Concept development with elements of feasibility study for (bio-)LNG (liquefied biogas) installations for Żegluga Gdańska Sp. z o.o.

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Contents

1. Introduction

The energy sector is waiting for significant changes. Ensuring energy security through the diversification of energy sources has become a priority issue. The amount of fossil energy resources is limited, and their extraction is associated with increasing financial outlays. The issue of dependence on imported fuels is not without significance. This situation forces local authorities and private entrepreneurs to search for new energy sources. One of such sources with still untapped potential is biogas, obtained in the process of gasification of organic waste, which as a renewable fuel can be used in many industries.

The Gdańsk-Gdynia-Sopot Metropolitan Area (OMGGS), as part of the Liquid Energy project, set itself the goal of exploring the possibilities of bioLNG - i.e. a liquefied form of biogas, responding to local needs. The area of application is the supply of public transport vehicles in the Tri-City area and water transport in the coastal and inland regions served by Żegluga Gdańska. This study focus on the last point.

2. Purpose of the study

The subject of the study is to present technology and identify possibility of modifying the existing power supply system with the application of the necessary components to use liquefied natural gas (LNG / bioLNG) as fuel for the selected vessel.

In the first part of the study, the description of the Implementation Partner, which is Żegluga Gdańska, providing material in form of two vessels for the analysis, was carried out. Later on, current international regulations are presented. Both ships are obliged to comply with it, focusing on the pollutant emission limits, allowed for water transportation of the Baltic Sea region. The regulations refers to construction and operation of the LNG-based fuel system, which must be met in order to be put into operation. Guidelines included in regulations constitute the boundary conditions for the conducted analysis.

The next part focuses on identifying needs of Żegluga Gdańska, which determines the potential directions of using the project.

On further stage, biogas fuel was characterized, taking into account the factors supporting its implementation to a wider use on the local market.

The next chapter describes available technologies that can be used for modernization of analysed units. Fuel combustion systems dedicated to gas engines are described. Therefore, a review of the gas fuel system components was carried out. They are used for storage, transport and preparation of medium before the proper delivery and combustion of the fuel in the combustion chamber.

In next part of the study, specific examples of ships selected for modification by Żegluga Gdańska are considered. Solutions are proposed, taking into account: requirements resulting from the regulations defining the conditions and profitability of the project.

The next chapter describes SWOT analysis, which in a broad sense correlates all factors related to the project and indicates the greatest challenges.

The conclusions include recommendations for development direction of the biogas use in water transportation.

3. Implementation partner characteristics

Żegluga Gdańska is the largest Polish shipping company providing coastal shipping services in the Pomeranian region. Its fleet includes cargo ships, but most of all passenger ships - which are main branch of the Company and the subject of this study.
The offered services include ship charter, tourist cruises and line services.

Table 1. Presentation of passenger ships owned by Żegluga Gdańska.

Ship name	Total length [m]	Width [m]	Gross capacity * [-]	Draft [m]	Engine power [kW]	Number of passengers	Construction year
Agat	37.72	11.50	674	3.04	2x838	450	1988
Onyx	34.09	11.50	659	2.23	2x840	450	1984
Opal	37.59	11.50	578	2.90	2x840	450	1981
Rubin	37.59	11.88	654	2.60	2x840	450	1984
Anita	33.46	6.12	-	0.96	1x140	270	1967
Danuta	33.04	5.57	-	0.96	1x140	275	1966
Elżbieta	33.08	5.57	-	0.96	1x140	225	1966
Małgorzata	33.57	6.05	-	0.96	1x140	225	1966
Ewa	36.50	6.50	-	1.55	2x140	207	1990
Marina	37.91	6.50	-	1.18	n/a	200	1990
Smiltyne	36.13	6.00	-	1.31	2x110	140	1989
Smile	36.19	6.00	-	1.40	2x110	140	1987
Sonica	20.80	5.56	-	0.60	1x132	40	2004
Sonica I	20.54	5.50	-	0.61	1x132	40	2005

* According to international regulations, the measure of gross tonnage has been used for ships since 1982, replacing ton register. Due to the fact that the ships were designed according to the Russian Classification Society, the gross capacity might not have been used in next years as well.

Source: Own study based on https://www.naszbaltyk.com/statki-bialej-floty/1311-sonica-i-sonica-i-rzeczne-tramwaje-w-gdansku

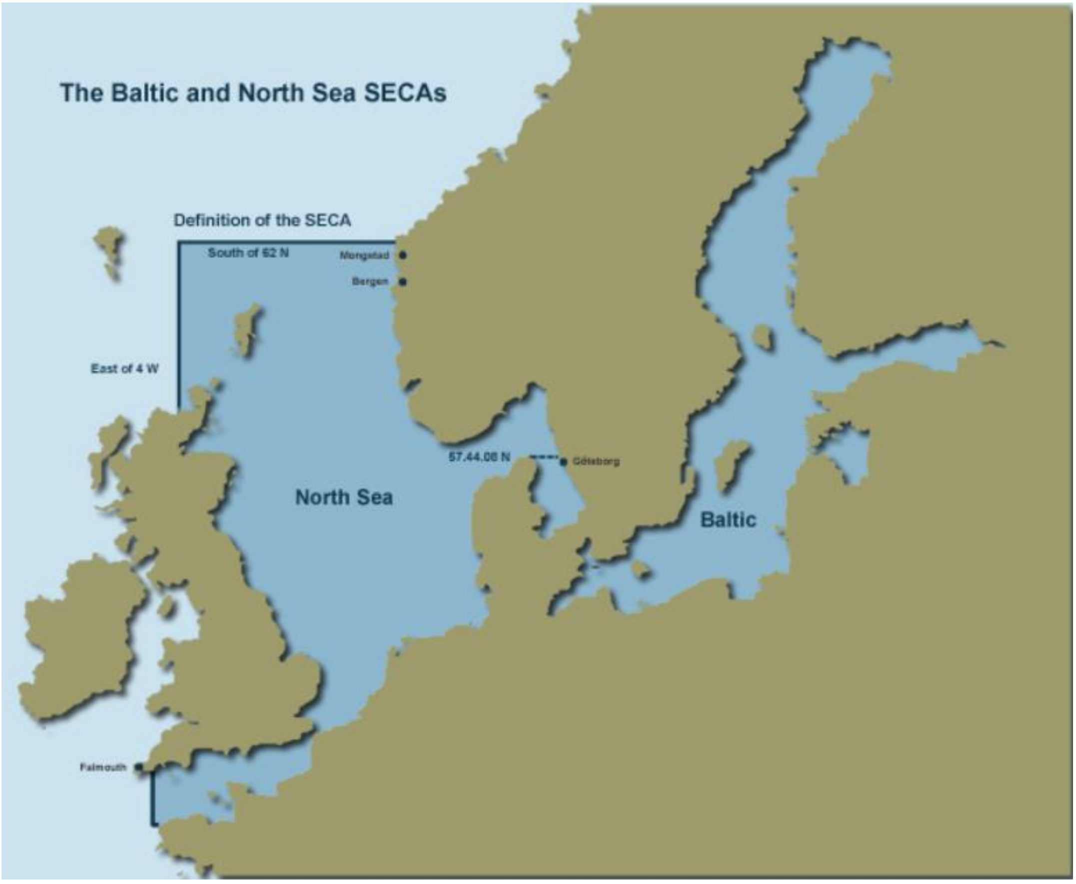
Line transports are carried out mainly within the Zatoka Gdańska. Mainly there are excursions provided by Gdańsk's and Gdynia's water ferry and the cruises between the Tri-City marinas - Gdańsk, Sopot and Gdynia. The next destinations are Hel, popular among tourists, located on the other side of the bay, and Westerplatte. There is a complement connection within the Zalew Wiślany between Krynica Morska and Frombork. The ferries was also carried out year-round duty-free cruises from Gdynia to Bałtijsk. In 2021, the number of vessels owned by Żegluga allows for one trip a day during the season on longer routes, and several during the day within Gdańsk-Westerplatte route and visiting Gdynia Port.

The vessels operated by the implementation partner can be divided into two types. The first type are catamarans, which include Agat, Onyx, Opal, Rubin. These are twin units equipped with, among others, restaurant rooms and internal lounges that can act as, for example, dance halls. The catamaran's capacity is estimated at 450 people. The remaining units can be called passenger ships with a carrying capacity of 40 to 275 people [2]. The "Sonica" and "Sonica I" units stand out among them. These are the youngest ships, purchased by Gdańsk shipping in 2012. They were bought in order to service the newly built lines as part of the program of revitalizing the waterways in Gdańsk, subsidized from the European Union fund. They are able to carry up to 40 people, and additionally, they allow the transport of bicycles. The structure of the ships was adapted to the specific navigation conditions on the Stara Motlawa River resulting from the small clearances above the water surface under the bridges [3].

4. Legal basis – control of pollution emission

Operation areas of Żegluga Gdańska are Zatoka Gdańska, Zalew Wiślany and inland waters within Gdańsk. These are the areas of the Baltic Sea, which in 2011 were added to the so-called "Emission Controlled Area" (abbreviated - ECA), shown in the map below:

Figure 1. The Baltic and North Sea SECAs.



Source: https://www.croceanx.com/about-us/514-2/

Each vessel staying within an ECA must adapt to strict guidelines for fuel combustion emissions. The regulations are contained in the International Convention for the Prevention of Pollution from Ships (shortcut - MARPOL) [4]. Annex VI of the above document is entitled "Regulations for the Prevention of Air Pollution from Ships". It addresses two key issues related to the emission of nitrogen oxides (NOx) and sulphur oxides (SOx), which are a by-product of marine fuel combustion. More detail of these emissions are described in the following chapters.

4.1 Sulphur oxides (SOx) emission

The sulphur content of the combusted fuel is determined by the percentage ratio of the mass of sulphur in the mass of the exhaust gas solution. This value should not exceed:

- 0.5% m / m from 1 January 2020 for each vessel,
- 0.1% m / m from 1 January 2015 for ships operating within the Baltic Emission Control Zone and within each port.

These requirements can be met by:

- Switching from high sulphur fuel oil (HSFO) to diesel oil (MGO) and the use of fuel oil with low sulphur content, currently applied on all Żegluga's units - specification below [9],
- Use of alternative fuels (liquefied natural gas (LNG), liquefied petroleum gas (LPG), etc.)
- Use of alternative technologies, such as exhaust gas cleaning systems - scrubbers (in this case such an equivalent solution must be approved by the administration of the ship's flag state).

Table 2. The most important parameters of the diesel fuel (MGO) used by the implementation partner.

Parameter	**Value**
Viscosity at 40°C [mm^2/s]	2.0 – 6.0
Density at 15°C [kg/m^3]	890.0
Cetane index	40
Sulphur content [% m/m]	0.10
Flash point [°C]	62

Source: https://www.lotos.pl/321/p,218,c,94/dla_biznesu/paliwa_i_dodatki/paliwa_zeglugowe/mgo#tab-2

Moreover, the International Maritime Organization (IMO) at March 1, 2020, introduced a prohibition of fuel carriage which do not comply with the obligatory 0.5% sulphur limit on ships and used for combustion for propulsion and operational purposes, unless applicable alternative systems are used to clean exhaust gases [5].

4.2 Nitrogen oxides (NOx) emission

In the case of nitrogen oxide, we define the mass of nitrogen in grams per unit of energy generated in the engine. The regulations define three emission levels depending on the production date of a given unit - they are as follows:

- I emission level:

Applies to ships built before January 1, 2000 and until January 1, 2011 with a power above 130 kW. NOx emission from the engine must not exceed:

- 17 g/kWh, when engine speed is less than 130 rpm,

- 45* $n^{(-0.2)}$ g/kWh, when engine speed within limits 130 rpm – 2000 rpm,

- 9.8 g/kWh, when engine speed above 2000 rpm.

- II emission level:

Applies to ships built after 1 January 2011 and with a power above 130kW, the NOx emission from the engine may not exceed:

- 14.4 g/kWh, when engine speed is less than 130 rpm,
- 44* $n^{(-0.23)}$ g/kWh, when engine speed within limits 130 rpm – 2000 rpm,
- 7.7 g/kWh, when engine speed above 2000 rpm.

- III emission level:

For ships built after 1 January 2021 with a power above 130kW, with a gross tonnage more than 500 and with a length more than 24 m and located in the Emission Control Area of the Baltic Sea, NOx emissions must not exceed:

- 3.4 g/kWh, when engine speed is less than 130 rpm,
- 9.0* $n^{(-0.2)}$ g/kWh, when engine speed within limits 130 rpm – 2000 rpm,
- 2.0 g/kWh, when engine speed above 2000 rpm.

There are several cases where a ship may be excluded from NOx Emission Control:

- ship uses engines for emergency purposes,
- ship has alternative NOx emission control measures approved by a classification society,
- ship was built or its engine was significantly rebuilt before May 19, 2005 and sails only to ports within the waters of the flag state.

This means that the vast majority of vessels belonging to Żegluga Gdańska meet the requirements resulting from the described regulations using diesel oil as fuel to power their ships. If decided to rebuild the engines to adapt them to the combustion of gaseous fuel, the units will be subject to the latest standards. The rules are written in a way that, until major modifications are made, the Implementation Partner's catamarans and passenger ships can continue to operate as usual. Failure to act in this regard will constantly increase technical problems, which will directly translate into operating costs and passenger travel comfort. In the longer term, profitability will decline and the potential for the development of shipping in the region will not be used.

5. Legal basis - LNG installations on ships other than gas carriers

The construction and use of installation in the ship's space are strictly regulated by appropriate regulations. In Poland, the classification society which deals with safety standards development for vessels is Polski Rejestr Statków (PRS). The scope of his jurisdiction covers the use of LNG installations on ships sailing under the polish flag.

In January 2020, Polski Rejestr Statków (PRS) published the regulations entitled: “Using LNG or other low-flashpoint fuels onboard ships other than gas carriers”. They are identical to the international regulations issued by IMO entitled: "International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels" abbreviated as IGF Code.

They apply to ships built after January 1, 2021, which are used for commercial use. For existing ships, it is subject to PRS decision insofar as it deems it necessary.

For ships of less than 500 gross tonnage, the technical and safety requirements will be considered by the classification society in consultation with the Administration represented by the director of the maritime office of the related area.

The following chapters of the provisions focus on:

Arrangement - describes arranging the space of a ship equipped with a fuel system in a safe way and lists protection measures against mechanical damage which should be applied,

- Fuel storage system,
- Execution of pipeline installations,
- Bunkering process - describes the arrangement of the on-board fuel loading station,
- Supplying fuel to equipment,
- Production of energy from gas powered appliances,
- Fire regulations - describe firefighting measures, detection and firefighting systems for all devices in the fuel system,
- Prevention of explosions,
- Ventilation,
- Electrical installation,
- Management and monitoring of security systems.

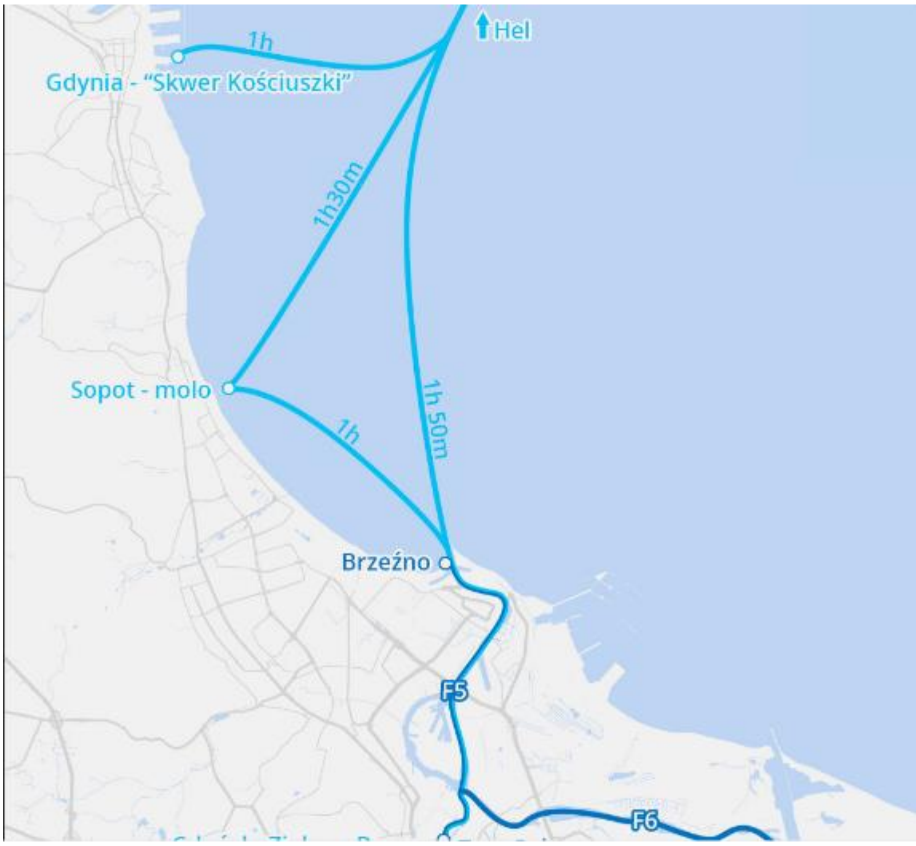
For purposes of the study, the above-mentioned regulations are sufficient to conduct feasibility analysis of converting the power supply system in ships selected by Żegluga Gdańska.

In fact, to carry out the modification design process, Classification Society’s current general regulations for ships - "Rules for the Classification and Construction of Sea-going Ships" or "Rules for the Classification and Construction of Inland Ships", as well as international conventions, primarily "International Convention for the Safety of Life at Sea ”- SOLAS, should be taken into consideration.

6. Diagnosis and analysis of the implementation partner's needs

Due to the constantly growing population of the region, there is enormous potential in using passenger ferries of Żegluga Gdańska for tourist purposes as well as for servicing inhabitant’s communication needs. Passengers are mainly driven by the convenience and speed of given means of transport. In these aspects, shipping seems to be highly competitive compared to other means of communication in the region. The ecological subject is also very important. In line with the concept of sustainable transport development, there is a need of better integration with the various modes of transport and using more environmentally friendly options, such as inland waterway transport or coastal shipping.The most desired traveller’s destination is Półwysep Helski.

Figure 2. Map of connections launched during the season from both Gdynia, Gdańsk and Sopot.



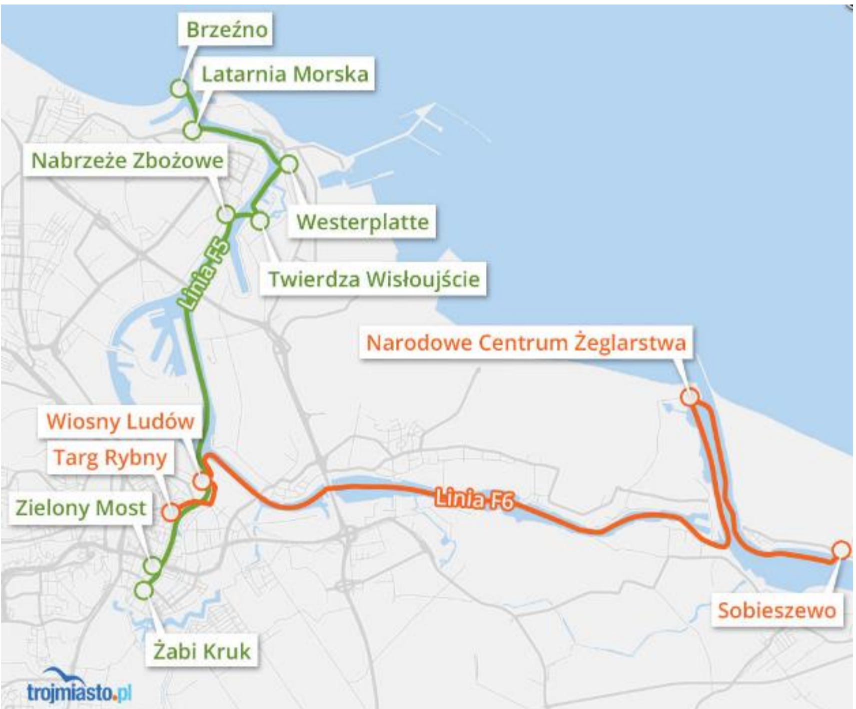
Source: https://www.trojmiasto.pl/wiadomosci/Statki-pasazerskie-na-Zatoce-Co-plywa-i-czemu-nie-wodoloty-n126141.html

During the vacation season, Półwysep Helski is frequently visited by tourists, which often contributes to communication paralysis along the entire access route. Due to environmental issues, there are currently no plans to develop road infrastructure on the peninsula. The authorities focus on the modernization of rail transport, which could be successfully supported by ferry transport.

Communication difficulties observed on the peninsula are not caused only by travellers going to Hel. Equally popular destinations are towns such as Jastarnia, Chałupy and Kuźnica. In order to meet the expectations of passengers, Żegluga Gdańska should increase the frequency of existing routes to Hel and introduce new connections to the above-mentioned destinations. There is potential in this area which would be mutually beneficial to both travellers and the transportation company [6].

Water ferries running along the Martwa Wisła and the Wisła Śmiała Rivers (lines F5 and F6) were very popular connections. These transports were carried out in agreement with the Zarząd Transportu Miejskiego w Gdańsku and co-financed by the authorities of the city of Gdańsk. Unfortunately, in 2020 the connections were suspended for an indefinite period and so far have not been restored. [6, 29].

Figure 3. Map showing the routes of lines F5 and F6 ferries.



Source: https://www.trojmiasto.pl/wiadomosci/Rejsy-statkiem-na-Wyspe-Sobieszewska-n158395.html

Another direction with great development potential is the Zalew Wiślany, including connections between Krynica Morska, Frombork, Kąty Rybackie and Elbląg. Cruises in these directions were gaining more and more popularity from year to year. In addition, the effect of the currently implemented Mierzeja WIślana ditch attractiveness of this reservoir will increase and ease an access to its ports.

Figure 4. Marking of possible connection route between Gdańsk and Elbląg, and the ports of Mierzeja Wiślana.

Source: Opracowanie goodjob - Wstępna koncepcja i ocena ekonomiczna uruchomienia żeglugi przybrzeżnej i śródlądowej na wodach Zatoki Gdańskiej, Zalewu Wiślanego i dróg wodnych Delty Wisły jako elementu publicznego transportu zbiorowego województwa pomorskiego.

Another region with great potential for shipping development is delta of Wisła river area. It is about connecting cities such as Tczew or Malbork by river roads.

Figure 5. Map of river roads for the Wisła delta area.

Source: Opracowanie goodjob - Wstępna koncepcja i ocena ekonomiczna uruchomienia żeglugi przybrzeżnej i śródlądowej na wodach Zatoki Gdańskiej, Zalewu Wiślanego i dróg wodnych Delty Wisły jako elementu publicznego transportu zbiorowego województwa pomorskiego.

Presented development directions for Żegluga Gdańska should be used not only for tourist purposes, but also as urban and intercity transport - for employees and students. However, a condition for success is related with treatment of inland and coastal shipping in a similar way to other means of transport, also in terms of coordination of timetables with the residents and tourists transport needs. Taking into account the current state of Implementation Partner fleet, the number of owned vessels, their technical condition, it will be challenging to achieve intended goals. Current units should be gradually modernized before the next units will be purchased. Investment support must also be provided by local and regional authorities, otherwise operator will not be able to effectively expand its business. In case of development of the project, it will be possible to use bioLNG for a larger number of new ships, which will complement Żegluga Gdańska's fleet. The conclusion from the above is a promising development prospect, which is hindered mainly by the issue of financial outlays required for investments implementation.

7. Conditions and potential for biogas use

7.1 Definition

Biomass - according to the current European directive, is a biodegradable waste or residues of biological origin from agriculture. Waste includes, among the others, plant and animal substances. Those coming from the agricultural industry, but also municipal waste. [1].

Biogas – a product of anaerobic fermentation of organic compounds containing starch, proteins, cellulose and other carbohydrates. The biogas consists mainly of methane (60-70%), carbon dioxide (30-40%) and traces of ammonia, nitrogen, carbon monoxide and hydrogen sulphide (<1%). During fermentation process, waste is crushed in order to obtain the appropriate granularity, which makes it more susceptible to biodegradation. After shredding, waste fermentation is applied [1].

7.2 Development directions

Preferred direction of the national and European energy sector development are renewable energy sources, supported by low-emission energy blocks with a stable nature of work. The goal for renewable energy sources is distributed generation and increasing the by-products and organic waste use also for biogas production. It is particularly important regarding conditions resulting from the European Union energy policy, expressed in the Directive of the European Parliament 2018/2021 from December 11, 2018. It put the pressure on promotion of using the energy from renewable sources. A number of programs are available to support new ideas and technologies, which are a potential source of funding for biogas production initiatives:

- National Fund for Environmental Protection and Water Management (NFOŚiGW) under the program "Rational waste management Part 3) Use of alternative fuels for energy purposes" intended for the construction of new / extension or modernization of existing installations for thermal processing of waste or other alternative fuels produced from municipal waste with generation energy in energy production in the conditions of high-efficiency cogeneration [30]
- The European Funds for Infrastructure, Climate, Environment 2021-2027 (FEnIKS), which prioritising support for the energy and environment sectors. Support from the program may be granted to RES generating units, including biomass or biogas utilization [31].
- The South Baltic Interreg Program, one of the priorities is to support the transition towards green energy by developing, presenting and implementing green energy solutions for the distribution and storage of energy from renewable sources, including biomass and biogas sources [32].
- The Interreg Central Europe program, which involves cooperation for a greener Central Europe, by supporting the energy transformation for climate neutrality. One of the priorities is to promote low-carbon strategies, especially in urban areas [33].
- European Funds for Pomerania, one of its goals of which is an effective supporting the renewable energy use in individual sectors, including biogas and biomass technologies [36].

Biogas utilization is a great opportunity for Poland to increase the share of renewable energy sources in the national energy mix. Development of this branch of energy also means obtaining a stable source of gas fuel supplies. Due to large agricultural production, Poland has the potential to become one of the leaders in the biogas market in Europe. Increasing energy production from biogas, including bioLNG, is another step towards increasing diversification of energy sources and increasing energy security, which is one of assumptions of the European Union's energy and climate policy [7]. Additional stimulus for of this technology development is the amendment of Directive 2009/28 / EC by the European Economic and Social Committee, which aims to increase the share of agricultural by-products used for energy purposes. The use of animal excrements, manure or organic waste will reduce their uncontrolled decomposition, which is a major source of methane emissions.

Biogas can be obtained from landfills, wastewater treatment plants, but also from meat and dairy plants, mass caterers, out-of-date food and feed, and many other substrates. In the context of the Tri-City, which is a large urban agglomeration, the main source of raw materials for the production of bioLNG will be Zakład Utylizacyjny, located directly on the outskirts of Gdańsk, in Szadółki district, allows for efficient waste distribution. Leaving waste without using it for energy purposes is very costly and burdensome both for the environment and for the inhabitants of nearby districts. Obtaining energy in this process should be treated as a positive side effect [8].

In Poland, the potential of biogas production from municipal waste was estimated at 796 million m3 / year, of which only 12% was used in 2015. In addition, there is potential in production of the sewage treatment plant of 97 million m^3/year, effectively used at the level of 76%. Furthermore, there are huge opportunities in the agricultural industry estimated at 3,000 million m^3/year.

Table 3. Raw materials used for the agricultural biogas production in 2016.

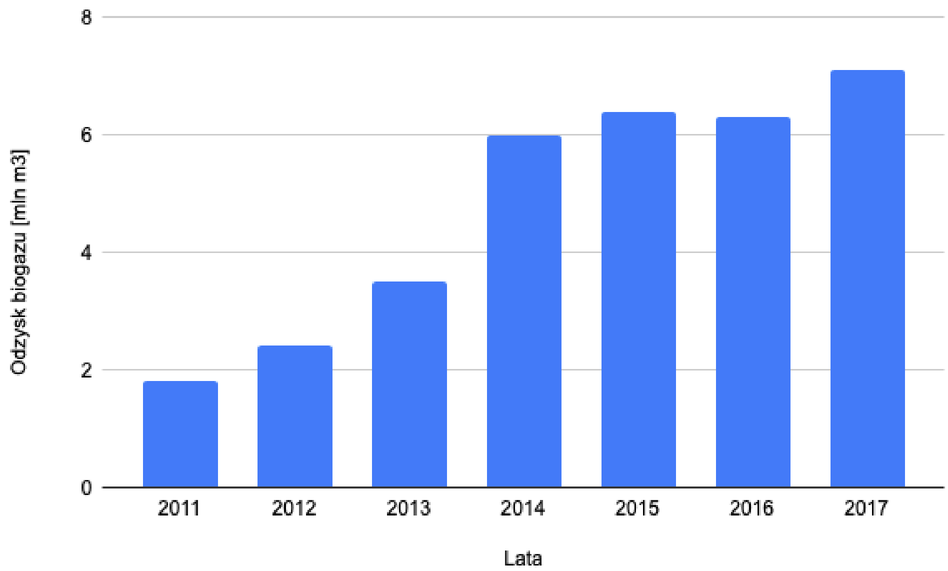
	2011		**2016**	
Type of substrate	**Quantity [thou. t]**	**Participation [%]**	**Quantity [thou. t]**	**Participation [%]**
Liquid manure	266	56.7	775	24.0
Residues from fruit and vegetables	11	2.3	665	20.6
Distillery waste	30	6.4	476	14.8
Corn silage	109	23.2	439	13.6
Sugar beet waste	7	1.5	222	6.9
Technological sludges from the food industry	6	1.3	125	3.9
Wastes from the dairy industry	2	0.4	89	2.8
Manure	12	2.6	86	2.7
Grass	13	2.8	57	1.8
Waste plant mass	2	0.4	33	1.0
Expired food	0	0.0	29	0.9
Other	11	2.3	228	7.0
Total	469	100.0	3224	100.0

Source: Own study based on data from the Agricultural Market Agency

Analysing the data above, we can notice a significant increase in the use of waste materials for biogas production. Nevertheless, the total capacity of the installed biogas power plants in Poland in 2016 was only 187 MW, of which 101 MW were agricultural biogas plants. For comparison, in Germany, with a similar raw material potential, these values were respectively 3905 MW and 3596 MW. Part of the Poland's energy policy project established, until 2030 several hundred new agricultural biogas plants will be built. In average one biogas plant is allocated in each commune [8].

Looking at the local possibilities of biogas production, Zakład Utylizacyjny in Gdańsk has the greatest potential. Currently, biogas is recovered there through a network of 291 degassing wells. As part of the expansion, 7 new wells were built, and 21 existing ones, where gas is currently flared, will be connected by pipelines to the plant's power plant.

Figure 6. Diagram showing increasing biogas production in the Zakład Utylizacyjny.



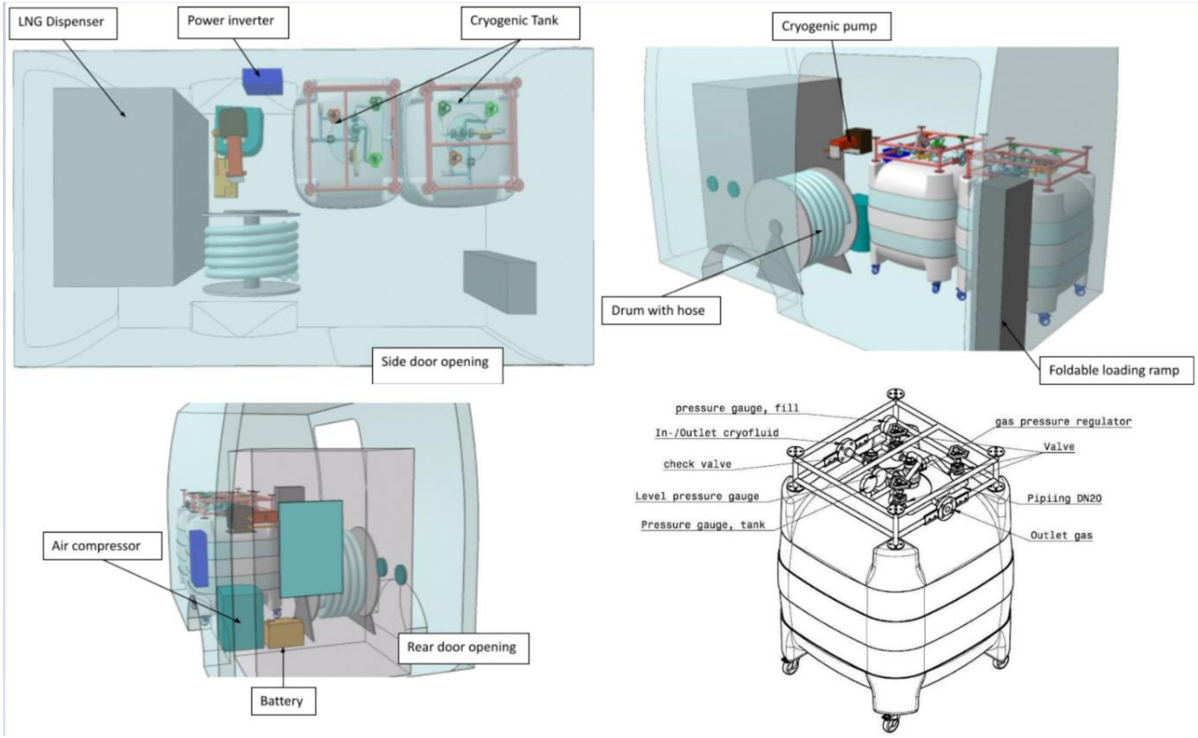
Source: Own study based on data from the Zakład Utylizacyjny in Gdansk.

In 2011 - 2017, Zakład Utylizacyjny recovered nearly 35 million m^3 of biogas. This allows to fully meet the current energy needs of the company. Increasing of the amount of waste and expansion of the biogas recovery system is a fact. It gives the opportunity to sell the raw material for external energy purposes, for example for Żegluga Gdańska [10].

The fuel obtained in this way should be efficiently delivered to the local end users. The network of refuelling stations and transport by tankers should be supplemented with solutions for the smallest recipients.

One of the ideas is to use mobile refuelling stations for liquefied biogas, a pilot project created as part of the Liquid Energy project. It is a delivery truck with a maximum weight of 3.5 tons, equipped with a refuelling installation. The main components are cryogenic tanks capable of holding approx. 200l (90 kg) LNG / bioLNG each, made of composite with passive thermal insulation [34].

Figure 7. Model of the mobile bioLNG refueling station and used cryogenic tank.



Source: D. Andrich, S. Andrich, Design concept of a vehicle with a permissible total weight of 3.5 tons used as a mobile refueling station for LNG fuel, 29. October 2021

8. Description and visualization of proposed technologies

There are two ways to adapt a compression ignition engine to burn a different type of fuel:

- Changing the principle of operation of the compression ignition engine (CI) to the system of operation with spark ignition (SI)
- Adaptation of the system to dual-fuel operation.

These systems are described in the following chapters.

8.1 Spark ignition engine

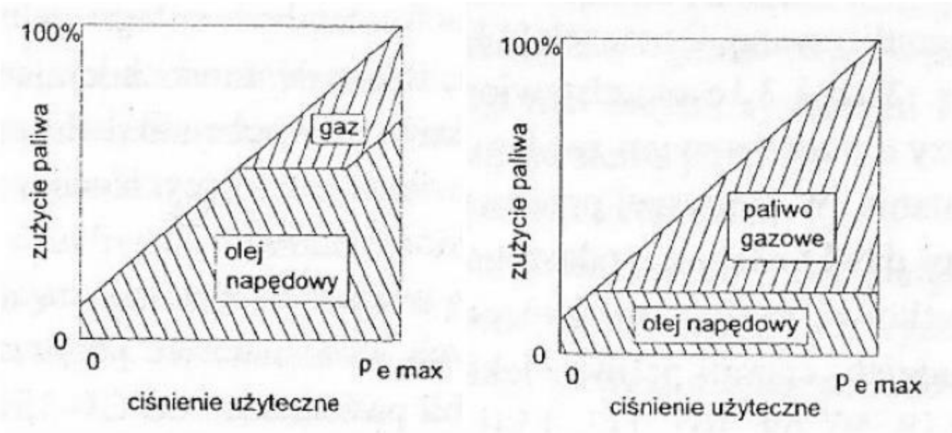
The choice of a given solution determines the specificity of the fuel combustion system. If the engine operation principle is changed from CI to SI system, only gaseous fuel is burned in the entire engine load range. The above assumption is implemented thanks to the modification of the supply system and the installation of a gas tank. Changes to the fuel system involve the replacement or adaptation of the following components:

- The injector should be replaced with a spark plug, which will cause a spot ignition of the gas-air mixture.
- The liquid fuel supply system must be modified to allow a flow of the gas mixture. This is done in two ways. The first method is a direct injection of natural gas into the charging manifold where it is mixed with air. Another solution is a system with a gas mixer. The amount of the flowing medium is regulated by the throttle and cut-off valves. The gas-air mixture of appropriate concentration is charged by the turbocharger, then through the cooler flows to the intake manifold, from where it goes to the combustion chamber.
- In case of a high-power engine, additional replacement of the pistons should be performed in order to properly burn the supplied mixture. In result it lowers the compression ratio. Knocking during combustion is a significant problem of marine engines with large cylinder diameters. It is caused by insufficient spark range from the spark plug. Replacing pistons with a specially shaped bottom eliminates this unfavourable phenomenon. Although it cause reduction overall efficiency and maximum power of the engine from a few to several percentage points.
- Installation of precise regulation system. The lack of proper adjustment of the gas-air ratio may cause operational difficulties in terms of low engine loads and at low rotational speed [13].

8.2 Dual fuel engine

When a dual fuel system is used, gaseous fuel is burned only within a certain engine load range. Currently, two dual-fuel systems are applicable. The first one allows the transition from liquid to gaseous fuel at medium and high engine loads (Fig. 4.1), which means approx. 70% of energy is supplied in liquid fuel, while the remaining part is supplemented by gaseous fuel. It allows to increase the thermal efficiency of the engine, as well as the possibility of burning lean gas-air mixtures, due to the high content of liquid fuel. Depending on the conditions and volatility of demand, the system allows for any choice of the fuelling method and the proportion of fuel supplied to the engine [13].

Figure 8. Operating characteristics of dual-fuel engine (left) and dual-fuel engine with a fixed minimum fuel oil dose.



Source: Stelmasiak Z.: Studium procesu spalania gazu w dwupaliwowym silniku o zapłonie samoczynnym zasilanym gazem ziemnym i olejem napędowym. Wydawnictwo ATH, Bielsko - Biała 2003.

The second of the dual-fuel systems requires the use of the pilot dose. It is a dose of diesel oil, used to initiate ignition of a homogeneous mixture in combustion chamber. The ignition temperature of the main component of natural gas, methane, is very high, around 450 °C. Without the provision of adequate energy contained in the liquid fuel, self-ignition and combustion will not take place. At partial loads, the proportion of liquid fuel covers 100% of the energy requirement, gradually decreasing at higher loads. The power and torque of the engine are strongly dependent on the size of the pilot dose, therefore it is necessary to precisely control the amount of fuel supplied, both liquid and gaseous. The aim is to minimize the initial dose, which will reduce operating costs. An equally important factor is reduction in emission of toxic compounds contained in exhaust gases and carbon dioxide, due to the introduction of more and more stringent standards [12].

Dual-fuel systems used in shipbuilding is based on a low-pressure natural gas supply. At the start of the compression stroke, the gas is supplied to the cylinder head through the valve at a pressure of 0.3 to 0.5 MPa. The high-pressure system is used to supply the engine with liquefied natural gas. LNG is gasified and, under a pressure of 25 MPa, supplied to the combustion chamber at the end of the compression stroke [12].

In case of a positive-ignition engine, the introduction of a dual-fuel combustion system for high-power engine requires a number of modifications:

- Connecting gas manifold with an injection valve to air intake manifold. This valve is electromagnetically controlled and regulates the amount of gas depending on the operating parameters of the unit. There is a separate valve for each cylinder (sequential system),
- Replacement of the injection system,

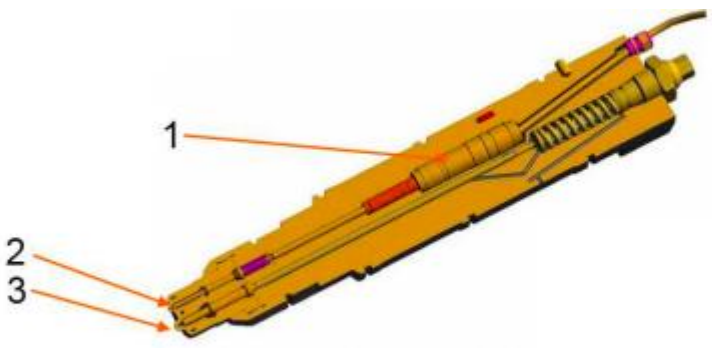
- Installing a kick-off system that includes the fuel pump and injector tubing,
- Modification of individual components: pistons, cylinder head and camshaft, for dual fuel adaptation,
- Implementation of the measurement and regulation system of gas supply,
- Modifications regarding control system for the engine operation parameters.

In the case of an electronically controlled engine, there is no need to modify the structure of the engine itself and its accessories. The modification focuses primarily on the method of controlling gas installation and its integration with existing control, as well as on supervision of the engine's operation to ensure appropriate parameters.

For dual fuel systems, gas supply can be accomplished in several ways. One of them is by use of a mixer placed directly in front of the compressor. The flow is regulated by system which controls the rotational blower speed. After mixture is formed in the right concentration, it is compressed and delivered to the inlet channel, and then directly to each of the engine's cylinders. A common solution is to isolate two supply circuits. One of them is used when the engine is fully loaded. The second one is used during engine start until the pressure in the combustion chamber is reached. Both circuits are connected by a solenoid valve which switches between the modes.

In dual-fuel engines used as power units, very common solution is to inject gas into the intake manifold. At the start of the intake stroke, the gaseous fuel mixes with air in the correct proportion. A certain amount of liquid fuel is required for ignition. Supply of diesel fuel for both gas combustion and traditional operation is carried out by a two-nozzle injector [13].

Figure 9. Dual-fuel injector cross-section.



1 - pilot dose solenoid valve, 2 - pilot dose needle, 3 - main fuel needle

Source: Tirelli G.: Go for Gas - Wärtsilä DF technology & applications. Wartsila's Presentation of the Ship Power, 2011

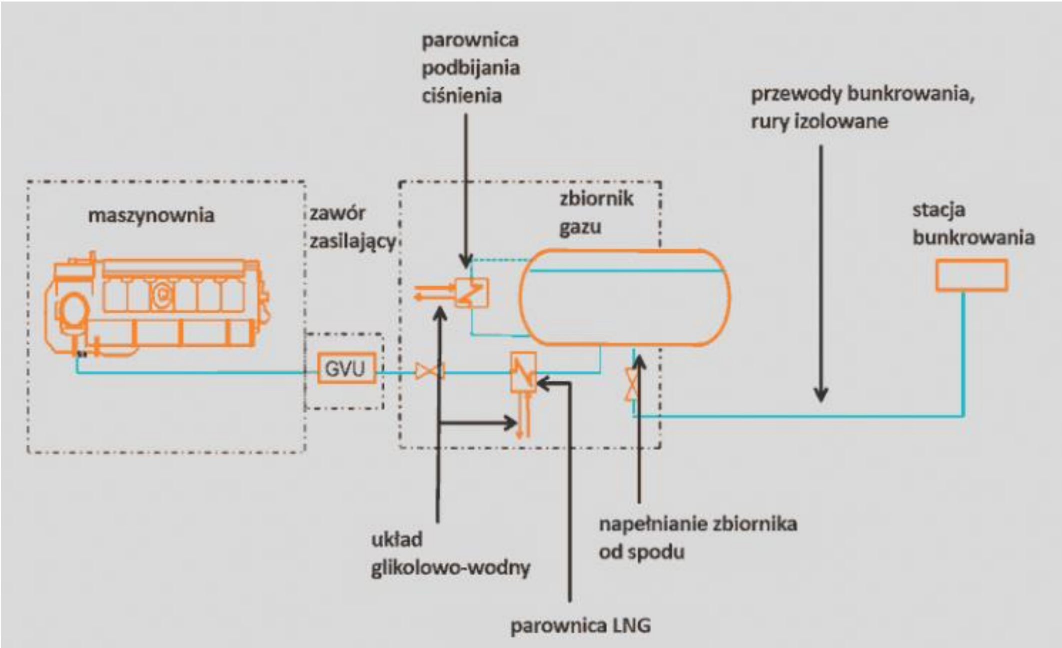
The third way is to deliver gaseous fuel directly to the combustion chamber. Intake manifold injection system development is described above. In this solution, diesel and gas fuel are supplied with one injector.

In addition to supplying engine with gas fuel, other design and operational issues should also be taken into account. In order to achieve satisfactory parameters, attention should be paid to the heat resistance of the materials of individual elements. This applies to both head and piston seals, as well as parameters of working fluids. In case of self-ignition, due to the appropriate geometry, the chamber allows a proper atomization and shaping of the fuel stream, while for spark ignition, it provides the most effective spreading of the flame.

8.3 LNG storage tank

There are several types of LNG storage tanks – built-in hull or stand-alone tanks. The last one are tanks with an internal pressure of about 2 bar, usually cylinder-shaped (cylindrical with convex ends). The main advantage of this type of tank is the low level of gas evaporation. For example, with a capacity of 200 m^3, a half-filled tank is able to hold the entire load for 25 days without dropping it.

Figure 10. Diagram of the installation with LNG tank for engine supply.



Source: https://www.konstrukcjeinzynierskie.pl/magazyn/192-f2019/2677-systemy-paliwowe-lng-w-jednostkach-morskich

This type of tank does not have a gas compressor supplying the system. It is achieved by regulating the pressure value and changing the state of fuel aggregation. If the pressure is too low, part of the LNG is directed to the exchanger, where it flows through the pipes and releases heat and evaporates. At the end of the cycle, it returns back to the tank, raising the pressure. For the safety and proper operation of the storage installation, you can fill up to 98% of the tank's capacity. Pressure, temperature and liquid level in the tank are also monitored on ongoing basis. All fittings (tank and pipelines) filled with liquefied gas should be thermally insulated in a proper way. It is necessary to prevent undesirable cooling of the ship's space [13].

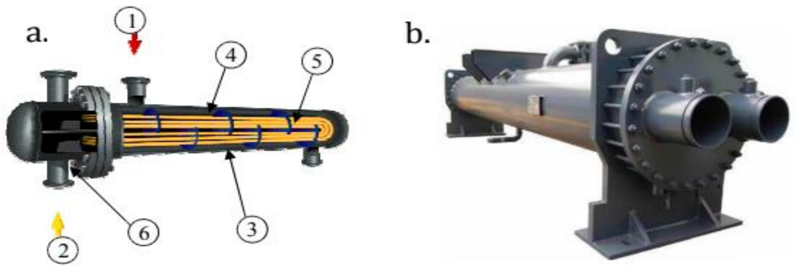
8.4 Regasification part

A liquefied gas regasification system is used for two purposes. First one is to regulate the pressure in the tank, what was described in previous chapter. Second, main function of the system is to supply gaseous fuel to the engine manifold while maintaining the appropriate parameters, by the use of a heat exchanger. Several solutions are used in the gas industry. Their selection is determined by:

- Limited space in the ship room,
- Source of heat transferred to the fuel - on vessels, the waste heat generated in the production of electricity is so large that it easily covers the need for LNG evaporation,
- The required capacity to provide a sufficient heat flux.

Heat from the engine, exhaust gases and oil system is supplied through the coolant to the evaporator, which is a mixture of water and glycol with a strictly defined concentration. It prevents the refrigerant from freezing in the circuit and ensures efficient heat transfer to the fuel. Insufficient glycol content can lead to the formation of ice plugs, limiting the flow, and consequently leading to clogging of the exchanger, causing damage due to local overheating. Too high glycol content increases the density of the solution and significantly lowers the specific heat of the coolant, limiting the possibility of heat transfer. For the purpose of this project, the proposed solution is a shell and tube heat exchanger [13].

Figure 11. An exemplary diagram of shell and tube heat exchanger.



1 - coolant inlet, 2 - LNG inlet, 3 - pipe bundle, 4 - jacket, 5 - baffle, 6 - head

Source: [13]

In the proposed solution, the evaporating natural gas flows through the bundle of pipes placed between the screens, which is washed by the heat transferring solution. To increase the efficiency of the evaporation process, baffles are installed inside the jacket, which change the direction of the solution flow. To further increase the amount of heat transferred to the fuel, the evaporators are mounted vertically. At the outlet connection there are sensors monitoring temperature and pressure. They are used to transmit information to the controller. It regulates the flow when permissible value is exceeded or it notifies about too high pressure drop [13].

8.5 Integrated power systems

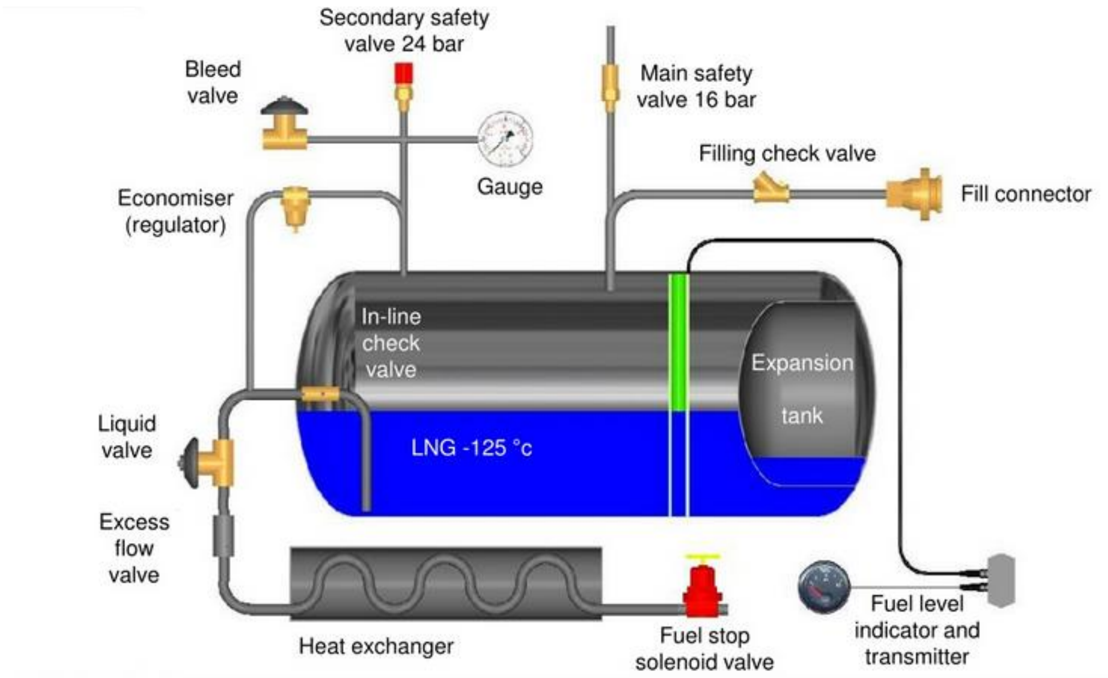
In land transportation, natural gas supply technology is much more developed – heavy truck units are equipped with LNG / CNG installations on a mass scale by the largest manufacturers - Iveco, Scania, Renault and Volvo. It is worth paying attention to the possibility of using engines from trucks for smaller marine units to drive marine propellers.

Figure 12. LNG tank by Chart Inc. for truck units.

Source: https://autoline.com.pl/-/sprzedaz/zbiorniki-paliwa/do-ciagnika-siodlowego/SCANIA-LNG--22041301005454068600

Such systems use a double-walled LNG tank, separated by insulation, entirely made of stainless steel. Contrary to the previously described large-volume tanks, they are pressure tanks with higher operating pressure from 4 to 10 bar. As a result, the temperature inside can be reduced from about –140 to –125°C. The tank is equipped with a hydraulic pump which causes the LNG flow through the exchanger with the engine cooling medium circuit. This causes the conversion of fluid medium to gas under a pressure of about 300 bar. Next, the compressed gas enters the expansion tank, allowing the flow pressure to stabilize, before the gas is supplied to the engine's combustion chamber through the reducer. The tank is equipped with a safety valve, which releases the gas into the atmosphere in a controlled manner when the pressure inside (usually 16 bar) is exceeded. In order to minimize this process, leaving the fuel in the tank for more than 7 days should be avoided [25].

Figure 13. Schematic diagram of the integrated LNG installation.



Source: Presentation "LNG Tank" Iveco; https://www.slideserve.com/teal/lng-in-ground-tank

Control of gas supply system is linked to the engine control system. In modern self-ignition engines, fuel injection and valve operation are regulated by the processor of the control unit. It can be relatively easily adapted to supplying LNG without significant interfering with engine's structure.

The use of the truck engine with the LNG installation must be preceded by an analysis and approved by the Classification Society for use on ships.

9. Description of units selected for modification by the Implementation Partner

For the purpose of the study, the Implementation Partner selected two units as a platforms for modification the current power supply, consists installing components of the liquefied gas installation. Description is presented below, together with an analysis of legitimacy of their use in the "Liquid Energy" project.

9.1 "Opal" unit

Figure 14. The "Opal" vessel during the voyage.

Source: photo provided by Żegluga Gdańska

"Opal" is a KP-2 catamaran with a steel hull. After birth, it has served shipowners in many regions of the Baltic Sea - it has sailed both in the territorial seas of Poland, Russia, Sweden, Denmark and Germany. In a year 2000 "Opal" has travelled across the ocean to Sierra Leone, later has chartered in Gambia and Guinea-Bissau. It is surprising by the fact, the ship has operated without the sea class, not mention the ocean class. In 2006 the ship returned to Gdańsk and since then has served Żegluga Gdańska [35].

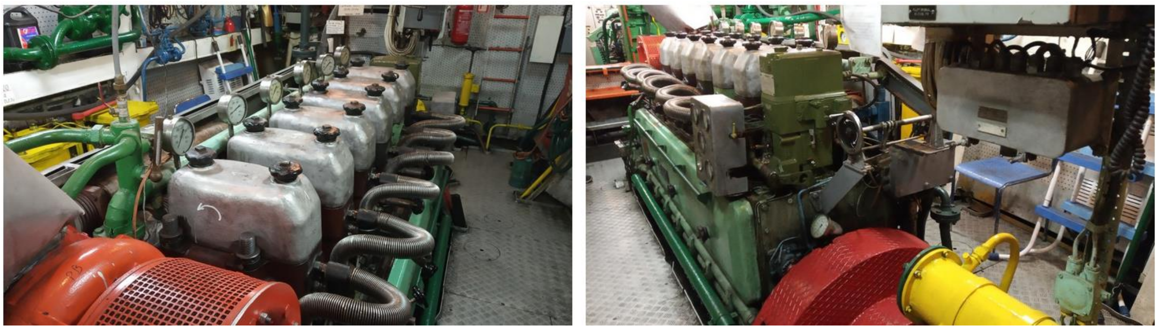
Table 4. Basic parameters of the "Opal" unit.

Ship type	Passenger
Year and place of construction	1981, Gdańsk
Total length of the KLW *	37.6 [m]
Total width of the KLW *	11.5 [m]
Overall height	4.4 [m]
Draft	2.9 [m]
Number of passengers	450 + 9 people of the crew
The power of the engines	840 [kW]
Speed	13 knots

Source: Own study based on the Rejestr Statków Morskich

In each of the catamaran's floats there is a power plant with a separate part for the main engine by H. Cegielski, type 6AL20 / 24, which is coupled with the propeller shaft through a gearbox. In this room there are also devices of the systems necessary for the operation of the unit - water and oil cooling pumps, etc.).

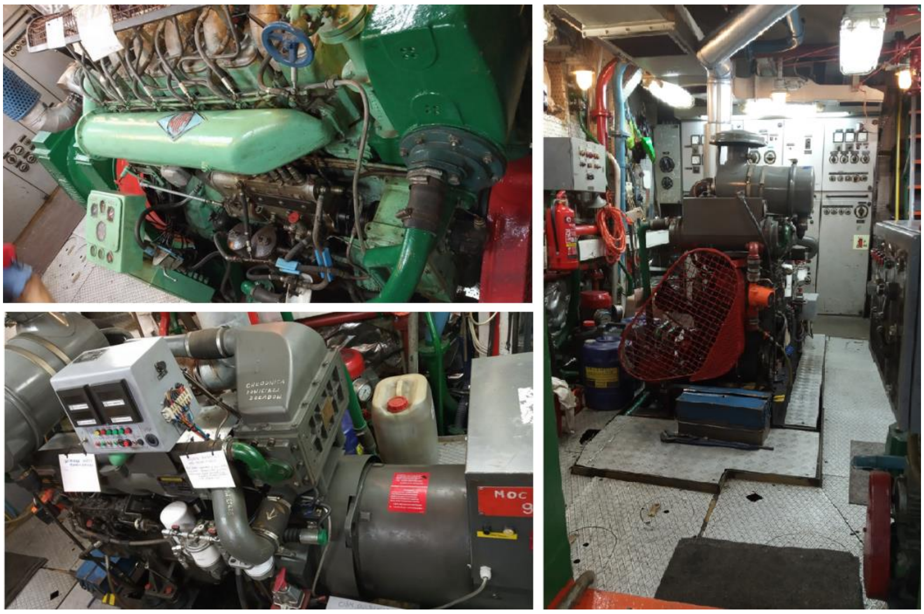
Figure 15. View of the main engine in the engine room.



Source: own photographic documentation

In the room adjacent to the main engine room, there is an auxiliary power unit used to power all electrical devices and lighting on the ship. One float houses a Wola engine, type 52H6A, and the other one, the Chinese R6105A ZLD engine. Apart from the auxiliary engines, electrical cabinets are located in the room.

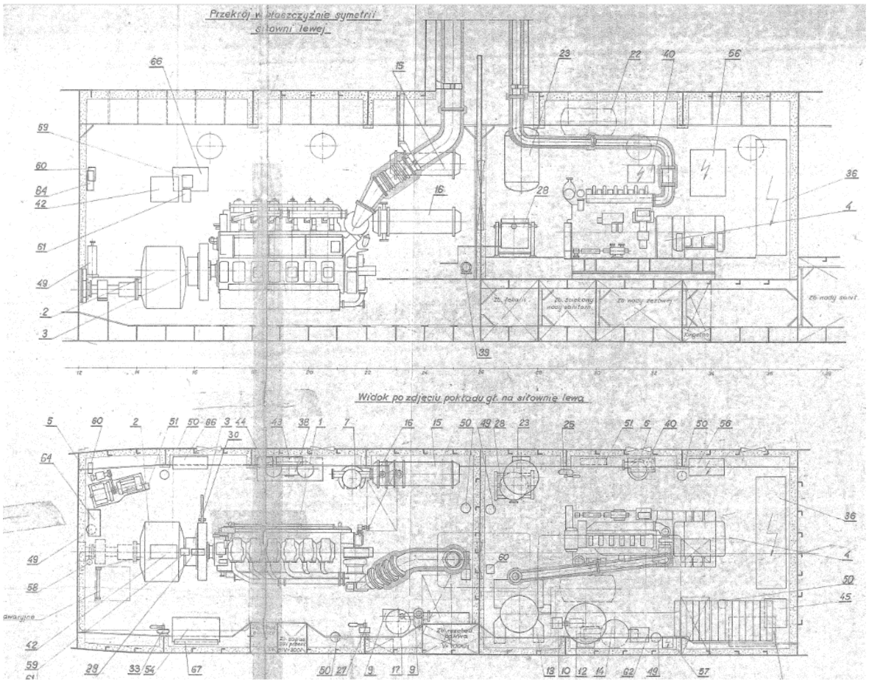
Figure 16. Auxiliary engines on the "Opal" ship.



Source: own photographic documentation

Both rooms are connected from the top by a chimney shaft leading exhaust pipes from engines through all internal decks to the boat deck. Each float also has hull tanks carrying the necessary media and ballast water on the ship.

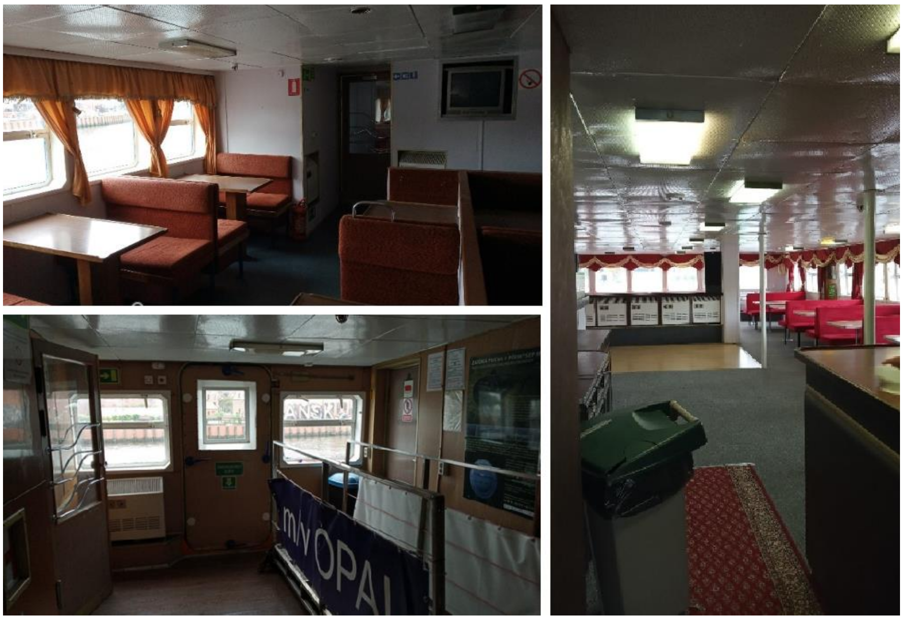
Figure 17. Longitudinal section and a top view of the engine room in one of the catamaran's floats.



Source: technical documentation provided by Żegluga Gdańska

The main deck is located above the engine room. It is a spot for emergency exits. Two of them are located symmetrically amidships on both sides, leading directly to the passenger compartment, one on the stern and on the port side. On main deck there is a passenger lounge and a bar, separated by a lobby. Both the stern and the bow part of this deck are available to passengers for outdoor observation during the voyage.

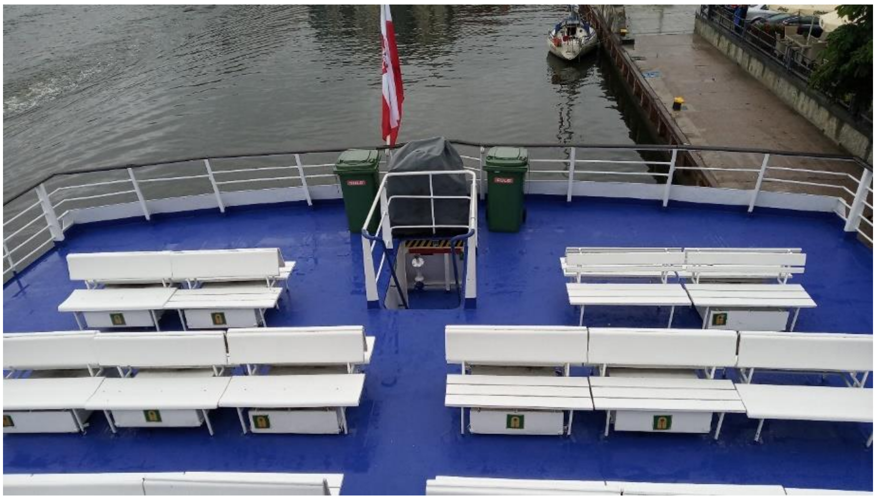
Figure 18. Passenger area on the main deck.



Source: own photographic documentation

On the upper deck there is a restaurant area with a kitchen. The large stern space is filled with benches during the voyage. This is also main escape route from the top deck.

Figure 19. View on the stern on the upper deck.



Source: own photographic documentation

Above upper deck, a boat deck is located. It is a place for a lifeboat, operated by cranes on both sides. They used to be used for transport the cargo transportation also in container form - mounting feet are visible in the deck plate.

Figure 20. View of the boat deck.

Source: own photographic documentation

The rest of free space is used by the passengers. On this deck there is a wheelhouse room, in which operations for the engine room are issued. A control panel for on-board devices, as well as a navigation and communication part are located there.

Figure 21. View showing the wheelhouse room.

Source: own photographic documentation

The engine control system is carried out in two ways - through the engine speed and power regulator or in emergency mode - indirectly by tilting the throttle to the appropriate position, transmitting a signal to the engine room. Crew member operating the engine reads the setting and, accordingly, manually regulates the operation of the drive unit.

Figure 22. Emergency control panel with measuring indicators.

Source: own photographic documentation

Adjacent to the wheelhouse room are the crew accommodation space and battery locker. On wheelhouse roof there is a mast located. It serves as mounting point for telecommunication, radiolocation devices and for navigation lighting.

Figure 23. View towards the bow showing superstructure and the mast.

Source: own photographic documentation

9.2 “Sonica” unit

Figure 24. The "Sonica" vessel during the voyage.

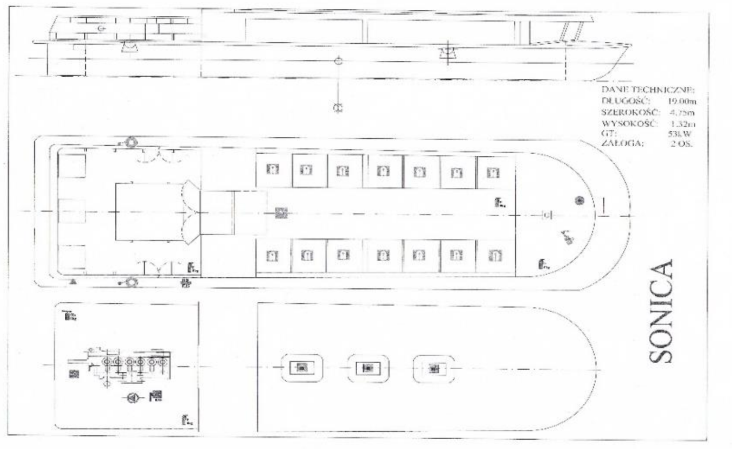
Source: https://www.naszbaltyk.com/sylwetki-statkow/1311-sonica-i-sonica-i-rzeczne-tramwaje-w-gdansku.html

Another vessel selected by Żegluga Gdańska is the ship called "Sonica". This ferry has the shortest length of service in the Carrier’s fleet. It was built in 2004, purchased in April 2012 from a Russian shipowner. Several years have passed since its construction, before ship was in use. After entering service in June 2004, it sank as a result of an explosion at the Central Yacht Club in St. Petersburg. It was a sinking deliberately planned by the competition. The vessel was lifted on July 13, 2004. After repairs, it still was not in operation and was kept on shore. For this reason, the unit was in a deplorable technical condition and completely devoid of equipment. It arrived in Gdańsk at the beginning of May 2012, and towed to the Repair Base at an express pace to enter service on June 1, 2012 [16].

The first season showed a lot of problems with its exploitation. There were frequent failures of engines and auxiliary equipment, with addition of enormous difficulties in manoeuvring, especially in stronger winds. Practically every day after dark, "Sonika" went to the Repair Base, where it underwent repairs. Specific improvements, including the replacement of the engine, installation of bow thrusters and change of engine control, underwent in March 2013. Since then, failures have occurred much less frequently, and the ferry's manoeuvrability has significantly improved. From this time it became a part of the Gdańsk’s Old town landscape [16].

Unfortunately, the contract with the City to subsidize the operation of the ship has been terminated. The operating costs significantly exceeded the revenues obtained from the tickets, which contributed to the decision to end the courses. Currently, the unit is stationed at the Repair Base, it has also lost its Inland Navigation class, and there is no sign that this state of affairs will change in the near future.

Figure 25. M / S Sonica general arrangement.



Source: technical documentation provided by Żegluga Gdańska

Table 5. Basic parameters of the M/S Sonica unit.

Ship type	Passenger
Year and place of construction	2004, St. Petersburg
Total length of KLW *	19 [m]
Total width of the KLW *	4.75 [m]
Overall height	1.3 [m]
Max. hull draft to KLW *	0.65 [m]
Number of passengers	40+2 crew members
Number of bicycles transported	5 pcs
Engine power	132 [kW]
Drive	Stream water
Speed	8 knots

* The line of the yacht's draft without a crew is called the Design Waterline

Source: https://www.naszbaltyk.com/statki-bialej-floty/1311-sonica-i-sonica-i-rzeczne-tramwaje-w-gdansku

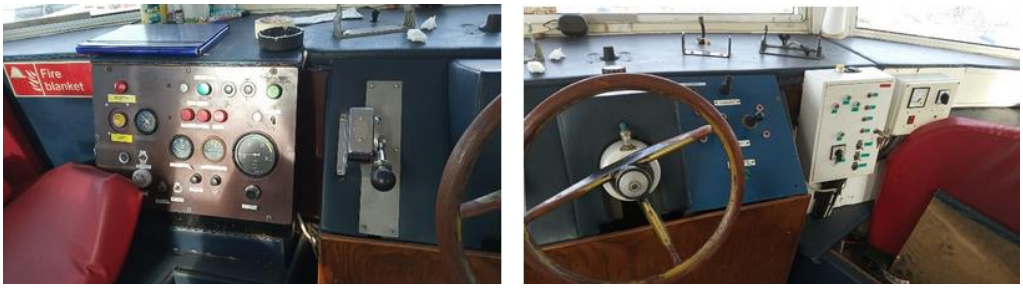
The entrances to "Sonica" are located on both sides in the aft part. Additional seats for passengers are provided on board during the voyage. Below deck, there is a power plant with an engine (JaMZ-238 eight-cylinder V-type) and two fuel tanks. Photos below depict the engine room from the deck perspective after opening the hatch and a view of the fuel tanks on each side.

Figure 26. View of the engine room from the deck perspective after opening the hatch and a view of the fuel tanks on each side.

Source: own photographic documentation

Going down the stairs towards the amidships, we enter the roofed part of the ship. Here is the passenger area with tables, where travellers can rest and enjoy the view during the cruise. At the end of the passenger section - at the bow is a wheelhouse located. There is a steering wheel, a panel with sensors for operating on-board equipment, as well as communication and navigation devices. Wheelhouse is shown in the photo below. Underneath there is an electric bow thruster, which greatly facilitates port manoeuvres.

Figure 27. View in the wheelhouse room.



Source: own photographic documentation

The passenger compartment is covered with a roof. It is a glass roof based on a lightweight structure, which can be used to store rescue equipment. A greater load may cause damage.

Figure 28. View on the roof with the lifebuoys placed on it.

Source: https://www.trojmiasto.pl/wiadomosci/Gdansk-wycofuje-sie-z-tramwaju-wodnego-n155460.html

10. Technical analysis for implementation of power supply system modification

The first thing to consider is fuel supplement to the ship's engines, using the characteristics described in sections 8.1 and 8.2.

For the purpose of the project, the most optimal solution for the "Opal" unit is a dual-fuel system with a pilot dose of liquid fuel. This solution involves less interference in the structure of the engine, compared to the gas supply system alone. Such system allows a smooth switch from one type of fuel to another. It will increase a level of redundancy, which is desirable in the event of failure of any of the components of the gas system, or a reduction in fuel supply. This choice will cause a significant reduction in modernization costs. Compared to the method of fuel supply without a pilot dose, there is a possibility of limiting the combustion of liquid fuel in a much greater range of engine operation, and not only at high loads. It will reduce emission of harmful compounds of the exhaust gas.

10.1 Analysis for the "Opal" unit

After determining the type of fuel supply, it should be considered how the fuel will be stored. In the case of a catamaran, the fuel demand is very high. The ship's crew determined the level of daily diesel oil consumption during season, considering about 8 hours of continuous operation, at the level of 1 m^3 per day. Currently installed fuel tanks have a capacity of about 20 m^3, which allows continuous sailing for about 2 weeks. After consulting with Żegluga Gdańska, it was found that time between refuelling could be significantly reduced. Despite, there is still a need to arrange a large volume for gas fuel, and the possibilities on the ship are limited. Detailed guidelines on fuel storage are provided in Part 1-A, Chapter 6.4 of the Regulations (References to regulations in this and the following sections refer to: "Using LNG or other low-flashpoint fuels onboard ships other than gas carriers" issued by PRS in January 2020).

Regardless of selected location, vessel must be verified for two key elements:

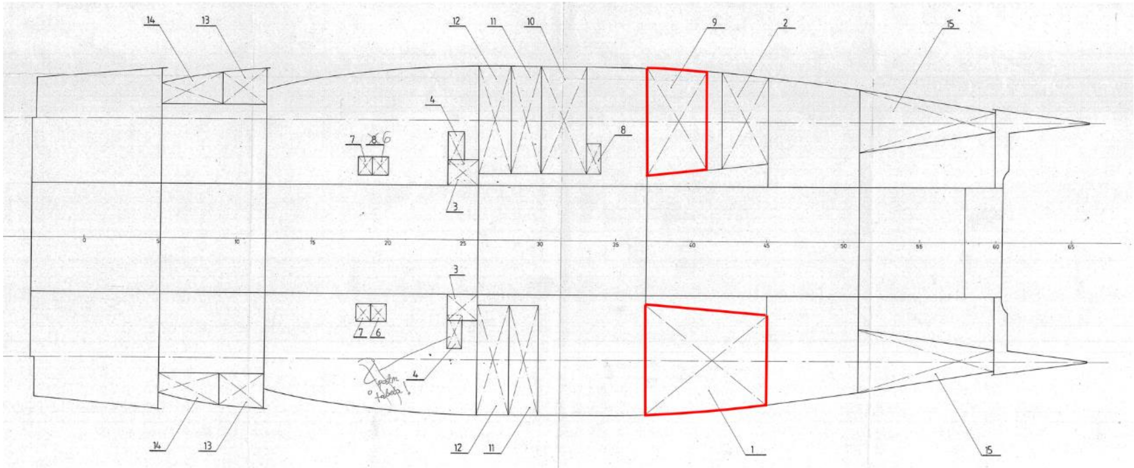
1) The issue of safety valves for each of the installation components. They are used to release part of the gas into the atmosphere so as to avoid excessively high pressure build-up. This is important due to the regulations, which are very strict in terms of the location of the air outlet outlets. Regulations 6.7.2.7 and 6.7.2.8 assume that they should be separated by:
   - 6 m from the working deck and passageways,
   - 10 m from air intake and exhaust points, transitions to places of accommodation, services and control or other safe zones.

In case of the first restriction, the Classification Society allows the application of an exception and reducing the distance. The fulfilment of the second criterion is obligatory and will be very problematic to achieve.

2) Stability. The larger and heavier the tank, the centre of gravity of the ship moves upwards. It may affect the manoeuvrability and behaviour of the hull in the water. In no case it is allowed to deteriorate the performance of the unit. As described in the previous chapter, "Opal" in the past was used to transport a container mounted on the boat deck perpendicular to the ship's axis, which make the location of the tank in a same place possible. Nevertheless, the rules for the classification and construction of sea-going ships, part IV, "Stability and Subdivision", issued in January 2022, clearly states that for passenger ships, changes of more than 2% or 2 tonnes (whichever is greater) of the lightweight of the ship, an inclining test is required.

The description of the modifications in the following paragraphs is a certain assumption, justified only if both requirements are positively considered, and which is not possible to assess at this stage.

Figure 29. Fuel oil tanks location on Tank Plan.



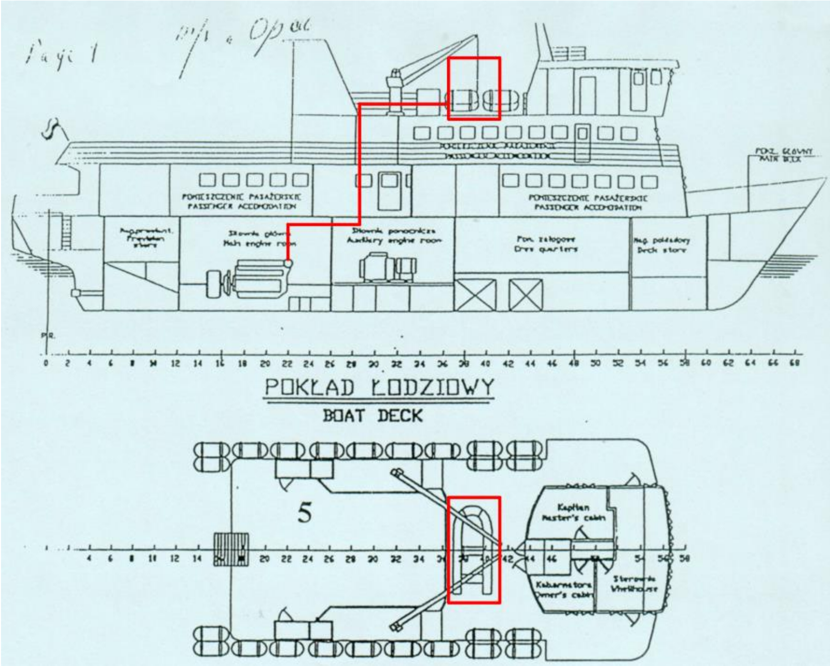
Source: technical documentation provided by Żegluga Gdańska

The first idea is to use the existing fuel tanks in the floats. This solution is hindered by the properties of the LNG fuel described earlier.

The main problem is lack of adaptation to hold this type of fuel. The use of adequate insulation inside the tank would greatly reduce the space available. Moreover, the material used for the steel structure of the existing fuel tanks is not designed for contact with a low temperature liquid. Gas fuel leakage can cause the weakening and damage of the structure adjacent to the ship's side. As a consequence, the plating may be interrupted and the ship may sink. Even a well-insulated LNG fuel tank must be separated from the plating and other spaces by a "cofferdam" (double bulkhead). In case of external damage (e.g. in a collision or grounding), it prevents from forming an explosive mixture of natural gas and air. This is mentioned in chapter 5.3 in part 1-A of the Regulations. LNG tank, unlike a diesel fuel tank, must also be able to maintain a high pressure inside caused by a gradual change of liquid aggregate state into a gas.

Taking into account arguments presented above, the use of existing fuel tanks should be completely ruled out. Due to lack of other space within the hull, a viable alternative is to install an independent LNG tank (type C) on the boat deck. This solution will eliminate many problematic issues. Such tank will be properly insulated and will not be exposed to damage. In addition tank will be located in the open air, and will not require additional ventilation.

Figure 30. Proposal of LNG tank location and supply pipeline.



Source: technical documentation provided by Żegluga Gdańska

Currently, the lifeboat is installed in marked location. Nevertheless, its light structure allows replacing with life rafts located on side. Lifeboat still remains within the reach of the deck crane.
The option of placing the tank along the ship's axis on boat deck is also under consideration. It allows the installation of a larger capacity tank and extended period between refuelling. The disadvantages is a need to remove some of the railing, and reduce in number of benches for passengers. By the fact that part of the view is blocked by the tank unit may also be an important matter.
Possibility of arranging a fuel tank to be installed on the upper deck could be considered, but it will significantly limit the space for passengers and block access to an escape route.

Figure 31. LNG cryogenic tank offered by Zakład Aparatury Chemicznej “CHEMET” S.A.

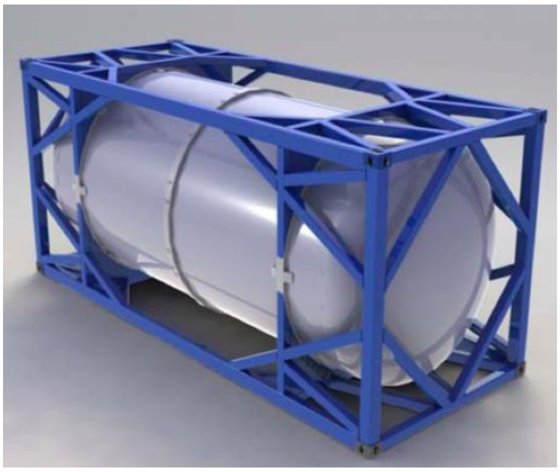


Table 6. "CHEMET" cryogenic tank parameters.

Total length	605 [cm]
Overall height	259 [cm]
Overall width	244 [cm]
Outer diameter of the tank	236 [cm]
Max. permissible working pressure	7 [bar]
Water capacity	19 000 [dm^3]
Max. fill level	80 [%]
Max. mass of transported cargo	10 000 [kg]

Source: https://chemet.eu/app/uploads/sites/2/2020/06/ISO-Kontener-kriogeniczny.pdf

The next step is to consider how the refuelling of the tank will be carried out, considering Chapter 8 of the Regulations. Therefore, choice of components must be adapted to technology used by the supplier.

Taking into account, there is no LNG refuelling station on the quayside, refuelling must be carried out with the participation of a fuel tanker, able to fill at once the entire tank volume on ship. The refuelling time should be limited to a maximum of 1-2 hours (similar to refuelling operation for diesel fuel).

Because of the height between the quay and boat deck, selected for the location of the tank, it will be necessary to purchase a long, flexible fuel hose that can be lowered, for example, with a deck crane.

Another necessary element of the system for refuelling is an inert gas station, e.g. in the form of high-pressure nitrogen-filled cylinders or a nitrogen generator. They should be located in the vicinity of the tank to purge the system before and after loading, and to enable safe disconnection of the fuel line.

Another element is the regasification station. It should be located near the tank to avoid troublesome of routing cryogenic pipes through all decks to the engine room. There is a need to thermally insulate the piping and avoid contact with the ship's structure. More information about the pipeline management is provided in Chapter 7 of the Regulations. Leaving the regasification station on the open deck, however, involves the installation of a pump from the ship's float and cooling water supply pipelines (using e.g. ballast water) to the LNG evaporator. The prepared fuel in gaseous form should be brought to the engine room, using the space adjacent to the chimney shafts. In addition pipe-in-pipe system to be applied - gas pipe inside, ventilated in case of leakage - connected to the regulation units located next to engines (Chapters 7, 9, 13 of the Regulations).

Figure 32. A proposal of a deck penetration with a gas pipe and cooling water (supply + return) and marking a new shaft along the existing one on passenger decks.

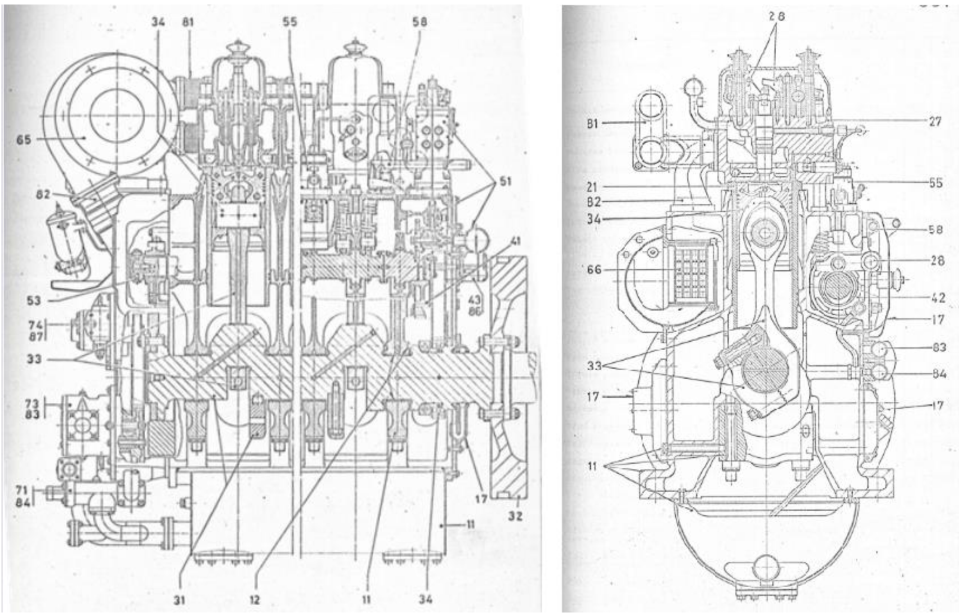
Source: own photographic documentation

At this point, it should be considered whether the modification should apply to main engines only or to auxiliary units as well. Due to the small share of auxiliary engines in overall ship exhaust emissions, the complexity of the power supply system and the need of conversion for three different types of engines, it is proposed to apply modifications for propulsion engines only.

Engine modernization concerns:

- installation of nozzles supplying gas to air collectors (28), or a mixer in front of the turbocharger (65) - depending on the selected system,
- adding of a pilot dose pump and modification of the injection system (55),
- replacement of pistons (34), cylinder head (27) and camshaft (42) to adapt to new operating parameters and conditions in the combustion chamber,
- adding sensors to monitor the parameters of the engine and the power supply system.

Figure 33. Longitudinal and cross-section of the AL 20/24 H. Cegielski engine.



Source: technical and operational documentation of the H. Cegielski marine engine, type 6AL20 / 24, provided by Żegluga Gdańska

The last element that connects the system is the control system. Its implementation means collecting all electrical cables from the measuring and control devices and lead them to the control cabinet in the engine room, simultaneously insert and connect control panel on the bridge. It may be required to partially rearrangement the passenger part of the ship.

It is very difficult to predict the total scope of shipbuilding work for the modification of the ship as well as the modernization of the engines. This knowledge can only be obtained by detailed inventory provided by specialized design office and shipyard with experience in this type of work. Based on the experience of the shipyard in Szczecin implementing a similar modification, for the long time in duty vessel ("Magda 1"), estimated financial outlay may radically differs from the actual demand, which makes the decision to modernize more complicated.

10.2 Analysis for the "Sonica" unit

Similar as for "Opal" vessel, key issue to begin with analysis of the power supply system modification analysis is selection of tank and find appropriate location for them based on the regulations.

It would seem that hull structure of the "Sonica" vessel allows for a significant simplification of the gas supply system. The ferry's engine is located just below the open deck, in which the service hatch is embedded. This allows the engine, equipment and fuel tanks to be quickly removed from the engine room. A natural choice seems to be use of the space currently occupied by fuel tanks on both sides. On each side, they take up a space of approx. 1x1x3 m, which is enough to install two LNG tanks there.

However, based on the information provided in chapter 5 of this study, the ship does not meet the basic criteria necessary for fuel storage. For passenger ships, the LNG tank should be located at a distance of not less than 0.8 m from the ship's side. Moving the tanks towards the ship's axis is not an option due to the too small distance from the engine. The ship also does not have a double bottom and double shell structure.

Another problem, similar as for "Opal" unit, is location of gas outlets from installation after safety valves. It is impossible to avoid the air intake to the engine room, located on both sides. Moreover, the entrance to the passenger compartment is located next to the engine room, i.e. in the 10m zone required for the gas outlet.

On the other hand, chapter 2.7 of the Regulations indicates that ships below 500 gross tonnage - as in case of „Sonica", will be considered separately by the Classification Society. It is also problematic installed engine does not have technical documentation, which makes the analysis for approval much more difficult by the Class and increases its costs significantly. For purposes of the study, it was assumed, above reservations will be recognized and allow for modification. It cannot be verified at this stage.

Taking into account assumption above, it is necessary to consider how much fuel will be needed to supply the unit. According to information provided by the Employees of the Żegluga Gdańska shipyard, propulsion engine consumes 160-200l of fuel oil during the day of intensive sailing (about 8 hours of work). For LNG, it would be 400-500l / day.

Two LNG tanks with a total capacity of approx. 1100 litres should be sufficient for approx. 2 days of continuous operation. This time is acceptable for a ferry operating only within Gdańsk inland waters. Currently, the ferry can run for 2 weeks on one refuelling, but there is no justification for maintaining such long period, especially in regards of small mobile LNG refuelling stations development, which could provide fuel in a convenient place for the ship. It should be noted, refuelling time for LNG and fuel oil is comparable. List below shows examples of cryogenic tanks used in trucks.

Table 7. List of cryogenic tanks examples used for trucks.

SPECIFICATIONS (EXAMPLES OF VARIOUS SIZES)								
MODEL*	HLNG-52		HLNG-72		HLNG-119		HLNG-150	
Dimensions	in	mm	in	mm	in	mm	in	mm
Diameter	26	660	26	660	26	660	26	660
Length	41	1032	51	1286	76	1921	90	2296
Capacity	gal	ltr	gal	ltr	gal	ltr	gal	ltr
Net	45	170	65	246	108	410	135	511
Gross	52	196	73	272	120	450	149	564
Weight	lbs	kg	lbs	kg	lbs	kg	lbs	kg
Empty	342	155	406	184	525	238	635	288
Full**	498	226	633	287	904	410	1109	503

* Available in custom sizes from 1016 mm to 2591 mm in length for R110 tanks or up to 1,000 L capacity for TPED tanks. Custom diameters are also available.
** Full weight calculations are based on 0,42 kg/ltr density LNG.

Source: Chart Inc. LNG tanks catalogue

Regardless of whether the applied system will use ready-made solutions or will be built of system components solely for the needs of the unit's operation, the issue of the engine remains. It seems irrational to leave the current drive unit regarding lack of approval by the Class.

It seems, the best option would be exchange of existing engine to new generation gas unit which allows for electronical adjustment of ignition conditions in combustion chamber. Factory fitted indicators helps to define crucial engine parameters, to improve cooperation with LNG installation. However, such change will cause rebuilding of the unit’s power supply control system.

11. SWOT analysis

To consider successful ship modification for Żegluga Gdańska, a SWOT analysis was applied. It will help to recognize all internal and external factors influencing the legitimacy of such a complex undertaking in a broad sense.

After defining all the components - strengths and weaknesses, as well as opportunities and threats related to the project, their mutual interactions should be defined. The compilation was made in the form of a matrix with assigned points declaring the strength of this impact on a scale from 0 to 2. Based on the obtained result, conclusions were presented answering the questions whether the proposed modification is possible and justified.

11.1 Strong points

S1: Brand. The biggest advantage of Żegluga Gdańska is its recognizable brand. It is a company with an established position that has been operating on the market for many years, which has permanently entered the landscape of the Tri-City space.

S2: Experience. The company has a unique "know-how" of conducting this type of activity. Knowledge of the industry realities allows for cooperation with important entities, such as the Tri-City authorities, with whom Żegluga has already gained experience.

S3: Uniqueness. Currently, there is no ship-owner on the coast that would match the number of ships and the number of cruises performed per year. The lack of more serious competition allows to focus on achieving the assumed goals without the risk of losing part of the market. As the largest player, it can apply for subsidies and funding.

S4: Location. Żegluga Gdańska operates in the vicinity of dynamically developing coastal agglomerations, in which the number of inhabitants is constantly increasing and new jobs are created. Every year there are more and more tourists for whom the Tri-City is main place of stay, or a base point, where travels to surrounding towns and their attractions begins. The undeniable advantage is access to the open sea and the highly branched delta of the Wisła River, allowing for the activity expansion.

S5: Repair base. Żegluga Gdańska has its own repair base. Thanks to it, the company is able to carry out periodic inspections and repairs. This allows you to ensure the continuity of the fleet's operation and the resilience of the logistic node in the event of a failure.

11.2 Weak points

W1: Fleet status. Both ships taken under consideration, are already quite technologically outdated. The hull made of steel is very heavy and cause the vessel to be deeply submerged. It directly translates into water resistance during the voyage. This means a significant reduction in speed and manoeuvrability of the vessel.

W2: No profitability. The prices of the same transport services provided by Żegluga Gdańska continue to increase due to the increasing operating costs, compared to road or rail transport, which translates into a decline in the interest of travellers in this form of communication.

W3: Fuel supplier. Gas fuel consumption for seawater units towards planned production of bioLNG at the Zakład Utylizacji in Gdańsk will not able to maintain continuous operation during the season.

W4: Lack of information. Information regarding cost of: LNG/bioLNG installation, new or retrofitted engines, shipyard works, could be achieved by realization of specific investment projects. Publicly available sources for this topic are not reliable and do not take into account certification to use on ship issue. Therefore, such data is not included within this study.

11.3 Chances

O1: Infrastructural development. There is enormous potential for connecting cities and towns in the Pomeranian region. New water routes and river roads development is expected. Opening of the Mierzeja Wiślana ditch and activation the area of Zatoka Wiślana will also be an important matter.

O2: bioLNG. Gaseous fuel obtained from animal and vegetable waste, as well as from sewage treatment plants and landfills, is a solution that has a chance of a significant share in the sources of energy in the future. The Regulations will strive to further reduction of harmful substances emission for the environmental benefit. In the economic dimension, this may translate into the popularity of low-emission energy sources, including natural gas supply.

O3: "Liquid Energy". Initiatives such as Liquid Energy project can drive change, showing need for modernization in the energy field.

11.4 Threats

T1: Market instability. It is possible to replace fuel with LNG obtained from conventional sources, but its prices are very unstable and constantly rising - already at the end of 2021 diesel oil price was lower than LNG fuel. Now the price of LNG is 3 times higher than the last year [30].
Due to the increase in energy, installation and specialist's work costs and the overall price of modification will also go up.

T2: Competition. The development area of the Pomerania region cannot go unnoticed by the competition for a long time. Foreign shipowners, having experience and resources to build a new fleet, may be interested in expansion into perspective market.

T3: **Legal regulations**. Presented ships do not meet the basic criteria set out in the regulations for the use of on-board LNG systems. Adapting the units can be very cumbersome and carries the risk that the Classification Society will not approve such installations for use.

As presented in chapter 4, currently used diesel fuel complies with the regulations in force. In this case, change of the fuel system is not justified and will not be an incentive for the Implementation Partner to incur such high financial cost and labour input.

T4: Investment payback time. There is a high chance that payback time of a possible investment will far exceed the remaining lifetime of the units. Large financial outlays related to the conducted modification should compensate the LNG fuel prices, compared to diesel oil prices, currently used on ships. Taking into account the price difference over several years will be a measure of project profitability. Unfortunately, since December 2021, the prices of LNG fuel were equal to the price of diesel, and during the next year it exceeded [30]. This tendency should not be expected to change in the coming time, due to the sudden shift of the market towards gaseous fuels, and hence - increased demand.

11.5 Matrix of factor relations

The following factors in form of a matrix, correlates with answer to a series of questions:

- Will a given strength allow the use of a given opportunity?
- Will a given strength allow to eliminate a given threat?
- Does a given weakness limit the possibility of using a given opportunity?
- Does a given weakness increase the risk associated with the threat??

Table 8. Factor relationships matrix for SWOT analysis.

	O1	O2	O3		T1	T2	T3	T4
S1	1	0	0		2	1	0	0
S2	1	0	0		1	2	1	0
S3	2	0	0		1	2	0	0
S4	2	1	0		0	1	0	0
S5	0	0	0		1	1	1	1
W1	2	1	1		2	2	2	2
W2	1	1	1		2	2	0	2
W3	1	2	1		2	0	1	2
W4	1	2	2		2	1	2	2

Marking the points: 0 - no impact, 1 - low impact, 2 - strong impact

From the perspective of the legitimacy of project implementation, the strongest connections occur in the lower right quarter, responsible for correlation of weaknesses and threats. Conclusion, based on these results, assumes that implementation of proposed solutions is associated with a high risk of failure.

This should be taken in mind if further steps to implement the project will be applied. SWOT analysis also prompts to consider whether project assumptions should not be revised to minimize impact of the negative factors (threats).

12. Conclusions

The purpose of the study was a presentation of all aspects related to the idea of modifying specific water transportation units in the service of Żegluga Gdańska. As a result, correctness of the approach and development direction was determined. Also, definition of threats standing in a way to achieve the goals was detected. Due to technical requirements set by the regulations. It is uncertain whether the threats corresponding with ship after modification will be approved for commercial use. Moreover, modernization will not solve the problems related to the amount of currently consumed fuel, which directly translates into the amount of exhaust fumes emitted into the atmosphere.
It is worth paying attention to the costs of gas conversion together with reconstruction of the ship, which are much comparing to installation of exhaust gas purification installation (so -called "scrubbers"), which for the shipowner is a factor that may prevail from making a decision, especially because of the reimbursement time of investment even after with funds support.

It is worth considering if construction of new units should replace modernization of existing ships. In this case, basic design should be carried out under the supervision of the Classification Society. They will be able to define problematic aspects related to technical requirements for LNG installations at an early stage, and will help to develop recommendations to reduce their impact. Unique experience of the Class achieved by supporting other units in the past, will reduce operational problems appearing over time.
Correct preparation of ship building process allows the most effective funds use. What's more, the new units will be tailored to the challenges and conditions of the shipping routes. Moving speed around the waters and effective use of engine's power will significantly reduce the amount of the emitted pollutant.

This approach will be in line with water routes development, expansion of town's port infrastructure located within the Zatoka Wiślana and Wisła River. This will create a demand for new communication lines served by ships and ferries, which is a great opportunity for Żegluga Gdańska. However, along with increase of the water traffic, excessive growth of harmful substances in the atmosphere should be expected. Therefore, use of low -emission sources, including biogas, should be considered. Gas fuel -powered ships will help to avoid harmful environmental impact.

Biogas, in particular its liquefied version is convenient alternative for fuel oil for driving the ships. There are proven technologies, successfully used around the world for more and more ships. Introducing them for use on a large scale, and producing more effective solutions, will cause reduction in prices incurred for investments. This will encourage other ship-owners to implement gas installations in their fleets.

In addition to the functioning LNG installation, possibility of cooperation between power supply system and new technologies, e.g. fuel cells or electric energy storage batteries, remains open. It will provokes further reduction of exhaust emissions and helps to obtain more reliable ship units.

Another aspect is that potential for obtaining biogas from biomass is not fully used. The change this state of affairs will certainly be influenced by EU and national subsidies. They are aimed at facilitating implementation of this type of solutions, as well as increasing public awareness and commitment regarding this aspect of the energy transformation locally and globally.

Profits from biomass use are doubled. We obtain a stable source of energy, and significant contribution in the reduction in the increasingly problematic waste production which comes from human activity and living.

What's more, the energy obtained in this way allows diversification of supplies and reducing import of the fossil fuels. It should have positive effect on market prices.

To sum up, there are many factors favouring implementation of low -emission bioLNG/LNG installations for maritime and inland transport. However, it requires to press a constant efforts on further work and analyses to develop the most effective solutions.

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List of Tables

List of Figures

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