Feasibility study of bioLNG (liquefied biogas) installations for Zakład Utylizacyjny Sp. z o.o. in Gdańsk in order to use bioLNG as a source of electrical energy

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Content

Introduction

The development of civilization is inevitably associated with the production of large amounts of organic and inorganic waste and with an increased demand for energy. The waste is stored in areas known as landfills. Thanks to the selective collection of waste, it is possible to select and partially recover secondary raw materials. The process of building a landfill is difficult due to many requirements that must be met to ensure tightness, minimal impact on the environment, long-term operation and a large area. The three types of landfills there are hazardous, inert, and non-hazardous and inert landfills, which include municipal waste [1].

Waste that is not hazardous and not suitable for further processing is stored in the so-called heaps of waste. They are mixed waste containing organic and inorganic matter of different humidity. As a result of rotting dead organic matter, aerobic degradation occurs under the influence of microorganisms. The end product of the decomposition is a gas mixture consisting mainly of methane and carbon dioxide.

Leaking gas from a waste heap is a threat to plants, people and the atmosphere, and can also lead to a fire. To prevent uncontrolled gas release into the atmosphere, the operation of the waste heap includes, among others, active degassing systems.

Recovered landfill gas can be regarded as highly polluted biogas. Due to the economic and energy potential of biogas, it is profitable to dry, clean and uses it. Biogas is produced in the process of methane fermentation of biomass and is a mixture of methane, carbon monoxide, hydrogen sulphide and water vapour. Depending on the type of substrate, the concentrations of these gases vary [2]. The energy-efficient use of biogas occurs in the case of direct combustion, the use of biogas as a fuel for internal combustion engines, turbine engines or by supplying biogas to a local gas pipeline.

The technology of using biogas in direct combustion is applied in Zakład Utylizacji Sp. z o.o. in Gdańsk (ZU). After drying and cleaning, the gas is directed to the cogenerator where electricity and heat are produced and used for the company's needs.

Currently, the construction of the Port Czystej Energii waste incineration plant is underway on the premises of the ZU and the construction of a biogas utilization plant is planned. Therefore, it can be assumed that the own needs of the ZU can be covered with new energy sources, and the recovered biogas can be used in other ways, for example by transforming it into bioLNG fuel.

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 reaching ranges by vehicles - up to 1,500-1,600 km on one refuelling. Thanks to this, 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 the diesel drive, reduces greenhouse gas emissions by 90% (by 70% nitrogen oxides) with the total elimination of solid particles in the exhaust gas, which makes it an excellent proposition in the ecological context.

BioLNG production technology is relatively new. Until 2014, liquid biomethane was produced only at 4 sites in Europe. Installations were used in them to demonstrate their capabilities and test 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 [3].

One of the partners in the Liquid Energy project, Cryo Pur has developed a new, integrated technology that combines biogas treatment with liquefaction [4]. Both processes use cryogenic technologies. Figure 1 shows the process of liquefying biomethane into bioLNG. It should be noted that the same installation can be used to liquefy natural gas, e.g. for transport over long distances.

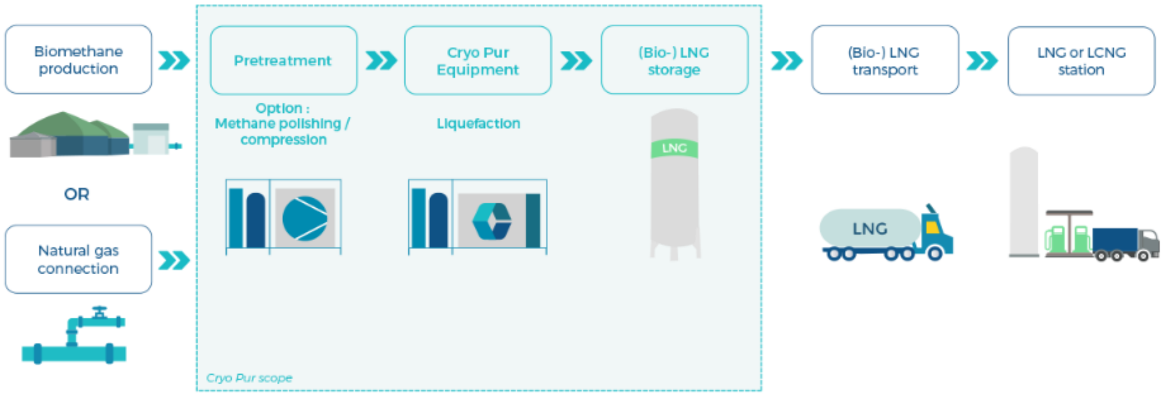

Figure 1. The process of liquefying biomethane or natural gas in the Cryo Pur installation [4]

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 with 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 m³/h and produced 1 t of bioLNG and 1.6 t of bioCO_2 per day. This 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/m³ volatile organic compounds and 7 mg/m³ siloxanes [3].

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 [5], biogas is listed as essential fuel for reducing methane emissions from the agricultural and rendering sectors. These emissions, both anthropogenic and biogenic, come from raw materials that are not currently used for the production of renewable energy.

The benefits of using methane as a bioLNG fuel are, for example, the avoidance of methane emissions into the atmosphere and the use of methane as a replacement fuel for fossil fuels, while allowing CO_2 to be emitted into the atmosphere. Another big positive effect that the biogas sector provides is the necessary 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) [6], 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 quality and, in addition, reduce nitrogen emissions. In this way, sustainable biomethane is produced, which is embedded in agroecology.

This study contains a feasibility study of bioLNG installation for use as an electricity source, developed for Zakład Utylizacji Sp. z o.o. in Gdańsk (ZU) company. As mentioned above, the company is currently supplied with electricity and heat from the combustion of recovered landfill biogas, and it is planned to supply the company with other sources of electricity and heat. Taking the above into account, as part of the study, an analysis of the technical and economic profitability of building a bioLNG refuelling station on the premises of the ZU was carried out.

The study presents the purpose of the study, the legal basis and characterizes the ZU company in terms of biogas production and energy demand. The conditions and potential for the use of biogas, including bioLNG, were described and the technology was proposed. The technical and economic analysis of the proposed technologies was also presented, taking into account the SWOT analysis, and recommendations were presented.

The aim of the study

The study aims to present a feasibility study of the bioLNG installation - liquefied biogas, for Zakład Utylizacyjny Sp. z o.o. in Gdańsk company to use bioLNG as a source of electrical energy.

Legal basis for the study

Poland, as one of the Member States of the European Union, is obliged to adjust its national law to the provisions of the Community. The principles of waste management are defined in Directive 2008/98 / EC of the European Parliament and of the Council of 19 November 2008 [7] which aims to define waste prevention measures and reduce the environmental impact of the generated waste. Under the provisions of the Directive, the hierarchy of waste management is ranked accordingly:

- preventing,
- reusing,
- recycling,
- energy recovery,
- neutralization.

If it is not possible to reuse the waste, it should be stored in appropriate conditions, in a way that does not pose any risk to the natural and human environment.

Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98 / EC on waste strengthened the provisions on waste prevention and required the Member States to take measures to limit the production of non-recyclable waste. Municipal waste recycling rates have also been defined: by 2025, municipal waste recycling will be increased to a minimum of 55% by weight. By 2030, this level will be increased to 60%, and by 2035 to 65% [8].

Another directive to which the legislation in Poland should be adapted is the Directive of the Parliament and of the Council (EU) 2018/2001 of December 11, 2018, on the promotion of the use of energy from renewable sources (RED II). The Directive describes the need to extend the Guarantee of Origin scheme to gas from renewable sources (including waste) as a consistent way to prove 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 [9].

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 [10], 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 generating installations to the natural gas network, which consists in 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.

Characteristics of the implementation partner

The implementation partner is Zakład Utylizacyjny Sp. z o.o. in Gdańsk (ZU), which is one of the largest waste management plants in Poland. ZU has been operating for 29 years and serves 5 municipalities, including Gdańsk. Annually, 317,000 tons of waste are managed at the ZU. Electricity from landfill gas is generated in the area of the ZU.

On the premises of ZU, there are devices related to:

- Sorting of waste

Waste sorting plant where raw materials are recovered for recycling and waste sorting for management. This installation works around the clock and its capacity is 140,000 tons per year. In the sorting plant, it is possible to separate and thoroughly clean the biodegradable fraction for composting or fermentation.

- Composting

The composting complex has a processing capacity of 80,000 tons per year and processes organic waste from mixed waste sorting plants as well as green and “wet” waste from waste collection areas in Gdańsk. The composting plant includes biofilters, a bioreactor, and the upgrading and distribution segment. The amount of waste going to the composting plant covers its processing capacity, therefore the construction of fermentation tanks can be considered at the ZU. The plant accepts organic and green waste in the amounts shown in Table 1.

- Degassing

The landfill degassing installation enables controlled gas recovery in the amount of about 800 m^3 per hour (average parameters: CH_4: 48%, CO_2: 40%, O_2: 2%, H_2S: 2500ppm), which is converted into electricity allowing for self-sufficiency of the ZU in terms of electricity and heat. The amount of recovered gas varies due to the conditions in the quarters and depends on flooding the quarters with rainwater.

The amount of recovered gas does not provide a surplus to supply local residents with electricity or heat.

- Biogas power plant

A biogas power plant with target parameters: 1,9 MWe and 2,6 MWt powered by gas recovered from a landfill. There are 3 cogeneration units on the premises of the plant. Two CHP units are currently awaiting renovation and one is under renovation. The two operating units generate a total of 700 kW of electricity, while heat is lost and consumes 600 m^3 per hour of gas with parameters of approximately 48% methane and maximum oxygen content of 2%, the remaining part of the gas approximately 150-200 m^3 per hour is utilized in flares.

- A pre-treatment facility

The pretreatment plant, using the reverse osmosis method, purifies leachate and technological sewage to obtain clean water.

Table 1. Quantities of organic waste accepted by the ZU [11]

Year	Waste code	The name of the waste	Ilość odpadów												Total waste	Total August 20, 01 and February 20, 01
			January	February	March	April	May	June	July	August	September	October	November	December		
2016	200108	Biodegradable kitchen waste - wet waste	1 891	1 919	2 388	2 848	3 141	3 282	3 324	3 713	3 390	3 029	3 467	2 512	34 903	**45 471**
2016	200201	Biodegradable waste	151	345	458	584	644	912	948	1 249	1 174	1 255	1 711	1 138	10 569	
2017	200108	Biodegradable kitchen waste - wet waste	2 168	1 837	2 746	2 584	3 438	3 281	3 035	3 472	2 987	3 106	3 147	2 471	34 271	**42 057**
2017	200201	Biodegradable waste	204	199	476	530	732	704	755	722	671	973	1 196	626	7 786	
2018	200108	Biodegradable waste	2 327	1 657	2 123	3 125	3 623	3 202	3 288	3 619	3 115	3 439	3 314	2 359	35 192	**42 807**
2018	200201	Biodegradable waste	336	118	279	685	984	623	650	766	650	875	1 054	596	7 616	
2019	200108	Biodegradable waste	2 422	2 016	2 531	3 189	3 645	3 697	3 697	3 502	3 196	3 823	3 104	2 764	37 586	**47 553**
2019	200201	Biodegradable waste	306	208	521	736	911	1 184	1 156	1 021	707	1 151	1 211	855	9 968	
2020	200108	Biodegradable waste	2 711	2 331	3 014	3 718	4 021	4 939	4 603	3 768	3 999	3 978	3 913	3 202	44 195	**54 063**
2020	200201	Biodegradable waste	556	313	580	524	910	1 307	1 255	737	719	948	1 095	923	9 868	
2021	200108	Biodegradable waste	2 554	2 098	3 305	3 623	4 043	3 985	4124	3847	3984	3898	3171	3403	42035	**51 566**
2021	200201	Biodegradable waste	382	109	511	840	816	1 068	928	813	1069	1282	856	857	9531	

Analysis of the energy needs of Zakład Utylizacyjny Sp. z o.o. in Gdansk

Currently, design, renovation and modernization works are carried out on the premises of the plant. A utilization biogas plant is being designed to transform bio-waste into biogas. Renovation works of the degassing installation and the modernization of the sorting plant are in progress.

At ZU, it is not possible to estimate the demand for electricity with a breakdown into processes (sorting plant, biogas plant) or any other division existing in the company. Renovation works of the degassing installation are currently carried out at the ZU, and the measurement of the installation is not carried out continuously. At the ZU, forecasts of future electricity and heat demand for the company's needs are not performed, and the amount of biogas obtained is not forecasted. ZU also does not have historical data on the amount and composition of the obtained biogas.

3 hectares of land for the construction of a waste incineration plant, called the Port Czystej Energii (PCE), have been developed in the area of the ZU. PCE includes an installation that will produce heat and electricity as a result of the thermal treatment of municipal waste.

To sum up, the area of the ZU produces electricity and heat from the combustion of biogas recovered from waste heaps, as well as from PCE waste incineration plants and the planned biogas plant in the near future. The amounts of electricity and heat produced from these three sources have not been made available for the study, but it is estimated that they will significantly exceed the ZU demand. Therefore, taking into account the fact that there are farm buildings at a distance of about 800 m, the sale of electricity and heat for households can potentially be considered. In addition, the biogas recovered in ZU after conversion to bioLNG fuel could be used by the company or sold.

Conditions and potential for the use of biogas, including bioLNG

The biogas recovered at the Utilization Plant in Gdańsk is a mixture of gases with approximate composition and proportions: methane (CH_4) - 48%, carbon dioxide (CO_2) - 40%, oxygen (O_2) - 2%, hydrogen sulphide (H_2S) - 2500ppm (as of October 2021). 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. Internal combustion engines of this type of aggregates are adapted to the combustion of fuels with a low methane content [3].

After the enrichment process, dried, cleaned and liquefied biogas can be used for:

- propulsion of engines in heavy commercial vehicles (for example in refuse collection trucks). In this case, the biogas is treated so that the methane content is not less than

96%, such gas is called biomethane. It can be used in liquid form - bioLNG or compressed – bioCNG,

- loading cryogenic tanks to use bioLNG elsewhere, for example, to supply the trolleybus traction network in Gdynia or the tram power line in Gdańsk,
- refuelling buses for bus transport in the Tri-City area.

To reduce the volume of fuel, which is crucial in the context of the construction of tanks in vehicles and to limit the occupied space of storage tanks, after drying, cleaning and enrichment, biomethane changes the state of matter from gas to liquid - bioLNG under the influence of pressure and low temperature (-162°C) [12], as shown in Figure 2.

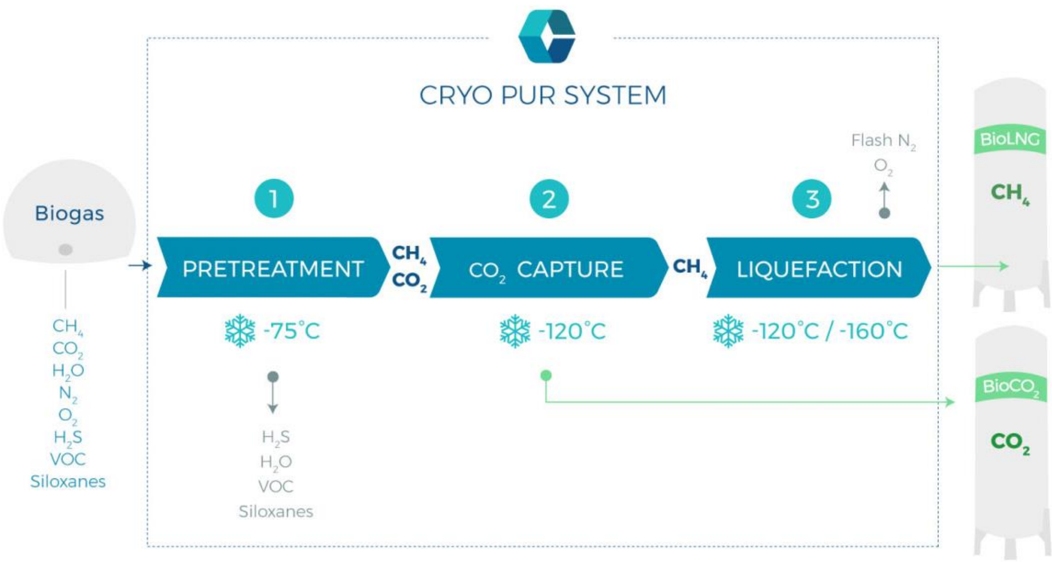

Figure 2. Diagram of the biogas liquefaction process [3]

BioLNG is liquefied biomethane obtained from organic waste, such as agricultural, municipal, organic waste and animal fertilizer, and is produced after cooling biomethane to a temperature of -162°C. Carbon dioxide emission for biomethane ranges from – 88 g CO_2/MJ to +50 g CO_2/MJ, it differs depending on the raw material used for its production (according to the Directive on renewable energy sources II EU).

Both natural gas and biogas can be compressed (CNG- Compress Natural Gas) or liquefied (LNG- Liquid Natural Gas or bioLNG). BioLNG, LNG and CNG are commonly used in transport due to their low emissions of carbon dioxide, NOx and SOx. Of the three, bioLNG and LNG have the advantage of:

- degree of volume reduction, which is 600 for LNG (600 m^3 to 1 m^3) [13] and 200-250 for CNG [14],
- ease of sea and car transport,
- as a result of LNG liquefaction, gas is cleaned of oxygen, carbon dioxide, water and sulfur compounds, therefore it is considered a clean fuel.

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 - via gas networks or tanks.

Advantages of bioLNG:

- contains 99% of CH_4
- bioLNG and LNG can be used in the same way and by using the same installations,
- the production and consumption of bioLNG have a positive environmental impact.

The bioLNG production installation consists of:

- installations for obtaining biomethane,
- cleaning and drying installations,
- gas liquefaction installations,
- gas storage installations,
- tanker loading installations.

Potential recipients of bioLNG could be companies dealing with cleanliness and order as well as municipal management in the field of transporting waste from customers to the ZU. The company Gdańskie Usługi Komunalne (GUK) has 28 diesel-powered garbage trucks. In connection with the obligation to implement the provisions of the Act on electromobility concerning the share of low-emission vehicles, the Company purchased two delivery vehicles and one passenger electric vehicle. Annually, the vehicles servicing the Company consume about 260 thousand litres of diesel oil at a cost of approximately PLN 1,100,000 (net). Currently, in the area served by GUK, there is a refuelling station 5.7 km away. GUK's plans to replace the current fleet are related to the technological wear of vehicles and if new sectors of the city are allocated to service. The fleet will be replaced by specialized low-emission vehicles, which depends on the availability of CNG, LNG, hydrogen refuelling points or fast-charging stations for electric vehicles. GUK has expressed interest in replacing the fleet with LNG-powered vehicles if the refuelling station is located on the premises of the ZU.

PreZero Service Północ has in its fleet specialized vehicles for waste collection, such as garbage trucks - 93 vehicles, hook lifts - 43 vehicles and box vehicles - 7 vehicles, running on diesel fuel or CNG. The company fulfils the obligation to use low-emission vehicles thanks to the possession of vehicles powered by CNG fuel. The vehicles of the PreZero fleet consume 1,894.5 thousand. litres of fuel with a total value of PLN 7,700,000. In the case of CNG-powered vehicles, there is a need to cover considerable distances to the refuelling station, which is why PreZero is interested in building a refuelling station on the premises of ZU, as this will increase the possibility of expanding the vehicle fleet with specialized LNG-fueled vehicles.

BioLNG has a higher methane content than its fossil counterpart because it does not contain higher hydrocarbons. BioLNG produced from biogas has roughly the same chemical formula as LNG, relatively pure methane, but without the higher hydrocarbons present in LNG.

BioLNG is 100% biofuel and can be produced in any location where it is possible to build a traditional biogas plant. This means that every farmer, energy community, city or municipality can build their biogas plant and produce bioLNG.

The advantage of bioLNG's distributed production is that it is easy to distribute by road and sea. Due to the significant volume reduction, relatively large amounts of gas can be transported without the need to build gas pipelines.

The bioLNG truck transport enables the location of refuelling stations without being connected to the gas pipeline. This type of solution reduces the investment costs of connecting to the gas pipeline and compression stations by 25% in relation to LNG stations.

Distributed production of bioLNG will keep the prices of this fuel low and provide access in places that are remote from the supply of other fuels.

For a small-scale bioLNG installation, factors such as:

- high methane content, approx. 99%,
- simplicity and easy operation, the customer can simply connect the gas stream to the inlet of the CHP unit and start producing electricity and/or heat - plug and play principle,
- the flexibility of the system in terms of the changing volume of the gas obtained,
- no waste,
- energy efficiency

are important.

Technology proposal

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 can support the production of bioLNG. As shown below, there are 505 LNG refuelling stations in operation in Europe (Figure 3).

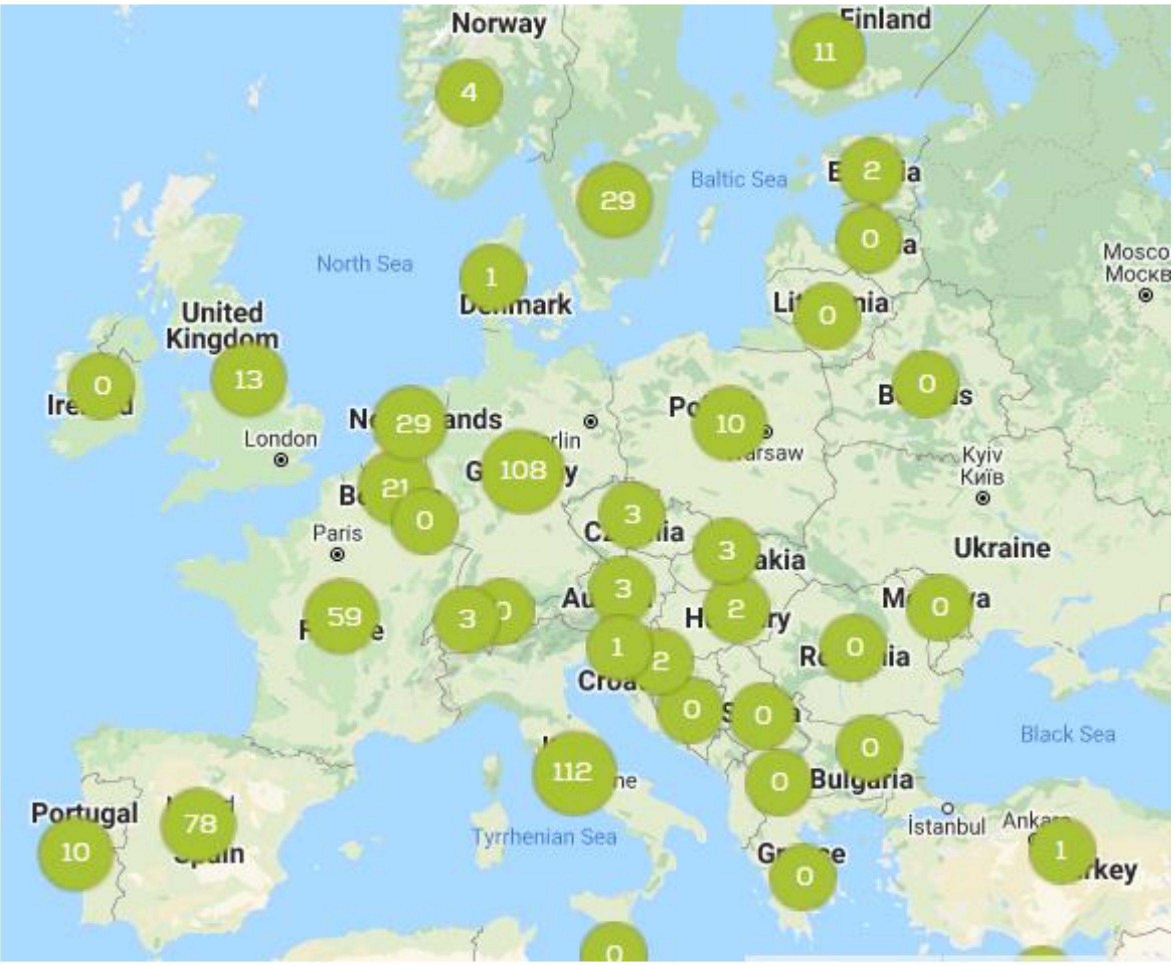

Figure 3. 505 LNG refuelling stations in 2022, NGVA Europe / Gibas

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 [15]

Technologically, the construction of an LNG refuelling station is known. However, in Europe and as presented above, Poland still lacks economies of scale, as is the case, for example, in China (at least 1,500 LNG refuelling stations) or in America - several hundred refuelling stations.

Currently, there are various solutions for LNG refuelling stations that differ in technological solutions. The choice of a specific solution depends on the economic viability and technical conditions. There are simple refuelling stations, supplying only LNG trucks, as well as complex LNG and CNG fuel supply installations, the so-called L-CNG concept (Figure 5). The L-CNG station increases the cost of the installation but has its advantages such as: providing access to CNG fuel without the need for access to the gas pipeline, entering the CNG market, which has a lot of customers, production of CNG without the use of an expensive and energy-consuming compressor (solution in the form of L- CNG pumping liquids instead of compressing the gas, saving 90% of energy while maintaining the same CNG final pressure of 200 bar) [16].

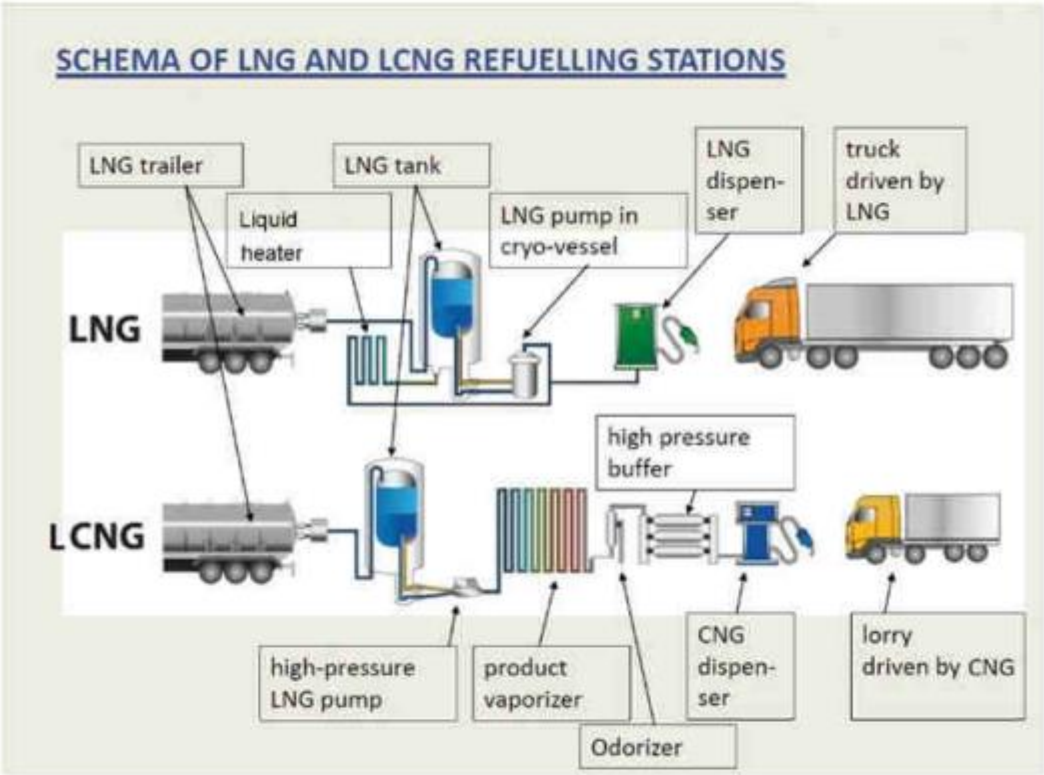

Figure 5. Comparison of schematic diagrams of LNG and L-CNG refuelling stations [16]

An important parameter in the context of the construction of an LNG refuelling station is the handling of evaporation. Vaporization occurs as a result of temperature differences between the inside and outside of the tank, which occur despite the use of thermal insulation. Modern tanks use a double-walled structure, with a vacuum between the walls and insulation on the outside (insulation is not used in LNG tanks used in trucks (Figure 6)).

Figure 6. VOLVO truck LNG tank

Thanks to the use of double walls of the tank and a vacuum, there is little heat exchange between the inside of the tank and the surroundings. However, the amount of heat delivered to the tank from the environment is sufficient to raise the temperature of the liquid contained in the tank to the boiling point for a given operating pressure (the chart of boiling points at different pressures is shown in Figure 7). The generated LNG vapours increase the pressure in the tank.

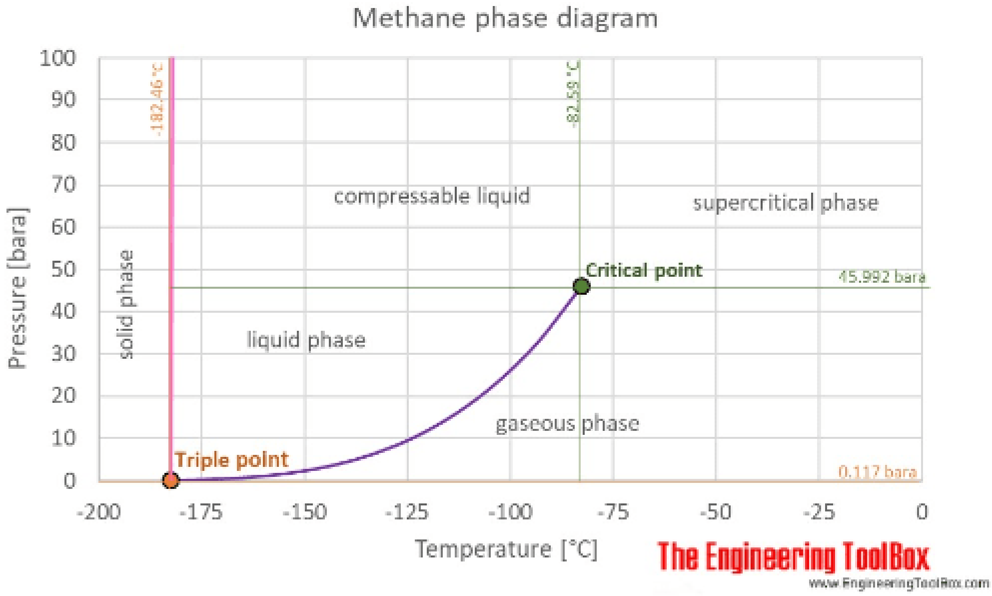

Figure 7. LNG temperature chart for different pressure values [17]

With sustainable operation and regular emptying and loading, appropriate pressure and temperature conditions are maintained inside the LNG tanks. If the fuel is kept in the tank and some of its parts evaporate, and the pressure in the tank increases, to avoid overpressure, use a pressure relief valve (PRV), which is designed to release some of the gas until the pressure in the tank returns to the appropriate values. The vaporized gas should be properly disposed of, taking into account safety and environmental protection. Therefore, the design of the refuelling station must take into account the method of evaporating gas management, e.g. by using a compressor and converting the gas to CNG. You can also cool the gas again, liquefy it and send it to the tank in the form of LNG, but due to the significant energy expenditure on the refrigeration unit, this method is not commonly used.

Cryogenic tanks are available in vertical and horizontal versions and sizes depending on the requirements for daily capacity and annual consumption levels. As standard, the market offers tanks with a capacity of 20-60 m^3 (Table 2). The 60 m^3 tank holds about 23 tons of LNG, from which, after regasification, 30 777 Nm^3 of volatile natural gas and about 351 MWh of energy can be obtained. It should be noted that for technical reasons, LNG tanks cannot be 100% full, and the amount of stored LNG is determined by specific temperature parameters, therefore, in different sources, different values of the amount of fuel stored in the cryogenic tank and the energy obtained from gas after the regasification process can be found. In case of special needs, it is possible to make tanks to order or to combine several standard tanks.

Table 2. List of sizes and capacities of LNG tanks depending on the annual consumption and daily capacity of the LNG installation [18]

type of tank	tank capacity	tank capacity	tank capacity	LNG consumption		LNG consumption		LNG consumption		average daily capacity of the installation		
m^3	t	MWh	Nm^3	t/a	t/a	MWh/a	MWh/a	Nm^3/a	Nm^3/a	t	MWh	Nm^3
20	8	122	10 704	250	500	3 810	7 620	333 500	669 000	1,3	20,9	1 8333
40	15	229	20 070	500	1 000	7 620	15 240	669 000	1 338 000	2,7	41,8	3 666
60	23	351	30 774	1 000	2 000	15 240	30 480	1 338 000	2 676 000	5,5	83,5	7 332
2x60	46	701	61 548	>2 000		>30 480		>2 676 000		>5,5	>83,5	>7 332

The main components of the LNG refuelling station are LNG cryogenic tank, high-pressure cryogenic pump, control panel, and LNG atmospheric vaporizer. Below is a photo of the LNG refuelling station at Bisek in Kosomłoty.

Figure 8. LNG refuelling station, Bisek company, Kostomłoty

The cryogenic vessel is a super-insulated, double-sided vessel with vacuum separation. Fuel in liquid form from the condensation installation is directed to it or it receives fuel from the tanker. Then the LNG fuel can be distributed to trucks or garbage trucks using the charging connector. The capacity of LNG tanks ranges from 5 to 130 m^3 (1 m^3 of LNG equals approximately 0,5 t). The pressure in the tank is 5-15 bar.

In the case of the construction of a station servicing CNG fuel vehicles, a cryogenic high-pressure LNG pump with an atmospheric evaporator is also required, which is to increase the LNG pressure to 200-250 bar, and then the fuel is directed to the heat exchanger where evaporation takes place and in the form of CNG it can be distributed to the recipient.

A cryogenic low-pressure pump (Figure 9) is used to transfer LNG from the station's tank to the tank in the refuelled vehicle. The flow of such a pump is approximately 700-800 kg/min, at a maximum operating pressure of 34 bar. In solutions with high cryogenic tanks, the low-pressure pump may be omitted in the design due to a sufficiently large LNG flow rate due to the difference in pressure and levels between the station tank and the tank in the refuelled vehicle, then the station tank should be 15-20 m high. The lack of a low-pressure pump allows you to save energy and capital expenditure on its construction, and also reduces the complexity of the technical system of the refuelling station.

Figure 9. Low-pressure cryogenic pump [19]

Biogas recovery from waste heaps irregularly takes place, both quantitatively and qualitatively. In simple terms, it can be assumed that 800 m^3 of gas is recovered per hour on the premises of the ZU.

Gas storage in liquefied form is possible in cryogenic tanks. The design of such a tank allows to maintain the temperature of the fuel. The most common for sale are cryogenic tanks with a capacity of 60 m^3.

BioLNG is distributed using tanks (Figure 10) or cryogenic tanks (mini tanks) (Figure 11) and is used as fuel for energy production in a gas cogenerator. Cryogenic tanks and cisterns can also be used for fuel storage.

Transport of bioLNG and LNG from the production station to the regasification station takes place in specialized cryogenic tanks that maintain a low temperature of liquefied biogas during transport. The tanker has a capacity of about 18.5 tons, which after the regasification process allows for the production of 25, 600 m^3 of fuel [11].

Figure 10. BioLNG transport tank [20]

The cryogenic tank (mini tanker) for the transport of bioLNG / LNG is used to transport smaller amounts of fuel.

Figure 11. Cryogenic tank (mini-tank) for the transport of bioLNG / LNG - Microfueler LNG (own materials)

The diagram of the cryogenic tank (mini-tank) for the transport of bioLNG / LNG - Microfueler LNG is shown in Figure 12, and the description of its functions is described in Table 3.

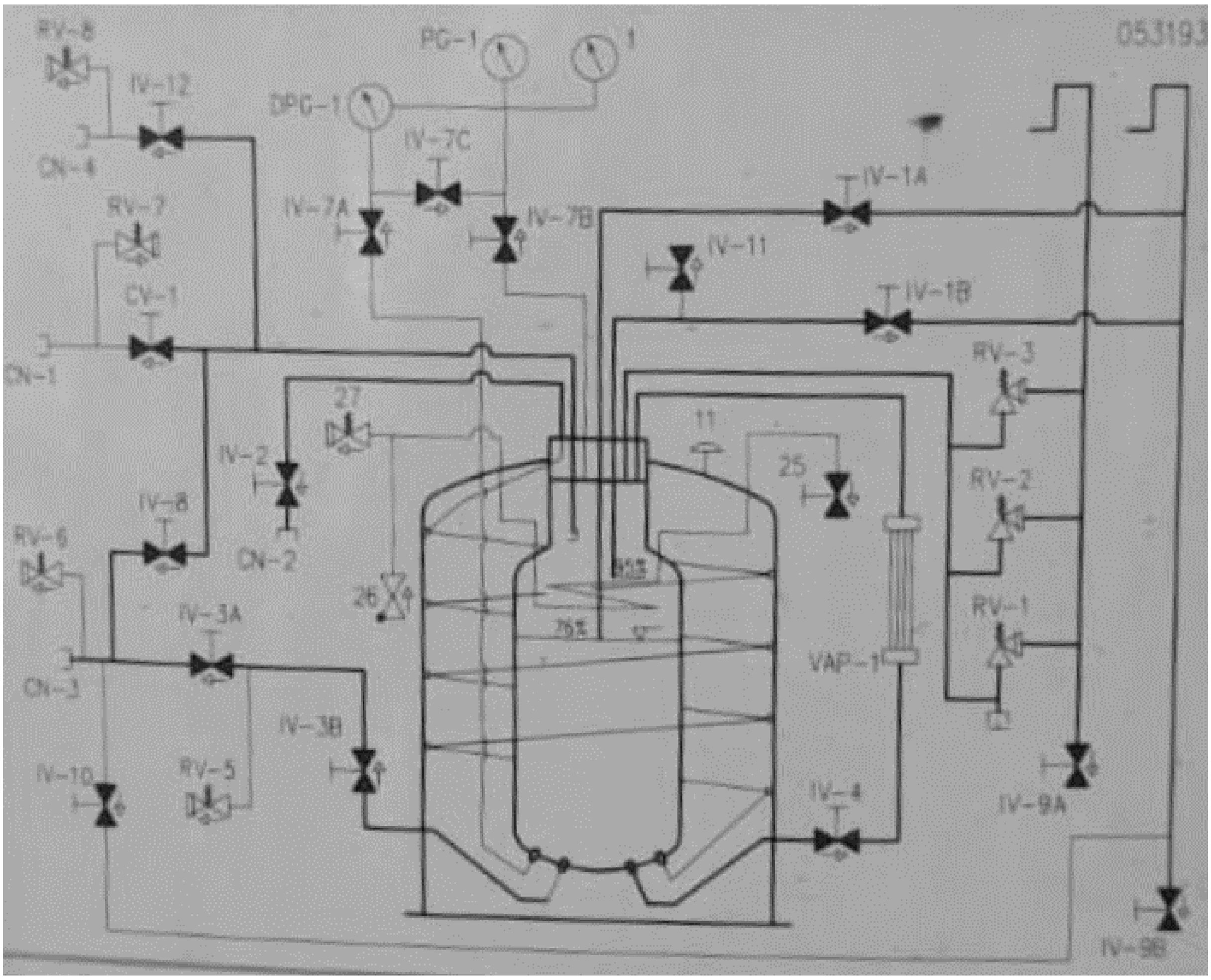

Figure 12. Diagram of a bioLNG / LNG Microfueler cryogenic tank (mini-tank)

Table 3. Description of the functions of the bioLNG / LNG Microfueler cryogenic tank (mini-tank)

CN-1	LNG filling connection	11	Vacuum fuse
CN-2	Connection to saturation - gas	IV-1A	Blow off valve
CN-3	Connection to	IV-1B	Shut-off valve in the discharge line
CN-4	Connection to	IV-3A	Shut-off ball valve in the refuelling line
DPG-1	Level indicator	IV-3B	Shut-off ball valve in the refuelling line
PG-1	Pressure gauge	IV-2	Shut-off ball valve on the saturation line
IV-7	Low/high phase shut-off valve	IV-4	Shut-off ball valve on the outlet line of the PBU evaporator
RV-1	Safety valve	IV-8	Top filling
RV-2	Safety valve	IV-9	Drain (drain) valve on the discharge line
RV-3	Safety valve in the pressure housing line	IV-10	Drain valve on the refuelling line
RV-5	Safety valve in the refuelling line	IV-11	Fuel tank exhaust line
RV-6	Safety valve in the refuelling line	IV-12	Draining the fuel tank
RV-7	Safety valve in the tank emptying line	1	Second pressure gauge
RV-8	Safety valve in the filling line	25	Option - valve to the coil
CV-1	Safety valve	26	Option - valve to the coil
VAP-1	Pressure housing vaporizer	27	Option - safety valve to the coil

Source: own study

An alternative to using mini tanks is a mobile refuelling station. The mobile refuelling station is a pilot project implemented by the partners of the Liquid Energy project, which is located in the trunk of a Volkswagen Crafter 35 motor vehicle. The installation consists of a bioLNG tank with a capacity of 450-900l, a refuelling pump and a refuelling system. The second option for using a mobile refuelling station is the possibility of replacing the tank. The tank can be connected directly to the regasification station to then power a gas cogenerator or a fuel cell. The cost of such a solution is approximately EUR 150,000.

Figure 13. Mobile refuelling station [21]

The bioLNG refuelling station is based on a well-developed and safe technology. The devices and installation of the refuelling station are located in the vicinity of a low wall, which prevents the fuel from escaping outside the refuelling station area in the event of unsealing of the installation.

The area of the refuelling station should be fenced and a safety zone should be designated around the tanks. The size of the fenced area and the safety zone depends on the efficiency of the installation and the type of cryogenic tank [22]. Figure 14 shows the development of the LNG station area along with the marking of the area of the fence and the safety zone.

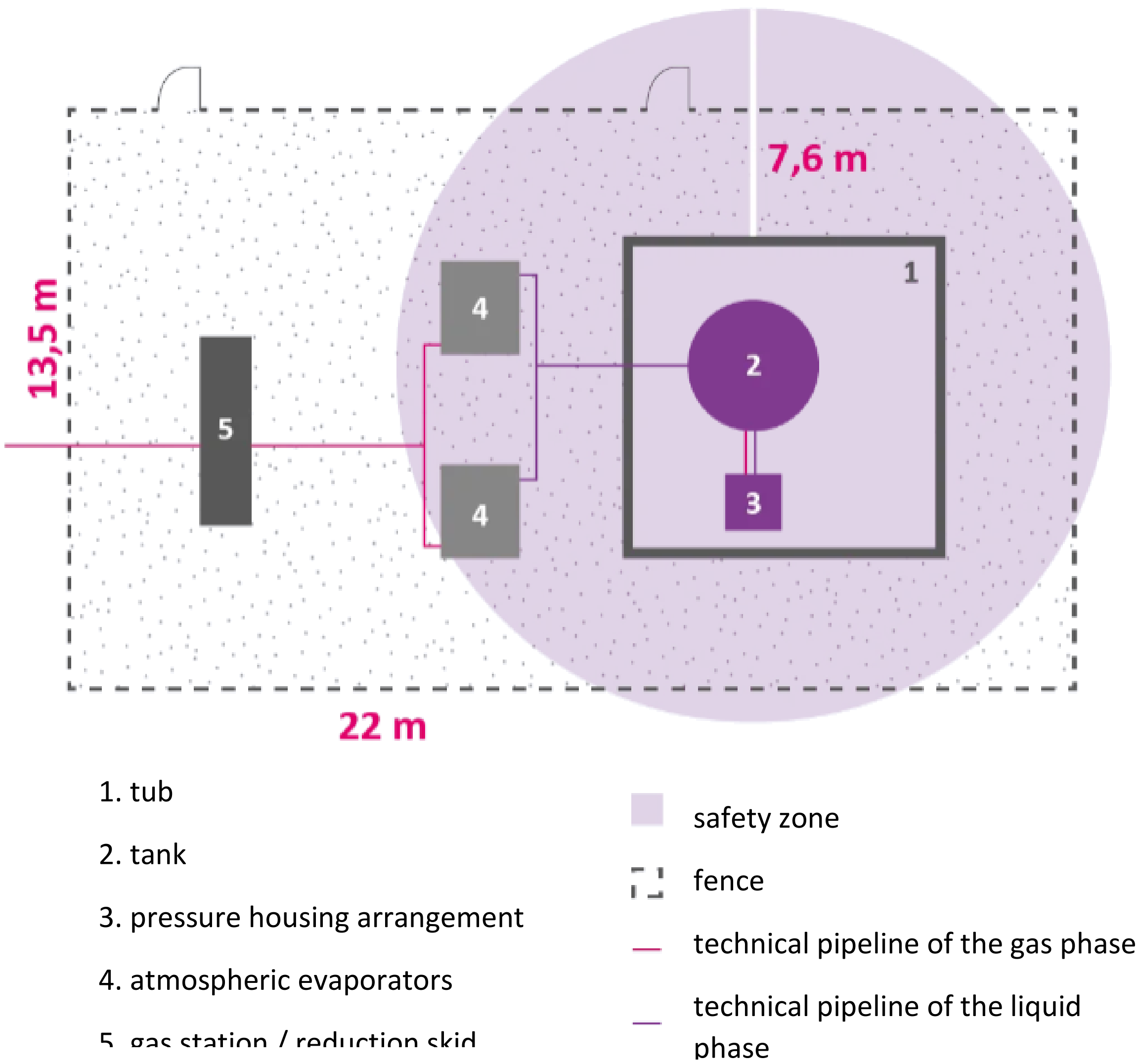

Figure 14. Designation of a safety zone and dimensions of 10 MW LNG stations [22]

Proposed application of bioLNG utilization technology

BioLNG production estimate

To estimate the production of bioLNG, the following assumptions were made:

Amount of biogas obtained at the ZU $\dot{v}_{biogas} = 800\frac{m^3}{h}$

Biogas composition: CH_4: 48%, CO_2: 40%, O_2: 2%, H_2S: 2500ppm (data for October 2021).

Natural gas has a methane content of 99%.

Determination of the amount of pure CH_4 methane in the obtained biogas was made according to the formula:

$$\dot{v}_{CH_4\,in\,biogas} = \frac{\dot{v}_{biogas} \cdot 0{,}48}{0{,}99} = 387{,}9\ \frac{m^3}{h} \tag{1}$$

where:

$\dot{v}_{CH_4\,in\,biogas}$ – the volume of methane in biogas, $\left[\frac{m^3}{h}\right]$

$\dot{v}_{biogas}$ – the volumetric flow of obtained biogas, $\left[\frac{m^3}{h}\right]$

LNG tanker filling parameters (97% of CH_4) [11]:

Amount of loaded LNG $m_{LNG} = 18\ 500\ kg$.

The amount of energy contained in LNG fuel in one tanker $E_{LNG_{tanker}} = 283\ 790\ kWh$.

LNG parameters:

Combustion heat $H_s = 15{,}34\,\frac{kWh}{kg} = 11{,}30\,\frac{kWh}{Nm^3}$.

Density $\rho = 429{,}5\,\frac{kg}{m^3}$.

Temperature $t_{LNG} = -159{,}4\ °C$.

The energy contained in a gas unit was determined following the formula:

$$E_{LNG} = \frac{E_{LNG_{tanker}}}{m_{LNG}} = \frac{28\ 3790}{18{,}5} = 15\ 340\,\frac{kWh}{t} \tag{2}$$

The production of bioLNG in the Cryo Pur installation is characterized in Figure 15.

Product	**Nominal** biogas flowrate (Nm^3/h)	**Minimal** biogas flowrate (Nm^3/h)	**Maximal** biogas flowrate (Nm^3/h)	Nominal **bio-LNG** production* (t/d)	Nominal **bio-CO_2** production* (t/d)
CP 250	250	125	300	2,3	4,7
CP 500	500	250	600	4,6	9,4
CP 800	800	400	960	7,4	15,1
CP 1000	1000	500	1200	9,2	18,9
CP 1500	1500	750	1800	13,8	28,4
CP 2000	2000	1000	2400	18,5	37,9

* Production is calculated for a biogas composition of 55% CH_4 and 45% CO_2

Figure 15. Production of bioLNG in the Cryo Pur condensation installation [4]

Approximate production of bioLNG at ZU at the Cryo Pur installation (linear interpolation method) $\dot{m}_{bioLNG} = 7{,}4\frac{t}{d}$.

Analysis of bioLNG's ability to meet energy needs

The energy needs of the waste disposal plant are currently covered by the combustion of landfill gas in a gas cogenerator. As a result, the plant is supplied with electricity and heat. Covering the energy needs with bioLNG would require energy expenditure on liquefaction, storage and regasification of bioLNG, which is not justified from an environmental and economic point of view, as energy inputs would significantly outweigh the amount of energy obtained. Therefore, as part of this study, the construction of a biogas liquefaction station with a vehicle refuelling station was analyzed, which is described in further parts of the study.

The refuelling station can supply bioLNG or bioCNG fuel to vehicles operated by both ZU and municipal companies dealing with waste collection or passenger transport.

Technical and economic analysis

After analyzing the needs and possibilities of the ZU and taking into account the assumptions of the Liquid Energy project, it is proposed to supplement the current installation operating on the premises of the ZU with:

- condensation station,
- bioLNG tank,
- regasification station,
- vehicle refuelling station

to power the car base, loaders and excavators or for the sale of bioLNG or bioCNG fuel. Additionally, it is possible to sell liquid carbon dioxide CO_2, which is a by-product of the gas liquefaction process.

Due to the low yield of biogas, 3 variants are proposed: a condensation station + a refuelling station:

(W1): Variant 1. Liquefaction station + low pressure bioLNG refuelling station,

(W2): Variant 2. Liquefaction station + bioLNG and bioCNG refuelling station (called L-CNG),

(W3): Variant 3. Condensing station + mobile refuelling station.

A diagram of the proposed technology is shown in Figure 16.

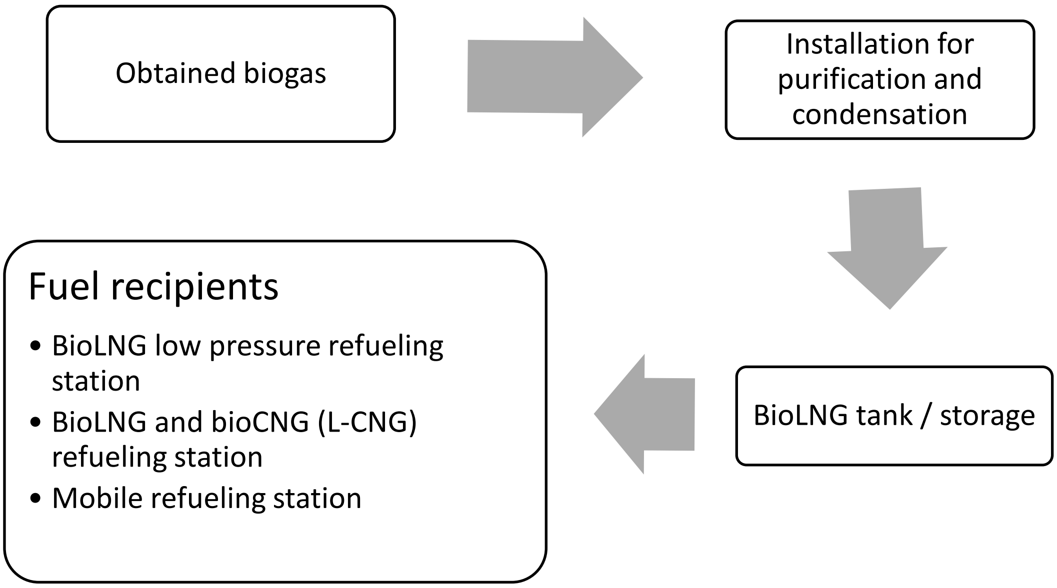

Figure 16. Schematic diagram of the proposed technologies

The installation of all the proposed variants could be located on the premises of the ZU in the place marked in Figure 17. There are containers with suction stations and a desulphurizer at this location.

Figure 17. The area of the IU plant with the location marked for bioLNG refuelling stations

The economic analysis of the biogas liquefaction station together with the bioLNG storage and refuelling station for vehicles powered by gas engines powered by LNG fuel was performed for all 3 variants described above.

The analysis takes into account the estimated and actual costs of construction and operation of the station, indicating various technologies, based on information obtained from project partners, current market prices and literature analysis. Due to the low yield of biogas from ZU, mobile bioLNG refuelling stations were also analyzed. Mobile bioLNG refuelling stations have a reduced storage capacity (approximately 20 m^3 or ~10 tons) and a limited maximum number of filling operations per day (assuming 115 kg per charge) but offer great operational flexibility. It should be noted that some items to be taken into account when carrying out the economic analysis are specific to each station and depend on the site conditions and the specifics of the construction company, e.g. labour costs, and logistics costs. In addition, in Europe, LNG has been used relatively recently as a fuel for specialized vehicles such as garbage trucks or buses (Natural Gas for Vehicles (NGV)), which is why there is a lack of a large amount of publicly available data. Some data is only available in contractual contracts and is not provided in RFPs. In such cases, some assumptions had to be made.

The construction of the refuelling station infrastructure requires large financial outlays due to the technological advancement and the still small scale of such solutions. The purpose of the economic analysis is to estimate the costs and benefits of building a bioLNG refuelling station on the territory of an IU, taking into account a reasonable level of uncertainty. However, the level of uncertainty will decrease with the technological development and construction of new LNG refuelling stations in Poland and the increase in the demand for gaseous fuel in liquid form.

The analysis of the costs of building an LNG refuelling station includes:

- equipment,
- installation,
- construction works,
- permits,
- engineering works,
- operations/tests needed to start the station.

The land lease costs were not included in the analysis due to the availability of development space in the ZU.

The project involves the construction of a refuelling station considered in 3 variants of technological solutions, although each solution assumes a connection to the existing biogas recovery installation. Accordingly, the availability of operational personnel after appropriate training was assumed, and thus the costs were reduced. The costs of concessions and permits are determined in separate procedures and have not been included in the economic analysis.

The considered variants differ in costs related to the technology used. These are costs related to earthworks, LNG storage, LNG filling management systems (pumping, cooling, condensation), CNG management systems (evaporation management, pressure regulation, compression, storage), or LNG, CNG dispensers, or in the case of mobile charging station, operating costs of the vehicle in which the tank is built.

The main element of the refuelling station is the LNG tank, or in the case of the W3 variant, the L-CNG tank. Typical tank volumes are 20, 30 and 60 m^3. The cost of the tanks with these capacities ranges from EUR 95,000 to EUR 135,000. The capacity of such a tank should be selected according to the amount of bioLNG obtained and the frequency of emptying the tank. The larger the tank, the longer the fuel stays in it, and the absence of regular emptying, the formation of a gas part (LNG fuel vaporization process). This affects operational costs such as reliquefying or compressing to convert to CNG. The analysis assumes that the refuelling station will be used by specialized cars such as buses or garbage trucks, therefore it was assumed that such vehicles are equipped with 704 l tanks, which allows you to refuel 280 kg of LNG and travel about 1000 km (Irizar - Scania bus) [23].

Capital expenditures for the construction of refuelling stations are subject to trade secrets and depend on the location, planned capacity, planned number of fuel recipients, costs of fuel storage technology, methods of managing evaporated gas from bioLNG and the costs of obtaining permits. Therefore, in this study only approximate costs for building bioLNG refuelling stations, which are available in the literature, are given.

In Europe, investment outlays for the construction of L-CNG refuelling stations are in the range of EUR 850,000 - EUR 1,150,000, excluding the cost of land purchase. For stations without CNG sales, it is possible to reduce investment outlays to the range of EUR 500,000 - 600,000, although the use of vaporized LNG fuel should be planned or the operation of the station should be ensured so that no evaporation occurs. In the case of small refuelling stations, it is possible to reduce the investment outlays to the level of EUR 300,000 - 500,000 [16].

The variability of the given investment outlays results from the dependence of the station's destination, i.e. whether it will be single or dual-fuel (only LNG or L-CNG sales), the type of fuel sold (saturation level), the size of the warehouse, or the pump flow rate.

The introduction to the economic analysis is the determination of the annual yield of biogas in the area of the ZU, it was determined following the formula:

$$\dot{v_{biogas,t}} = \dot{v}_{biogas} \cdot 8760 = 7\,008\,000{,}00\,\frac{m^3}{a} \tag{3}$$

where:

$\dot{v_{biogas,t}}$ – annual biogas production, $\left[\frac{m^3}{a}\right]$

$\dot{v}_{biogas}$ – biogas production, $\left[\frac{m^3}{h}\right]$

The annual methane production was then determined:

$$\dot{v_{CH_4}} = \frac{\dot{v_{biogas,t}} \cdot u_{CH_4 in\ biogas}}{u_{CH_4 in\ natural\ gas}} \cdot 8760 = 3\,397\,818{,}18\ \frac{m^3}{a} \tag{4}$$

where:

$\dot{v_{CH_4}}$ – annual methane production, $\left[\frac{m^3}{a}\right]$

$\dot{v_{biogas,t}}$ – annual biogas production, $\left[\frac{m^3}{a}\right]$

$u_{CH_4 in\ biogas}$ – share of methane in biogas, [-]

$u_{CH_4 in\ natural\ gas}$ – share of methane in natural gas, [-]

The annual production of bioLNG in the Cryo Pur installation was determined by the formula:

$$\dot{B_{bioLNG,t}} = (\dot{m}_{bioLNG} \cdot 365) \cdot 1000 = 2\ 701\ 000{,}00\ \frac{kg}{a} \tag{5}$$

where:

$\dot{B_{bioLNG,t}}$ – annual production of bioLNG in the Cryo Pur installation, $\left[\frac{kg}{a}\right]$

$\dot{m}_{bioLNG}$ – daily production of bioLNG in the Cryo Pur installation at the ZU, $\left[\frac{t}{d}\right]$

The situation in the fuel and electricity market can now be described as difficult. The increase in fuel and electricity prices depends on the geopolitical situation. Therefore, making fuel and electricity price predictions on the market is subject to high uncertainty and a margin of error. In the course of this study, the price of LNG ranged from PLN 5-14 per kilogram, therefore, for the first year of the analysis, the value was PLN 12.50 per kilogram (as of June 2022). Electricity price predictions at the beginning of 2023 indicate that it will be at the level of PLN 1,000 per MWh. For the analysis, the price of 1000 PLN/MWh of electricity was assumed in the first year of operation.

For this analysis, it was assumed that the price of LNG fuel and the price per MWh of electricity will increase by 5% per year for the first 5 years, after which the price will stabilize and the growth will be slower, by 1.5% per year. This approach to determining the price of fuels and electricity is currently used in the research community.

The cost of cleaning, liquefying and storing bioLNG was estimated at 30% of the revenues from the sale of bioLNG, due to the energy consumption of the process [24]. Employing new employees is not required to operate the station, therefore it was assumed that after the training, the station will be operated by the current employees.

The annual revenue from the sale of bioLNG fuel was determined as:

$$R_{bioLNG,t} = \dot{B_{bioLNG,t}} \cdot c_{bioLNG,t} = 33\ 762\ 500{,}00\ PLN \tag{6}$$

where:

$R_{bioLNG,t}$ – annual revenue from the sale of bioLNG fuel, [PLN]

$\dot{B_{bioLNG,t}}$ – annual production of bioLNG in the Cryo Pur installation, $\left[\frac{kg}{a}\right]$

$c_{bioLNG,t}$ – bioLNG sales price, $\left[\frac{PLN}{kg}\right]$

As mentioned, the revenue from the sale of fuel is the basis for determining the costs of purification, liquefaction and storage of bioLNG, which was determined following the formula:

$$K_{prep.of\ bioLNG,t} = R_{bioLNG,t} \cdot u_{prep.of\ bioLNG} = 10\ 128\ 750{,}00\ PLN \qquad (7)$$

where:

$K_{prep.of\ bioLNG,t}$ – the cost of purification, liquefaction and storage of bioLNG, [PLN]

$R_{bioLNG,t}$ – annual revenue from the sale of bioLNG fuel, [PLN]

$u_{prep.of\ bioLNG}$ – fuel preparation cost share, [-]

The total profit from the sale of bioLNG fuel will amount to the first year of operation of the installation:

$$P_t = R_{bioLNG,t} - K_{prep.of\ bioLNG,t} = 23\ 633\ 750{,}00\ PLN \qquad (8)$$

where:

P_t – total annual profit from the sale of bioLNG fuel, [PLN]

$R_{bioLNG,t}$ – annual revenue from the sale of bioLNG fuel, [PLN]

$K_{prep.of\ bioLNG,t}$ – the cost of purification, liquefaction and storage of bioLNG, [PLN]

The economic analysis was performed for 25 years of operation of the installation. The results are shown below in Table 4.

Table 4. Results of the financial flows related to the sale of bioLNG

	Annual gas production	The content of methane in biogas	Annual production of bioLNG	BioLNG selling price	The cost of cleaning, liquefaction and storage	Revenue from sales of bioLNG	Profit
	m3/a	m3/a	kg/a	PLN/kg	PLN	PLN	PLN
1	7 008 000,00	3 397 818,18	2 701 000,00	12,50	10 128 750,00	33 762 500,00	23 633 750,00
2	7 008 000,00	3 397 818,18	2 701 000,00	13,13	10 635 187,50	35 450 625,00	24 815 437,50
3	7 008 000,00	3 397 818,18	2 701 000,00	13,78	11 166 946,88	37 223 156,25	26 056 209,38
4	7 008 000,00	3 397 818,18	2 701 000,00	14,47	11 725 294,22	39 084 314,06	27 359 019,84
5	7 008 000,00	3 397 818,18	2 701 000,00	15,19	12 311 558,93	41 038 529,77	28 726 970,84
6	7 008 000,00	3 397 818,18	2 701 000,00	15,95	12 927 136,88	43 090 456,25	30 163 319,38
7	7 008 000,00	3 397 818,18	2 701 000,00	15,98	12 946 527,58	43 155 091,94	30 208 564,36
8	7 008 000,00	3 397 818,18	2 701 000,00	16,00	12 965 947,37	43 219 824,58	30 253 877,20
9	7 008 000,00	3 397 818,18	2 701 000,00	16,03	12 985 396,29	43 284 654,31	30 299 258,02
10	7 008 000,00	3 397 818,18	2 701 000,00	16,05	13 004 874,39	43 349 581,29	30 344 706,91
11	7 008 000,00	3 397 818,18	2 701 000,00	16,07	13 024 381,70	43 414 605,67	30 390 223,97
12	7 008 000,00	3 397 818,18	2 701 000,00	16,10	13 043 918,27	43 479 727,57	30 435 809,30
13	7 008 000,00	3 397 818,18	2 701 000,00	16,12	13 063 484,15	43 544 947,17	30 481 463,02
14	7 008 000,00	3 397 818,18	2 701 000,00	16,15	13 083 079,38	43 610 264,59	30 527 185,21
15	7 008 000,00	3 397 818,18	2 701 000,00	16,17	13 102 704,00	43 675 679,98	30 572 975,99
16	7 008 000,00	3 397 818,18	2 701 000,00	16,19	13 122 358,05	43 741 193,50	30 618 835,45
17	7 008 000,00	3 397 818,18	2 701 000,00	16,22	13 142 041,59	43 806 805,29	30 664 763,71
18	7 008 000,00	3 397 818,18	2 701 000,00	16,24	13 161 754,65	43 872 515,50	30 710 760,85
19	7 008 000,00	3 397 818,18	2 701 000,00	16,27	13 181 497,28	43 938 324,28	30 756 826,99
20	7 008 000,00	3 397 818,18	2 701 000,00	16,29	13 201 269,53	44 004 231,76	30 802 962,23
21	7 008 000,00	3 397 818,18	2 701 000,00	16,32	13 221 071,43	44 070 238,11	30 849 166,68
22	7 008 000,00	3 397 818,18	2 701 000,00	16,34	13 240 903,04	44 136 343,47	30 895 440,43
23	7 008 000,00	3 397 818,18	2 701 000,00	16,37	13 260 764,39	44 202 547,98	30 941 783,59
24	7 008 000,00	3 397 818,18	2 701 000,00	16,39	13 280 655,54	44 268 851,80	30 988 196,26
25	7 008 000,00	3 397 818,18	2 701 000,00	16,41	13 300 576,52	44 335 255,08	31 034 678,56

Variant 2 assumed the construction of a liquefaction station with a bioLNG and bioCNG refuelling station (called L-CNG). In connection with the above, the financial flows of the L-CNG hybrid station were analyzed assuming that the ratio of bioLNG sales to bioCNG will be 30/70 (specific shares refer to the total production of bioLNG). The L-CNG station requires an additional gas compression installation, therefore higher costs related to fuel preparation were assumed and estimated at the level of 32% of total profits from fuel sales. After analyzing the dependence of LNG and CNG fuel prices, it was found that the difference in the price of both these fuels does not exceed PLN 0.3, therefore, in the prediction of selling prices, such a difference was proposed, leaving a price increase of 5% for the first 5 years and then an increase of 1.5 % in subsequent years.

Taking the above into account, the formula for the annual revenue from the sale of bioLNG fuel will change and bioCNG has been designated as:

$$R_{bioLNG,t} = \left(\dot{B}_{bioLNG,t} \cdot 0{,}3\right) \cdot c_{bioLNG,t} + \left(\dot{B}_{bioLNG,t} \cdot 0{,}3\right) \cdot c_{bioCNG,t} = 33\ 195\ 290{,}00\ PLN \quad (9)$$

where:

$R_{bioLNG,t}$ – annual revenue from the sale of bioLNG fuel, [PLN]

$\dot{B}_{bioLNG,t}$ – annual production of bioLNG in the Cryo Pur installation, $\left[\frac{kg}{a}\right]$

$c_{bioLNG,t}$ – bioLNG sales price, $\left[\frac{PLN}{kg}\right]$

$c_{bioCNG,t}$ – bioCNG sales price, $\left[\frac{PLN}{kg}\right]$

The results of the financial flows of bioL-CNG stations are presented in Table 5.

Table 5. Results of the financial flows of bioL-CNG stations

	Annual gas production	The content of methane in biogas	Annual production of bioLNG	BioLNG selling price	BioCNG selling price	The cost of cleaning, liquefaction and storage	Revenue from sales of bioLNG and bioCNG	Profit
	m3/a	m3/a	kg/a	PLN/kg	PLN/kg	PLN	PLN	PLN
1	7 008 000,00	3 397 818,18	2 701 000,00	12,50	12,20	10 622 492,80	33 195 290,00	22 572 797,20
2	7 008 000,00	3 397 818,18	2 701 000,00	13,13	12,83	11 162 692,80	34 883 415,00	23 720 722,20
3	7 008 000,00	3 397 818,18	2 701 000,00	13,78	13,48	11 729 902,80	36 655 946,25	24 926 043,45
4	7 008 000,00	3 397 818,18	2 701 000,00	14,47	14,17	12 325 473,30	38 517 104,06	26 191 630,76
5	7 008 000,00	3 397 818,18	2 701 000,00	15,19	14,89	12 950 822,33	40 471 319,77	27 520 497,44
6	7 008 000,00	3 397 818,18	2 701 000,00	15,95	15,65	13 607 438,80	42 523 246,25	28 915 807,45
7	7 008 000,00	3 397 818,18	2 701 000,00	15,98	15,68	13 628 122,22	42 587 881,94	28 959 759,72
8	7 008 000,00	3 397 818,18	2 701 000,00	16,00	15,70	13 648 836,66	42 652 614,58	29 003 777,91
9	7 008 000,00	3 397 818,18	2 701 000,00	16,03	15,73	13 669 582,18	42 717 444,31	29 047 862,13
10	7 008 000,00	3 397 818,18	2 701 000,00	16,05	15,75	13 690 358,81	42 782 371,29	29 092 012,48
11	7 008 000,00	3 397 818,18	2 701 000,00	16,07	15,77	13 711 166,61	42 847 395,67	29 136 229,05
12	7 008 000,00	3 397 818,18	2 701 000,00	16,10	15,80	13 732 005,62	42 912 517,57	29 180 511,95
13	7 008 000,00	3 397 818,18	2 701 000,00	16,12	15,82	13 752 875,89	42 977 737,17	29 224 861,27
14	7 008 000,00	3 397 818,18	2 701 000,00	16,15	15,85	13 773 777,47	43 043 054,59	29 269 277,12
15	7 008 000,00	3 397 818,18	2 701 000,00	16,17	15,87	13 794 710,39	43 108 469,98	29 313 759,59
16	7 008 000,00	3 397 818,18	2 701 000,00	16,19	15,89	13 815 674,72	43 173 983,50	29 358 308,78
17	7 008 000,00	3 397 818,18	2 701 000,00	16,22	15,92	13 836 670,49	43 239 595,29	29 402 924,80
18	7 008 000,00	3 397 818,18	2 701 000,00	16,24	15,94	13 857 697,76	43 305 305,50	29 447 607,74
19	7 008 000,00	3 397 818,18	2 701 000,00	16,27	15,97	13 878 756,57	43 371 114,28	29 492 357,71
20	7 008 000,00	3 397 818,18	2 701 000,00	16,29	15,99	13 899 846,96	43 437 021,76	29 537 174,80
21	7 008 000,00	3 397 818,18	2 701 000,00	16,32	16,02	13 920 969,00	43 503 028,11	29 582 059,11
22	7 008 000,00	3 397 818,18	2 701 000,00	16,34	16,04	13 942 122,71	43 569 133,47	29 627 010,76
23	7 008 000,00	3 397 818,18	2 701 000,00	16,37	16,07	13 963 308,15	43 635 337,98	29 672 029,83
24	7 008 000,00	3 397 818,18	2 701 000,00	16,39	16,09	13 984 525,38	43 701 641,80	29 717 116,43
25	7 008 000,00	3 397 818,18	2 701 000,00	16,41	16,11	14 005 774,43	43 768 045,08	29 762 270,66

The various options in terms of capital expenditure, bioCNG refuelling, amount of space occupied by the station, the need to meet the minimum bioLNG refuelling requirement, work flexibility, adaptation of the installation to small amounts of bioLNG, operating costs and the possibility of storing bioLNG surplus production compared below.

Variant W1 is characterized by relatively low capital expenditure and operating costs, requires little land and is highly available. It is not possible to refuel with CNG. In the W2 variant, the capital expenditure and operating costs are higher than in the W1 variant, also it does not require a large amount of space for development, and it is highly available. In addition, it allows you to use CNG fuel, therefore it does not require a minimum amount of LNG refuelling. The W3 variant is characterized by a high flexibility of operation, it is adapted to small quantities of LNG (3.5 tons tank) and can be used to supply LNG fuel directly to the cogenerator or serve as a mobile vehicle refuelling station. It is characterized by relatively low investment and operating costs and does not require any space for development. The disadvantage of this solution is the necessity to build a gas liquefaction installation without the possibility of storing production surpluses. A summary of the above comparison is presented in Table 6.

Table 6. Comparison of the proposed variants

	W1	W2	W3
Investment outlays	medium	maximum	minimum
Possibility to refuel bioCNG	no	yes	no
The amount of space occupied	medium	maximum	minimum
The need to meet the minimum bioLNG refuelling requirement	no	no	yes
Working flexibility	big	big	small
Adaptation of the installation to small quantities of bioLNG	no	no	yes
Operating costs	medium	maximum	minimum

Recommendations

Profitability of investment in one of the three proposed variants:

(W1): Variant 1. Liquefaction station + low pressure bioLNG refuelling station,

(W2): Variant 2. Liquefaction station + bioLNG and bioCNG refuelling station (called L-CNG),

(W3): Variant 3. Condensing station + mobile refuelling station,

depends on capital expenditure, operating costs and profits from the sale of bioLNG or bioCNG.

Due to the level of development and the number of recipients, the W2 variant is considered the most likely to be implemented. The possibility of selling a single fuel station in the form of liquefied LNG and compressed CNG increases the likelihood of fuel sales. The SWOT analysis for each of the variants is presented in Table 7 below.

Table 7. SWOT analysis for the proposed variants

	Strengths	Weaknesses	Opportunities	Threats
Variant 1. Liquefaction station + low pressure bioLNG refuelling station	- availability of new technologies - lower investment costs - 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 - requires a minimum amount of bioLNG refuelling - limited biogas production	- a growing market of LNG recipients - rising LNG fuel prices	- the uncertain situation related to the crisis and the possibility of reducing the sales market - in the event of a failure of the installation, the risk related to the leakage of biogas into the atmosphere
Variant 2. Liquefaction station + bioLNG and bioCNG refuelling station (called L-CNG)	- availability of new technologies - lower investment costs - local biogas production - the possibility of additional revenues from the sale of liquid CO_2	- high operating and fuel preparation costs - the need to train the Staff - limited biogas production	- a growing market of LNG and CNG recipients - rising fuel prices	- the uncertain situation related to the crisis and the possibility of reducing the sales market - in the event of a failure of the installation, the risk related to the leakage of biogas into the atmosphere

Variant 3. Condensing station + mobile refuelling station	- availability of new technologies - lower investment costs - a small area - local biogas production - does not require a minimum amount of bioLNG refuelling - 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 - the mobile refuelling station is not on sale yet - limited biogas production	- a growing market of LNG recipients - rising LNG fuel prices	- the uncertain situation related to the crisis and the possibility of reducing the sales market - in the event of a failure of the installation, the risk related to the leakage of biogas into the atmosphere - the project of a mobile refuelling station will not reach the commercialization phase

Summary

The amount of organic waste produced increases with the development of civilization. The waste is stored in areas known as waste landfills, where, with the use of appropriate technologies, it is possible to recover waste biogas. This biogas, after appropriate cleaning, drying and condensation, can be used as bioLNG fuel, for example in vehicle engines. The advantage of bioLNG is the high density of stored energy in a small volume, which allows the vehicles to achieve ranges - up to 1,500-1,600 km with one refuelling. Thanks to this, 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 refuelling station without taking into account the access to the gas pipeline.

This study presents the possibilities of using the waste gas recovered at Zakład Utylizacyjny Sp. z o.o. in Gdańsk (ZU) as bioLNG fuel to meet the energy demand of the ZU and the possibility of building a bioLNG refuelling station for fuel sales was presented.

During the work of the study, it was found that the ZU can meet the demand for electricity and heat from the nearby Clean Energy Port (PCE) waste incineration plant, therefore all recovered biogas can be converted into bioLNG fuel.

The variants of bioLNG production at the ZU site presented in this study include the construction of a biogas liquefaction station with a refuelling station in variants:

(W1): Variant 1. Liquefaction station + low pressure bioLNG refuelling station,

(W2): Variant 2. Liquefaction station + bioLNG and bioCNG refuelling station (called L-CNG),

(W3): Variant 3. Condensing station + mobile refuelling station, The variants proposed above are proposals that can be described as rare in waste treatment plants in Poland.

The production and sale of bioLNG fuel are profitable for the ZU, which was demonstrated by presenting the financial flows in the previous chapters of the study. It should be noted, however, that the investment outlays were not presented in the study for individual solutions, which were caused by trade secrets related to the construction of the installation. Therefore, when building bioLNG refuelling stations on the company's premises, it is necessary to describe the specification of essential terms of the contract and collect specific offers for the implementation of the installation. After identifying the installation costs and using this study, the final decision to build a bioLNG refuelling station should rest with the company's management.

Based on the analysis of the bioLNG production theory, the analysis of the sales market for both bioLNG and bioCNG, taking into account the possibility of selling also bioCNG, Variant 2 is indicated as the recommended technology variant, which includes the construction of a biogas liquefaction station and a refuelling station for both bioLNG and bioCNG. Such a solution will allow to increase the fuel sales market and enable its sale in a form that will be attractive in terms of price. Thanks to the possibility of refuelling with bioCNG, it is possible to replace the bus fleet in the Tri-City with low-emission vehicles, which will reduce pollution into the atmosphere and improve the quality of life of the local community.

It should also be noted that the process of biogas purification produces 99% methane, which means that the biogas is also cleaned of odorous compounds, which, after escaping into the atmosphere, can be felt by the local community. To maximize the biogas yield, it is also necessary to secure the heap as tightly as possible so that the biogas is directed only to the well, without escaping into the atmosphere.

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