Electricity is supplied to the OMGGS grounds from electricity sources with a total installed capacity of approximately 1,540 MW. Electricity is generated in combined heat and power plants, pumped storage hydropower plants, wind farms, small hydropower plants, agricultural biogas plants, photovoltaic farms and individual photovoltaic installations.

Due to legal conditions and the desire to reduce carbon dioxide emissions, the greatest potential for building new generation sources in the area of OMGGS is in photovoltaic installations, offshore wind farms and biogas plants.

Construction of a biogas plant powered by agricultural waste, and utilization of waste or waste from municipal wastewater treatment plants are in line with the development policy of the metropolitan area K.2.5 - increasing the level of energy security and efficiency of production systems for the transmission and distribution of electricity and heat, gas, crude oil and petroleum products, and in including a focus on increasing electricity production from sources located in the metropolitan area, increasing the share of green energy in the energy balance of the metropolitan area and increasing the possibilities and efficiency of using the heating infrastructure.

11 biogas plants are operating in the area of OMGGS, which is presented in Table 1.

Table 1. List of renewable energy sources in the area of OMGGS

		Type of RES				RES installation capacity [MW]
LP	County	Solar power plant	Wind power plant	Water power plan	Biogas power plant	
1	m. Gdańsk	23	1	0	2	16
2	gdański	21	2	14	0	58
3	m. Gdynia	15	1	0	0	5
4	kartuski	37	4	6	0	27
5	lęborski	7	3	5	1	87
6	malborski	5	2	3	2	54
7	nowodworski	5	3	0	0	45
8	pucki	18	7	1	2	67
9	m. Sopot	1	0	0	0	1
10	starogardzki	23	2	12	1	30
11	tczewski	8	5	5	1	78
12	wejherowski	20	8	10	1	33

Biogas is produced in biogas plants, and waste from agricultural production and sludge from sewage treatment plants are used as input. In waste treatment plants, biogas is recovered from waste heaps. The produced biogas is used in gas cogenerators to produce heat and electricity. Due to the high content of pollutants, biogas is not injected into the gas network.

About 60.4% of OMGGS residents use the gas network [23], of which 83.3% are city dwellers. The gas supply system is based on high-pressure gas pipelines, reduction and measurement stations, high-pressure gas distribution centres, gas pipelines of the distribution network and local liquefied natural gas distribution systems - LNG. The Underground Gas Storage Facility in Kosakowo is an element of the country's energy security, and the salt structures in the Puck-Łeba range represent a strategic potential for the expansion of gas storage systems [23].

On the premises of OMGGS, there are 7 gas plants in Gdańsk, Gdynia, Malbork, Pruszcz Gdański, Rumia, Tczew and Żukowo.

Figure 5 shows a map of the area of operation of Polska Spółka Gazownictwa sp.z o.o..

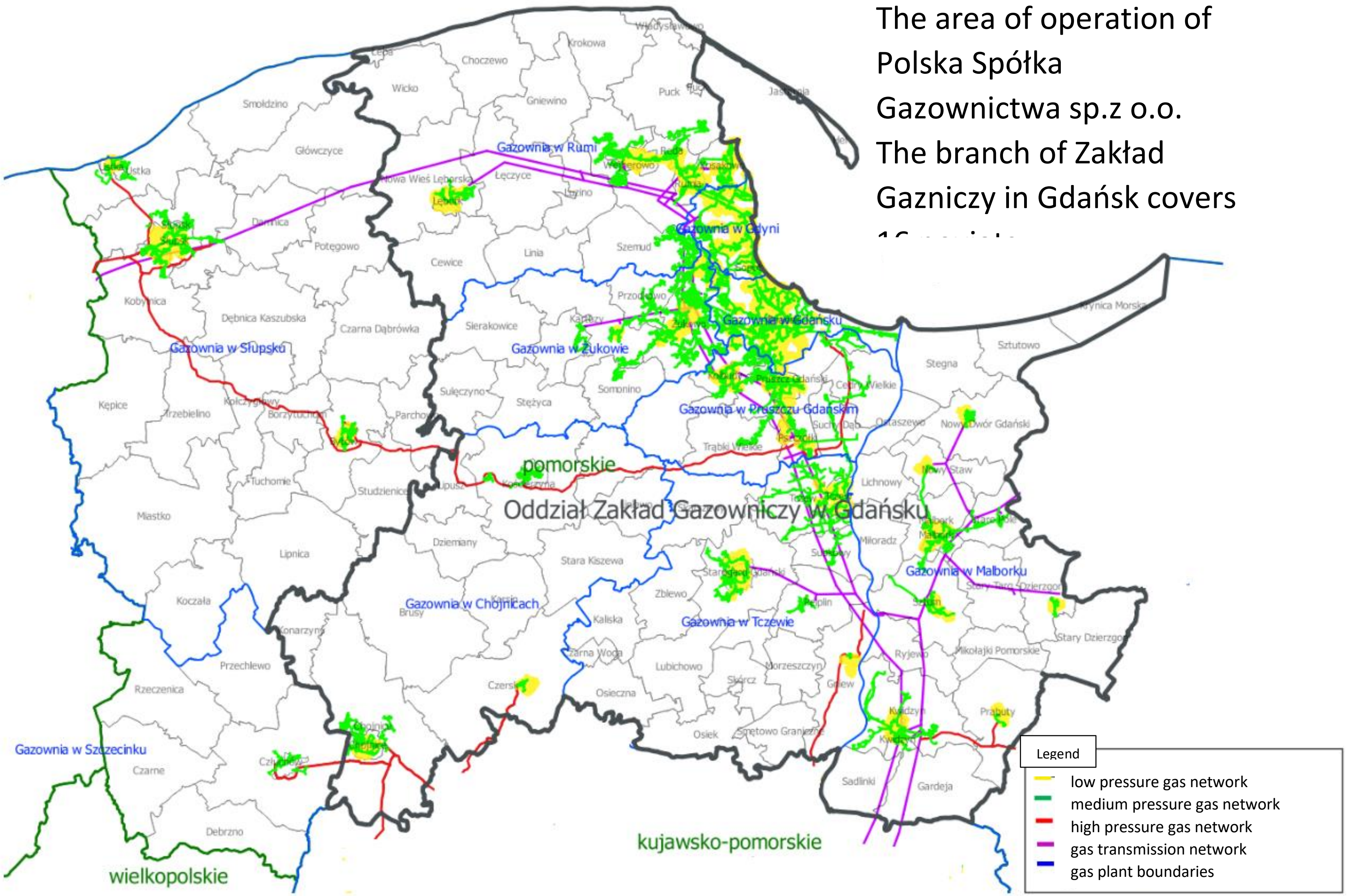

Figure 5. The area of operation of Polska Spółka Gazownictwa sp.z o.o. in Gdansk [24]

The technical potential of biogas production from animal manure and agricultural production was determined based on assumptions:

- 1 ha of cereal crops is 2.5 tons of yield, including about 35% of dry weight, 50% of cereal crops can be used as input in a biogas plant,
- 1 pig can obtain 5 t/year of slurry, about 10% of the slurry is dry matter, and 85% of dry weight,
- 1 pig can obtain 2 t/year of manure, manure contains 20-25% dry matter and about 80% o.d.m.,
- 1 piece of cattle allows to obtain 13 t/year of slurry, cattle slurry contains 8-11% dry matter and about 80% o.d.m.,
- 1 cattle can obtain 7 t/year of manure, manure contains 25% dry matter,
- 1 poultry can obtain about 0.1 t/year of manure, and 30% of dry matter.

To determine biogas production and methane content in biogas, the yield values were adopted for further analysis following Table 2.

Table 2. Biogas yield values depend on the type of input

Type of load	The amount of charge per 1 pc.	A dry mass	Average o.d.m content	Biogas yield	The average value of biogas yield	Methane content CH_4	The average value of methane CH_4
	t/year/pcs	%	%	m³/t o.d.m		% by volume	
cattle slurry	13	0,11	0,8	200-500	350	60	0,6
pig slurry	5	0,1	0,85	300-700	500	60-70	0,65
cattle manure	7	0,25	0,72	210-300	255	60	0,6
pig manure	2	0,25	0,775	270-450	360	60	0,6
chicken manure	0,1	0,3	0,715	250-450	350	60	0,6
maize silage		0,35	0,8595	450-700	575	50-55	0,525
rye		0,5	0,9298	550-680	615	55	0,55
grass silage		0,5	0,825	550-620	585	54-55	0,545
brewing delays		0,25	0,75	580-750	665	59-60	0,595
grain broth		0,07	0,855	430-700	565	58-65	0,615
potato broth		0,07	0,9	400-700	550	58-65	0,615
fruit pomace		0,4	0,925	590-660	625	65-70	0,67
shop waste		0,2	0,85	400-600	500	60-65	0,63
stomach content		0,15	0,7586	250-450	350	60-70	0,65
mown grass		0,12	0,875	550-680	615	55-65	0,6
sewage sludge			0,85	80-377	300	55-70	0,65

Source: own study based on [25]

The technical potential of biogas from animal manure

The technical potential of biogas production from animal manure was calculated based on the formula [26]:

$$P_{animal\ manure} = SZ \cdot M_{SZ} \cdot P_{d.m.} \cdot P_{o.d.m.} \cdot B$$

Where:

P- biogas production, $\left[\frac{m^3}{year}\right]$

SZ – number of animals, [-]

M_{SZ} – load weight per animal, $\left[\frac{t}{rok}\right]$

$P_{d.m.}$– the percentage of dry matter in the load, [%]

$P_{o.d.m.}$ – the percentage of dry organic matter in the dry matter of the input [%]

B – biogas yield from dry organic matter, $\left[\frac{m^3}{t\ o.d.m.}\right]$

The values of individual components were assumed based on literature data. The calculators available on the Internet were not used in the biogas yield calculations due to the lack of access to the biogas yield calculation method.

The calorific (energy) value of biogas obtained from animal excrements was assumed for further calculations – 23 MJ/m^3.

The technical potential of biogas from cereal crops and grasslands

The technical potential of biogas production from cereal crops and grasslands was calculated based on the formula [26]:

$$P_{agricultural} = \left(P_{crop} \cdot P_{o.d.m.}\right) \cdot M_{crop} \cdot U \cdot B$$

Where:

P- biogas production, $\left[\frac{m^3}{year}\right]$

P_{crop} – total arable land area, $[m^2]$

$P_{o.d.m.}$– the percentage of dry organic matter from total cereal production, [%]

U– crop utilization rate, $[-]$

M_{crop} – the mass of the crop obtainable from 1 ha of cereal crops, [t]

B – biogas yield from dry organic matter, $\left[\frac{m^3}{t\ o.d.m.}\right]$

The technical potential of biogas from sewage sludge

The technical potential of biogas and the production of bioLNG produced from sewage sludge in sewage treatment plants was determined based on information on the amount of treated sewage. The unit average indicator for the amount of stabilized sludge produced in municipal wastewater treatment plants was used for the calculations, given in the National Program of the Municipal Wastewater Treatment Plant, amounting to 0.25 kg of dry weight per m^3 of treated wastewater. [27],[26].

The technical potential of biogas production from sewage sludge was determined based on the formula:

$$P_{sewage\ sludge} = P_{sewage} \cdot U_{d.m.\ of\ sewage} \cdot U_{o.d.m\ of\ sewage} \cdot B$$

gdzie:

P- biogas production, $\left[\frac{m^3}{year}\right]$

P_{sewage} – the amount of treated wastewater, $\left[\frac{m^3}{year}\right]$

$U_{d.m.\ of\ sewage}$ – dry matter shares in sewage sludge, $[kg\ d.m.]$

$U_{o.d.m\ of\ sewage}$ – share of dry organic matter in sewage sludge, $[t\ o.d.m.]$

B – biogas yield from dry organic matter, $\left[\frac{m^3}{t\ o.d.m.}\right]$

The potential of biogas production depending on the type of input was determined based on information presented in the Central Statistical Office in the General Agricultural Census 2022 [28].

County of the City of Gdańsk

Table 3 presents the potential of biogas and biomethane production from agricultural waste for the County of the City of Gdańsk.

Tables 4 and 5 present the potential of biogas and biomethane production from animal production waste for the County of the City of Gdańsk.

Table 3. The potential of biogas and biomethane production from agricultural waste for the County of the City of Gdańsk

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
Gdańsk	2303,17	915,57	150341,17	90204,70	619696,68	340833,17	770037,85	431037,88	4919,69	207,79	269,57

Table 4. The potential of biogas and biomethane production from animal production waste for municipalities from the County of the City of Gdańsk - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
Gdańsk	136,00	77,79	27227,20	16336,32	85,68	51,41	30,84	115,00	24,44	12218,75	7942,19	22,28	8021,25	4812,75

Table 5. The potential of biogas and biomethane production from animal production waste for municipalities from the County of the City of Gdańsk - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
Gdańsk	4789,00	51,36	17976,71	10786,03	65495,32	39908,13	7,48	418,44	22,93	150,23

County of the City of Gdynia

Table 6 presents the potential of biogas and biomethane production from agricultural waste for the County of the City of Gdynia.

Tables 7 and 8 present the potential of biogas and biomethane production from animal production waste for the County of the City of Gdynia.

Table 6. The potential of biogas and biomethane production from agricultural waste for the County of the City of Gdynia

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
Gdynia	603,28	496,03	81450,61	48870,36	162320,03	89276,01	243770,63	138146,38	1557,42	65,78	85,34

Table 7. The potential of biogas and biomethane production from animal production waste for municipalities from the County of the City of Gdynia - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
Gdynia	230,00	131,56	46046,00	27627,60	144,90	86,94	52,16	78,00	16,58	8287,50	5386,88	15,11	5440,50	3264,30

Table 8. The potential of biogas and biomethane production from animal production waste for municipalities from the County of the City of Gdynia - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
Gdynia	1748,00	18,75	6561,56	3936,93	66422,50	40267,87	7,58	424,37	23,25	152,36

County of the City of Sopot

Table 9 presents the potential of biogas and biomethane production from agricultural waste for the County of the City of Sopot.

Tables 10 and 11 present the potential of biogas and biomethane production from animal production waste for the County of the City of Sopot.

Table 9. The potential of biogas and biomethane production from agricultural waste for the County of the City of Sopot

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
Sopot	29,23	57,89	9505,83	5703,50	7864,70	4325,58	17370,52	10029,08	110,98	4,69	6,08

Table 10. The potential of biogas and biomethane production from animal production waste for municipalities from the County of the City of Sopot - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
Sopot	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 11. The potential of biogas and biomethane production from animal production waste for municipalities from the County of the City of Sopot - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
Sopot	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Gdańsk County

Table 12 presents the potential of biogas and biomethane production from agricultural waste for the communes of Gdańsk County.

Tables 13 and 14 present the potential of biogas and biomethane production from animal production waste for the communes of Gdańsk County.

Table 12. The potential of biogas and biomethane production from agricultural waste for the communes of the Gdańsk County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
Cedry Wielkie	5153,46	537,84	88316,02	52989,61	1386602,83	762631,56	1474918,85	815621,17	9423,09	398,01	516,33
Kolbudy	812,92	410,24	67363,46	40418,08	218726,29	120299,46	286089,75	160717,53	1827,80	77,20	100,15
M. Pruszcz Gdański	167,49	48,14	7904,83	4742,90	45065,28	24785,90	52970,11	29528,80	338,42	14,29	18,54
Pruszcz Gdański	3560,80	710,17	116613,46	69968,08	958077,75	526942,76	1074691,21	596910,84	6866,08	290,01	376,22
Przywidz	1089,22	991,35	162784,63	97670,78	293068,26	161187,54	455852,88	258858,32	2912,39	123,01	159,58
Pszczółki	2612,94	330,87	54330,51	32598,31	703044,17	386674,29	757374,68	419272,60	4838,78	204,38	265,14
Suchy Dąb	2708,50	124,47	20438,60	12263,16	728755,78	400815,68	749194,38	413078,84	4786,52	202,17	262,28
Trąbki Wielkie	2633,75	534,15	87710,10	52626,06	708643,36	389753,85	796353,46	442379,91	5087,81	214,90	278,78

Table 13. The potential of biogas and biomethane production from animal production waste for the communes of the Gdańsk County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]
Cedry Wielkie	1482,00	847,70	296696,40	178017,84	933,66	560,20	336,12	401,00	85,21	42606,25	27694,06	77,69	27969,75	16781,85
Kolbudy	262,00	149,86	52452,40	31471,44	165,06	99,04	59,42	234,00	49,73	24862,50	16160,63	45,34	16321,50	9792,90
M. Pruszcz Gdański	66,00	37,75	13213,20	7927,92	41,58	24,95	14,97	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Pruszcz Gdański	579,00	331,19	115915,80	69549,48	364,77	218,86	131,32	314,00	66,73	33362,50	21685,63	60,84	21901,50	13140,90
Przywidz	1360,00	777,92	272272,00	163363,20	856,80	514,08	308,45	379,00	80,54	40268,75	26174,69	73,43	26435,25	15861,15
Pszczółki	304,00	173,89	60860,80	36516,48	191,52	114,91	68,95	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Suchy Dąb	451,00	257,97	90290,20	54174,12	284,13	170,48	102,29	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Trąbki Wielkie	1176,00	672,67	235435,20	141261,12	740,88	444,53	266,72	368,00	78,20	39100,00	25415,00	71,30	25668,00	15400,80

Table 14. The potential of biogas and biomethane production from animal production waste for the communes of the Gdańsk County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/h]	[MWh/year]	[kW]	[kW]
Cedry Wielkie	2877,00	30,86	10799,54	6479,72	378632,13	229309,59	43,22	2419,04	132,55	868,48
Kolbudy	1718,00	18,43	6448,94	3869,37	100184,38	61353,75	11,44	640,07	35,07	229,80
M. Pruszcz Gdański	0,00	0,00	0,00	0,00	13238,15	7942,89	1,51	84,58	4,63	30,36
Pruszcz Gdański	3556,00	38,14	13348,34	8009,00	184747,00	112516,32	21,09	1180,33	64,68	423,76
Przywidz	23414,00	251,12	87890,30	52734,18	427380,38	258441,67	48,79	2730,49	149,62	980,29
Pszczółki	1689,00	18,11	6340,08	3804,05	67315,80	40389,48	7,68	430,07	23,57	154,40
Suchy Dąb	2266,00	24,30	8506,00	5103,60	98966,68	59380,01	11,30	632,29	34,65	227,00
Trąbki Wielkie	44805,00	480,53	168186,77	100912,06	468834,50	283255,70	53,52	2995,33	164,13	1075,38

Kartuzy County

Table 15 presents the potential of biogas and biomethane production from agricultural waste for the communes of Kartuzy County.

Tables 16 and 17 present the potential of biogas and biomethane production from animal production waste for the communes of Kartuzy County.

Table 15. The potential of biogas and biomethane production from agricultural waste for the communes of the Kartuzy County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
Kartuzy	3554,12	1744,12	286393,22	171835,93	956280,41	525954,23	1242673,64	697790,16	7939,30	335,34	435,03
Żukowo	3549,50	1104,73	181402,19	108841,31	955037,34	525270,54	1136439,53	634111,85	7260,59	306,67	397,84
Chmielno	1493,21	682,51	112071,55	67242,93	401766,82	220971,75	513838,37	288214,68	3282,86	138,66	179,88
Przodkowo	2815,19	1413,28	232067,64	139240,59	757462,06	416604,13	989529,70	555844,72	6322,00	267,02	346,41
Sierakowice	5542,74	2260,48	371182,12	222709,27	1491343,48	820238,91	1862525,60	1042948,19	11899,47	502,60	652,03
Somonino	2027,69	820,87	134790,96	80874,58	545575,34	300066,44	680366,30	380941,01	4346,78	183,60	238,18
Stężyca	3179,55	704,28	115646,30	69387,78	855497,67	470523,72	971143,97	539911,50	6204,53	262,06	339,97
Sulęczyno	2279,90	549,60	90247,07	54148,24	613435,59	337389,58	703682,66	391537,82	4495,75	189,89	246,34

Table 16. The potential of biogas and biomethane production from animal production waste for the communes of Kartuzy County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]
Kartuzy	4334,00	2479,05	867666,80	520600,08	2730,42	1638,25	982,95	3704,00	787,10	393550,00	255807,50	717,65	258354,00	155012,40
Żukowo	2744,00	1569,57	549348,80	329609,28	1728,72	1037,23	622,34	3933,00	835,76	417881,25	271622,81	762,02	274326,75	164596,05
Chmielno	3724,00	2130,13	745544,80	447326,88	2346,12	1407,67	844,60	2742,00	582,68	291337,50	189369,38	531,26	191254,50	114752,70
Przodkowo	3203,00	1832,12	641240,60	384744,36	2017,89	1210,73	726,44	6073,00	1290,51	645256,25	419416,56	1176,64	423591,75	254155,05
Sierakowice	6912,00	3953,66	1383782,40	830269,44	4354,56	2612,74	1567,64	21210,00	4507,13	2253562,50	1464815,63	4109,44	1479397,50	887638,50
Somonino	2188,00	1251,54	438037,60	262822,56	1378,44	827,06	496,24	837,00	177,86	88931,25	57805,31	162,17	58380,75	35028,45
Stężyca	4394,00	2513,37	879678,80	527807,28	2768,22	1660,93	996,56	5546,00	1178,53	589262,50	383020,63	1074,54	386833,50	232100,10
Sulęczyno	2732,00	1562,70	546946,40	328167,84	1721,16	1032,70	619,62	3210,00	682,13	341062,50	221690,63	621,94	223897,50	134338,50

Table 17. The potential of biogas and biomethane production from animal production waste for the communes of Kartuzy County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
Kartuzy	376100,00	4033,67	1411785,38	847071,23	2932994,43	1779474,16	334,82	18738,58	791,47	1026,77
Żukowo	567246,00	6083,71	2129299,67	1277579,80	3371893,70	2044030,29	384,92	21542,65	909,91	1180,42
Chmielno	31733,00	340,34	119117,75	71470,65	1348662,22	823764,21	153,96	8616,45	363,94	472,13
Przodkowo	347736,00	3729,47	1305314,01	783188,41	3016613,34	1842230,82	344,36	19272,81	814,03	1056,04
Sierakowice	1394299,00	14953,86	5233849,87	3140309,92	10353205,01	6324601,13	1181,87	66145,48	2793,82	3624,41
Somonino	63176,00	677,56	237146,91	142288,15	823323,57	498440,71	93,99	5260,12	222,17	288,23
Stężyca	71398,00	765,74	268010,24	160806,15	2125445,97	1304730,71	242,63	13579,24	573,55	744,07
Sulęczyno	141458,00	1517,14	530997,97	318598,78	1643937,06	1003415,36	187,66	10502,93	443,62	575,50

Lębork County

Table 18 presents the potential of biogas and biomethane production from agricultural waste for the communes of Lębork County.

Tables 19 and 20 present the potential of biogas and biomethane production from animal production waste for the communes of Lębork County.

Table 18. The potential of biogas and biomethane production from agricultural waste for the communes of Lębork County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
Lębork	316,68	402,89	66156,55	39693,93	85206,71	46863,69	151363,26	86557,62	967,04	40,85	52,99

Table 19. The potential of biogas and biomethane production from animal production waste for the communes of Lębork County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
Lębork	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 20. The potential of biogas and biomethane production from animal production waste for the communes of Lębork County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
Lębork	1426,00	15,29	5352,85	3211,71	5352,85	3211,71	0,61	34,20	1,44	1,87

Malbork County

Table 21 presents the potential of biogas and biomethane production from agricultural waste for the communes of Malbork County.

Tables 22 and 23 present the potential of biogas and biomethane production from animal production waste for the communes of Malbork County.

Table 21. The potential of biogas and biomethane production from agricultural waste for the communes of Malbork County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[MWh/year]	[kW]	[kW]
M. Nowy Staw	4499,43	133,90	21987,05	13192,23	1210627,88	665845,34	1232614,93	679037,57	7875,04	332,62	431,51
M. Malbork	456,02	36,43	5981,99	3589,19	122697,88	67483,83	128679,87	71073,03	822,12	34,72	45,05
Lichnowy	5797,20	295,03	48445,40	29067,24	1559809,13	857895,02	1608254,53	886962,26	10274,96	433,99	563,01
Miłoradz	2822,78	415,66	68253,45	40952,07	759504,24	417727,33	827757,69	458679,40	5288,45	223,37	289,78

Table 22. The potential of biogas and biomethane production from animal production waste for the communes of Malbork County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas			Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]
M. Nowy Staw	1057,00	604,60	211611,40	126966,84	665,91	399,55	239,73	2052,00	436,05	218025,00	141716,25	397,58	143127,00	85876,20
M. Malbork	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Lichnowy	2342,00	1339,62	468868,40	281321,04	1475,46	885,28	531,17	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Miłoradz	1298,00	742,46	259859,60	155915,76	817,74	490,64	294,39	1161,00	246,71	123356,25	80181,56	224,94	80979,75	48587,85

Table 23. The potential of biogas and biomethane production from animal production waste for the communes of Malbork County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
M. Nowy Staw	2137,00	22,92	8021,76	4813,06	581184,71	359612,08	66,35	3713,12	156,83	203,46
M. Malbork	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Lichnowy	1333,00	14,30	5003,75	3002,25	474757,42	284854,45	54,20	3033,17	128,11	166,20
Miłoradz	0,00	0,00	0,00	0,00	464686,24	284979,56	53,05	2968,83	125,40	162,68

Nowy Dwór Gdański County

Table 24 presents the potential of biogas and biomethane production from agricultural waste for the communes of Nowy Dwór Gdański County.

Tables 25 and 26 present the potential of biogas and biomethane production from animal production waste for the communes of Nowy Dwór Gdański County.

Table 24. The potential of biogas and biomethane production from agricultural waste for the communes of Nowy Dwór Gdański County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
M. Nowy Dwór Gdański	7559,97	992,20	162924,20	97754,52	2034104,43	1118757,44	2197028,63	1216511,96	14036,57	592,87	769,13
M. Krynica Morska	5,26	42,88	7041,11	4224,67	1415,27	778,40	8456,38	5003,06	54,03	2,28	2,96
Ostaszewo	2454,64	150,13	24652,10	14791,26	660451,58	363248,37	685103,67	378039,62	4377,05	184,88	239,84
Stegna	5335,64	1561,50	256406,11	153843,66	1435620,64	789591,35	1692026,75	943435,02	10810,17	456,59	592,34
Sztutowo	1839,11	209,61	34419,01	20651,41	494835,53	272159,54	529254,54	292810,95	3381,35	142,82	185,28

Table 25. The potential of biogas and biomethane production from animal production waste for the communes of Nowy Dwór Gdański County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
M. Nowy Dwór Gdański	3669,00	2098,67	734533,80	440720,28	2311,47	1386,88	832,13	632,00	134,30	67150,00	43647,50	122,45	44082,00	26449,20
G. i M Krynica Morska	41,00	23,45	8208,20	4924,92	25,83	15,50	9,30	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ostaszewo	316,00	180,75	63263,20	37957,92	199,08	119,45	71,67	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Stegna	1247,00	713,28	249649,40	149789,64	785,61	471,37	282,82	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Sztutowo	558,00	319,18	111711,60	67026,96	351,54	210,92	126,55	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 26. The potential of biogas and biomethane production from animal production waste for the communes of Nowy Dwór Gdański County County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
M. Nowy Dwór Gdański	3430,00	36,79	12875,36	7725,22	860028,04	519374,33	98,18	5494,62	232,08	301,08
M Krynica Morska	0,00	0,00	0,00	0,00	8223,70	4934,22	0,94	52,54	2,22	2,88
Ostaszewo	1227,00	13,16	4605,85	2763,51	67988,50	40793,10	7,76	434,37	18,35	23,80
Stegna	3805,00	40,81	14283,02	8569,81	264403,78	158642,27	30,18	1689,25	71,35	92,56
Sztutowo	0,00	0,00	0,00	0,00	111922,52	67153,51	12,78	715,06	30,20	39,18

Puck County

Table 27 presents the potential of biogas and biomethane production from agricultural waste for the communes of Puck County.

Tables 28 and 29 present the potential of biogas and biomethane production from animal production waste for the communes of Puck County.

Table 27. The potential of biogas and biomethane production from agricultural waste for the communes of Puck County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
M. Hel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M. Jastarnia	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M. Puck	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Puck	5254,27	2552,07	419062,65	251437,59	1413727,02	777549,86	1832789,68	1028987,45	11709,49	494,58	641,62
Kosakowo	885,86	640,28	105137,18	63082,31	238351,71	131093,44	343488,88	194175,74	2194,51	92,69	120,25
Władysławowo	348,13	230,20	37799,99	22679,99	93668,73	51517,80	131468,72	74197,80	839,94	35,48	46,02

Table 28. The potential of biogas and biomethane production from animal production waste for the communes of Puck County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
M. Hel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M. Jastarnia	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M. Puck	41,00	23,45	8208,20	4924,92	25,83	15,50	9,30	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Puck	5782,00	3307,30	1157556,40	694533,84	3642,66	2185,60	1311,36	6947,00	1476,24	738118,75	479777,19	1345,98	484553,25	290731,95
Kosakowo	412,00	235,66	82482,40	49489,44	259,56	155,74	93,44	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Władysławowo	149,00	85,23	29829,80	17897,88	93,87	56,32	33,79	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 29. The potential of biogas and biomethane production from animal production waste for the communes of Puck County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
M. Hel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M. Jastarnia	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M. Puck	0,00	0,00	0,00	0,00	8223,70	4934,22	0,94	52,54	2,22	2,88
Puck	13524,00	145,04	50765,72	30459,43	2433179,71	1496813,76	277,76	15545,31	656,59	851,80
Kosakowo	1290,00	13,84	4842,34	2905,40	87480,47	52488,28	9,99	558,90	23,61	30,62
Władysławowo	0,00	0,00	0,00	0,00	29886,12	17931,67	3,41	190,94	8,06	10,46

Tczew County

Table 30 presents the potential of biogas and biomethane production from agricultural waste for the communes of Tczew County.

Tables 31 and 32 present the potential of biogas and biomethane production from animal production waste for the communes of Tczew County.

Table 30. The potential of biogas and biomethane production from agricultural waste for the communes of Tczew County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[MWh/year]	[kW]	[kW]
M.Pelplin	5572,13	362,47	59519,39	35711,63	1499251,23	824588,18	1558770,61	860299,81	9958,81	420,63	545,69
M. Gniew	6206,50	875,11	143697,44	86218,46	1669936,41	918465,02	1813633,84	1004683,49	11587,11	489,41	634,91
M. Tczew	323,46	48,20	7914,68	4748,81	87030,96	47867,03	94945,64	52615,83	606,60	25,62	33,24
Tczew	5431,13	715,65	117513,31	70507,98	1461313,42	803722,38	1578826,72	874230,36	10086,95	426,05	552,71
Subkowy	4084,06	341,03	55998,83	33599,30	1098867,39	604377,07	1154866,22	637976,37	7378,31	311,64	404,29

Table 31. The potential of biogas and biomethane production from animal production waste for the communes of Tczew County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]
M.Pelplin	3008,00	1720,58	602201,60	361320,96	1895,04	1137,02	682,21	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M. Gniew	2781,00	1590,73	556756,20	334053,72	1752,03	1051,22	630,73	5072,00	1077,80	538900,00	350285,00	982,70	353772,00	212263,20
M. Tczew	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Tczew	2363,00	1351,64	473072,60	283843,56	1488,69	893,21	535,93	3128,00	664,70	332350,00	216027,50	606,05	218178,00	130906,80
Subkowy	1436,00	821,39	287487,20	172492,32	904,68	542,81	325,68	2710,00	575,88	287937,50	187159,38	525,06	189022,50	113413,50

Table 32. The potential of biogas and biomethane production from animal production waste for the communes of Tczew County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
M.Pelplin	110129,00	1181,13	413396,73	248038,04	1016735,36	610041,21	116,07	6495,81	274,37	355,93
M. Gniew	5376,00	57,66	20180,16	12108,10	1470659,58	909340,75	167,88	9395,88	396,86	514,84
M. Tczew	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Tczew	8992,00	96,44	33753,72	20252,23	1058247,53	651566,02	120,80	6761,03	285,57	370,47
Subkowy	9763,00	104,71	36647,86	21988,72	801637,87	495379,60	91,51	5121,58	216,32	280,63

Wejherowo County

Table 33 presents the potential of biogas and biomethane production from agricultural waste for the communes of Wejherowo County.

Tables 34 and 35 present the potential of biogas and biomethane production from animal production waste for the communes of Wejherowo County.

Table 33. The potential of biogas and biomethane production from agricultural waste for the communes of Wejherowo County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[MWh/year]	[kW]	[kW]
M. Reda	182,54	672,01	110347,40	66208,44	49114,67	27013,07	159462,07	93221,51	1018,79	43,03	55,82
M. Rumia	275,38	224,94	36936,27	22161,76	74094,43	40751,94	111030,70	62913,70	709,36	29,96	38,87
Gniewino	2312,78	485,20	79672,27	47803,36	622282,37	342255,30	701954,63	390058,66	4484,71	189,42	245,74
Łęczyce	2283,47	1637,81	268936,59	161361,95	614396,15	337917,88	883332,74	499279,84	5643,51	238,37	309,23
Linia	2820,06	994,03	163224,70	97934,82	758772,39	417324,82	921997,09	515259,63	5890,54	248,80	322,77
Luzino	2201,43	1584,78	260228,80	156137,28	592322,26	325777,24	852551,06	481914,52	5446,85	230,06	298,46
Szemud	5637,07	2206,99	362398,79	217439,28	1516724,15	834198,28	1879122,94	1051637,56	12005,51	507,08	657,84
Wejherowo	1253,85	1784,70	293056,66	175834,00	337364,02	185550,21	630420,68	361384,21	4027,69	170,12	220,70
M. Wejherowo	109,30	350,69	57585,05	34551,03	29408,53	16174,69	86993,58	50725,72	555,79	23,48	30,45

Table 34. The potential of biogas and biomethane production from animal production waste for the communes of Wejherowo County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
M. Reda	236,00	134,99	47247,20	28348,32	148,68	89,21	53,52	41,00	8,71	4356,25	2831,56	7,94	2859,75	1715,85
M. Rumia	49,00	28,03	9809,80	5885,88	30,87	18,52	11,11	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Gniewino	516,00	295,15	103303,20	61981,92	325,08	195,05	117,03	1160,00	246,50	123250,00	80112,50	224,75	80910,00	48546,00
Łęczyce	3185,00	1821,82	637637,00	382582,20	2006,55	1203,93	722,36	2817,00	598,61	299306,25	194549,06	545,79	196485,75	117891,45
Linia	2968,00	1697,70	594193,60	356516,16	1869,84	1121,90	673,14	7538,00	1601,83	800912,50	520593,13	1460,49	525775,50	315465,30
Luzino	3838,00	2195,34	768367,60	461020,56	2417,94	1450,76	870,46	2635,00	559,94	279968,75	181979,69	510,53	183791,25	110274,75
Szemud	5505,00	3148,86	1102101,00	661260,60	3468,15	2080,89	1248,53	5871,00	1247,59	623793,75	405465,94	1137,51	409502,25	245701,35
Wejherowo	2497,00	1428,28	499899,40	299939,64	1573,11	943,87	566,32	456,00	96,90	48450,00	31492,50	88,35	31806,00	19083,60
M. Wejherowo	273,00	156,16	54654,60	32792,76	171,99	103,19	61,92	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 35. The potential of biogas and biomethane production from animal production waste for the communes of Wejherowo County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
M. Reda	581,00	6,23	2180,93	1308,56	56733,34	34257,81	6,48	362,46	15,31	19,86
M. Rumia	1598,00	17,14	5998,49	3599,10	15826,81	9496,09	1,81	101,12	4,27	5,54
Gniewino	61098,00	655,28	229346,62	137607,97	537004,87	328365,42	61,30	3430,86	144,91	187,99
Łęczyce	5941,00	63,72	22301,03	13380,62	1156933,96	709125,69	132,07	7391,52	312,20	405,01
Linia	34037,00	365,05	127766,39	76659,83	2049769,89	1269907,56	233,99	13095,75	553,13	717,58
Luzino	35878,00	384,79	134677,04	80806,23	1368255,41	834951,68	156,19	8741,63	369,22	478,99
Szemud	203250,00	2179,86	762949,69	457769,81	2900427,58	1771446,23	331,10	18530,51	782,68	1015,37
Wejherowo	208054,00	2231,38	780982,70	468589,62	1362081,97	819671,68	155,49	8702,19	367,56	476,83
M. Wejherowo	30542,00	327,56	114647,03	68788,22	169404,83	101642,90	19,34	1082,31	45,71	59,30

Kościerzyna County

The Commune of Liniewo, for which the potential of biogas and biomethane production from agricultural waste was estimated, belongs to the OMGGS from Kościerzyna County (Table 36).

Tables 37 and 38 present the potential of biogas and biomethane production from waste from animal production for the Liniewo commune of Kościerzyna County.

Table 36. The potential of biogas and biomethane production from agricultural waste for the communes of Kościerzyna County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[MWh/year]	[kW]	[kW]
Liniewo	2824,39	596,51	97949,92	58769,95	759937,43	417965,59	857887,36	476735,54	5480,95	231,50	300,33

Table 37. The potential of biogas and biomethane production from animal production waste for the communes of Kościerzyna County - part 1

Community	Cattle							Pigs	Community					
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[t/year o.d.m.]	[m^3/year]	[m^3/year]
Liniewo	2941,00	1682,25	588788,20	353272,92	1852,83	1111,70	667,02	4261,00	905,46	452731,25	294275,31	825,57	297204,75	178322,85

Table 38. The potential of biogas and biomethane production from animal production waste for the communes of Kościerzyna County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/year]	[m^3/h]	[MWh/year]	[kW]	[kW]
Liniewo	40435,00	433,67	151782,88	91069,73	1491618,78	917607,83	170,28	9529,79	402,51	522,18

Starogard County

The Commune of Skarszewy, for which the potential of biogas and biomethane production from agricultural waste was estimated, belongs to the OMGGS from Starogard County (Table 39).

Tables 40 and 41 present the potential of biogas and biomethane production from waste from animal production for the Skarszewy commune of Starogard County.

Table 39. The potential of biogas and biomethane production from agricultural waste for the communes of Starogard County

Community	Cereal area	Meadow and grass area	Biogas production - meadows	Methane production - meadows	Biogas production - agricultural	Methane production - agricultural	Total biogas production	Total methane production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
[-]	[ha]	[ha]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[MWh/year]	[kW]	[kW]
Skarszewy	4705,77	881,62	144766,41	86859,85	1266146,24	696380,43	1410912,65	783240,28	9014,16	380,74	493,93

Table 40. The potential of biogas and biomethane production from animal production waste for the communes of Starogard County - part 1

Community	Cattle							Pigs						
		Slurry			Manure				Slurry			Manure		
		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane		Mass of substrates	Production of biogas	Production of methane	Mass of substrates	Production of biogas	Production of methane
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[t/year o.d.m.]	[m³/year]	[m³/year]
Skarszewy	2090,00	1195,48	418418,00	251050,80	1316,70	790,02	474,01	21327,00	4531,99	2265993,75	1472895,94	4132,11	1487558,25	892534,95

Table 41. The potential of biogas and biomethane production from animal production waste for the communes of Starogard County - part 2

Community	Poultry				Total biogas production	Total biomethane production	Temporary biogas production	The amount of primary energy in biogas	Electric power installed	Thermal power installed
		Mass of substrates	Production of biogas	Production of methane						
[-]	pcs	[t/year o.d.m.]	[m³/year]	[m³/year]	[m³/year]	[m³/year]	[m³/h]	[MWh/year]	[kW]	[kW]
Skarszewy	4491,00	48,17	16858,09	10114,85	4189618,11	2627070,55	478,27	26767,00	1130,57	1466,69

Biogas production potential for OMGGS

The total annual biogas production potential for OMGGS by poviat is presented in Table 42.

Table 42. Total annual biogas production potential for OMGGS by counts

County	Total biogas production in the commune	Total biomethane production	Electric power installed	Installed thermal power
	[m^3/year]	[m^3/year]	[kW]	[kW]
Gdańsk County	7 386 744,32	1 416 182,93	1 993,32	2 585,92
County of the City of Sopot	17 370,52	5 703,99	4,69	6,08
County of the City of Gdańsk	835 533,17	130 151,74	225,47	292,50
County of the City of Gdynia	310 193,13	89 148,43	83,71	108,59
Kartuzy County	33 716 275,09	16 535 380,91	9 098,35	11 803,26
Lębork County	156 716,11	42 910,99	42,29	54,86
Malbork County	5 317 935,40	1 016 476,16	1 435,05	1 861,68
Nowy Dwór Gdański County	6 424 436,52	1 082 453,42	1 733,64	2 249,04
Puck County	4 866 517,28	1 909 477,44	1 313,23	1 703,65
Tczew County	10 548 323,38	2 897 478,95	2 846,47	3 692,72
Wejherowo County	15 843 304,15	6 858 585,45	4 275,32	5 546,36
Kościerzyna County	2 349 506,14	976 425,50	634,02	822,51
Starogard County	5 600 530,76	2 714 009,90	1 511,31	1 960,61

Table 43 shows the potential of the obtained electric power installed in the sewage treatment plant based on the determined potential of biogas production.

Table 43. Potential of the obtained electric power installed in the sewage treatment plant based on the determined potential of biogas production

Name	Localisation	Amount of treated wastewater	The amount of primary energy in biogas	Electric power installed	Installed thermal power
		[m^3/year]	[MWh/year]	[kW]	[kW]
Municipal Sewage Treatment Plant in Cedry Wielkie	Cedry Wielkie and Trutnowy	226605,00	59,99	2,53	3,29
Żukowo sewage treatment plant	Żukowo	0,00	0,00	0,00	0,00
Przodkowo sewage treatment plant	Przodkowo	141050,00	37,34	1,58	2,05
Kartuskie Przedsiębiorstwo Wodociągów i Kanalizacji Sp. z o.o.	Kartuzy	0,00	0,00	0,00	0,00
Dębogórze PEWIK Gdynia sewage treatment plant	Gdynia	22703876,20	6010,61	253,87	329,35
New Sewage Treatment Plant in Przywidz	Przywidz	195275,00	51,70	2,18	2,83
Sławki wastewater treatment plant	Sławki	518351,00	137,23	5,80	7,52
Suchy Dąb sewage treatment plant	Suchy Dąb	no data			
Luzino sewage treatment plant	Luzino	no data			
The sewage treatment plant in Ostaszewo	Ostaszewo	no data			

Description of the significant generation sources based on biogas

There are sewage treatment plants and municipal waste treatment plants on the premises of OMGGS, which currently produce or recover biogas. This section estimates the possible bioLNG production from biogas produced in individual treatment or rendering plants, and the calculation results are presented in Table 44. The possible bioLNG production was determined from the estimated bioLNG production from the instantaneous biogas production at the Cryo Pur plant. [29].

Table 44. BioLNG production potential in existing wastewater treatment plants and municipal waste treatment plants on the premises of OMGGS

Name	Localisation	Biogas yield	Temporary biogas production	Possible bioLNG production
		[m^3/year]	[m^3/h]	[t/d]
Oczyszczalnia Ścieków Gdańsk Wschód (GIWK)	Gdańsk	6 500 000,00	742,01	7,4
Zakład Utylizacyjny Sp. z o.o. w Gdańsku	Gdańsk	7 008 000,00	800,00	7,4
Zakładu Utylizacji Odpadów Stałych Sp. Z o.o. (Tczew)	Tczew	1 209 700,00	138,09	2,3
Ekodolina	Wejherowo	4 529 081,00	517,02	4,6
Oczyszczalnia Ścieków w Ostaszewie	Ostaszewo	4 080 000,00	465,75	4,6

Possibilities of biogas and bioLNG distribution

The ability to distribute biogas and bioLNG differ due to the physical properties of both fuels. Biogas is transported via a gas pipeline, while bioLNG is transported in liquid form in cryogenic pressure tanks and does not require access to the gas pipeline.

In Poland, work is currently underway on regulations enabling the injection of biomethane into the gas distribution network. The Minister of Climate and Environment is responsible for the regulation of the detailed conditions for the operation of the gas system, which should regulate the quality parameters of biomethane injected into the gas network. Despite the passage of time, work on the new content of the regulation has not been completed yet, which is due to the lack of a common position of all entities working on the content of the document.

Therefore, when analyzing the location of the biogas plant, it should be assumed that the biogas will be used to power cogeneration engines to produce electricity and heat. The produced heat can be directed to the local heating network, if there is one, or it can be the reason for the construction of a heating system in a location where there is no heating network.

As mentioned, it is much easier to manage the transport of the liquefied version of biomethane, or bioLNG. In this case, a biomethane purification, drying and liquefaction station should be located on the site of the biogas plant, and bioLNG storage tanks and fuel refuelling stations should be provided. Elements of bioLNG stations significantly increase the costs of the entire investment, although in the final economic calculation they may turn out to be profitable, due to the price of bioLNG fuel.

A refuelling station can supply bioLNG or bioCNG fuel to vehicles operated by municipal companies for waste collection or passenger transport, or the fuel can be sold on the market for profit.

Part 3
Locations with the greatest potential for building a biogas plant, diagnosis of resources and potential for the studied area, analysis of potentials for selected locations, scenarios for selected locations for biogas production, SWOT analysis

Locations with the greatest potential for building a biogas plant

After analyzing the potential of building biogas plants in the areas of individual municipalities belonging to OMGGS, locations for the construction of biogas plants were selected, which were then divided depending on the planned installed capacity and the substrate used for the production of biogas or bioLNG.

In the Regulation of the Council of Ministers of 9 November 2010 on projects that may have a significant impact on the environment, agricultural biogas plants with electric power installed up to 500 kW [30] were excluded, which means that for such biogas plants it is not required to obtain an environmental decision, which shortens the process investment and reduces capital expenditure.

The location of the biogas plant should ensure the collection of heat generated as a result of the process of converting the energy contained in the biogas into electricity transferred to the power system. Due to the transmission-related heat losses, the distance between the biogas plant and the recipients should not be too large to ensure the qualitative and quantitative parameters of the heating medium.

The locations of biogas plants have been divided according to the possible installed electric power and the possibility of producing bioLNG, according to the division:

- biogas plants from agricultural and animal waste with a capacity of more than 500 kW,
- biogas plants from agricultural and animal waste with a capacity between 50 kW and 499 kW,
- biogas plants from agricultural and animal waste with a capacity of up to 50 kW,
- utilization of biogas plants from sewage treatment plants,
- biogas plants producing bioLNG from biogas in existing biogas plants.

Possible locations for the construction of biogas plants are presented below, taking into account the above division.

Biogas plants from agricultural and animal waste with a capacity of over 500 kW

Under the Regulation on projects that may significantly affect the environment [30], for biogas plants with a capacity of over 500 kW, it is necessary to obtain a decision on environmental conditions, the so-called environmental decision the process of which is time-consuming. The investment outlays for a biogas plant with a large installed capacity of 1-3 MW are estimated at PLN 15 million/MW. Operating costs related to the maintenance and operation of a large biogas plant amount to approximately PLN 2 million.

Table 45 presents the proposed locations of a biogas plant with an installed electrical power above 500 kW, which additionally includes the possible installed electrical power, installed thermal power and population density index in a given commune.

Table 45. Proposals for the location of a biogas plant with an installed electrical capacity of over 500 kW

County	Community	Electric power installed	Installed thermal power	Population density indicator
		[kW]	[kW]	[person/km^2]
Kartuzy County	Sierakowice	3 296,42	4 276,44	111
Starogard County	Skarszewy	1 511,31	1 960,61	138
Wejherowo County	Szemud	1 289,76	1 673,21	105
Kartuzy County	Żukowo	1 216,58	1 578,26	224
Powiat pucki	Puck	1 151,17	1 493,41	175
Kartuzy County	Kartuzy	1 126,81	1 461,80	264
Kartuzy County	Przodkowo	1 081,06	1 402,45	117
Kartuzy County	Gniew	886,27	1 149,75	79
Kartuzy County	Stężyca	835,62	1 084,04	67
Nowy Dwór Gdański County	Nowy Dwór Gdański	824,95	1 070,20	1972
Wejherowo County	Linia	801,93	1 040,34	54
Tczew County	Tczew	711,62	923,18	90
Tczew County	Pelplin	695,00	901,62	118
Kościerzyna County	Liniewo	634,02	822,51	42
Kartuzy County	Sulęczyno	633,51	821,85	43
Wejherowo County	Luzino	599,29	777,45	152
Malbork County	Lichnowy	562,10	729,21	52
Wejherowo County	Łęczyce	550,57	714,25	52
Wejherowo County	Wejherowo	537,68	697,53	140
Tczew County	Subkowy	527,96	684,93	71
Nowy Dwór Gdański County	Stegna	527,94	684,90	57
Kartuzy County	Chmielno	502,60	652,02	100
Gdańsk County	Cedry Wielkie	500,18	648,88	56

Construction of a biogas plant with an installed electrical capacity of over 500 kW is possible in 17 municipalities. The largest biogas plant can be located in the commune of Sierakowice, and its installed electric power will be 3,296.42 kW. This biogas plant can produce 4 276.44 kW of thermal energy, which should be used in local heating. The construction of the second largest biogas plant is possible in the Skarszewy commune, and its installed electric power is 1,511.31 kW. Another high-power biogas plant may be located in the Szemud commune, and its installed electrical capacity may amount to 1,298.76 kW. Subsequently, the locations of high-power biogas plants may be indicated in the communes of Przodkowo, Gniew, Stężyca, Linie, Tczew, Pelplin, Liniewo, Sulęczyno, Luzino, Lichnowy, Łęczyce, Wejherowo, Subkowy, Stegna, Chmielno and Cedry Wielki. All the above-mentioned locations are characterized by a low population density, which is a significant obstacle in the management of thermal energy generated in the process of converting energy contained in biogas into electricity. Among the communes mentioned, only in the Skarszewy commune there is a gas pipeline that could be used to transmit biogas to other locations. Access to gas pipelines for biogas plants and the possibility of injecting biogas are currently not supported by legislation and by gas pipeline operators, therefore the location of the biogas plant in the Skarszewy commune will not be taken into account in further analyzes.

The highest biogas yield in the Kartuzy poviat occurs in the communes of Żukowo, Kartuzy, Stężyca, Sulęczyno, Chmielno and Somonino. Due to the population density of the Kartuzy district and the possibility of supplying the biogas plant with feed to the fermenter, it is possible to build a biogas plant based on energy cooperatives.

The communes of Puck, Kartuzy and Nowy Dwór Gdański are characterized by access to a heating network and a relatively high population density indicator, therefore the location of biogas plants in these communes will be analyzed.

Biogas plants from agricultural and animal waste with a capacity between 50 kW and 499 kW

Table 46 presents the proposed locations of a biogas plant with an installed capacity between 50 kW and 499 kW, which additionally includes possible installed electric power, installed heat capacity and population density index in a given commune.

Table 46. Proposals for the location of agricultural biogas plants with an installed capacity between 50 kW and 499 kW

County	Community	Electric power installed	Installed thermal power	Population density indicator
		[kW]	[kW]	[person/km^2]
Malbork County	Nowy Staw	489,45	634,97	90
Kartuzy County	Somonino	405,77	526,41	98
Malbork County	Miłoradz	348,77	452,45	36
Gdańsk County	Trąbki Wielkie	341,41	442,91	69
Gdańsk County	Pruszcz Gdański	339,86	440,90	224
Wejherowo County	Gniewino	334,33	433,73	42
Gdańsk County	Przywidz	238,34	309,20	46
Gdańsk County	Suchy Dąb	228,88	296,92	50
Gdańsk County	Gdańsk	225,47	292,50	1797
Gdańsk County	Pszczółki	222,54	288,70	199
Nowy Dwór Gdański County	Ostaszewo	203,22	263,64	53
Nowy Dwór Gdański County	Sztutowo	173,02	224,46	32
Powiat pucki	Kosakowo	116,30	150,87	328
Gdańsk County	Kolbudy	104,24	135,23	219
County of the City of Gdynia	Gdynia	83,71	108,59	1815
Wejherowo County	Wejherowo	69,19	89,76	1818
Wejherowo County	Reda	58,34	75,68	786

Small installations with a capacity of up to 500 kW and micro-installations with a capacity of over 50 kW are currently the most popular among investors in biogas plants in Poland. This type of installation can be decided by farmers who want to produce electricity and heat for their own needs, based on the substrates they produce themselves.

The investment outlays for micro-installations are estimated at approximately PLN 1.5 million for installations with an installed capacity of approximately 50 kW. However, the construction of micro-installations is not much cheaper than the construction of a low-power biogas plant, due to the need to install fittings and automation equipment. Therefore, it is profitable to build a small biogas installation based on the cooperation of several farmers, e.g. as part of an energy cooperative or an energy cluster.

Biogas plants from agricultural and animal waste with a capacity of up to 50 kW

Table 47 presents the proposed locations of agricultural biogas plants with an installed capacity of up to 50 kW.

Table 47. Proposals for the location of agricultural biogas plants with an installed capacity of up to 50 kW

County	Community	Electric power installed	Installed thermal power	Population density indicator
		[kW]	[kW]	[person/km^2]
Puck County	Władysławowo	43,54	56,49	188
Lębork County	Lębork	42,29	54,86	1950
Malbork County	Malbork	34,72	45,05	2241
Wejherowo County	Rumia	34,23	44,41	1651
Tczew County	Tczew	25,62	33,24	2701
Gdańsk County	Pruszcz Gdański	17,87	23,18	1974
County of the City of Sopot	Sopot	4,69	6,08	2076
Nowy Dwór Gdańsku County	Krynica Morska	4,50	5,84	11
Puck County	Puck	2,22	2,88	2228
Puck County	Hel	-	-	140
Puck County	Jastarnia	-	-	536

The locations of biogas plants with an installed capacity of less than 10 kW are characterized by low profitability and individual character. In addition, micro-biogas plants are characterized by a high risk related to continuous operation due to factors affecting the amount of obtained substrates. A biogas plant with a capacity of up to 50 kW usually operates in a prosumer system, in which electricity and heat are used for the needs of the farm. For the construction of a biogas plant with a capacity of up to 50 kW, you can apply for funding from the AGROENERGIA Priority Program [31].

Utilization of biogas plants from sewage treatment plants

Construction of a biogas plant, in which the feed to the fermenter would be dehydrated sewage from the sewage treatment plant, is possible in Gdynia at the Oczyszczalnia ścieków Dębogórze PEWIK Gdynia. Construction of a biogas plant would not require obtaining a decision on environmental conditions and could be used to cover the energy needs of the sewage treatment plant and residents. Table 48 presents a proposed location for a sewage treatment plant based on the determined biogas production potential.

Table 48. Location of a biogas plant in a wastewater treatment plant based on the designated biogas production potential

Name	Localisation	Amount of treated wastewater	The amount of primary energy in biogas	Electric power installed	Installed thermal power
		[m^3/year]	[MWh/year]	[kW]	[kW]
Oczyszczalnia ścieków Dębogórze PEWIK Gdynia	Gdynia	22703876,20	6010,61	253,87	329,35

Biogas plants from agricultural and animal waste that produce bioLNG based on the Cryo Pur technology

The bioLNG production technology in the Cryo Pur installation allows for the production of the amount of bioLNG fuel depending on the flow of biomethane expressed in m^3 per hour. Depending on the biomethane flow rate, the amount of fuel produced varies. For the analysis, nominal values of bioLNG fuel production were assumed for individual installations and the technology:

- Cryo Pur CP250, nominal biogas flow – 250 m^3/h, nominal bioLNG production – 2,3 tons per day,
- Cryo Pur CP500, nominal biogas flow – 500 m^3/h, nominal bioLNG production – 4,6 tons per day,
- Cryo Pur CP800, nominal biogas flow – 800 m^3/h, nominal bioLNG production – 7,4 tons per day,
- Cryo Pur CP1000, nominal biogas flow – 1000 m^3/h, nominal bioLNG production – 13,8 tons per day.

For the above values, the locations were divided according to the technology that could be used.

It should be noted that the division is significantly simplified due to the lack of detailed information on the possible yields of bioLNG fuel. Detailed calculations of fuel production and estimation of investment outlay for the construction of the installation should be made at the stage of the investment feasibility study.

Table 49 presents suggestions for the location of agricultural biogas plants producing bioLNG based on the Cryo Pur CP250 technology, where approximately 2.3 tons of bioLNG can be obtained per day.

Table 49. Proposals for the location of agricultural biogas plants producing bioLNG based on the Cryo Pur CP250 technology

County	Community
Gdańsk County	Cedry Wielkie
Gdańsk County	Pruszcz Gdański
Gdańsk County	Trąbki Wielkie
Kartuzy County	Chmielno
Kartuzy County	Somonino
Malbork County	Nowy Staw
Malbork County	Lichnowy
Malbork County	Miłoradz
Nowy Dwór Gdański County	Stegna
Tczew County	Subkowy
Wejherowo County	Gniewino
Wejherowo County	Łęczyce
Wejherowo County	Wejherowo

Table 50 presents the proposed locations of biogas plants producing bioLNG based on the Cryo Pur CP500 technology, which can produce about 4.6 tons of bioLNG per day.

Table 50. Proposals for the location of biogas plants producing bioLNG based on the Cryo Pur CP500 technology

County	Community
Kartuzy County	Kartuzy
Kartuzy County	Przodkowo
Kartuzy County	Stężyca
Kartuzy County	Sulęczyno
Nowy Dwór Gdańsku County	Nowy Dwór Gdański
Puck County	Puck
Tczew County	Pelplin
Tczew County	Gniew
Tczew County	Tczew
Wejherowo County	Linia
Wejherowo County	Luzino
Kościerzyna County	Liniewo

Table 51 presents suggestions for the location of biogas plants producing bioLNG based on the Cryo Pur CP800 technology, which can be obtained daily by about 7.4 tons of bioLNG.

Table 51. Proposals for the location of biogas plants producing bioLNG based on the Cryo Pur CP800 technology

County	Community
Kartuzy County	Żukowo
Wejherowo County	Szemud
Starogard County	Skarszewy

Table 52 presents suggestions for the location of biogas plants producing bioLNG based on the Cryo Pur CP1000 technology, which can be obtained daily by about 13.8 tons of bioLNG.

Table 52. Proposals for the location of biogas plants producing bioLNG based on the Cryo Pur CP1000 technology

County	Community
Kartuzy County	G. Sierakowice

Biogas plants producing bioLNG from biogas in existing biogas plants

On the premises of OMGGS, existing biogas plants have the potential to build a biogas purification, drying and condensation installation in the Cryo Pur installation and a refuelling station to supply vehicles with bioLNG, as shown in Table 53.

Table 53. Proposals for the location of bioLNG production stations in existing biogas plants in the area of OMGGS

Name	Localisation	Amount of treated wastewater	The amount of primary energy in biogas	Electric power installed	Installed thermal power
		[m^3/year]	[m^3/h]	[t/d]	[-]
Oczyszczalnia Ścieków Gdańsk Wschód (GIWK)	Gdańsk	6500000,00	742,01	7,40	CP800
Zakład Utylizacyjny Sp. z o.o. w Gdańsku (ZU)	Gdańsk	7008000,00	800,00	7,40	CP800
Zakładu Utylizacji Odpadów Stałych Sp. Z o.o. (Tczew)	Tczew	1209700,00	138,09	2,30	CP250
Ekodolina	Łężyce	4529081,00	517,02	4,60	CP500

The Ekodolina company located in Łężyce is located about 9 km from the national road s6, and the access to it leads through green areas and roads not intended for large delivery vehicles. Zakład Utylizacji Odpadów Stałych Sp. Z o.o. in Tczew, is located 7.6 km from the A1 motorway, in addition, the production of bioLNG in this plant is the lowest. Therefore, customers at the bioLNG station located in the vicinity of the Plant should include owners of local transport vehicles or communal services.

In both Zakład Utylizacyjny Sp. z o.o. in Gdańsk (ZU) and the Gdańsk Wschód Sewage Treatment Plant (GIWK) there is a biogas recovery or production installation. Biogas is used to produce electricity and heat for local needs. Due to the current expansion of the ZU area and the construction of a waste incineration plant, the Port of Clean Energy, the biogas recovery and purification plant can be expanded with a biogas condensation station, for example using the Cryo Pur solution, and the liquefied fuel in the form of bioLNG can power public transport vehicles or vehicles municipal. A similar situation occurs at GIWK, where there is a biogas plant. The conversion of biogas into bioLNG fuel would increase the company's profits and make its operation independent of heat recipients.

Analysis of potentials for selected locations

Identification of the location of the generating source is the most important element of the investment process. Incorrect identification of the location results in the failure of the investment project. Already at the stage of identifying the location, the type of generation source to be built should be taken into account, because the characteristics of the location change depending on the type of source.

The location of the biogas plant depends on the distance of the power plant (or CHP) from the power system and the existing gas and heating networks. An important element is also the proximity of the supply of substrates for biogas production (primarily raw materials) and the sites for the disposal of post-fermentation residues. Due to the nature of primary raw materials (waste from the agri-food industry, waste from livestock production) causing the emission of unpleasant odours, a biogas plant should have the least possible impact on human habitats, by maintaining appropriate distances and taking into account the directions of winds. The supplies of primary raw materials should also cross built-up areas as little as possible. The proximity of the post-fermentation residue management areas is required to minimize transport costs. As part of the development of a strategy for the use of bioLNG in the area of OMGGS, taking into account the possibility of biogas production and locating biogas plants by "biogas plant location", one should understand the area of a commune or city where there is a potential for biogas production.

Due to the complexity of the problem, which is the determination of the location of a biogas plant on the premises of OMGGS, a simplified method of multi-criteria analysis was used in the development of the Strategy, which allows describing the proposed locations in terms of various assessment criteria.

The selection of optimization criteria will be made based on:

- scientific literature,
- consultations with OMGGS implementation partners,
- Diagnosis of adaptation and mitigation to climate change OMGGS [33],
- Bałtycka Agencja Poszanowania Energii Sp. Z o.o .: The energy potential of the communes of the Pomeranian Voivodeship in the context of the possibility of building energy islands, Gdańsk 2021 [34],
- strategic and sectoral documents and legal acts:
    - Poland's energy policy until 2040 [35],
    - Assumptions or draft assumptions for heat, electricity and gas fuel supply plans in communes,

- OMGGS strategy until 2030 [16],
- Act of 3 October 2008 on the provision of information on the environment and its protection, public participation in environmental protection and environmental impact assessments (Dz. U. z 2020 r., poz. 283 ze zm.) [36],
- Act of April 10, 1997 - Energy Law (Dz. U. z 2019 r., poz. 833 ze. zm.) [37],
- The Act of May 20, 2016, on energy efficiency (Dz. U z 2020 r., poz. 264 ze. zm.) [38],
- The Act of February 20, 2015, on renewable energy sources (Dz. U z 2020 r., poz. 261 ze zm.) [39].

To present the Strategy, optimization criteria were selected so that it was possible to compare individual biogas plant locations with bioLNG stations.

The initial proposal of optimization criteria includes groups of environmental, technical, economic and socio-legal criteria.

The environmental criteria include the CO_2 Avoidance Index, the Land Surface Index, and the location of the site for digestate management.

The technical criteria are, for example, planned electrical installed capacity, planned installed thermal capacity, planned fuel production, technology maturity and system reliability.

Economic criteria include, among others, capital expenditure, operating costs, and total profit from the sale of electricity, heat, and bioLNG fuel.

Socio-legal criteria are criteria concerning the favour of the local society, the favour of local authorities, the fulfilment of the goals of the local energy policy, and the need to obtain a positive environmental decision.

The previous chapter describes the potential of biogas and bioLNG production for municipalities belonging to the OMGGS. Although only the locations with the highest potential were selected for detailed analysis from among the locations described, it does not mean that the decision to build a biogas plant in other locations cannot be made. The decision to take action to build a biogas plant (with or without a bioLNG refuelling station) should lead to a Feasibility Study describing the exact location of the biogas plant and the specific directions for obtaining substrates.

The selection of the locations adopted for further analyzes was based on the criteria:

- increasing the energy security of OMGGS in gaseous fuel - access to the local gas pipeline,
- construction of a biogas plant in a sewage treatment plant,
- construction of the largest possible biogas plant above 500 kW,
- construction of biogas plants for the needs of energy communities
- construction of bioLNG fuel supply stations for local public transport and municipal services.

Table 54 shows the location identification of biogas plants and bioLNG stations.

Table 54. Identification of the location of biogas plants and bioLNG stations

Symbol	Localisation	Type	Installed power [kW]/ bioLNG production [t/d]
L1	Nowy Dwór Gdański	An agricultural biogas plant with an installed capacity of over 500 kW	824,95
L2	Kartuzy	An agricultural biogas plant with an installed capacity of over 500 kW	1 126,81
L3	Puck	An agricultural biogas plant with an installed capacity of over 500 kW	1 151,17
L4	Żukowo and its vicinity	An agricultural biogas plant with an installed capacity of over 500 kW	1 216,58
L5	Oczyszczalnia Ścieków Gdańsk Wschód (GIWK)	BioLNG refuelling station from biogas	7,4
L6	Zakład Utylizacyjny Sp. z o.o. w Gdańsku	BioLNG refuelling station from biogas	7,4

As is clear from the analyzes of the biogas production potential in the area of OMGGS, the municipalities of Nowy Dwór Gdański, Kartuzy and Puck have the greatest potential for the construction of an agricultural biogas plant. In the Żukowo commune, it has been estimated that there is a potential to build an agricultural biogas plant with a capacity above 1 MWe, which may be additionally increased thanks to the cooperation of neighbouring communes in the supply of substrates to biogas plants. Thanks to this, it is possible to build a biogas plant based on the energy community, which will improve the energy security of the region. BioLNG refuelling stations can be located in two places in Gdańsk, the Gdańsk East Sewage Treatment Plant and Zakład Utylizacyjny Sp. z o.o. in Gdansk. Both sites have a biogas production plant that could be supplemented with biogas liquefaction plants and a bioLNG refuelling station. In Gdańsk, bioLNG would also be picked up by municipal vehicles, public transport vehicles or by commercial customers.

Due to the dynamically changing geopolitical situation in the world, the assessment of individual locations in terms of economic profitability, determination of investment outlays, operating costs and planned financial flows should be carried out at the stage of the Feasibility Study.

In terms of socio-legal criteria, it should be noted that the favour of the local society is ensured only after conducting an information campaign on the biogas production technology used, and the advantages in the form of reduced odour nuisance in the surrounding areas (the smell of post-fermentation pulp is similar to the smell of moist soil), the possibility of participating in profits from the sale of energy (energy communities), positive environmental impact.

All locations, due to the selection criterion which was the greatest potential for biogas production, require the process of obtaining the Decision on environmental conditions for the consent to implement the project (abbreviated as "environmental decision").

The technology of biogas production and management of a biogas plant is a well-known topic in Poland, there are companies on the market that specialize in the construction of biogas plants from the investment planning stage to its construction, commissioning and management. These companies can be considered competitive in the market. The technology of producing bioLNG from biogas is relatively new and there are only a few companies on the Polish market that build installations for liquefying, storing or refuelling bioLNG. It is worth noting, however, that this technology is the same as for classic LNG, thanks to which it is possible to store and transport both fuels.

Table 55 presents the SWOT analysis for the construction of biogas plants and bioLNG refuelling stations.

Table 55. SWOT analysis for the construction of biogas plants and bioLNG refuelling stations

	Strengths	Weaknesses	Opportunities	Threats
An agricultural biogas plant with an installed capacity of over 500 kW	- reduction of odour nuisance in the surrounding areas - waste management - financial benefits from the sale of electricity and heat - development of the commune and activation of the area - new work places - reduction of CO_2 emissions	- the need to provide an appropriate substrate (availability, cost, transport) - the need for access to the heating network to sell heat - high investment expenditures - the uncertainty of the state's energy policy - low public support	- improving the energy security of the state - the possibility of obtaining funding	- little support in legislation and local authorities - problem with the connection to the power system - inconsistent, unstable and complicated law
BioLNG refuelling station from biogas	- availability of new technologies - a small area - local biogas production - the possibility of additional revenues from the sale of liquid CO_2	- currently a small number of recipients - high operating and fuel preparation costs - the need to train the staff	- a growing market of LNG recipients - rising prices of LNG fuels	- the uncertain situation related to the crisis and the possibility of reducing the sales market - in the event of an installation failure, the risk of biogas escaping into the atmosphere

		- requires a minimum amount of bioLNG refuelling - limited biogas yield		

Construction of biogas plants and bioLNG refuelling stations should begin with the potential analysis presented in this Strategy for individual municipalities belonging to OMGGS. The next step is to prepare a construction feasibility study, which should include a draft of the project for the construction of a biogas plant or bioLNG refuelling station, recommendations for the investor and an analysis of the financing options (subsidies), establishing first contacts with potential contractors. At this stage, it is important to assess the long-term supply of substrates and their treatment, the choice of the fermentation method, the possibility of selling electricity and managing waste heat and post-fermentation pulp. Site visits should also be made to examine the area for development, its distance from the supply of substrates, heat recipients and buildings. At this stage, the acceptance of the local population should also be ensured through promotional and information campaigns. Obtaining permits such as a building permit or environmental decision should be made in contact with the designer of the installation and the manufacturer.

The next stage is the contract for the installation or purchase. Contracts should be signed following generally applicable rules so that both the client and the contractor achieve benefits.

After completion of construction, the plant should be commissioned by the operator of the biogas plant. Currently, there are companies on the market that specialize in the management of biogas plants, which monitor their work remotely.

The steps to be taken to build a biogas plant or bioLNG station can serve as a model for analyzing other sites.

Summary

The strategy of using bioLNG in the area of OMGGS, taking into account the possibility of producing biogas and locating the biogas plant, has been divided into three parts. Part 1 contains general information related to the purpose of the development, a description of biogas and bioLNG production technologies and their possible uses. This part is supplemented by Annex 1 at the end of the study. Part 2 describes the characteristics of OMGGS and estimates the production potential of biogas and bioLNG for the municipalities belonging to the Association. Part 3 presents an analysis of the location of biogas plants and bioLNG refuelling stations with a construction scenario and a SWOT analysis.

After analyzing the potential of building biogas plants in the areas of individual municipalities belonging to OMGGS, locations for the construction of biogas plants and bioLNG refuelling stations were selected, which were then divided depending on the planned installed

capacity and the substrate used for the production of biogas or bioLNG. The study also takes into account the possibility of waste heat management, which depends on the presence of a heating network, and the population density in individual municipalities to estimate the possibility of receiving heat in the future. The communes of Puck, Kartuzy and Nowy Dwór Gdański are characterized by access to a heating network and a relatively high population density indicator, therefore the locations of biogas plants in these communes have been indicated.

The production of bioLNG from already recovered biogas is possible both at Zakład Utylizacyjny Sp. z o.o. in Gdańsk (ZU) and the Gdańsk Wschód Sewage Treatment Plant (GIWK), in which there are installations for recovery or production of biogas. Biogas is used to produce electricity and heat for local needs. Due to the current expansion of the ZU area and the construction of a waste incineration plant, the Port of Clean Energy, the biogas recovery and purification plant can be expanded with a biogas condensation station, for example using the Cryo Pur solution, and the liquefied fuel in the form of bioLNG can power public transport vehicles or vehicles municipal. A similar situation occurs at GIWK, where there is a biogas plant. The conversion of biogas into bioLNG fuel would increase the company's profits and make its operation independent of heat recipients.

This document was carried out at the turn of 2021 and 2022 when the economy in Poland had to face the energy crisis caused by the SARS-CoV-2 virus epidemic and Russia's invasion of Ukraine. The prices of energy fuels such as coal, wood and gas currently reach record levels compared to 2020, posing a threat to the country's energy security. Membership in the European Union obliges Poland to significantly reduce the share of coal in the energy mix of fuels in the electricity sector and the municipal economy. One of the key actions that should be taken to reduce the share of coal in the power industry is to define a strategy for its alternative - gas. In the future, the industrial, electricity, heating and transport sectors will compete for both natural mine gas and the so-called green gas - hydrogen and biomethane. Therefore, it is necessary to adapt the generation and transmission infrastructure to the transmission of biomethane and to fix the guidelines in the legislation. Therefore, the priority should be the construction of renewable energy sources, such as biogas plants and bioLNG refuelling stations, which can significantly improve the energy security of a given region.

Main conclusions from the study

1. The biogas plant reduces odour nuisance related to the production of manure and slurry.

2. Agricultural biogas plants allow for the management of waste from agricultural and animal production.

3. The source of cheap substrates for a biogas plant is crucial for its profitability.

4. Education of the local community increases the chances of its support for investment.

5. The income from the sale of electricity should not be the most important reason for building a biogas plant, it is more important to avoid the costs of waste disposal, the environmental aspect or supplying heat to the local community.

6. The construction of a large biogas plant with an installed electrical capacity of over 500kW requires specific and complicated administrative procedures and the need to obtain the necessary permits, conditions and arrangements with various state administration organizations.

7. The profitability of micro-biogas plants is low, which, with the simultaneous lack of a greater number of reference plants, practical experience and financial data, prevents a reliable assessment of this type of installation.

8. The study sets the maximum production of biogas and bioLNG for individual municipalities with OMGGS, which may serve as the beginning of research on the location of biogas plants within individual municipalities or to analyze the possibility of creating energy communities or energy clusters within several municipalities.

9. The construction of a biogas plant in the area of OMGGS will increase the energy security of the region

10. The construction of a biogas plant with a bioLNG refuelling station will supply vehicles with ecological fuel, reducing the emission of pollutants into the atmosphere.

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Annexe 1

A detailed description of the biogas and bioLNG production technology

Biogas is a mixture of methane, carbon monoxide, hydrogen sulfide and water vapour. Depending on the type of substrates, the concentrations of these gases differ [17]. It is possible to obtain the substrates from the sources shown in Figure 6:

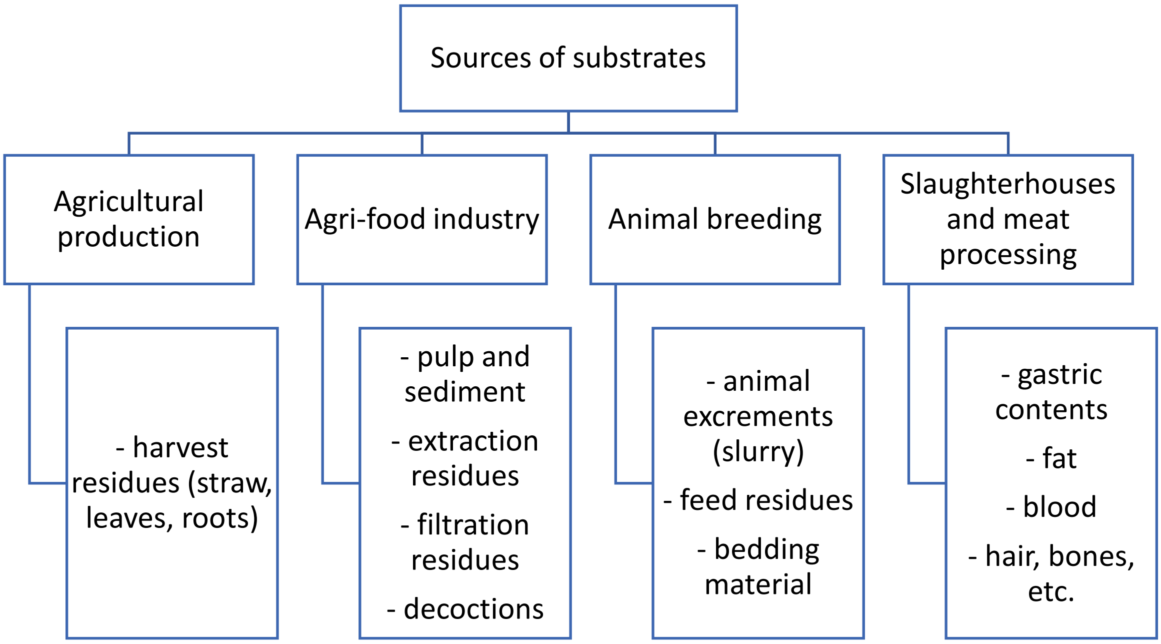


Figure 6. Sources of substrates for biogas production

The productivity of methane depends on the parameters and quality of the substrates. The greatest amount of methane from a dry matter of waste can be obtained by using slaughterhouse waste and potato leaves, fodder beet, cheese and oil waste as input. Biogas is obtained in a biogas plant in the process of anaerobic digestion, in which organic biomass is decomposed by bacteria under conditions without oxygen access and in the presence of water. The biogas obtained in this way can contain up to 85% methane.

Biogas produced in a biogas plant is a mixture of gases with the approximate composition:

- methane (CH_4) 55-70%,

- carbon dioxide (CO_2) up to 40%,

- oxygen (O_2) up to 5%,

- hydrogen sulfide (H_2S) 1-3%.

The cycle of anaerobic biochemical reactions that produces biogas from organic matter consists of steps:

- Hydrolysis, where polymers (hydrocarbons, fats and proteins) are broken down into monomers (amino acids, fatty acids, simple sugars and glycerin).
- Acidogenesis (acid fermentation), in which short-chain fatty acids, alcohols as well as H_2, CO_2 and CH_4 are formed from monomers as a result of the activity of acid-forming bacteria.
- Acetogenesis (the formation of acetates), in which acetic acid, as well as H_2 and CO_2, are formed from fatty acids.
- Methanogenesis produces the final product from acetic acid and H_2 a mixture of CH_4 and CO_2.

Both hydrogen and oxygen can be burned or oxidized, which gives off energy and does not interfere with the use of biogas as fuel. Hydrogen sulfide and water vapour will corrode the system and must be removed. The dried and hydrogen sulphide-free (purified) biogas can be used in cogeneration units to produce electricity and heat. The combustion engines of this type of aggregates are adapted to the combustion of fuels with a low methane content [1].

The dried and purified biogas after the enrichment process can be used to drive traction motors in heavy commercial vehicles (for example in garbage trucks). In this case, the biogas is treated so that the methane content is not less than 96%, such gas is called biomethane. To reduce the volume of fuel, which is crucial in the context of the construction of tanks in vehicles and the reduction of the occupied space of storage tanks, after drying, cleaning and enrichment, biomethane changes the state of matter from gaseous to liquid - bioLNG under the influence of pressure and low temperature (-162^{o}C) [15].

Biogas can arise naturally as a decomposition product of organic substances, or it can be produced on purpose. It is naturally recovered in landfills and is intentionally produced in agricultural or utilization biogas plants.

The biogas production technology is based on the anaerobic fermentation of the supplied substrates. A simplified structure of a classic biogas plant is shown in Figure 7.

Depending on the composition of the input material, the biogas production plant has an individual structure. The choice of equipment depends on the availability of substrates, which determines the size of aggregates, tanks and digestion chamber. The qualitative parameters of the substrates, such as dry matter content, structure or origin, determine the design of the processing technique [18]. A schematic diagram of a biogas plant, taking into account the type of substrates, is shown in Figure 7.

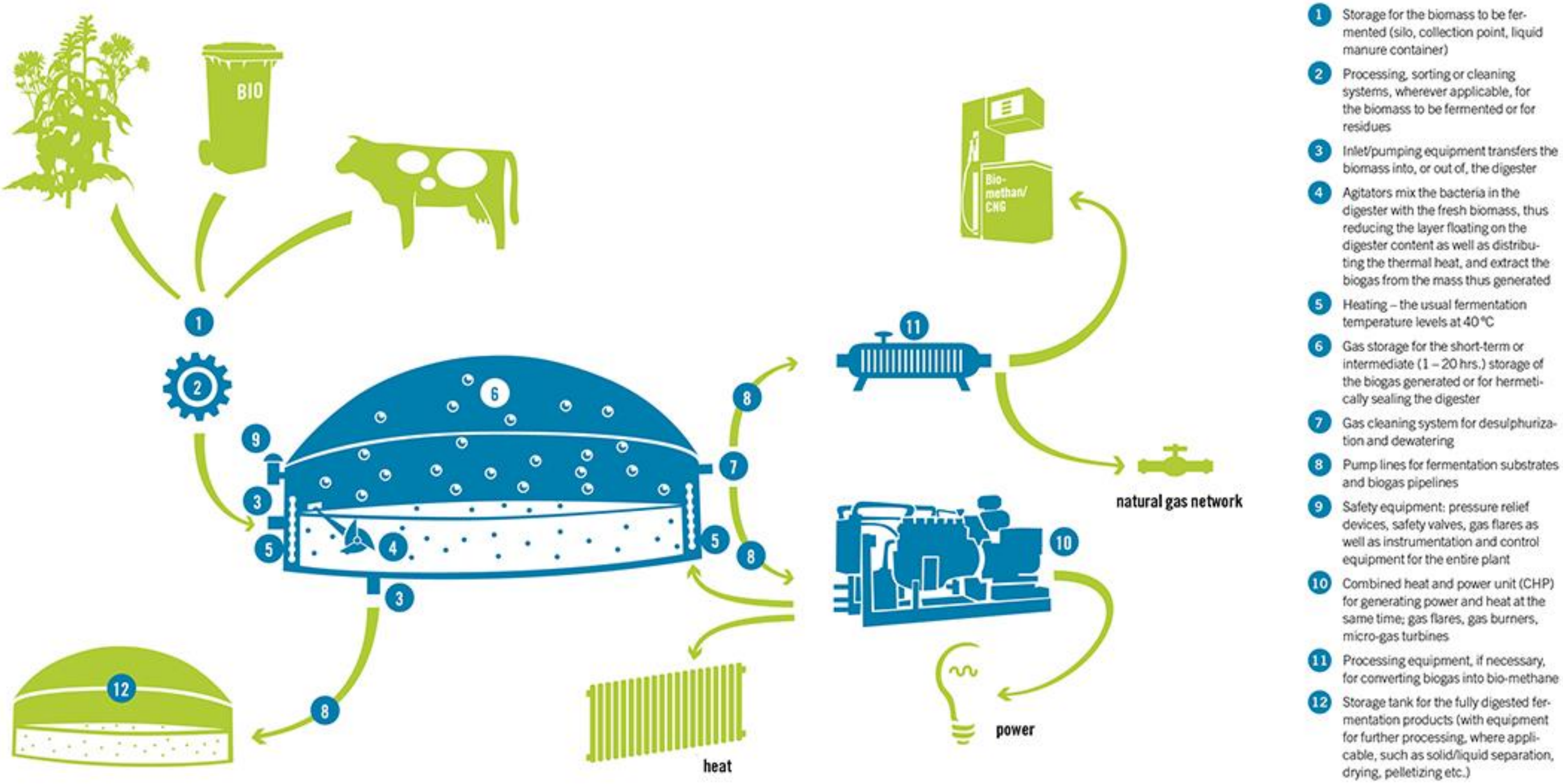


Figure 7. Schematic diagram of a biogas plant taking into account the type of substrates [18]

Factors influencing the quality of fermentation

Bacteria are characterized by a long reproduction time and high sensitivity to environmental conditions. Slowing down or inhibition of bacterial activity occurs as a result of temperature changes or wrong choice of temperature, access to oxygen or light, inadequate acidity or inappropriate humidity. To support the appropriate quality of fermentation, it is, therefore, necessary to block the access of oxygen and light using structural solutions, regulate the fermentation temperature using a heating system (the highest yield of biogas occurs in the temperature range of 35-55^{o}C), maintain an appropriate pH in the range of 4.5-6.3 - regulated by the amount of the introduced substrate and by letting in CO_2. The time of decomposition of the fermentation mass depends on the type of organic mass and ranges from 15 to 110 days. The gas yield depends on

• process temperature,

• decomposition time,

• dry matter content in substrates.

Fermentation bacteria are sensitive to temperature levels, however, they vary depending on the type of bacteria (10-25°C - psychrophilic, 32-42°C - mesophilic, 50-57°C - thermophilic).

The so-called inhibitors of the fermentation process and (optionally) addition of auxiliary substances, i.e. enzymes.

Inhibitors of the fermentation process are substances that, even in small amounts, are toxic to fermentation bacteria, which slows down the decomposition process and may also lead to poisoning the fermentation chamber. An example of such a substance is, for example, ammonia, which is formed in the event of an excess of nitrogen. Ammonia concentration exceeding 3000 g/m^3 has a toxic effect on methane bacteria, while from 1500 g/m^3 it is an inhibitor of the fermentation process. Other inhibitors are copper, chromium, and nickel (if the content exceeds 100 g/m^3). The reason for the disappearance of fermentation may also be the increased content of antibiotics in animal faeces. It is also important, especially for the population of bacteria responsible for fermentation, for the ratio of carbon to nitrogen (C:N), which in the material subjected to fermentation should not exceed 100: 3.

Storage and transport of the substrate

To maintain the continuity of biogas production, the substrate must be stored. This is especially important when the raw material is obtained from remote locations and allows the production to be made independent of the frequency of deliveries. The warehouse capacity is selected based on the size of one-off deliveries and the length of the longest probable break between deliveries. The design of the tank depends on the consistency of the substrate material. Sealed tanks are required for liquid or hygienically questionable substrates (Figure 8).

Figure 8. Substrate storage in a biogas plant
Photo: C. Eckhardt, Wikimedia cc0 1.0

The transport of the substrates inside the biogas plant depends on the consistency of the substrate material. Front loaders, augers or moving floor conveyors are used for loose materials. Liquid substrates are transported through pipelines with the use of rotor pumps (liquid substances) or displacement pumps (thick substances). Bellows pumps are used in the presence of high foreign matter content.

Preparation and management of the substrate

Grinding allows increasing the surface of bacteria access to the substrate. The grinding system can be realized with the help of a free-standing mill. Substrates posing an epidemiological threat, mainly slaughterhouse waste, are subject to hyalinization. Hygienization consists in bringing the substrate to a temperature of 70°C and maintaining it for an hour, it takes place in stainless steel tanks.

Homogenization consists of making the mash a homogeneous pumped mass before the substrate enters the fermentation chamber. Homogenization is performed by mixing loose and liquid substrates (slurry). The main task of homogenization is to minimize the impact of changes in the composition of the substrate on the fermentation process. As a liquid substrate, in the case of a slurry shoulder, it can be liquid from the drained digestate, less often fresh water.

In a biogas plant, the fresh substrate must be fed in appropriate doses and intervals (Figure 9). At the commissioning stage of the facility, they are defined and appropriate settings of the automation controlling the process are made. The automation systems responsible for the dosing process include timers and, in more complex systems, devices for measuring fermentation conditions. The substrate is measured by measuring the mass flow. Measurement of the loss of mass regulates the dosing of loose substrates.

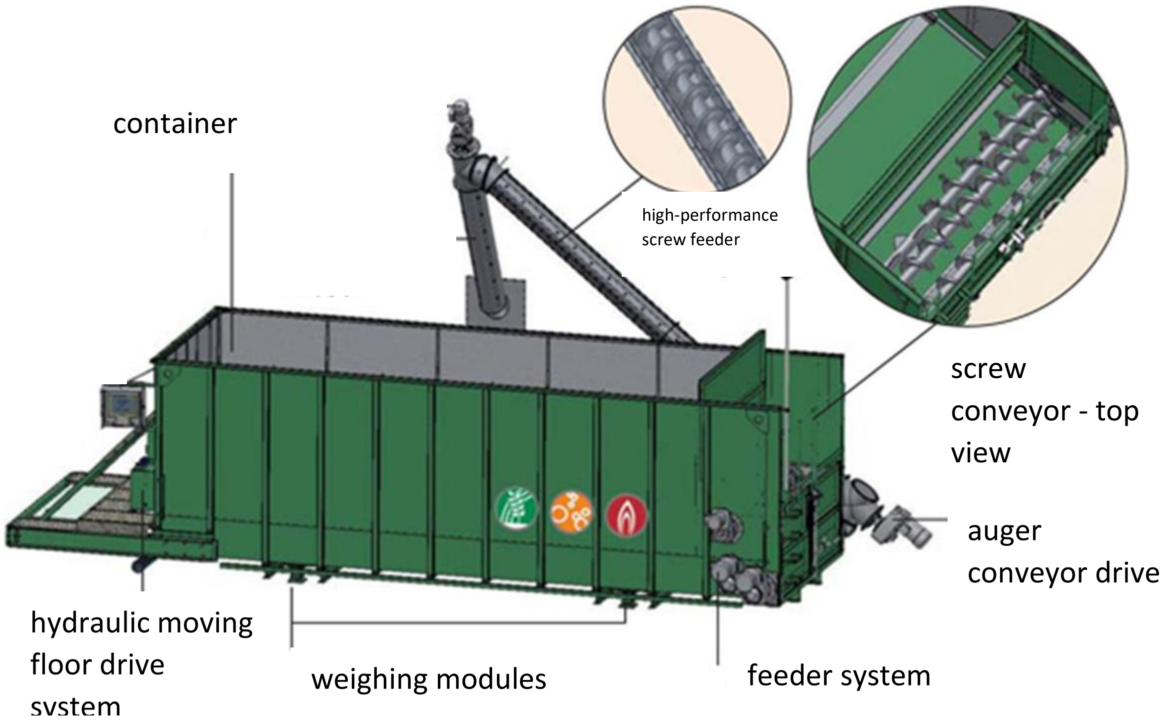


Figure 9. Solid substrate dosing system in a biogas plant

The dry matter content of the substrates is the basic criterion for selecting the filling mode of the fermentation tanks. It affects:

- stability of biogas production,
- the amount of input used,
- size of storage tanks,
- size of post-fermentation tanks.

There are two filling modes - discontinuous and continuous. In the discontinuous filling mode, the tank is filled once, before being filled, the fermented biomass (except for a portion of the biomass left to inoculate the next process) is transferred to the digestate tank. The method is used for dry fermentation. In continuous operation, the fermentation tank is filled regularly and kept full, and the entire process is automated. Table 56 shows a comparison of the two filling modes.

Table 56. Comparison of both modes of filling the fermentation chamber

Description	Discontinuous filling	Continuous filling
Production of biogas	uneven	constant
Involvement of operators during operation	small	big
The retention time of biomass	long	short

Installation performance	low	high
Control of biomass fermentation	easy	possible
Risk of discharge of unfermented biomass from the fermentation chamber	low	high

There are two types of fermentation - dry and wet. In dry fermentation processes, the basis of the feedstock is substrates with a high dry matter content and is stored in bulk. They are used by farms that do not have a sufficient amount of slurry used as the basic substrate. In such a situation, obtaining gas in wet fermentation would mean the need to liquefy the batch or prepare a mash, which means additional expenditure. In practice, there are already installations operating with the method of dry fermentation, but in the case of agricultural biogas plants it is more appropriate to use a wet process, therefore in agricultural practice, the vast majority of biogas installations operate in the wet fermentation system. Here, biogas plants with plug flow and full flow are used. The simplest to build are biogas plants using the full flow method. The reactors are built in the form of a vertical cylinder. In principle, the fermentor can be a conventional slurry tank with a concrete bottom and steel or concrete walls. Such a tank should be covered with a gas-tight roof and equipped with fittings for supplying substrate and draining sludge. Proper flow is ensured by a vertical agitator mounted inside. Table 57 presents the advantages and disadvantages of both types of fermentation.

Table 57. Comparison of advantages and disadvantages of dry and wet fermentation

	Dry fermentation	Wet fermentation
Advantages	Low substrate transport costs	Easy transfer of batch and digestate by pumping
	Possible use of smaller fermentation and post-fermentation chambers	Free choice of filling method
		Uniform bacterial growth and constant temperature throughout the volume of the fermentation tank
	Preheating the substrate in the oxidation process	Easy access to technological system devices
		Possibility to inoculate the process by adding slurry
Disadvantages	High costs for drying the substrates	High substrate transport costs
	Restriction of the filling method to the discontinuous mode	The need to use large fermentation and post-fermentation chambers

	The uneven development of bacteria in the fermentation process	
	The necessity to add fermentation process inoculants	Operational problems related to the renovation and servicing of devices inside the fermentation chamber
	Difficulty in acquiring technological system devices	

The prepared substrate is fed to the fermentation tank, where biogas is produced. The required temperature for a given type of bacteria should be maintained inside the tank. In turn, the nutrients must be evenly discharged, which is why systems are required that support the fermentation process inside the tank. Significant from the point of view of the profitability of the project is the high reliability of this element of the technological process. The construction form and the material from which the tank is made are also very important.

Types of fermentors, methods of maintaining the temperature and mixing the batch

Fermenters can be made lying or standing. Lying fermenters are in the form of cylindrical tanks with a horizontal arrangement. They are used in the wet fermentation of all types of substrates. Usually, they are made of material from which stainless steel or reinforced concrete. It is not possible to make the tank on site, hence the need to transport it, which limits its capacity to 800 m^3 and therefore can be used only in small biogas plants.

The upright fermenters, mostly cylindrical, are set in a vertical position. They are used in the wet fermentation of all types of substrates. They are made of galvanized, enamelled stainless steel, or reinforced concrete (Figure 10).

Figure 10. Fermenter (www.f-e.de)

Due to the similarity of the places of their construction and further operation, there are no restrictions as to their volume, but usually, it does not exceed 6,000 m^3. Table 58 compares the advantages and disadvantages of horizontal and vertical fermenters.

Table 58. Compare the advantages and disadvantages of horizontal and vertical fermenters

<table>
<tr><th></th><th>Horizontal fermenters</th><th>Vertical fermenters</th></tr>
<tr><td rowspan="3">Advantages</td><td>Easily mixed</td><td>The possibility of obtaining a large capacity of the tank</td></tr>
<tr><td rowspan="2">Short installation time of the tank</td><td>Low heat loss</td></tr>
<tr><td>It is possible to equip the tank with a gas storage</td></tr>
<tr><td rowspan="4">Disadvantages</td><td>Limited volume</td><td rowspan="2">The required high load capacity of the substrate</td></tr>
<tr><td>The need for frequent inoculation of the fermentation process</td></tr>
<tr><td>The necessity to use external biogas tanks.</td><td rowspan="2">A long time of tank construction</td></tr>
<tr><td>High heat loss</td></tr>
</table>

The fermentation tank is heated to maintain an even distribution and a constant temperature inside. In the event of disturbances in the distribution and temperature values, uneven production may occur, a decrease in the biogas yield, and extreme cases the process may stop completely. The most common are built-in heating installations inside the chamber, made in the form of stainless steel or plastic heating pipes (Figure 11). These pipes are located away from the tank walls due to the minimization of thermal stresses, additionally, it allows to limit the formation of deposits and guarantees the most effective heat conduction. Maintaining uniform heating of the chamber is possible with the use of mixing devices. The pipes can also be arranged on the outer wall of the chamber, which, despite the large heat losses, brings many advantages in terms of uniform heating. This solution is used in reinforced concrete tanks because it ensures the lowest thermal stresses. Heating pipes can also be arranged at the bottom of the tank, which has the advantage of reducing stress, but can make heat transfer difficult when the bottom is covered with deposits and sediment.

Figure 11. Heating pipes inside the fermentation chamber (globenergia.pl)

As mentioned, mixing is a process that helps to maximize the yield and ensure the consistency of biogas production. Its basic function is to ensure a constant distribution of nutrients in the fermentation tank.

Mixing is carried out mechanically, pneumatically and hydraulically. Mechanical mixing, the most common, is carried out using electrically powered mixers (Figure 12). In lying tanks, there are paddle mixers that require stopping the fermentation process to service them, which is a serious disadvantage. Pneumatic mixing, which is rare, consists in blowing the biogas in the lower part of the tank and can be a system supporting mechanical mixing. Similarly, hydraulic mixing, supporting mechanical agitators, is carried out by pumps forcing the substrate and is limited to easily pumpable substances.

Figure 12. Mechanical agitator inside the fermentation chamber (www.stallkamp.pl)

Post-fermentation waste management

The fermented biomass can be transported to the digestate tank or placed in lagoons. The primary role of a digestate is to store biomass between fertilization periods, which means that it should provide storage capacity for 4 months. The structure of the fermented biomass tank is similar to the fermentation tank, except that it has neither heating nor insulation. However, it requires the installation of a mixer due to the risk of delamination of the mass stored in it. Lagoons are characterized by lower investment outlays, but due to the high probability of the bottom of the lagoon becoming unsealed or the lack of cover causing an unpleasant odour, it may face considerable resistance from the sanitary inspectorate at the stage of agreeing on the conditions of the investment's impact on the environment (Figure 13).

Some difficulties for farmers who take up the fertilizer in the form of digestate in a biogas plant is the need to conduct a soil survey to determine the amount of digestate that is acceptable.

Figure 13. A lagoon in the area of an agricultural biogas plant (ph. Z. Ginalski)

Biogas management

The produced biogas should be adapted to the technology in which it will be used. When used to generate electricity and/or heat, it is required to be delivered uniformly to the engine, turbine, microturbine or fuel cell. Fluctuations in biogas production can be compensated for by using a biogas buffer. Additional biogas tanks are installed to increase the buffer reserve.

In the case of a standing fermentation tank, its construction makes it possible to store biogas in the roof structure (Figure 14). The warehouse is made of PVC film in the form of a dome that expands as the tank is filled with biogas. Double-membrane tanks are also used to eliminate the influence of a gust of wind.

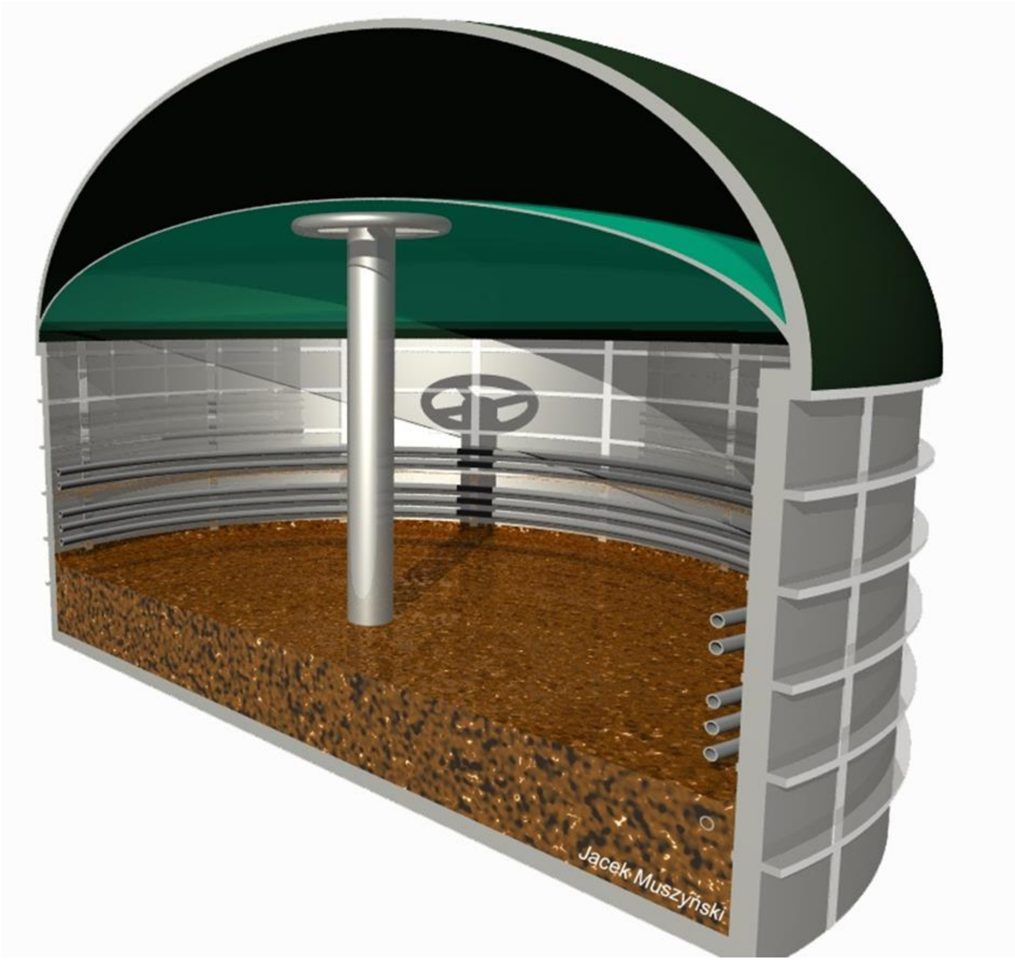


Figure 14. Biogas storage on the roof of the fermentation tank (http://biogazplant.pl/)

If the biogas stores are overfilled and at the same time it is not possible to use this fuel in a cogeneration system or a power generator, there is a need to burn the biogas in a flare (Figure 15), which is made of stainless steel. The safe operation of the torch requires its full automation.

Figure 15. Torches for burning biogas in the biogas plant (www.aat-biogas.at)

Biogas treatment

Biogas treatment includes at least desulphurization and drying. Desulphurization is required due to the presence of hydrogen sulphide in biogas and its disadvantageous effect, especially when combined with steam. The methods of biogas desulphurization include biological methods and chemical methods. Biogas drying is required because the water contained in it increases its volume, reduces the calorific value, and is the cause of increased corrosive action of hydrogen sulphide and carbon dioxide, as well as the formation of hydrate blockages.

Injection of biogas into the gas network

Based on the data in Table 59, it can be concluded that to inject biogas into the gas network, it must be purified and upgraded. Due to the unfavourable effects of hydrogen sulphide and water vapour on the natural gas distribution network, they must be removed, and the quality parameters of biomethane injected into the gas network must not differ from other types of fuels that are transmitted through this network. The unfavourable phenomena include erosion, abrasion and corrosion of the material from which the gas pipes are made and reduction of the patency of the gas system components.

Table 59. Comparison of properties of biogas with biomethane, natural gas

1	2	3	4	5
L.p.	Parameter	Biogas	Biomethane	Natural gas
1	Methane	45-75%	94-99%	93-98%
2	Carbon dioxide	28-45%	0,1-4%	1%
3	Nitrogen	<3%	<3%	1%
4	Oxygen	<2%	<1%	-
5	Hydrogen	trace amounts	trace amounts	-
6	Hydrogen sulfide	<10 ppm	<10 ppm	-
7	Ammonia	trace amounts	trace amounts	-
8	Ethane	-	-	<3%
9	Propane	-	-	<2%
10	Calorific value	5,5-7,7 kWh/m^3	10,2-10,9 kWh/m^3	9,0-11,0 kWh/m^3

Technologies of biogas refining

Among the technologies of biogas refining, the following can be distinguished:
• Pressure swing adsorption (PSA) - adsorption of carbon dioxide under pressure with the use of active carbon,
• Water scrubber - dissolving in water under high pressure,
• Chemical absorption - chemical reaction of carbon dioxide with monoethanolamine (MEA)
• Physical absorption - dissolving carbon dioxide in a solvent (Selexol, Rectisol, Purisol) under high pressure,
• Membrane separation - the use of different permeation rates of gas molecules,
• Cryogenic separation - temperature-dependent aggregation conditions.

Table 60. Comparison of biogas refining methods

Method	Readability CH_4	The energy demand of the process [kWh/Stm^3 biogazu]	Water demand	Heat demand
Water scrubber	97	0,3	Requires	Not required
Physical absorption	97	0,25	Requires	Requires
Chemical absorption	98	0,4	Not required	Requires

Pressure swing adsorption	97	0,25	Requires	Not required
Membrane separation	95	0,3	Not required	Not required

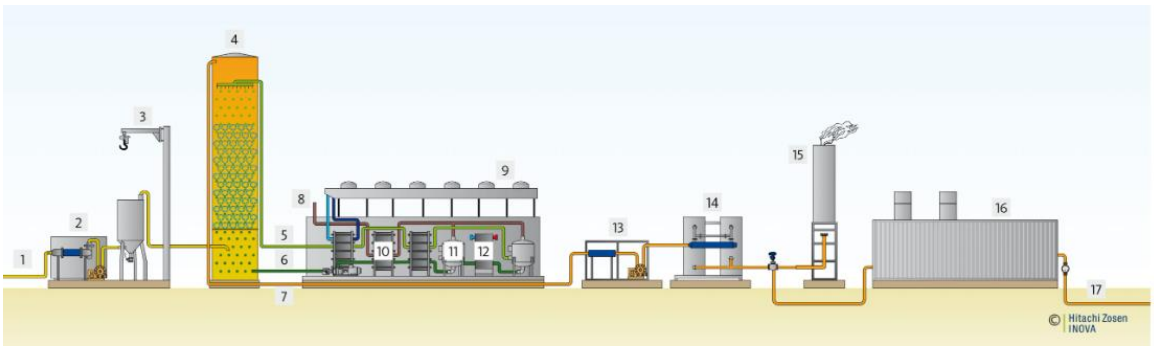
Own study based on [40]

These methods ensure the concentration of methane at the output of the process in the range of 95-99%. Methane losses do not exceed 4%. The pressure swing adsorption and water scrubber methods are the most widely used in Europe. The barrier to the use of the systems is high investment expenditure on biogas treatment installations, which for installations with a capacity of 500-1200 Nm^3/h are:

- from PLN 5 to 10 million in the case of a water scrubber,
- PLN 7-11 million for chemical adsorption,
- PLN 7-8 million for cryogenic separation.

An alternative to electricity-driven processes is a heat-driven amine scrubber separation process such as the HZI BioMethan® biogas purification technology. In this process, gas flows through a packed column in which the amine solution absorbs carbon dioxide and produces 99.9% pure biomethane. The amine solution is regenerated for reuse in the process. The process is very effective in removing contaminants in the biogas stream and, like the membrane technology, is distinguished by the high availability of the installation.

Figure 16 shows a diagram of the HZI BioMethan® biogas purification technology. Symbols used in the diagram:



1. Gas supply
2. Gas drying
3. Desulphurization installation
4. Amine scrubber column
5. Supply of the regenerated amine scrubber
6. Supply of an amine scrubber
7. Discharge of biomethane
8. Removal of CO_2
9. Cooler
10. Heat exchanger
11. CO2 separator
12. Heat input
13. Drying and compressing biomethane
14. Drying of biomethane
15. Torch
16. Injection unit
17. Gas pipeline

Figure 16. Diagram of HZI BioMethan® biogas purification technology

Problems of cooperation with the gas network

The process, in addition to recording and checking the calorific value of gas, requires periodic checking of the content of harmful substances. The amount of biomethane that is fed into the grid is limited by the balance of biogas introduced at the supply points and consumed at the receiving points of the distribution network. The problem that arises when introducing biogas to the gas distribution network is the high expenditure on the construction of an expedition gas pipeline. The unevenness of production and fluctuations in gas demand in the distribution network may additionally contribute to the need to build a gas storage facility.

Technologies of biogas liquefaction

After purification, the biogas can be liquefied to obtain its bioLNG liquefied form. BioLNG is a liquid renewable fuel, the volume of which is less than that of gaseous biomethane more than 600 times. This makes it easier to transport it, even if it is to be used in gaseous form.

BioLNG is a good solution for transport due to the ratio of the small volume of fuel to its high density of stored energy. It is characterized by a high refuelling speed, comparable to diesel oil, and the possibility of obtaining large ranges by vehicles - up to 1,500-1,600 km on one refuelling. As a result, the transport of bioLNG is cheaper than its gas counterpart and does not require access to the gas pipeline. This allows for the location of the biogas plant without taking into account the access to the gas pipeline.

BioLNG compared to diesel drive reduces greenhouse gas emissions by 90% (by 70% nitrogen oxides) with the complete elimination of solid particles in the exhaust gas, which makes it an excellent proposition in the ecological context.

The bioLNG production technology is relatively young. Until 2014, liquid biomethane was produced only at 4 sites in Europe. They used installations aimed at demonstrating their capabilities and testing the applied solutions before their commercialization. However, these were solutions based on many different technologies, which generated high costs and did not allow their use in small-scale biogas production [41].

One of the partners in the Liquid Energy project, Cryo Pur has developed a new integrated technology that combines biogas treatment with liquefaction. Both processes use cryogenic technologies. Figure 17 shows the liquefaction of biomethane into bioLNG. It should be noted that the same installation can be used to liquefy natural gas, e.g. for transport over longer distances.

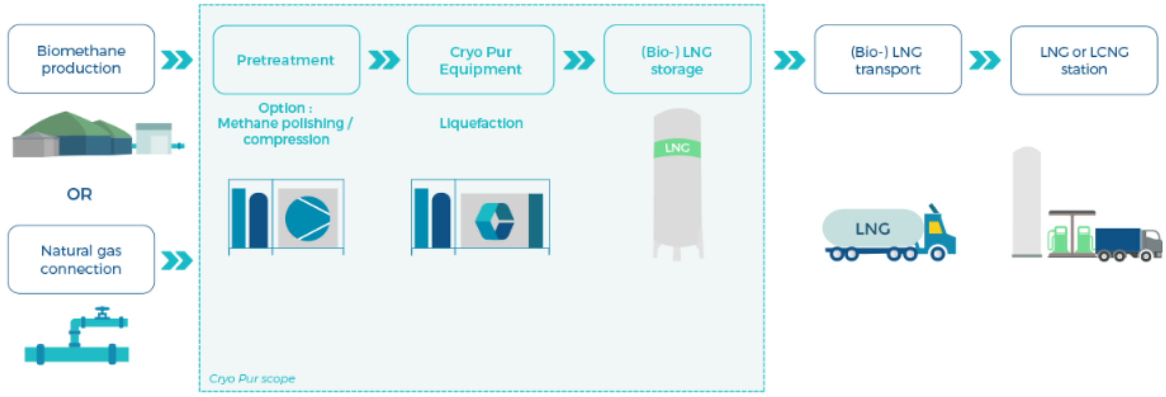


Figure 17. The process of liquefying biomethane or natural gas in the Cryo Pur installation

The process begins with cryogenic treatment, which includes the separation of carbon dioxide (CO_2) from biogas. This process takes place when the biogas passes through a heat exchanger at temperatures ranging from -90°C to -120°C. In this way, biomethane of appropriate purity is obtained, which can be subjected to the condensation process. Condensation takes place at -125°C under 15 bar pressure. Pre-generated cold is used to reduce energy consumption. The gas is then dried, removing water, VOCs and siloxanes from the gas.

A by-product of the process is the production of liquid carbon dioxide (bioCO_2), which can have many uses (e.g. in refrigeration or horticulture) and can be sold, which will increase the economic viability of the installation. The Cryo Pur technology can also be successfully used to treat biogas containing large amounts of nitrogen and oxygen, which is the case with landfill gas. The distillation column integrated into the treatment system allows for the effective removal of these gases.

Cryo Pur's technology was tested by the ADEME (French Agency for Environment and Energy Management) BioGNVAL project at the Valenton wastewater treatment plant, which is the second largest wastewater neutralization facility in Paris. Suez, a waste management company, also participated in the project. The plant operated with a biogas flow of 120 m^3/h and produced 1 t of bioLNG and 1.6 t of bioCO_2 per day. It confirmed the expected efficiency of the process and the assumed energy consumption. The operation of this trial installation allowed for the development of a fully automatic system for its control and security so that the entire system could work autonomously while maintaining an appropriate level of security, which was required by the commercialization of the project. The biogas from the methane reactors at the Valenton plant is typically about 60% methane and about 40% carbon dioxide, 2% nitrogen, 0.5% oxygen and 30 ppm hydrogen sulphide, 4.8 mg/m^3 volatile organic compounds and 7 mg/m^3 siloxanes [41].

The production of bioLNG in the Cryo Pur plant is divided into 5 main steps, including the treatment of raw biogas, liquefaction to bioLNG and the production of bioCO_2:

• Stage 1: Raw biogas from the reactors is passed through activated carbon filters that remove hydrogen sulphide (H_2S).

• Stage 2: the biogas is cooled down to -40°C. The process is repeated several times, which causes drying, and removal of volatile organic compounds and siloxanes.

• Stage 3: the biogas is cooled to -75°C and the remaining water vapour is removed.

• Stage 4: the biogas is cooled down to -120°C, which removes the carbon dioxide CO_2.

• Stage 5: the biomethane is compressed to 14 bar and liquefied at a temperature of -120°C. The liquid biomethane is then decompressed to a pressure of 2 bar and stored in a cryogenic vessel at -160°C.