Feasibility study of bioLNG (liquefied biogas) installation for Przedsiębiorstwo Komunikacji Trolejbusowej Spółka z o.o. in Gdynia as a backup source of energy supplying the trolleybus network

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Introduction

Living in the city is inevitably associated with moving around. The requirement for getting around the city by public transport is comfort and timeliness. An important aspect for local communities is also the impact of public transport on the environment. According to the European Low-Emission Mobility Strategy, transport is responsible for almost 25% of Europe's greenhouse gas emissions and is the main cause of air pollution in cities [1]. The environmental impact of transport is related, inter alia, to the noise and exhaust emissions of public transport vehicles such as buses that are powered by combustion engines.

To reduce pollutant emissions in cities, the share of environmentally friendly public transport vehicles should be increased. In 86 cities of the EU, residents can move using trolleybus communication [2]. An example of such a solution is also Przedsiębiorstwo Komunikacji Trolejbusowej in Gdynia (PKT), which supports public transport by trolleybuses. According to the report on the study of preferences and transport behaviour of Gdynia residents [3], approximately 25,3% of Gdynia residents commute to work downtown, and the average travel time by public transport takes 40 minutes. The most important reasons for using public transport (trolleybuses and buses) are difficulties in parking the car, parking fees at the destination and road congestion. The share of trolleybus trips in the structure of city trips in Gdynia is 7,7%, and the share of public transport is 37,1%.

A trolleybus is a motor vehicle with an electric drive which receives electricity from a traction substation through a two-wire overhead line via a bow current collector. The bars are mounted on the roof of the vehicle and, thanks to the possibility of rotational movement, ensure that the vehicle moves in road traffic in places where it is not possible to pass directly under the traction, with a limit of 4.5 m.

The European Commission points to a move away from biofuels produced from food crops in transport, due to their limited role in decarbonising transport, which means no support from public funds after 2020 [1]. For this reason, analytical work on cost-effectiveness and technology evaluation has been focused on more advanced biofuels such as biomethane and synthetic methane. These fuels will play a special role in passenger cars, buses and aviation. The transition to low-emission mobility in cities may increase the demand for electricity and force the energy sector to diversify in the context of the decarbonisation of this sector.

The trolleybus network is powered by electricity from the combustion of fossil fuels, specifically hard coal in the nearby CHP Plant in Gdynia, hence it can be considered friendly only to the local environment. Bearing in mind the above, it is necessary to investigate the possibility of supplying the trolleybus traction in Gdynia with a source that uses renewable energy to take care of the environment globally. Therefore, this study presents a feasibility study of the bioLNG installation for Przedsiębiorstwo Komunikacji Trolejbusowej Spółka z o.o. in Gdynia as a backup source of energy supplying the trolleybus network. It should be noted that although there is no tram network in Gdynia, due to the similar operation of the trolleybus and tram networks, if necessary, the solutions proposed in this study can also be transposed into tram networks.

The study presents the purpose of the study, the legal basis and characterizes the PKT for energy demand in trolleybus traction and substations. 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 aim of the study is to conduct a feasibility study of bioLNG (liquefied biogas) installation for Przedsiębiorstwo Komunikacji Trolejbusowej Spółka z o.o. in Gdynia (PKT) as a backup source of energy supplying the trolleybus network.

Legal basis

According to the Act on public collective transport, public utility transport is a commonly available service in the field of public collective transport, which is performed by the operator to meet the transport needs of the community in a given area on an ongoing and uninterrupted basis [4]. The above-mentioned act also introduces the concept of sustainable development of public collective transport, which means the process of transport development taking into account social expectations regarding ensuring universal availability of its services, as well as promoting environmentally friendly means of transport equipped with modern technical solutions. Collective public transport is carried out using transport such as buses, trams, trolleybuses and trains.

According to the provisions of the Act on Electromobility, the trolleybus is classified as a zero-emission vehicle (zero-emission bus) because it uses electricity to drive it, and the engine operation cycle does not emit greenhouse gases and other substances into the atmosphere [5]. The provisions of the Act impose an obligation on local governments to achieve a certain share of electric vehicles in public transport fleets, which will ultimately amount to 30%. Thanks to trolleybus communication, Gdynia is close to reaching the required threshold. However, the above Act does not specify the sources of energy origin in the overhead contact line.

Characteristics of the Implementation Partner

Przedsiębiorstwo Komunikacji Trolejbusowej Spółka z o.o. deals with trolleybus transport in Gdynia. The company was founded in January 1998 to increase the efficiency of trolleybus transport and improve the services provided to passengers. Trolleybuses cover 5 million vehicle kilometres per year and, operating on 14 lines, carry 26 million passengers annually.

Gdynia's trolleybuses are one of the three existing networks of this type of transport in Poland, and the creation of the first line dates back to 1943, during the fuel crisis caused by World War II. The traction, destroyed during the war, was rebuilt and reactivated in March 1946. Over time, as a result of low fuel prices and high electricity prices, lines were removed and trolleybuses were withdrawn from the city. However, this did not result in a complete resignation from trolleybuses in Gdynia. At the end of the 1980s, as a result of the division of municipal plants, Przedsiębiorstwo Komunikacji Trolejbusowej (PKT) was established, which dealt with the replacement of obsolete rolling stock, modernization and expansion of tram traction and the introduction of modern solutions.

The PKT rolling stock consists of about 100 vehicles. The core of the trolleybus fleet in Gdynia is low-floor Solaris vehicles: Trollino 12T, Trollino 12AC, Trollino 12M, Urbino 12T Trollino 18M, low-floor Mercedes-Benz vehicles: MB O405N, MB O530 CITARO. Trolleybuses are emission-free means of transport and are characterized by quiet operation and smooth, step-less acceleration and braking. They are equipped with, among others traction batteries enabling travel up to 30 km outside the catenary (Figure 1), automatically controlled current collectors, monitoring, USB sockets and a braking energy recovery system. Trolleybuses are equipped with power electronic drive systems, which allowed for the last 10 years to reduce energy consumption by 20% as a result of the use of recuperative braking systems. In the years 2009-2012, PKT carried out a comprehensive modernization of the power supply system, which allowed to increase its reliability and reduced transmission losses [6].

Figure 1. Trolleybus while running on battery power near the Nowowiczlińska station in Gdynia

All currently used trolleybuses are low-floor, equipped with a passenger information system and a ramp for trolleys. The list of the PKT rolling stock in Gdynia is presented in Table 1.

Table 1. List of PKT trolleybuses in Gdynia

Type	Producent	Properties	In operation from
MB 0405N	Mercedes Benz / PKT Gdynia (conversion)	- low-floor - DC drive with resistance regulation	2004
MB O530 CITARO	Mercedes Benz / PKT Gdynia (conversion)	- low-floor - asynchronous drive with inverter (IGBT) with braking energy recovery - autonomous power traction battery 84xSTH800 (SAFT)	2011
Solaris Troll ino 12T	PNTKM TROBUS, IEL, Solaris Bus&Coach	- low-floor - DC impulse drive (IGBT) with braking energy recovery	2001
Solaris Trollino 12AC	Cegelec, DP Ostrava, Solaris Bus&Coach	- low-floor - asynchronous drive with inverter (IGBT)	2003
Solaris Trollino 12M	Medcom, Solaris Bus&Coach	- low-floor - DC impulse drive (IGBT) with braking energy recovery - autonomous power traction battery 2x 84x STH800 (SAFT)	2009
Solaris Urbino 12T	Solaris Bus&Coach / PKT Gdynia (conversion)	- low-floor - DC impulse drive (IGBT) with braking energy recovery - autonomous power traction battery 2x 84x STH800 (SAFT)	2012
Solaris Trollino 12M	Solaris Bus & Coach	- low-floor - MEDCOM ANT, 3-phase, asynchronous - autonomous LTO traction battery (lithium-titanium) 58 kWh	2018
Solaris Trollino 18M	Solaris Bus & Coach	- low-floor - MEDCOM ANT, 3-phase, asynchronous - autonomous LTO traction battery (lithium-titanium) 87 kWh	2018

Source: [7]

Currently, 11 substations (named: Północna, Grabówek, Gdynia Główna (Dworzec), Wendy, Kielecka, Redłowo, Wielkopolska, Sopot, Sopot Reja (Figure 3), Nowowiczlińska, Rdestowa) are used to supply the traction network, which are approximately 2 -10 km, and the installed power of the substation is 500-4000 kW [8]. Substations are small buildings in which devices are supplying the trolleybus traction and network protection, such as 15kV switchgear, backup switches, rectifier sets, and traction power supplies. Figure 2 shows the Sopot Reja substation, which is located in the area belonging to PKT.

Figure 2. Sopot Reja substation

The rated output voltage from each substation is 660 V [9], and the voltage in the overhead contact line fluctuates as a result of changes in the power consumed by trolleybuses or changes in the resistance of the supply lines related to changes in weather conditions. The variability of the power consumed by trolleybuses also results from situations in which several vehicles start operating simultaneously on one supply section, which generates a significant power consumption and results in a significant voltage drop to a value that could immobilize other vehicles connected to the network. Voltage values higher than the rated voltage and amounting to over 750V may occur in a situation where no trolleybus starts or accelerates, therefore the current consumption is negligible [10].

Figure 3. The map of the traction network with the distribution of supply substations [9]

Przedsiębiorstwo Komunikacji Trolejbusowej Spółka z o.o. is a company that has been implementing projects related to the development of trolleybus communication with the support of the European Union for years. In recent years, projects were also financed by the Integrated Operational Program for Regional Development (2004-2006).

Thanks to the projects implemented in previous years, it was possible, among others, to introduce trolleybuses equipped with a battery drive into the rolling stock, which makes these vehicles independent of power supply from the traction network, and to install a supercapacitor energy storage on the traction network to increase the energy efficiency of the trolleybus system (CIVITAS DYN@MO project financed by under the 7th Framework Program of the European Commission). The funds were also allocated to the construction of a new depot in Leszczynki, the expansion of the trolleybus traction and the purchase of trolleybuses. The CIVITAS ELIPTIC project introduced a double-sided traction power supply at two points on the network, which allowed to stabilize the voltage in the network, optimize the energy balance of the power supply system and increase energy recovery from braking (saving about 2-5% energy). As part of the CAR project, the In Motion Charging (IMC) system was expanded and chargers for quick charging of battery trolleybuses were launched. The charger is equipped with a storage power system (based on a lithium-ion battery) and located outside the overhead contact line to charge vehicles when parked in locations where there is no trolleybus network infrastructure available [7].

The latest project implemented at PKT is the "Green public transport" project (Phase 1), which is co-financed by the National Fund for Environmental Protection and Water Management, and the subject of the project is the purchase of 6 zero-emission 12-meter trolleybuses with an alternative battery drive [7].

Analysis of the energy needs of Przedsiębiorstwo Komunikacji Trolejbusowej Spółka z o.o. in Gdynia

Technical characteristics of substations and depots

The annual electricity demand for individual substations varies, according to Table 2. The output power of the substation is 600 kW - 2 MW, but in practice, the maximum power is much lower: from 300 kW to 800 kW [9].

Table 2. Annual energy consumption of individual substations (traction energy consumption) and depots (non-traction energy consumption) [9].

Annual energy consumption	
	MWh
Traction energy consumption	
Północna	1830
Grabówek	2022
Kielecka	911
Dworzec	710
Wendy	1175
Redłowo	1475
Wielkopolska	328
Chwaszczyńska	1676
Sopot	246
Sopot Reja	127
Non-traction energy consumption	
Depot – 400 V AC	430

Each substation supplies a separate area, with some areas interconnected, but on a global scale, the power flow between the areas is small. Some substations have two 15 kV power lines, but no additional power sources. Part of the rolling stock is equipped with recuperative braking systems. The diagram of the trolleybus traction in Gdynia, which is located in the Redłowo substation, is shown in Figure 4. In the Figure, individual sections of the overhead line are distinguished with colours, and the measuring points for the overhead line voltage are also marked.

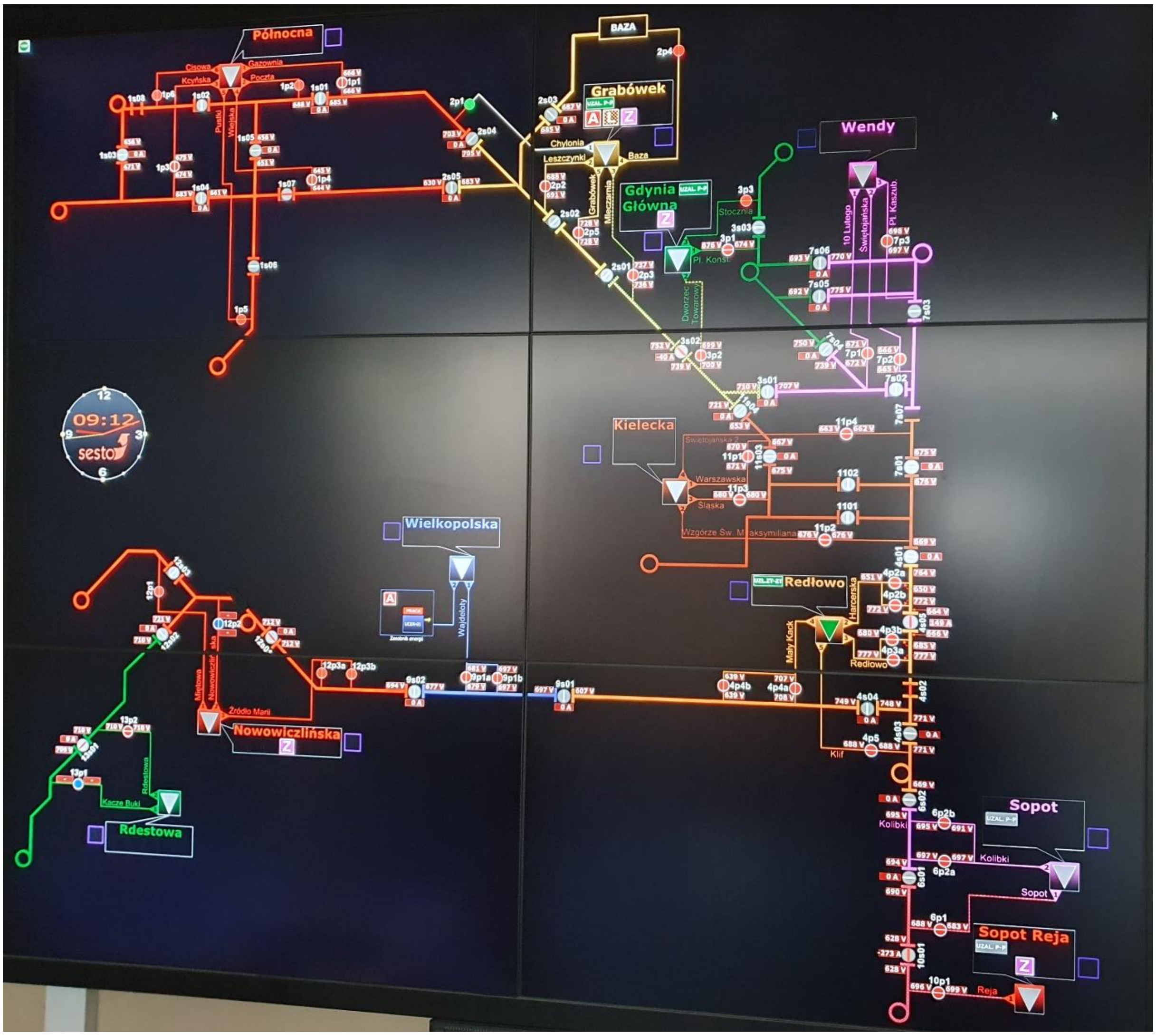

Figure 4. Diagram of trolleybus traction in Gdynia in the Redłowo substation (photo A. Lenarczyk)

In substations, devices are supplying the trolleybus traction and network protection, such as 15kV switchgear, backup switches, rectifier sets, and traction feeders.

Figure 5 shows photos of the power devices at the Sopot Reja substation.

Figure 5. Devices supplying the Sopot Reja trolleybus substation (photo by A. Lenarczyk)

Figure 6 shows a diagram of the substation and a cabinet with power devices for the Nowowiczlińska substation.

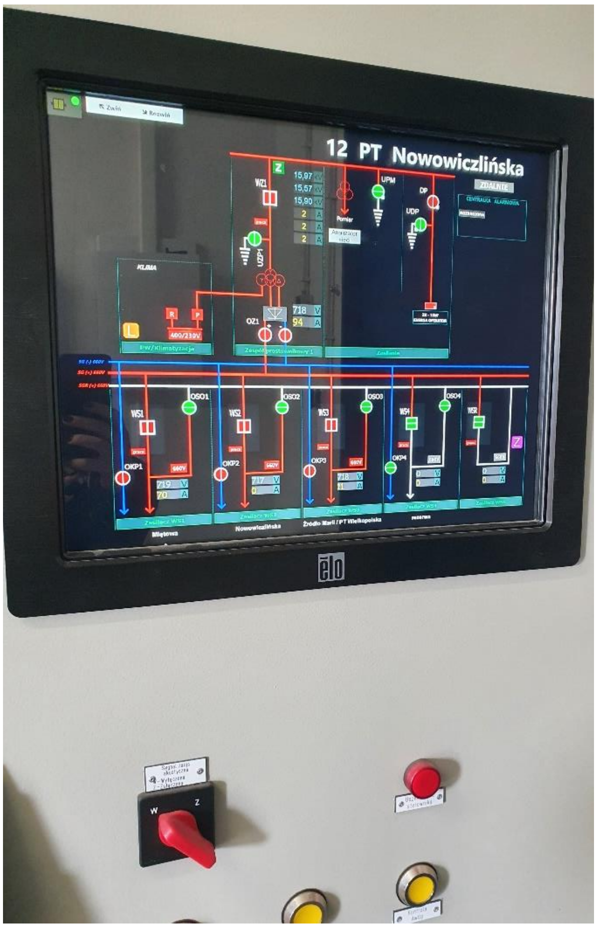
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Figure 6. Diagram of the substation and the cabinet with power devices of the Nowowiczlińska substation.

The trolleybus network has no backup power supply. In the event of a failure or modernization of a section of the network, it is possible to supply it from another substation. However, it is possible only for selected sections of the trolley network and for a specific energy demand (off-peak load).

Conditions and potential for the use of biogas, including bioLNG

Technology proposal

According to the provisions of the Act on Renewable Energy Sources [11], biogas is a gas obtained from biomass, and biomass is called biodegradable parts of products, waste or residues of biological origin from agriculture, including plant and animal substances, forestry and related industries, including fisheries and aquaculture, processed biomass, in particular in the form of briquettes, pellets, torrefaction and biochar, as well as the biodegradable part of the industrial or municipal waste of plant or animal origin, including waste from waste treatment installations and waste from water treatment and wastewater treatment, in particular, sewage sludge, under the provisions on waste in the scope of qualifying a part of the energy recovered from the incineration of waste. 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 may contain up to 85% methane and have a calorific value of 25 – 30 MJ/m^3.

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.

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 [12].

Figure 7 shows a schematic diagram of the proposed solution for supplying the PKT overhead contact line with biogas. Biogas produced in a biogas plant or recovered from waste is sent to the biogas refining station, where it is cooled and passes through an activated carbon filter to remove impurities, solid particles and other compounds (biogas purification takes place), then the gas is dried and condensed at a temperature of -162^{o}C to form bioLNG. BioLNG is stored in a cryogenic tank before it is transported by a tanker or mini-tank truck mounted on a delivery truck, to a cogenerator or to a fuel cell, which will generate electricity supplying a section of the trolleybus network of PKT.

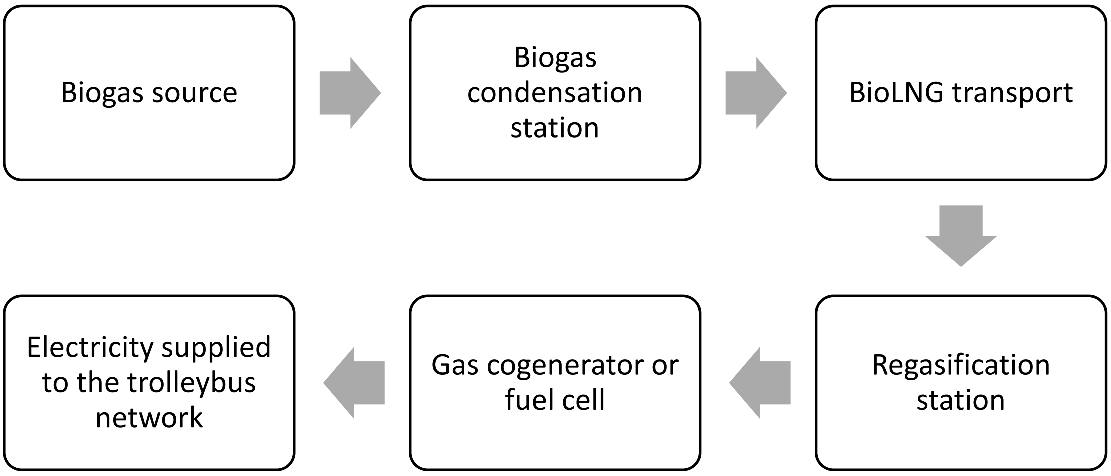

Figure 7. Schematic diagram of the proposed solution, own elaboration based on [13][7]

BioLNG is a liquid renewable fuel, the volume of which is over 600 times smaller than that of gaseous biomethane. 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 to the trolleybus traction. The use of bioLNG as fuel enables the reduction of greenhouse gas emissions by 90% (by 70% of nitrogen oxides) with the complete elimination of solids content in the exhaust gas. Thanks to the use of bioLNG to power the traction network of trolleybuses, it is possible to provide clean public transport not only in the place of its occurrence but also to resign from indirect participation in air pollution when using energy from fossil fuels.

Gas storage in liquefied form is possible in cryogenic tanks. The design of such a tank allows to maintain the temperature of the fuel. Most often, cryogenic tanks have a capacity of 60 m^3.

BioLNG is distributed in tankers (Figure 8) or cryogenic tanks (mini tanks) (Figure 9), which can also be used for storage, and is used as fuel for energy production in a gas cogenerator.

Transport of bioLNG and LNG from the production station to the regasification station 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.

Figure 8. BioLNG transport tank [14]

BioLNG/LNG cryogenic tank (mini-tank) is used to transport smaller amounts of fuel.

Figure 9. Cryogenic tank (mini-tank) for the transport of bioLNG / LNG - Microfueler LNG

The diagram of the cryogenic tank (mini-tank) for the transport of bioLNG / LNG - Microfueler LNG is shown in Figure 10, and the description of its functions is described in Table 3.

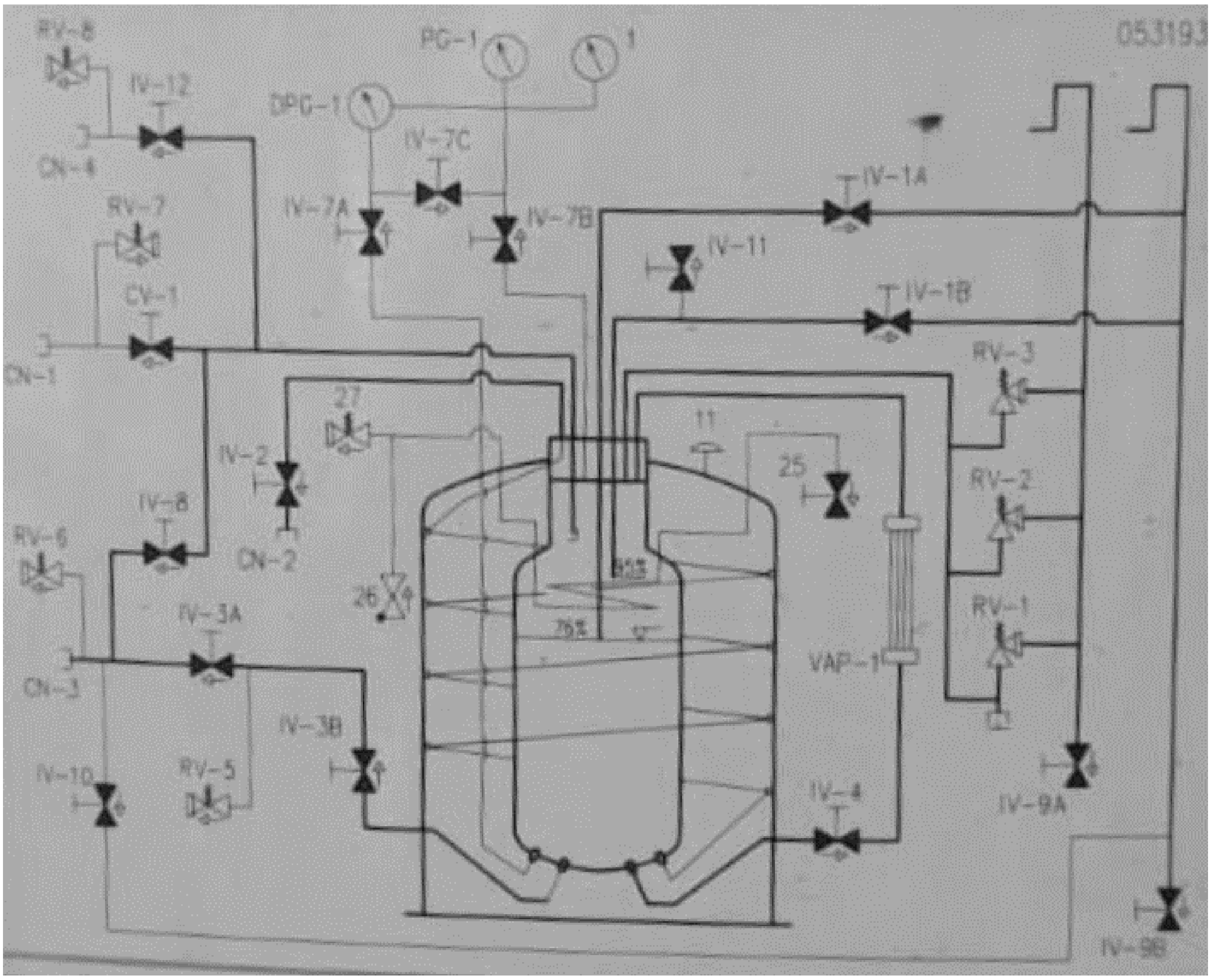

Figure 10. Diagram of a bioLNG / LNG Microfueler cryogenic tank (mini-tank)

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 11. Mobile refuelling station [15]

Regasification stations are equipped with evaporators used to change the form of gaseous fuel from liquid to gaseous, ensuring the regasification capacity required by the customer, expressed in m^3 per hour. The main components of the regasification station installation are:

- bioLNG fuel tank can be a cryogenic tank permanently located on the premises of a substation or a cistern, mini cistern or mobile refuelling station,
- atmospheric steamer,
- gas heater,
- 1st-degree reduction panel,
- odorization station for bioLNG fuel,
- compressed nitrogen system to drive pneumatic valves,
- installation of control and measurement equipment and automation.

The size of the cryogenic tank and the capacity of the installation is determined depending on the fuel demand [16]. Figure 12 shows the Chemet S.A. LNG regasification station.

Figure 12. Chemet S.A. LNG regasification station [16]

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 [17].

Biogas is used to power stationary reciprocating engines that are coupled to a generator. Expansion of the cooling system of this type of engine allows for the recovery of thermal energy, which is cooled in the cooler in a classic combustion engine. The process of producing electricity and heat in one thermodynamic process (using the same amount of fuel) is called cogeneration. Heat recovery increases the efficiency of energy conversion in an internal combustion engine and can be used to heat nearby rooms, e.g. substations, or supply a district heating network. Thanks to this, it is possible to achieve the efficiency of a cogeneration unit of the order of 90%, i.e. twice as efficient as a traditional combustion engine.

Cogeneration units can be powered by biogas with different methane content, which also allows them to be used in sectors related to municipal waste management, as the methane content in landfill gas is about 47-60%. Therefore, electronic controllers are used in the supply in mixers, which support the automation of the process. Figure 13 shows a Jenbacher CHP unit.

Figure 13. Jenbacher CHP unit [18]

To enable an economically viable use of a CHP plant, long operating periods must be ensured. The longer a CHP unit can reasonably release heat and electricity, the faster it will be amortized.

As mentioned, bioLNG fuel is a liquefied form of biomethane with high methane (CH_4) content. BioLNG fuel can be used to generate electricity using fuel cells.

Fuel cells convert the chemical energy contained in the fuel into electricity and heat and can therefore replace an internal combustion engine. Fuel cells are characterized by high efficiency of energy generation in a wide range of loads and low emission of pollutants. The principle of operation of fuel cells is based on an electrochemical reaction based on hydrogen, produced from natural gas, biogas or by steam reforming of other fuels. Figure 14 shows an example of a structure of a polymer fuel cell [19].

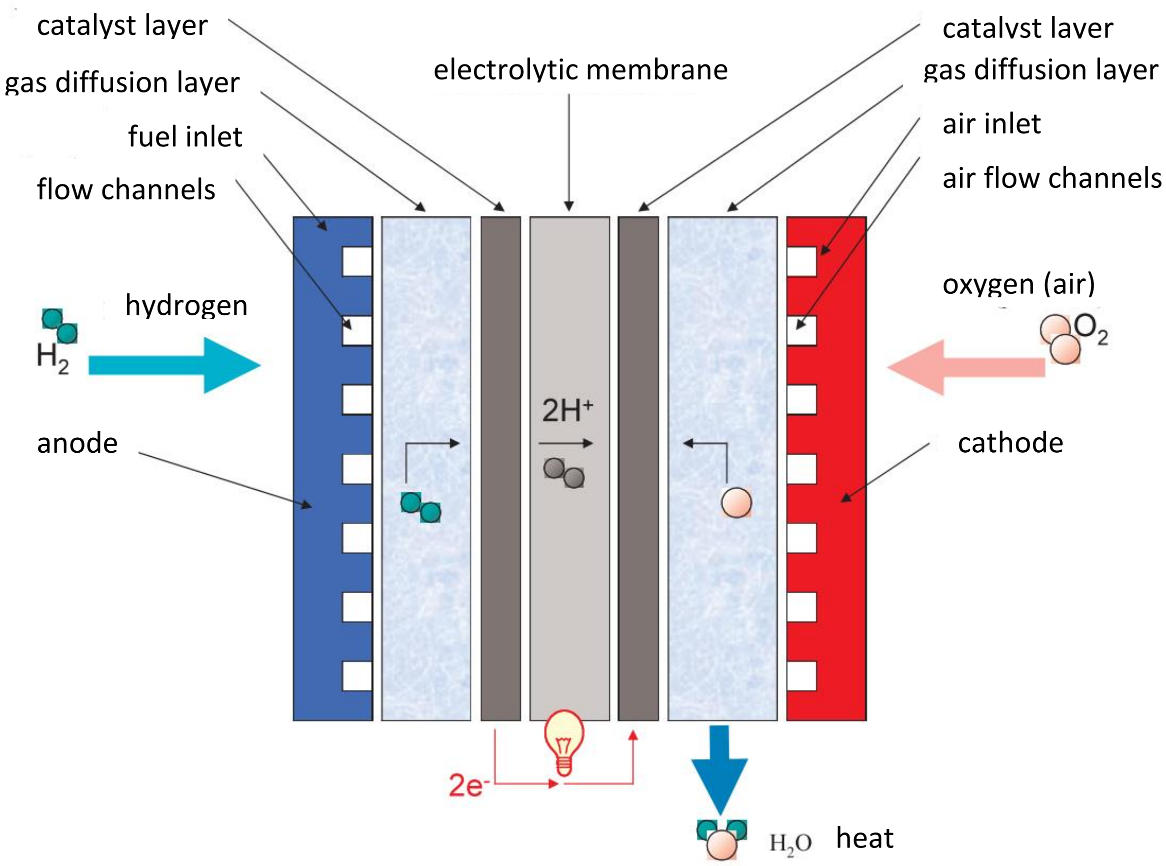

Figure 14. An exemplary structure of a polymer fuel cell [19].

In a fuel cell, an electrolyte is placed between the anode and the cathode, which donates ions but allows the flow of electrons. The substrate in the form of hydrogen is fed to the anode and oxygen is taken from the surroundings. A chemical reaction generates electricity and a by-product is a water. The system does not need an external power supply because the flow of electrons is the result of the natural tendency of the system to states with lower free energy [19].

The maximum voltage of a single cell does not exceed 1V, therefore the fuel cells are connected in series to obtain the appropriate voltage and power. The construction of fuel cells is modular, thanks to which it is possible to select systems with any parameters [19].

Fuel cells are characterized by the possibility of continuous operation, and the possibility of using various types of fuels, such as hydrogen, methane, methanol, and biogas, they emit a negligible amount of pollutants into the atmosphere. Some types of fuel cells, such as SOFC and MCFC, generate electricity and heat in a single process. Fuel cells can be combined modularly, which allows you to increase their power.

The disadvantages of fuel cells include the low voltage and low power obtained from a single module, and the high cost of materials used as catalysts.

To be able to use bioLNG in a fuel cell, it must be properly prepared through regasification processes and, depending on the technology chosen, the oxidation process, steam reforming or autothermal reforming. The hydrogen produced in this way from methane can power a fuel cell. It should be noted that the methods of recovering hydrogen from methane require energy expenditure because, in the hydrogen oxidation method, the reformer must be cooled down. In the steam reforming process, heat must be provided that reduces the amount of heating heat obtained from the fuel cell. The process of producing a liquid form of biomethane - bioLNG includes desulphurization, so in this case, there is no need for additional fuel desulphurization.

As a result of the methane reforming process, hydrogen is formed with a certain amount of carbon oxides, which contaminate the fuel cell by deposition on the catalyst surface, preventing access to hydrogen molecules. High-temperature cells have a greater tolerance to the presence of carbon monoxide, therefore they should be used with the use of hydrocarbon fuels.

Production of hydrogen directly from bioLNG is a relatively new technology and is based on the steam reforming method. In this method, methane molecules react with water vapour at a temperature above 750 ^{0}C which leads to the separation of LNG molecules into hydrogen and carbon dioxide. Hydrogen can be used to power the engine in the form of fuel cells, and carbon dioxide is condensed with cryogenic steam from LNG and can be used as an inert gas. The first installation of this type was launched by the Swedish company FKAB Marine Design and operates on a medium-sized tanker [20].

Supplying a section of the traction network with a fuel-cell-powered by bioLNG would require an installation consisting of:

- bioLNG fuel tank (tanker, mini-tank or mobile refuelling station),
- regasification stations,
- installations for the production of hydrogen from biomethane,
- fuel cell,
- connections to the substation.

As described above, the production of hydrogen from liquefied biogas requires significant energy expenditure on fuel evaporation, detachment of hydrogen molecules from carbon dioxide, and cooling of carbon dioxide. In addition, the installation would require energy expenditure for cooling cryogenic tanks with bioLNG and it would be necessary to provide for the use of the evaporated part of the fuel, which can be used as CNG fuel after prior compression.

Currently, the fuel cell market is a dynamically developing market. Due to the operating temperatures of fuel cells, the materials they are made of have a significant impact on the final price of the device.

The type and operating temperature of the device are defined by the type of electrolyte that is used in the device. The electrolyte in a fuel cell can be molten salt, concentrated potassium hydroxide solution, polymer membrane, or solid electrolyte. The operating temperature is in the range of 60-1000 ^{0}C. fuel cells achieve efficiency from 70% to 90%.

The selection of the appropriate type of fuel cell depends on the specific application, power and operating temperature of the device. Due to the power yield and the multitude of applications, fuel cells of the SOFC or PEMFC type could be used to supply the trolleybus traction.

The selection of a specific solution and the performance of technical and economic analysis of the overhead contact line supply from a fuel cell should be performed for a strictly defined section of the overhead contact line, taking into account its detailed energy demand characteristics.

A proposal for the use of bioLNG fuel technology

Taking into account the advantages of using bioLNG, this study proposes its use in variants:

- Variant 1: Powering the trolleybus network to charge vehicles while parked in locations where there is no trolleybus network infrastructure available
- Variant 2: Supplying a dedicated section of the trolleybus network - gas cogenerator
- Variant 3: Meet the energy needs of the PKT solely by bioLNG

The solutions require the construction of a power station built from an electricity source and a connection at the substation. The individual suggestions are described below.

Variant 1: Powering the trolleybus network to charge vehicles while parked in locations where there is no trolleybus network infrastructure available.

Charging trolleybus vehicles equipped with batteries outside the trolleybus line is not possible due to the vehicle structure. Trolleybuses are equipped with internal power supplies that are permanently installed in the vehicle and constitute its integral part. To be able to charge the battery in a trolleybus, it must be connected to the overhead contact line. In this case, it is possible to charge the trolleybus battery from a cogenerator or a bioLNG fuel cell via a traction substation or a charging point connected to the catenary. The trolleybuses of the PKT rolling stock are equipped with several types of traction batteries with different capacities and construction technology. PKT does not have data on the levels of discharge of trolleybus batteries, which are discharged to varying degrees, therefore it is not possible to determine the amount of energy needed to charge them. In connection with the above, it can be assumed that the trolleybus batteries will be charged from the overhead line (separated in the area in which they operate), which could be powered by a cogenerator or a fuel cell through substations. This solution excludes the identification of Variant 1, as it comes down to supplying the overhead contact line section, which is the basis for Variant 2 and Variant 3. Therefore, Variant 1 will not be analyzed further.

Variant 2: Supplying a dedicated section of the trolleybus network - gas cogenerator

The traction network is supplied through the power system in which the energy producers are coal-fired power plants. In the substation, there are devices for converting alternating current, available in the power grid, into direct current supplying the traction network. To reduce the indirect impact on the environment, it is possible to use a bioLNG fueled cogeneration unit to supply a dedicated section of the overhead line. The installation would consist of a bioLNG fuel tank (tanker, mini-tank or mobile refuelling station), a regasification station, a gas cogenerator coupled to a power generator and a connection to the substation.

The bioLNG tank and regasification station could be located in substations:

- Północna,
- Grabówek,
- Redłowo,
- Sopot Reja.

The choice of a specific location would depend on the size of the tank and installation. It should be noted that each area is supplied from a separate connection to the power grid located in the substation building. The profile of energy consumption within the area is variable and depends on the number of trolleybuses currently operating and the traffic intensity. Therefore, to supply individual areas with a bioLNG cogenerator, each area would need to be considered individually. PKT does not have information on the metering of energy consumption for individual areas, and their contract for energy supply is comprehensive for the entire enterprise. This means that the energy that is taken from the grid is used to supply the overhead contact line as well as for lighting and heating of PKT buildings, for example, substations. Due to the above, it is currently not possible to perform a detailed analysis of the supply of a trolleybus section with a bioLNG cogenerator, but only the analysis in a simplified version. The simplified version consists in determining the instantaneous energy demand in given traction sections based on data on annual energy consumption. It should be noted that, by simplifying, the supply of the traction network section, depending on the currently moving trolleybuses, is not tested. A simplified schematic diagram of the proposed solution is presented in Figure 15.

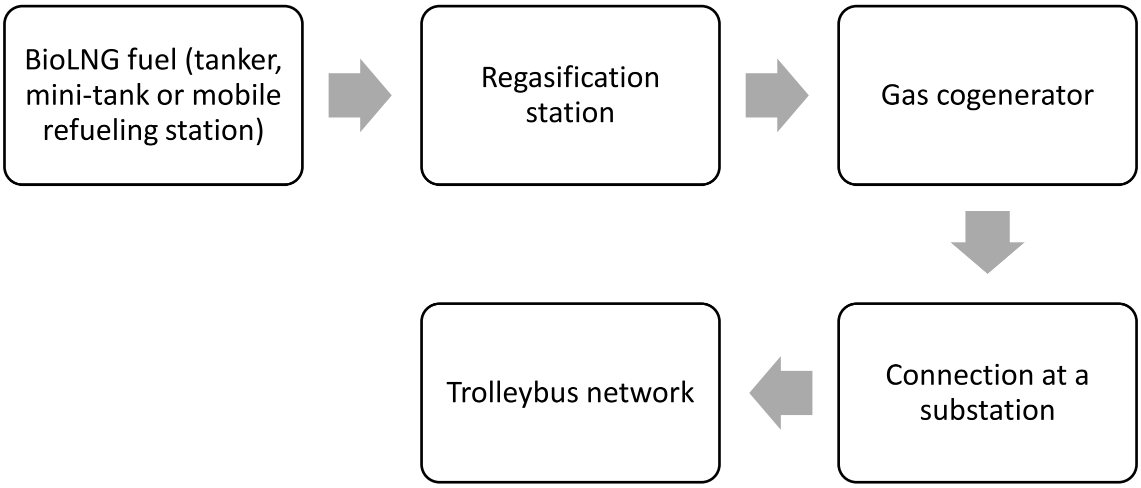

Figure 15. Schematic diagram of electricity supply to a section of the traction network from a gas cogenerator

Variant 3: Meet the energy needs of the PKT solely by bioLNG

The PKT trolleybus network consists of network sections supplying individual areas. Sections of the trolleybus network are connected with each other only in selected places, and connections are made in special cases, such as breakdowns, repairs or modernization of individual sections. Additionally, the substation buildings are supplied with power from the trolleybus network. The energy demand of individual sections of the traction network, and consequently of the entire network, depends on the number of trolleybuses currently in use, their type (whether they are equipped with batteries or a recuperative braking system) and weather conditions. Therefore, in the implementation of the item "analysis of the possibility of meeting the PKT energy needs only with bioLNG", the total annual electricity demand of the PKT was adopted as an input value.

Comparison of variants

Each of the proposed three variants of PTS with energy derived from the use of bioLNG has advantages and disadvantages, which are briefly described in Table 4.

Table 4. Comparison of the advantages and disadvantages of the analyzed variants

	Variant 1: Powering the trolleybus network to charge vehicles while parked in locations where there is no trolleybus network infrastructure available	Variant 2: Supplying a dedicated section of the trolleybus network - gas cogenerator	Variant 3: Meet the energy needs of the PKT solely by bioLNG
Advantages	- independence from the accessibility area of the trolleybus network	- operation with gas with low methane content - well-known technology - relatively cheap solutions	- powering trolleybuses and PKT buildings from renewable energy sources - an environmentally-friendly enterprise not only locally
Disadvantages	- it is not possible to charge trolleybus vehicles equipped with batteries outside the trolleybus network	- exhaust emissions - noise emission	- the traction network is divided into sections, which means that one installation is not enough - bigger costs - noise emission

The undoubted advantage of Variant 1 is the independence of trolleybus transport from the available trolleybus network, which would allow the Company to expand its operations to districts that are not currently serviced. However, due to the currently used technological solution for powering batteries in a trolleybus, which requires access to the trolleybus traction, it is not possible to charge them outside the area served by PKT. However, this is a proposal that should be considered in future development works in the company if it is possible to purchase new battery-powered tram vehicles that can be charged directly from the power system. Charging stations can be remote from human settlements so that noise is not a nuisance for residents. The use of bioLNG as a fuel would allow reducing the amount of exhaust fumes emitted into the atmosphere, due to the previously performed flue gas cleaning process.

The advantage of Variant 2 is the possibility of feeding the gas cogenerator with fuel with low methane content, which is characteristic of biogas, which allows saving the energy required to purify the biogas. Gas cogenerators that are fired with gas with different methane content are available on the market at relatively low prices. The disadvantage of feeding the cogenerator with gas with different methane content is the emission of exhaust gases into the atmosphere, resulting from the combustion of unpurified gas. To avoid exhaust emissions, the gas cogenerator should be operated with purified gas, for example from bioLNG regasification. In this variant, noise emission should also be mentioned, which may be troublesome for residents, especially if you want to build a power station in the area of the Redłowo substation.

Variant 3 assumes that the energy needs of the PKT will be satisfied solely by supplying the gas cogenerator with bioLNG fuel, which, if implemented, would contribute to reducing the environmental impact of local public transport. However, such a solution is associated with significant investment outlays in gas cogenerators, which would have to separately supply individual sections of the traction network, currently divided into sections.

Technical and economic analysis

Determination of the demand for fuel for individual sections of the trolleybus traction supplied from the Północna, Grabówek, Redłowo and Sopot Reja substations and for the entire PKT was performed analogously to the calculation example presented below, made for the Północna substation.

The total energy demand of the Północna substation during the year [21] was determined according to the formula:

$$E_{Północna} = 1830\,\frac{MWh}{a} \qquad (1)$$

where:

$E_{Północna}$ - total energy demand of the Północna substation, $\frac{MWh}{a}$

The average daily energy demand was determined in a simplified manner, assuming a constant and unchanging energy consumption from the traction network. The energy recovered as a result of braking was also omitted, obtaining:

$$E_d = \frac{E_{Północna}}{a} = \frac{1830}{365} = 5\,\frac{MWh}{d} = 208{,}90\,\frac{kWh}{h} \qquad (2)$$

gdzie:

E_d - average daily energy demand for the Północna substation, $\frac{MWh}{d}$

$E_{Północna}$ - total energy demand of the Północna substation, $\frac{MWh}{a}$

a – the number of days in the year, [-]

Assuming that about 3 MWh of electricity is obtained from a cryogenic tank with a capacity of $V_{LNG\ tank} =$ 500l of bioLNG, the number of tanks containing fuel covering the daily demand for the Północna substation traction network can be determined:

$$N_{\dot{B},d} = \frac{5}{3} = 1{,}7 \qquad (3)$$

gdzie:

$N_{\dot{B},d}$ - number of tanks which contain fuel covering the daily requirement for the trolleybus network, [-]

After taking into account the capacity of the cryogenic tank, the daily demand of the overhead line for bioLNG can be determined:

$$\dot{B}_{bioLNG} = N_{\dot{B},d} \cdot V_{LNG\ tank} = 1{,}7 \cdot 500 = 835{,}6\ \frac{l}{d} \qquad (4)$$

gdzie:

$\dot{B}_{bioLNG/LNG}$ - daily trolleybus network demand for bioLNG, $\frac{l}{d}$

$N_{\dot{B},d}$ - number of tanks which contain fuel covering the daily requirement for the trolleybus network, [-]

$V_{LNG\ tank}$ – capacity of the cryogenic tank, cisterns, l

Taking into account the assumption that 1 litre of liquid takes up a volume of 1 dm^3, which corresponds to 0,001 m^3, the daily volumetric requirement for bioLNG can be estimated as:

$$\dot{B}_{vbioLNG} = \dot{B}_{bioLNG} \cdot 0{,}001 = 835{,}6 \cdot 0{,}001 = 0{,}835\ \frac{m^3}{d} \qquad (5)$$

Assuming that 1 litre of LNG corresponds to 0,52 m3 of gas, the daily demand of the cogenerator feeding the trolleybus network for gas can be determined:

$$\dot{B}_{biogas} = \dot{B}_{bioLNG} \cdot 600 = 492{,}88 \frac{m^3}{d} \qquad (6)$$

Assuming the above results, it is possible to determine the time for which the fuel collected in a standard cryogenic tank with a capacity of 60 m^3 is sufficient. To determine this time, it should be assumed that the cryogenic tank can be loaded up to 95% of its capacity for technical reasons, and the formula:

$$N_{\ 60m^3\ tanks} = \frac{60 \cdot 0{,}95}{\dot{B}_{vbioLNG}} \cong 68\ d \qquad (7)$$

As a result of the presented calculations, filling the cryogenic tank with a capacity of 60 m^3 with bioLNG fuel is enough to cover about 2 months of the electricity demand of the Północna substation.

Similarly, the demand for bioLNG was determined for the Grabówek, Redłowo and Sopot Reja stations, the results are presented in the table below.

Table 5. Results of determining the daily gas fuel demand for selected substations and the entire PKT

	The total energy demand of the Północna substation	Average daily energy demand	Average energy demand	Number of tanks	Daily trolleybus network demand for bioLNG	Daily demand for biogas	The number of days that can be supplied from one 60 m^3 tank
	$\frac{MWh}{a}$	$\frac{MWh}{d}$	$\frac{kWh}{h}$	[-]	$\frac{l}{d}$	$\frac{m^3}{d}$	[-]
Północna	1830,00	5,01	208,90	1,67	835,62	492,88	68,21
Grabówek	2022,00	5,54	230,82	1,85	923,29	544,60	61,74
Redłowo	1475,00	4,04	168,38	1,35	673,52	397,27	84,63
Sopot Reja	246,00	0,67	28,08	0,22	112,33	66,26	507,44
PKT	11700,00	32,05	1335,62	10,68	5342,47	3151,22	10,67

After determining the PKT's demand for fuel in the form of bioLNG and transforming it into a gas form, a technical and economic analysis was performed for individual variants and proposed solutions, as presented below.

Assumptions for economic analysis:

- BioLNG and LNG cryogenic tanks are made based on contractual agreements, therefore their exact price is not possible to obtain. According to the prices shown in [22] tanks with a capacity of 20 m^3 to 60 m^3 cost from USD 95,000 to USD 135,000.
- Regasification stations degassing approximately 60 m^3 of gas per hour cost approximately USD 10,000.
- Due to the lack of data on the construction costs of a substation connection, this cost was omitted.
- The operating costs of the installation were not included in the analysis.
- Base year - the year when the project implementation begins.
- The operational period is set at 25 years, but it should be noted that technological progress may force the modernization of the installation in a period shorter than assumed in the analysis. In this case, a separate technical and economic analysis for modernization works should be performed.
- The analysis was carried out at constant prices - without taking into account the impact of inflation, assuming a constant annual price increase.

- 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 / kg, therefore, for the first year of the analysis, the value was PLN 12.50 / kg (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 fuel and electricity is currently used in the research community.
- The cost of regasification of fuel from liquid LNG to gaseous form, which can be used both in a cogenerator and in a fuel cell, was estimated based on interviews with people from the liquefied fuel industry and the amount was set at PLN 6 per 1 kg of LNG [9].
- For each year of the analysis, cash flows are presented, i.e. in each year, revenues, expenditure on project implementation and operating costs were indicated, and the difference between revenues and expenditure and costs was determined.
- The payback period for investment outlays on investments related to the generation of electricity, and thus also cogeneration is usually assumed to be 7-10 years from the beginning of the installation's operation. For the analysis, it was assumed that the investment outlays would be repaid in equal instalments over 10 years. This is a simplifying assumption because the actual debt repayment varies and results from the division into own funds and credit repayment, different interest rates and different methods of determining the number of instalments.
- The analysis assumes that the design phase, obtaining the necessary permits and construction will take 2 years. During these two years, capital expenditure related to the construction of the installation must be incurred. The analysis does not assume the structure of investment financing, in which the enterprise's funds, loans and obtaining financing can be distinguished.
- A complex method was used in the analysis (the complex method consists in estimating the transport costs and operating costs for each solution option in individual years. The difference in revenues between the two above scenarios (implementation of the proposed variant or not) constitutes revenues of the project (avoided costs), while the difference in costs between the above scenarios is the loss of failure to implement the variant.

Taking into account the above, the economic analysis presents calculations showing the amount of investment expenditure to achieve the economic profitability of the proposed solutions.

Variant 1: Powering the trolleybus network to charge vehicles while parked in locations where there is no trolleybus network infrastructure available.

Variant analyzed under Variant 2 and Variant 3.

Variant 2: Supplying a dedicated section of the trolleybus network - gas cogenerator

Supplying a section of the trolleybus network with a gas cogenerator powered by bioLNG will require an installation consisting of:

- bioLNG fuel tank (tanker, mini-tank or mobile refuelling station),
- regasification stations,
- gas cogenerator,
- connections to substations.

Table 6. The statement of capital expenditure was prepared based on the energy demand of the substation and the entire PKT

	Instantaneous energy demand	Gas turbine power		BioLNG fuel tank cost	Cost of the regasification station	The cost of purchasing a gas cogenerator	Total investment outlays
	kWh/h	kW	kWc	PLN	PLN	PLN	PLN
Północna	208,90	238,00	363,00	607 500,00	55 000,00	1 402 880,00	2 065 380,00
Grabówek	230,82	363,00	498,00	607 500,00	55 000,00	1 625 570,00	2 288 070,00
Redłowo	168,38	199,00	263,00	405 000,00	55 000,00	1 224 380,00	1 684 380,00
Sopot Reja	28,08	50,00	81,00	607 500,00	55 000,00	178 500,00	841 000,00
PKT	11 700,00	1560,00	1884,00	1 215 000,00	110 000,00	7 000 000,00	8 325 000,00

Północna substation

The instantaneous electricity demand for the Północna substation is **208,9 kWh/h**, which corresponds to bioLNG fuel consumption of about 0,84 m3 per day.

For these values, examples of possible gas cogenerators are listed below:

- Viessmann Vitobloc 200, EM-238/363, 238 kWe, 363 kWc [23]
- Set of 3 cogenerators * OEKO 2x100 kW and OEKO 30 kW [24]
- Jenbacher 2 type J208, 350 kWe, 370 kWc

To meet the energy demand, the delivery of 2 tankers a day with a capacity of 500l of bioLNG/LNG is required.

Companies constructing bioLNG and LNG regasification stations:

- CryoGas
- Novatek Green Energy
- CHEMET S.A.

Calculation example based on the analysis of the first year of operation of the station supplying the Północna substation with bioLNG fuel.

The annual demand for bioLNG fuel expressed in litres was determined from the formula:

$$\dot{B}_{bioLNG,t,l} = \dot{B}_{bioLNG/LNG} \cdot 365 = 305\ 000\ l \quad (8)$$

where:

$\dot{B}_{bioLNG,t,l}$ – annual bioLNG fuel requirement, l

$\dot{B}_{bioLNG/LNG}$ - daily trolleybus network demand for bioLNG/LNG, $\frac{l}{dzień}$

Fuel prices are given in PLN per kilogram, so consumption should be expressed in kilograms per year. For the analyzed case, it was assumed that 1 l of bioLNG equals 0,4 kg and the formula was used:

$$\dot{B}_{bioLNG,t} = \dot{B}_{bioLNG,t,l} \cdot 0{,}4 = 122\ 000\ kg \quad (9)$$

In the first year of operation of the installation, the costs of regasification were determined based on the formula:

$$K_{reg,t} = \dot{B}_{bioLNG,t} \cdot c_{reg} = 732\ 000\ PLN \quad (10)$$

where:

$K_{reg,t}$ – the cost of regasification of fuel from liquid LNG to gaseous form in year t, PLN

$\dot{B}_{bioLNG,t}$ – annual bioLNG fuel requirement, kg

c_{reg} – bioLNG fuel regasification price, PLN/kg

The annual cost of bioLNG fuel was determined from the formula:

$$K_{bioLNG,t} = \dot{B}_{bioLNG,t} \cdot c_{bioLNG,t} + K_{reg,t} = 2\ 257\ 000\ PLN \quad (11)$$

where:

$K_{bioLNG,t}$ - the cost of purchase of bioLNG fuel in year t, PLN

$\dot{B}_{bioLNG,t}$ – annual bioLNG fuel requirement, kg

$c_{bioLNG,t}$ – purchase price of bioLNG fuel, $\frac{PLN}{kg}$

$K_{reg,t}$ – the cost of regasification of fuel from liquid LNG to gaseous form in year t, PLN

The use of cogeneration to generate electricity to supply a trolleybus network is associated with the production of large amounts of heat energy in a cogenerator. Thermal energy can be used for the company's own needs or sold. For the analysis, it was assumed that the energy will be sold to the local heating network, thanks to which it is possible to obtain revenue from the sale of heat, following the presented formula:

$$R_{c,t} = 3{,}6 \cdot P_{TG} \cdot T_i \cdot c_{c,t} = 522\,720\ PLN \tag{12}$$

where:

$R_{c,t}$ – revenue from the sale of thermal energy in year t, PLN

P_{TG} – gas turbine power, MW

T_i – time of use of gas turbine power, h

$c_{c,t}$ – selling price of thermal energy, $\frac{PLN}{GJ}$

To determine the profit from the application of the solution proposed in Variant 2, i.e. feeding a section of the trolleybus network in the Północna substation from cogeneration, the cost of purchasing electricity required to supply this section of the trolleybus network should be determined if the solution proposed in Variant 2 was not applied. The cost of purchasing electricity was determined from the formula:

$$K_{ee,t} = E_{Północna} \cdot c_{ee,t} = 1\,830\,000\ PLN \tag{13}$$

where:

$K_{ee,t}$ – the cost of purchasing electricity to supply a section of trolleybus traction, PLN

$E_{Północna}$ - total energy demand of the Północna substation, $\frac{MWh}{a}$

$c_{ee,t}$ – electricity purchase price, $\frac{PLN}{MWh}$

In the next step, the difference between the cost of purchase of fuel and electricity reduced by the revenue from the sale of thermal energy was determined, following the formula:

$$R_{k,t} = K_{ee,t} - \left(K_{bioLNG,t} - R_{c,t}\right) = 95\,720\ PLN \tag{14}$$

where:

$R_{k,t}$ – the difference between the cost of purchasing fuel and electricity less the revenue from the sale of thermal energy, PLN

$K_{ee,t}$ – the cost of purchasing electricity to supply a section of trolleybus traction, PLN

$K_{bioLNG,t}$ - the cost of purchase of bioLNG fuel in year t, PLN

$R_{c,t}$ – revenue from the sale of thermal energy in year t, PLN

Due to the lack of key data, such as investment outlays for a specific solution (as mentioned, these are confidential data, not provided at the stage of the bioLNG feasibility study), the investment outlays were determined based on the data available on the producers' websites and publicly available commercial offers. The cost of the installation was determined as the sum of the costs of purchasing a bioLNG fuel tank, building a regasification station, and purchasing a gas cogenerator, following the formula:

$$K_n = K_{tank} + K_{reg.} + K_{cog.} = 2\ 065\ 380{,}00\ PLN \qquad (15)$$

where:

K_n – maximum investment expenditure, PLN

$K_{reg.}$ – costs of building a regasification station, PLN

K_{tank} – construction costs of a bioLNG fuel tank, PLN

$K_{cog.}$ – costs of purchasing a gas cogenerator, PLN

The costs of financial outlays are repaid in 10 equal instalments, and the amount of a single instalment is determined by the formula:

$$K_r = \frac{K_n}{10} = 206\ 538{,}00\ PLN \qquad (16)$$

where:

K_r – the amount of the instalment for the repayment of financial outlays, PLN

K_n – maximum investment expenditure, PLN

The financial flows related to the modernization of the North substation supply method were determined as the difference between the fuel and electricity purchase, less the loan repayment instalment, following the formula:

$$PF_t = R_{k,t} - K_{r,t} = -110\ 818\ PLN \qquad (17)$$

where:

PF_t – financial flows related to the modernization of the substation supply method, PLN

$R_{k,t}$ – the difference between the cost of purchasing fuel and electricity less the revenue from the sale of thermal energy, PLN

$K_{r,t}$ – instalment of return on investment in year t, PLN

The analysis was carried out for 25 years of operation of the cogeneration unit. The results obtained based on the above calculation example for each year of operation are presented in Table 7:

Table 7. Financial flows for the construction of a regasification station and bioLNG fuel supply gas cogenerator to supply the Północna substation

	Energy demand	BioLNG demand	BioLNG demand	LNG fuel price	Cost of regasification	BioLNG fuel purchase costs	Energy price	Energy purchase costs	Cost difference	Revenue from the sale of heat	Investment outlays	The instalment of the return on investment	Financial flows
Year	MWh/a	l/a	kg/a	PLN/kg	PLN/a	PLN/a	PLN/MWh	PLN	PLN	PLN	PLN	PLN	PLN
-1											-1 032 690,00		
0											-1 032 690,00		
1	1 830,00	305 000,00	122 000,00	12,50	732 000,00	2 257 000,00	1 000,00	1 830 000,00	95 720,00	522 720,00		206 538,00	-110 818,00
2	1 830,00	305 000,00	122 000,00	13,13	732 000,00	2 333 250,00	1 050,00	1 921 500,00	113 583,60	525 333,60		206 538,00	-92 954,40
3	1 830,00	305 000,00	122 000,00	13,78	732 000,00	2 413 312,50	1 102,50	2 017 575,00	132 222,77	527 960,27		206 538,00	-74 315,23
4	1 830,00	305 000,00	122 000,00	14,47	732 000,00	2 497 378,13	1 157,63	2 118 453,75	151 675,69	530 600,07		206 538,00	-54 862,31
5	1 830,00	305 000,00	122 000,00	15,19	732 000,00	2 585 647,03	1 215,51	2 224 376,44	171 982,48	533 253,07		206 538,00	-34 555,52
6	1 830,00	305 000,00	122 000,00	15,42	732 000,00	2 613 451,74	1 233,74	2 257 742,08	180 209,68	535 919,34		206 538,00	-26 328,32
7	1 830,00	305 000,00	122 000,00	15,65	732 000,00	2 641 673,51	1 252,24	2 291 608,22	188 533,63	538 598,93		206 538,00	-18 004,37
8	1 830,00	305 000,00	122 000,00	15,89	732 000,00	2 670 318,62	1 271,03	2 325 982,34	196 955,65	541 291,93		206 538,00	-9 582,35
9	1 830,00	305 000,00	122 000,00	16,13	732 000,00	2 699 393,39	1 290,09	2 360 872,07	205 477,06	543 998,39		206 538,00	-1 060,94
10	1 830,00	305 000,00	122 000,00	16,37	732 000,00	2 728 904,30	1 309,45	2 396 285,15	214 099,24	546 718,38		206 538,00	7 561,24
11	1 830,00	305 000,00	122 000,00	16,61	732 000,00	2 758 857,86	1 329,09	2 432 229,43	222 823,54	549 451,97		0,00	222 823,54
12	1 830,00	305 000,00	122 000,00	16,86	732 000,00	2 789 260,73	1 349,02	2 468 712,87	231 651,38	552 199,23		0,00	231 651,38
13	1 830,00	305 000,00	122 000,00	17,12	732 000,00	2 820 119,64	1 369,26	2 505 743,57	240 584,15	554 960,23		0,00	240 584,15
14	1 830,00	305 000,00	122 000,00	17,37	732 000,00	2 851 441,43	1 389,80	2 543 329,72	249 623,31	557 735,03		0,00	249 623,31
15	1 830,00	305 000,00	122 000,00	17,63	732 000,00	2 883 233,05	1 410,64	2 581 479,67	258 770,31	560 523,70		0,00	258 770,31
16	1 830,00	305 000,00	122 000,00	17,90	732 000,00	2 915 501,55	1 431,80	2 620 201,86	268 026,63	563 326,32		0,00	268 026,63
17	1 830,00	305 000,00	122 000,00	18,17	732 000,00	2 948 254,07	1 453,28	2 659 504,89	277 393,77	566 142,95		0,00	277 393,77
18	1 830,00	305 000,00	122 000,00	18,44	732 000,00	2 981 497,89	1 475,08	2 699 397,46	286 873,24	568 973,67		0,00	286 873,24
19	1 830,00	305 000,00	122 000,00	18,72	732 000,00	3 015 240,35	1 497,21	2 739 888,42	296 466,61	571 818,54		0,00	296 466,61
20	1 830,00	305 000,00	122 000,00	19,00	732 000,00	3 049 488,96	1 519,66	2 780 986,75	306 175,42	574 677,63		0,00	306 175,42
21	1 830,00	305 000,00	122 000,00	19,28	732 000,00	3 084 251,29	1 542,46	2 822 701,55	316 001,27	577 551,02		0,00	316 001,27
22	1 830,00	305 000,00	122 000,00	19,57	732 000,00	3 119 535,06	1 565,60	2 865 042,08	325 945,78	580 438,77		0,00	325 945,78
23	1 830,00	305 000,00	122 000,00	19,86	732 000,00	3 155 348,09	1 589,08	2 908 017,71	336 010,58	583 340,97		0,00	336 010,58
24	1 830,00	305 000,00	122 000,00	20,16	732 000,00	3 191 698,31	1 612,92	2 951 637,97	346 197,33	586 257,67		0,00	346 197,33
25	1 830,00	305 000,00	122 000,00	20,46	732 000,00	3 228 593,78	1 637,11	2 995 912,54	356 507,72	589 188,96		0,00	356 507,72

Grabówek substation

The current demand for electricity for the Grabówek substation is **230,82 kWh/h**, which corresponds to bioLNG fuel consumption of about 0,92 m^3 per day.

For these values, examples of possible gas cogenerators:

- Viessmann Vitobloc 200, EM-363/498, 363 kWe, 498 kWc [23]
- Set of 3 cogenerators * OEKO 2x100 kW and OEKO 50 kW
- Cogenerator TEDOM Flexi 260 [25]

To cover the daily energy demand, it is required to have 2 cryogenic tanks with a capacity of 500l of bioLNG/LNG.

The analysis of financial flows was performed in the same way as for the Północna substation, the obtained results are presented in Table 8.

Table 8. Financial flows for the construction of a regasification station and bioLNG fuel supply gas cogenerator for the needs of supplying the Grabówek substation

	Energy demand	BioLNG demand	BioLNG demand	LNG fuel price	Cost of regasification	BioLNG fuel purchase costs	Energy price	Energy purchase costs	Cost difference	Revenue from the sale of heat	Investment outlays	The instalment of the return on investment	Financial flows
Year	MWh/a	l/a	kg/a	PLN/kg	PLN/a	PLN/a	PLN/MWh	PLN	PLN	PLN	PLN	PLN	PLN
-1											-1 144 035,00		
0											-1 144 035,00		
1	1 830,00	337 000,00	134 800,00	12,50	808 800,00	2 493 800,00	1 000,00	1 830 000,00	53 320,00	717 120,00		228 807,00	-175 487,00
2	1 830,00	337 000,00	134 800,00	13,13	808 800,00	2 578 050,00	1 050,00	1 921 500,00	64 155,60	720 705,60		228 807,00	-164 651,40
3	1 830,00	337 000,00	134 800,00	13,78	808 800,00	2 666 512,50	1 102,50	2 017 575,00	75 371,63	724 309,13		228 807,00	-153 435,37
4	1 830,00	337 000,00	134 800,00	14,47	808 800,00	2 759 398,13	1 157,63	2 118 453,75	86 986,30	727 930,67		228 807,00	-141 820,70
5	1 830,00	337 000,00	134 800,00	15,19	808 800,00	2 856 928,03	1 215,51	2 224 376,44	99 018,73	731 570,33		228 807,00	-129 788,27
6	1 830,00	337 000,00	134 800,00	15,42	808 800,00	2 887 649,95	1 233,74	2 257 742,08	105 320,31	735 228,18		228 807,00	-123 486,69
7	1 830,00	337 000,00	134 800,00	15,65	808 800,00	2 918 832,70	1 252,24	2 291 608,22	111 679,83	738 904,32		228 807,00	-117 127,17
8	1 830,00	337 000,00	134 800,00	15,89	808 800,00	2 950 483,19	1 271,03	2 325 982,34	118 097,99	742 598,84		228 807,00	-110 709,01
9	1 830,00	337 000,00	134 800,00	16,13	808 800,00	2 982 608,44	1 290,09	2 360 872,07	124 575,47	746 311,84		228 807,00	-104 231,53
10	1 830,00	337 000,00	134 800,00	16,37	808 800,00	3 015 215,57	1 309,45	2 396 285,15	131 112,98	750 043,39		228 807,00	-97 694,02
11	1 830,00	337 000,00	134 800,00	16,61	808 800,00	3 048 311,80	1 329,09	2 432 229,43	137 711,24	753 793,61		0,00	137 711,24
12	1 830,00	337 000,00	134 800,00	16,86	808 800,00	3 081 904,48	1 349,02	2 468 712,87	144 370,98	757 562,58		0,00	144 370,98
13	1 830,00	337 000,00	134 800,00	17,12	808 800,00	3 116 001,04	1 369,26	2 505 743,57	151 092,92	761 350,39		0,00	151 092,92
14	1 830,00	337 000,00	134 800,00	17,37	808 800,00	3 150 609,06	1 389,80	2 543 329,72	157 877,81	765 157,14		0,00	157 877,81
15	1 830,00	337 000,00	134 800,00	17,63	808 800,00	3 185 736,20	1 410,64	2 581 479,67	164 726,40	768 982,93		0,00	164 726,40
16	1 830,00	337 000,00	134 800,00	17,90	808 800,00	3 221 390,24	1 431,80	2 620 201,86	171 639,47	772 827,84		0,00	171 639,47
17	1 830,00	337 000,00	134 800,00	18,17	808 800,00	3 257 579,09	1 453,28	2 659 504,89	178 617,78	776 691,98		0,00	178 617,78
18	1 830,00	337 000,00	134 800,00	18,44	808 800,00	3 294 310,78	1 475,08	2 699 397,46	185 662,13	780 575,44		0,00	185 662,13
19	1 830,00	337 000,00	134 800,00	18,72	808 800,00	3 331 593,44	1 497,21	2 739 888,42	192 773,31	784 478,32		0,00	192 773,31
20	1 830,00	337 000,00	134 800,00	19,00	808 800,00	3 369 435,34	1 519,66	2 780 986,75	199 952,12	788 400,71		0,00	199 952,12
21	1 830,00	337 000,00	134 800,00	19,28	808 800,00	3 407 844,87	1 542,46	2 822 701,55	207 199,40	792 342,72		0,00	207 199,40
22	1 830,00	337 000,00	134 800,00	19,57	808 800,00	3 446 830,54	1 565,60	2 865 042,08	214 515,96	796 304,43		0,00	214 515,96
23	1 830,00	337 000,00	134 800,00	19,86	808 800,00	3 486 401,00	1 589,08	2 908 017,71	221 902,66	800 285,95		0,00	221 902,66
24	1 830,00	337 000,00	134 800,00	20,16	808 800,00	3 526 565,02	1 612,92	2 951 637,97	229 360,34	804 287,38		0,00	229 360,34
25	1 830,00	337 000,00	134 800,00	20,46	808 800,00	3 567 331,49	1 637,11	2 995 912,54	236 889,87	808 308,82		0,00	236 889,87

Redłowo substation

The current demand for electricity for the Redłowo substation is **168,38 kWh/h**, which corresponds to bioLNG fuel consumption of about 0,67 m^3 per day.

For these values, examples of possible gas cogenerators:

- Viessmann Vitobloc 200, EM-199/263, 199 kWe, 263 kWc [23]
- Set of 2 cogenerators* OEKO 2x100 kW
- Cogenerator TEDOM Cento 180 [25]

To cover the daily energy demand, it is required to have 2 cryogenic tanks with a capacity of 500l of bioLNG/LNG.

The analysis of financial flows was performed in the same way as for the Północna substation, the obtained results are presented in Table 9.

Table 9. Financial flows for the construction of the bioLNG regasification station and gas cogenerator to supply the Redłowo substation

	Energy demand	BioLNG demand	BioLNG demand	LNG fuel price	Cost of regasification	BioLNG fuel purchase costs	Energy price	Energy purchase costs	Cost difference	Revenue from the sale of heat	Investment outlays	The instalment of the return on investment	Financial flows
Year	MWh/a	l/a	kg/a	PLN/kg	PLN/a	PLN/a	PLN/MWh	PLN	PLN	PLN	PLN	PLN	PLN
-1,00											-842 190,00		
0,00											-842 190,00		
1,00	1 830,00	245 833,33	98 333,33	12,50	590 000,00	1 819 166,67	1 000,00	1 830 000,00	389 553,33	378 720,00		168 438,00	221 115,33
2,00	1 830,00	245 833,33	98 333,33	13,13	590 000,00	1 880 625,00	1 050,00	1 921 500,00	421 488,60	380 613,60		168 438,00	253 050,60
3,00	1 830,00	245 833,33	98 333,33	13,78	590 000,00	1 945 156,25	1 102,50	2 017 575,00	454 935,42	382 516,67		168 438,00	286 497,42
4,00	1 830,00	245 833,33	98 333,33	14,47	590 000,00	2 012 914,06	1 157,63	2 118 453,75	489 968,94	384 429,25		168 438,00	321 530,94
5,00	1 830,00	245 833,33	98 333,33	15,19	590 000,00	2 084 059,77	1 215,51	2 224 376,44	526 668,07	386 351,40		168 438,00	358 230,07
6,00	1 830,00	245 833,33	98 333,33	15,42	590 000,00	2 106 470,66	1 233,74	2 257 742,08	539 554,58	388 283,15		168 438,00	371 116,58
7,00	1 830,00	245 833,33	98 333,33	15,65	590 000,00	2 129 217,72	1 252,24	2 291 608,22	552 615,06	390 224,57		168 438,00	384 177,06
8,00	1 830,00	245 833,33	98 333,33	15,89	590 000,00	2 152 305,99	1 271,03	2 325 982,34	565 852,04	392 175,69		168 438,00	397 414,04
9,00	1 830,00	245 833,33	98 333,33	16,13	590 000,00	2 175 740,58	1 290,09	2 360 872,07	579 268,07	394 136,57		168 438,00	410 830,07
10,00	1 830,00	245 833,33	98 333,33	16,37	590 000,00	2 199 526,69	1 309,45	2 396 285,15	592 865,72	396 107,25		168 438,00	424 427,72
11,00	1 830,00	245 833,33	98 333,33	16,61	590 000,00	2 223 669,59	1 329,09	2 432 229,43	606 647,64	398 087,79		0,00	606 647,64
12,00	1 830,00	245 833,33	98 333,33	16,86	590 000,00	2 248 174,63	1 349,02	2 468 712,87	620 616,47	400 078,23		0,00	620 616,47
13,00	1 830,00	245 833,33	98 333,33	17,12	590 000,00	2 273 047,25	1 369,26	2 505 743,57	634 774,94	402 078,62		0,00	634 774,94
14,00	1 830,00	245 833,33	98 333,33	17,37	590 000,00	2 298 292,96	1 389,80	2 543 329,72	649 125,78	404 089,01		0,00	649 125,78
15,00	1 830,00	245 833,33	98 333,33	17,63	590 000,00	2 323 917,35	1 410,64	2 581 479,67	663 671,77	406 109,46		0,00	663 671,77
16,00	1 830,00	245 833,33	98 333,33	17,90	590 000,00	2 349 926,11	1 431,80	2 620 201,86	678 415,75	408 140,01		0,00	678 415,75
17,00	1 830,00	245 833,33	98 333,33	18,17	590 000,00	2 376 325,01	1 453,28	2 659 504,89	693 360,59	410 180,71		0,00	693 360,59
18,00	1 830,00	245 833,33	98 333,33	18,44	590 000,00	2 403 119,88	1 475,08	2 699 397,46	708 509,19	412 231,61		0,00	708 509,19
19,00	1 830,00	245 833,33	98 333,33	18,72	590 000,00	2 430 316,68	1 497,21	2 739 888,42	723 864,51	414 292,77		0,00	723 864,51
20,00	1 830,00	245 833,33	98 333,33	19,00	590 000,00	2 457 921,43	1 519,66	2 780 986,75	739 429,55	416 364,23		0,00	739 429,55
21,00	1 830,00	245 833,33	98 333,33	19,28	590 000,00	2 485 940,25	1 542,46	2 822 701,55	755 207,35	418 446,05		0,00	755 207,35
22,00	1 830,00	245 833,33	98 333,33	19,57	590 000,00	2 514 379,35	1 565,60	2 865 042,08	771 201,00	420 538,28		0,00	771 201,00
23,00	1 830,00	245 833,33	98 333,33	19,86	590 000,00	2 543 245,04	1 589,08	2 908 017,71	787 413,64	422 640,97		0,00	787 413,64
24,00	1 830,00	245 833,33	98 333,33	20,16	590 000,00	2 572 543,72	1 612,92	2 951 637,97	803 848,43	424 754,18		0,00	803 848,43
25,00	1 830,00	245 833,33	98 333,33	20,46	590 000,00	2 602 281,88	1 637,11	2 995 912,54	820 508,62	426 877,95		0,00	820 508,62

Sopot Reja substation

The current demand for electricity for the Sopot Reja substation is **28,08 kWh/h**, which corresponds to bioLNG fuel consumption of about 0,11 m^3 per day.

For these values, examples of possible gas cogenerators:

- Viessmann Vitobloc 200, EM-50/81, 50 kWe, 81 kWc [23]
- Cogenerator OEKO 30 kW
- Cogenerator TEDOM Flexi 260 [25]
- Cogenerator TEDOM Micro 30[25]

To cover the daily energy requirement, 1 cryogenic tank with a capacity of 500l of bioLNG/LNG is required.

Due to the lowest demand for energy in the Sopot Reja substation, the selected installation is oversized, therefore the legitimacy of this solution is questioned. In terms of energy expenditure, the construction of a bioLNG tank, regasification station and gas cogenerator are not profitable. In this area, the construction of a CNG station should be considered, which could also cooperate with a gas cogenerator. Along with the technological development, the use of bioLNG on such a small scale as powering the Sopot Reja substation may turn out to be a profitable solution in terms of economy and energy.

The analysis of financial flows was performed in the same way as for the Północna substation, the obtained results are presented in Table 10.

Table 10. Financial flows for the construction of a regasification station and bioLNG fuel supply gas cogenerator to supply the Sopot Reja substation

	Energy demand	BioLNG demand	BioLNG demand	LNG fuel price	Cost of regasification	BioLNG fuel purchase costs	Energy price	Energy purchase costs	Cost difference	Revenue from the sale of heat	Investment outlays	The instalment of the return on investment	Financial flows
Year	MWh/a	l/a	kg/a	PLN/kg	PLN/a	PLN/a	PLN/MWh	PLN	PLN	PLN	PLN	PLN	PLN
-1,00											-420 500,00		
0,00											-420 500,00		
1,00	1 830,00	41 000,00	16 400,00	12,50	98 400,00	303 400,00	1 000,00	1 830 000,00	1 643 240,00	116 640,00		84 100,00	1 559 140,00
2,00	1 830,00	41 000,00	16 400,00	13,13	98 400,00	313 650,00	1 050,00	1 921 500,00	1 725 073,20	117 223,20		84 100,00	1 640 973,20
3,00	1 830,00	41 000,00	16 400,00	13,78	98 400,00	324 412,50	1 102,50	2 017 575,00	1 810 971,82	117 809,32		84 100,00	1 726 871,82
4,00	1 830,00	41 000,00	16 400,00	14,47	98 400,00	335 713,13	1 157,63	2 118 453,75	1 901 138,99	118 398,36		84 100,00	1 817 038,99
5,00	1 830,00	41 000,00	16 400,00	15,19	98 400,00	347 578,78	1 215,51	2 224 376,44	1 995 788,01	118 990,35		84 100,00	1 911 688,01
6,00	1 830,00	41 000,00	16 400,00	15,42	98 400,00	351 316,46	1 233,74	2 257 742,08	2 026 010,93	119 585,31		84 100,00	1 941 910,93
7,00	1 830,00	41 000,00	16 400,00	15,65	98 400,00	355 110,21	1 252,24	2 291 608,22	2 056 681,24	120 183,23		84 100,00	1 972 581,24
8,00	1 830,00	41 000,00	16 400,00	15,89	98 400,00	358 960,86	1 271,03	2 325 982,34	2 087 805,62	120 784,15		84 100,00	2 003 705,62
9,00	1 830,00	41 000,00	16 400,00	16,13	98 400,00	362 869,28	1 290,09	2 360 872,07	2 119 390,87	121 388,07		84 100,00	2 035 290,87
10,00	1 830,00	41 000,00	16 400,00	16,37	98 400,00	366 836,32	1 309,45	2 396 285,15	2 151 443,85	121 995,01		84 100,00	2 067 343,85
11,00	1 830,00	41 000,00	16 400,00	16,61	98 400,00	370 862,86	1 329,09	2 432 229,43	2 183 971,56	122 604,99		0,00	2 183 971,56
12,00	1 830,00	41 000,00	16 400,00	16,86	98 400,00	374 949,80	1 349,02	2 468 712,87	2 216 981,08	123 218,01		0,00	2 216 981,08
13,00	1 830,00	41 000,00	16 400,00	17,12	98 400,00	379 098,05	1 369,26	2 505 743,57	2 250 479,62	123 834,10		0,00	2 250 479,62
14,00	1 830,00	41 000,00	16 400,00	17,37	98 400,00	383 308,52	1 389,80	2 543 329,72	2 284 474,47	124 453,27		0,00	2 284 474,47
15,00	1 830,00	41 000,00	16 400,00	17,63	98 400,00	387 582,15	1 410,64	2 581 479,67	2 318 973,05	125 075,54		0,00	2 318 973,05
16,00	1 830,00	41 000,00	16 400,00	17,90	98 400,00	391 919,88	1 431,80	2 620 201,86	2 353 982,89	125 700,91		0,00	2 353 982,89
17,00	1 830,00	41 000,00	16 400,00	18,17	98 400,00	396 322,68	1 453,28	2 659 504,89	2 389 511,63	126 329,42		0,00	2 389 511,63
18,00	1 830,00	41 000,00	16 400,00	18,44	98 400,00	400 791,52	1 475,08	2 699 397,46	2 425 567,01	126 961,07		0,00	2 425 567,01
19,00	1 830,00	41 000,00	16 400,00	18,72	98 400,00	405 327,39	1 497,21	2 739 888,42	2 462 156,90	127 595,87		0,00	2 462 156,90
20,00	1 830,00	41 000,00	16 400,00	19,00	98 400,00	409 931,30	1 519,66	2 780 986,75	2 499 289,30	128 233,85		0,00	2 499 289,30
21,00	1 830,00	41 000,00	16 400,00	19,28	98 400,00	414 604,27	1 542,46	2 822 701,55	2 536 972,30	128 875,02		0,00	2 536 972,30
22,00	1 830,00	41 000,00	16 400,00	19,57	98 400,00	419 347,34	1 565,60	2 865 042,08	2 575 214,13	129 519,40		0,00	2 575 214,13
23,00	1 830,00	41 000,00	16 400,00	19,86	98 400,00	424 161,55	1 589,08	2 908 017,71	2 614 023,15	130 166,99		0,00	2 614 023,15
24,00	1 830,00	41 000,00	16 400,00	20,16	98 400,00	429 047,97	1 612,92	2 951 637,97	2 653 407,83	130 817,83		0,00	2 653 407,83
25,00	1 830,00	41 000,00	16 400,00	20,46	98 400,00	434 007,69	1 637,11	2 995 912,54	2 693 376,77	131 471,92		0,00	2 693 376,77

Variant 3: Meet the energy needs of the PKT solely by bioLNG

The current demand for electricity for the PKT trolleybus network is **28,08 kWh/h**, which corresponds to bioLNG fuel consumption of about 5,34 m^3 per day.

For these values, examples of possible gas cogenerators:

- Cogenerator TEDOM Quanto 1600 [25]

To cover the daily energy demand, it is required to have 11 cryogenic tanks with a capacity of 500l of bioLNG/LNG.

The cost of the gas turbine was estimated based on [26] as 5 million PLN/MWe.

The location of the trolleybus power supply station should allow free access to the installation, due to its size and the supply of bioLNG. The proposed location is on the premises of PKT in the Grabówek district.

It should be noted that supplying the entire trolleybus traction from one source of energy may pose a threat to the continuity of operation and ensuring the continuity of public transport. Currently, the trolleybus traction is divided into sections, each of them powered by an individual substation connected to the power system. Thanks to this, in the event of failure of one traction section, the rest can function independently of the repair, renovation or modernization works.

Such a large cogeneration unit allows for the production of significant amounts of heat that can be sent to supply the local district heating network. In the analysis, revenues from the sale of district heat were determined.

The analysis of financial flows was performed in the same way as for substations, the results obtained are presented in Table 11.

Table 11. Financial flows for the construction of a regasification station and bioLNG fuel supply gas cogenerator to supply the entire PKT trolleybus network

	Energy demand	BioLNG demand	BioLNG demand	LNG fuel price	Cost of regasification	BioLNG fuel purchase costs	Energy price	Energy purchase costs	Cost difference	Revenue from the sale of heat	Investment outlays	The instalment of the return on investment	Financial flows
Year	MWh/a	l/a	kg/a	PLN/kg	PLN/a	PLN/a	PLN/MWh	PLN	PLN	PLN	PLN	PLN	PLN
-1,00											4 162 500,00		
0,00											4 162 500,00		
1,00	11 700,00	1 950 000,00	780 000,00	12,50	4 680 000,00	14 430 000,00	1 000,00	11 700 000,00	- 17 040,00	2 712 960,00		832500	- 849 540,00
2,00	11 700,00	1 950 000,00	780 000,00	13,13	4 680 000,00	14 917 500,00	1 050,00	12 285 000,00	94 024,80	2 726 524,80		832500	- 738 475,20
3,00	11 700,00	1 950 000,00	780 000,00	13,78	4 680 000,00	15 429 375,00	1 102,50	12 899 250,00	210 032,42	2 740 157,42		832500	- 622 467,58
4,00	11 700,00	1 950 000,00	780 000,00	14,47	4 680 000,00	15 966 843,75	1 157,63	13 544 212,50	331 226,96	2 753 858,21		832500	- 501 273,04
5,00	11 700,00	1 950 000,00	780 000,00	15,19	4 680 000,00	16 531 185,94	1 215,51	14 221 423,13	457 864,69	2 767 627,50		832500	- 374 635,31
6,00	11 700,00	1 950 000,00	780 000,00	15,42	4 680 000,00	16 708 953,73	1 233,74	14 434 744,47	507 256,38	2 781 465,64		832500	- 325 243,62
7,00	11 700,00	1 950 000,00	780 000,00	15,65	4 680 000,00	16 889 388,03	1 252,24	14 651 265,64	557 250,57	2 795 372,97		832500	- 275 249,43
8,00	11 700,00	1 950 000,00	780 000,00	15,89	4 680 000,00	17 072 528,85	1 271,03	14 871 034,62	607 855,60	2 809 349,83		832500	- 224 644,40
9,00	11 700,00	1 950 000,00	780 000,00	16,13	4 680 000,00	17 258 416,79	1 290,09	15 094 100,14	659 079,94	2 823 396,58		832500	- 173 420,06
10,00	11 700,00	1 950 000,00	780 000,00	16,37	4 680 000,00	17 447 093,04	1 309,45	15 320 511,65	710 932,17	2 837 513,56		832500	- 121 567,83
11,00	11 700,00	1 950 000,00	780 000,00	16,61	4 680 000,00	17 638 599,43	1 329,09	15 550 319,32	763 421,02	2 851 701,13		0	763 421,02
12,00	11 700,00	1 950 000,00	780 000,00	16,86	4 680 000,00	17 832 978,42	1 349,02	15 783 574,11	816 555,32	2 865 959,64		0	816 555,32
13,00	11 700,00	1 950 000,00	780 000,00	17,12	4 680 000,00	18 030 273,10	1 369,26	16 020 327,72	870 344,06	2 880 289,44		0	870 344,06
14,00	11 700,00	1 950 000,00	780 000,00	17,37	4 680 000,00	18 230 527,20	1 389,80	16 260 632,64	924 796,32	2 894 690,88		0	924 796,32
15,00	11 700,00	1 950 000,00	780 000,00	17,63	4 680 000,00	18 433 785,11	1 410,64	16 504 542,13	979 921,36	2 909 164,34		0	979 921,36
16,00	11 700,00	1 950 000,00	780 000,00	17,90	4 680 000,00	18 640 091,88	1 431,80	16 752 110,26	1 035 728,54	2 923 710,16		0	1 035 728,54
17,00	11 700,00	1 950 000,00	780 000,00	18,17	4 680 000,00	18 849 493,26	1 453,28	17 003 391,91	1 092 227,36	2 938 328,71		0	1 092 227,36
18,00	11 700,00	1 950 000,00	780 000,00	18,44	4 680 000,00	19 062 035,66	1 475,08	17 258 442,79	1 149 427,49	2 953 020,35		0	1 149 427,49
19,00	11 700,00	1 950 000,00	780 000,00	18,72	4 680 000,00	19 277 766,19	1 497,21	17 517 319,43	1 207 338,69	2 967 785,46		0	1 207 338,69
20,00	11 700,00	1 950 000,00	780 000,00	19,00	4 680 000,00	19 496 732,69	1 519,66	17 780 079,22	1 265 970,92	2 982 624,38		0	1 265 970,92
21,00	11 700,00	1 950 000,00	780 000,00	19,28	4 680 000,00	19 718 983,68	1 542,46	18 046 780,41	1 325 334,24	2 997 537,51		0	1 325 334,24
22,00	11 700,00	1 950 000,00	780 000,00	19,57	4 680 000,00	19 944 568,43	1 565,60	18 317 482,12	1 385 438,88	3 012 525,19		0	1 385 438,88
23,00	11 700,00	1 950 000,00	780 000,00	19,86	4 680 000,00	20 173 536,96	1 589,08	18 592 244,35	1 446 295,21	3 027 587,82		0	1 446 295,21
24,00	11 700,00	1 950 000,00	780 000,00	20,16	4 680 000,00	20 405 940,01	1 612,92	18 871 128,02	1 507 913,76	3 042 725,76		0	1 507 913,76
25,00	11 700,00	1 950 000,00	780 000,00	20,46	4 680 000,00	20 641 829,11	1 637,11	19 154 194,94	1 570 305,21	3 057 939,39		0	1 570 305,21

Recommendations

The construction of a cogeneration unit powered by bioLNG fuel to supply a dedicated section of the trolleybus network (Variant 2) has been indicated as a recommended solution. The installation would consist of a bioLNG cryogenic fuel tank, a regasification station, a gas cogenerator coupled with a power generator and a connection to a substation.

For Variant 2, the financial flows of power supply for four sections of the trolleybus traction for the Grabówek, Północna, Redłowo and Sopot Reja substations were analyzed. For both the Redłowo and Sopot Reja substations, the financial flows in the first years of the installation's operation are positive, however, the installation in the Sopot Reja substation is oversized, therefore it is not recommended to build a bioLNG powered station in this place. Positive financial flows were obtained at the Redłowo substation, therefore the construction of a pilot installation for powering a trolleybus section with bioLNG should be built within this substation.

Below is a SWOT analysis for the construction of a bioLNG cogeneration unit to supply a dedicated section of the trolleybus network for the Redłowo substation.

Table 12. SWOT analysis for the construction of a bioLNG cogeneration unit to supply a dedicated section of the trolleybus network for the Redłowo substation

Strengths	- availability of new technologies - a small area - the possibility of additional revenues from the sale of district heat
Weaknesses	- the need to train the staff - dependence on the amount of sold heat
Opportunities	- increasing the number of customers due to lower ticket prices - an environmentally friendly company
Threats	- the precarious situation related to the crisis and the possibility of reducing the fuel supply - in the event of an installation failure, the risk of fuel leakage - possible nuisance related to the operation of the generator for residents

Summary

About 25% of Europe's greenhouse gas emissions come from transport. Life is about movement, and transport is a major contributor to urban air pollution. To reduce pollutant emissions related to travelling in cities, public transport has been introduced, which allows groups of people to move in the same direction. An example of such a solution is Przedsiębiorstwo Komunikacji Trolejbusowej in Gdynia, which supports public transport by trolleybuses.

Currently, the trolleybus traction is powered by electricity from the power system, which only allows the transfer of pollutant emissions outside the PKT operating area.

The growing prices of electricity, related to the cost of its production and the need for the state to pay fees for greenhouse gas emissions, make public transport based on the use of electric energy to power vehicles more expensive, which affects ticket prices.

A proposal to solve the problem of rising electricity prices is to use bioLNG fuel to power a cogeneration unit to produce electricity for the trolleybus traction. As part of the study, 3 variants were presented:

- Variant 1: Powering the trolleybus network to charge vehicles while parked in locations where there is no trolleybus network infrastructure available
- Variant 2: Supplying a dedicated section of the trolleybus network - gas cogenerator
- Variant 3: Meet the energy needs of the PKT solely by bioLNG

The profitability of investment in one of the three proposed variants depends on the investment outlays, costs incurred and revenues from the sale of heat to the local heating network.

Variant 1 is not feasible due to the inability to charge trolleybus batteries outside the network infrastructure. For Variant 2, the financial flows of power supply for four sections of the trolleybus traction for the Grabówek, Północna, Redłowo and Sopot Reja substations were analyzed. For both the Redłowo and Sopot Reja substations, the financial flows in the first years of the installation's operation are positive, however, the installation in the Sopot Reja substation is oversized, therefore it is not recommended to build a bioLNG powered station in this place. Variant 3 assumes that the entire trolleybus traction is supplied from the bioLNG fuel installation. The advantage of this solution is the reduction of dependence on electricity supplies and prices and the possibility of selling district heat to the local heating network. The disadvantage is the need to connect all sections of the trolleybus traction, which may reduce the operational reliability of the entire trolleybus network in the event of a failure.

Positive financial flows were obtained at the Redłowo substation, therefore the construction of a pilot installation for powering a trolleybus section with bioLNG should be built within this substation. To cover the electricity needs of the Redłowo substation, the supply of bioLNG in the amount of 673,5 litres per day should be provided, which corresponds to over 400 thousand litres of gas after bioLNG regasification.

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