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Analysis and evaluation of the use of LNG as a fuel in the Polish road transport in terms of minimizing energy losses

Ewelina Złoczowska[1]✉, Wojciech Ślączka[2]

[1] https://orcid.org/0000-0003-0493-6562
[2] https://orcid.org/0000-0003-3265-9726

Maritime University of Szczecin
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: {e.zloczowska, w.slaczka}@pm.szczecin.pl
✉ corresponding author

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Abstract
This study characterizes the distribution chain of liquefied natural gas (LNG) in Poland, using the terminal in Świnoujście as the "source of LNG". The focus is primarily on the possibility of LNG distribution for road transport, taking into account the effective use of its energy potential. During the transport and storage of LNG it was found that the evaporation of LNG, the so-called boil-off gas (BOG), is a significant problem that leads to an increased pressure in the tank. Therefore, the possibility of using BOG in individual links of the LNG supply chain is indicated. One prospect is its compression to high pressure, which produces compressed natural gas (CNG) fuels. Thus, this paper specifies the influence of the initial BOG gas pressure on the unit compression work and analyses the change in the compression unit work, which depends on the final CNG fuel pressure, with a specific assumption for the BOG pressure.

Introduction

In recent years, a growing share of natural gas use in the global energy balance can be observed. The data published by the IEA show that, in 2015, the global consumption of natural gas amounted to 1401 Mtoe, which covered 22% of the total energy demand. While in 1973 this consumption was more than half this figure and amounted to 652 Mtoe, which corresponded to 16% of the total energy demand (IEA, 2017). According to the assumptions of the global energy policy, natural gas is required to cover a quarter of the global energy demand by 2040. The main reasons for this are: the constantly growing global demand for energy, the increasingly restrictive environmental protection regulations, and the elimination of the use of outdated, ineffective, and non-ecological heat and electricity generation technologies. The current unstable political situation caused by the aggression of the Russian Federation against Ukraine is not without significance. There is also an increasing use of natural gas as a fuel in sea or road transport. This is due to the lower emissions of CO_2 and other air pollutants compared to other fossil fuels. Currently, most investments aimed at popularizing the use of gas are carried out in developing countries (for example, India and China).

According to GUS data, gas consumption in Poland in 2016 was at the level of 16.2 billion m^3 (14.13 Mtoe) (Berent-Kowalska et al., 2017), which covered nearly 15% of the total energy demand. At the same time, there is a large disproportion in the use of natural gas between individual regions of Poland and sectors of its economy. Almost 47% of total consumption is attributable to what is broadly known as industry, 25% is consumption recorded by households, 12% is the production of electricity and heat, 13% are other sectors of the economy, such as services, and only or as much as 3% is transport. A similar situation with regard to natural gas consumption arose in 2020 (Figure 1) (Berent-Kowalska et al., 2021). In 2020, the consumption of natural gas (without taking into account consumption due to the technological needs of the gas sector) amounted to 694.7 PJ. The highest consumption of natural gas occurred in Mazowieckie voivodship (25.0% consumption in the country), and the lowest in Podlaskie voivodship (1.0%). The consumption of natural gas in industry and construction, along with the consumption as an electrical charge for transformations in coking plants and refineries, accounted for 44.7% of total consumption, while 18.9% is used in the energy sector, including 2.3% in transport, and 34% is for the small consumer sector. High consumption for transport in the Mazowieckie voivodship results from its high population and the fact that many entities operating throughout the country are located in this voivodship.

The growing demand for natural gas in various industries, and the desire to diversify its supplies, contribute to the development of various strategies and supply chains that guarantee energy security. The traditional model of gas supply is provided by the transport of gas from the place of extraction to the end user through the gas network. A certain limitation for this solution is the substantial distances, or obstacles such as large water bodies (e.g. ocean), that separate the manufacturer from the end user. In such situations, it makes economic sense to transport gas in liquid form (i.e. LNG – liquefied natural gas). At the same time, such a gas supply system requires the necessary infrastructure to enable its liquefaction and loading onto transport units at the place of production as well as the unloading, storage, and regasification at the recipient, which undoubtedly involves significant costs. An important advantage of this method of supply is the possibility of expanding the internal gas distribution system based on various means of transport, not only on the existing gas pipelines. Additionally, when considering LNG, one should bear in mind the significant "waste cold" potential of the regasification process, which should be properly managed. The cost of gas in the form of LNG includes both the price of the raw gas and the cost of its liquefaction, i.e. lowering its temperature to –162°C and its transport. The cost of liquefying gas accounts for 25% to 35% of the total cost of LNG production and transportation (Lim, Choi & Moon, 2013). Therefore, it is worth making every effort to wisely use

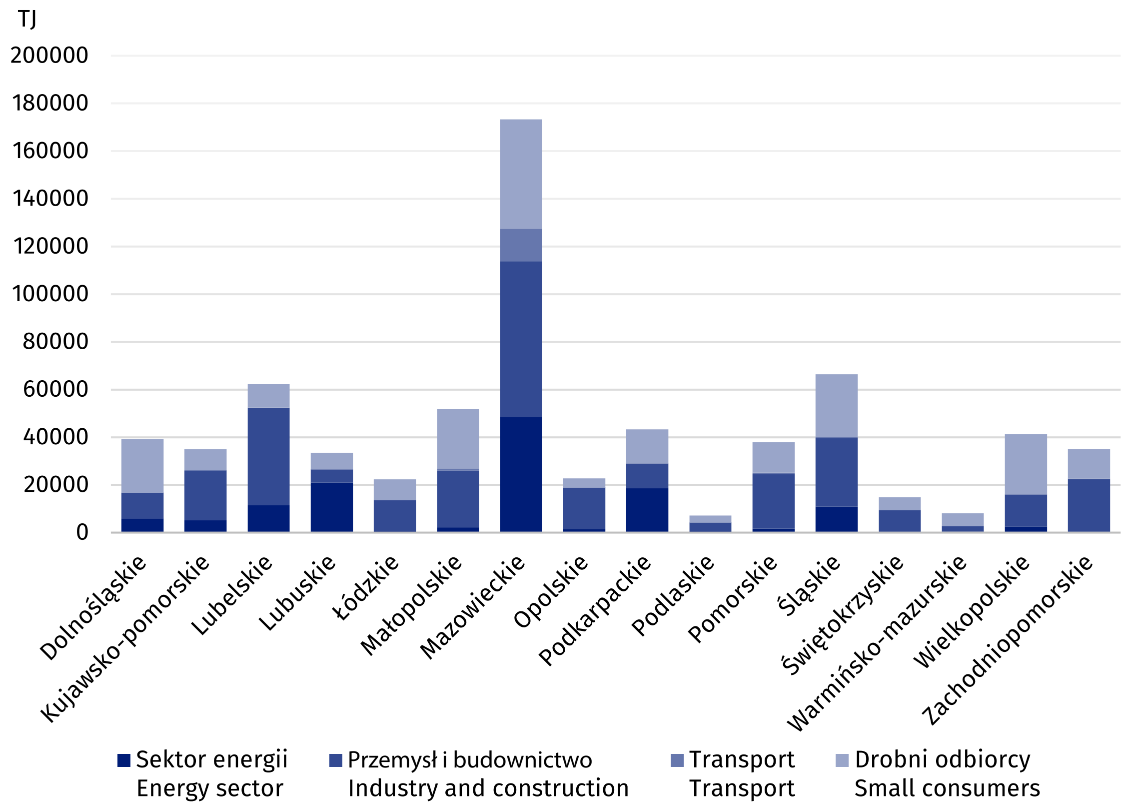

Figure 1. Consumption of natural gas in 2020 for various regions and sectors (Berent-Kowalska et al., 2021)

all the potential that is accumulated in the liquefied natural gas.

This article describes the LNG distribution chain in Poland using the terminal in Świnoujście as the "source of LNG". Main attention is focused on the possibilities of LNG distribution for the purposes of road transport, taking into account the effective use of its total energy potential.

Literature review

There are over 27 million NGV (natural gas vehicle) fueled by CNG (compressed natural gas), RNG (biomethane), and LNG in operation worldwide, which accounts for 1.3% of the entire global vehicle fleet (The International Association for Natural Gas Vehicles, 2019). CNG fueling engines are dominant in passenger cars and city buses. The average range of a CNG-powered vehicle is 300–400 km, while passenger vehicles with a range of up to 500 km are possible. On the other hand, more expensive LNG installations are designed to reach nearly twice as long distances, which is perfect for long-distance trucks. There are over 2 million NGVs registered in the EU, mainly heavy goods vehicles (buses, road service vehicles, or city cleaning vehicles). Tractor units used in long-distance transport are also rare. Nevertheless, the dynamic development of LNG technology, observed in recent years, contributes to the wider application of such solutions in practice. One limitation is the lack of a network of gas refueling stations, which is currently no more than half of the 5000 needed. In addition, CNG and LNG refueling points in the EU are located in Italy and Germany.

By using natural gas in the form of LNG and CNG (or RNG) as an alternative fuel in road transport, it is possible to significantly reduce greenhouse gas emissions and the sector's dependence on oil.

This is especially apparent in terms of long-distance truck and city transport. The use of CNG and LNG technologies in the truck and bus sector, depending on the engine solution, can reduce CO_2 emissions by up to 20% compared to conventional solutions. Generally, we can distinguish three main categories of gas fueled engines: dedicated engines (so-called OEM), operating only on a given fuel; bi-fuel engines (equipped with two fuel systems) and dual-fuel engines (gas burned with an admixture of diesel oil). In the literature on this subject, information about tri-fuel engines is also available. The greatest benefits were obtained in the dual-fuel technology. Table 1 lists the properties of the selected fuels. For the sake of simplicity, LNG and CNG were treated as pure CH_4-methane. Generally, the content of CH_4 in natural gas varies from 90 to 99%, which depends on where it is produced.

Table 1. Comparison of the properties of different fuels (Lemmin et al., 2018)

Fuel	Pressure [bar]	Temperature [°C]	Density [kg/m^3]	Caloric Value [MJ/kg]
Gas oil	1.013	15	848	43
LNG	1.013	–162	422.4	50
CNG	220	15	181.4	50

As can be seen in the data presented in Table 1, liquefied gas (LNG) has a much higher energy density compared to compressed gas (CNG). As a result, LNG-powered motor vehicles require much smaller tanks. However, to obtain the same amount of energy from LNG as from diesel, it is necessary to use a tank that is over 70% larger.

According to the EU guidelines, by 2021 car manufacturers had to reduce CO_2 emissions to 95 g/km for passenger cars and 147 g/km for vans (Regulation EU 2019/631, 2019). In the light of these regulations, natural gas may become the most widely used and environmentally friendly hydrocarbon fuel, provided that appropriate technology is used. The chemical composition of natural gas (NG) indicates that the combustion products of this fuel contain more hydrogen oxidation products, and less coal combustion products. An additional advantage is the sulfur content close to zero (i.e. a low emission of sulfur compounds), very low emission of solid particles, low emission of fuel vapor, high octane number (enabling a possibility of using higher compression ratios), reduced NOx emission, and lower aldehyde emission (almost completely eliminating benzene and 1–3 butadiene) (Uzdowski, 2012).

Effective transport of natural gas over long distances is possible thanks to its liquefaction, because in liquid form it occupies 600 times smaller a volume compared to non-liquefied gas. The gas prepared in this way is commonly abbreviated as LNG. Depending on the quantitative and qualitative composition of the natural gas, the transition from gaseous to liquid state requires reducing its temperature to about –162°C at a pressure of 1 bar. As already mentioned, reaching this temperature requires a significant investment of energy. During the condensation process, the unit amount of heat received from natural gas ranges from 600 to 650 kJ/m^3. The exact value is closely related to the composition of the liquefied gas, in particular to the methane content, for which the value is 654 kJ/m^3.

The individual steps in the supply of natural gas, from extraction to delivery to the final recipient, are called the LNG supply chain, which is graphically represented by Figure 2. This chain has existed almost unchanged since 1964.

Figure 2. LNG supply chain (the authors' elaboration based on (Mokhatab, et al., 2014))

According to the diagram shown in Figure 2, the LNG supply chain consists of three basic links: 1. The production sector, which includes: mining – locating a natural gas deposit, gas extraction, and delivery to a liquefaction station; liquefaction – change of the gas aggregate state in order to facilitate its transport and LNG storage; 2. Transport; 3. Consumption sector, including receipt, storage, and regasification of the LNG, as well as delivery to the final recipients. The presented supply chain assumes that the natural gas is delivered to the end user in the form of gas via a pipeline. An alternative to this solution is the transport of gas to the final recipient in liquid form, using various types of land or inland transport. The growing interest in the use of LNG as a fuel, especially in land or sea transport, is an incentive to develop new concepts for the supply chain of liquid natural gas inside the country.

Figure 3 shows a schematic diagram of the domestic LNG supply chain using the so-called small scale. Gas transported from the source to the final recipient can be carried out according to two main patterns. The choice of the LNG delivery method depends on the geographic location, infrastructure, specificity, and needs of the recipient. Liquefied natural gas from the offshore import terminal can be transported by road or inland to island stations (SSLNG). In island stations, LNG is stored and then distributed to the end recipients. The supply of gas from island stations to the final recipient can be carried out via gas pipelines (i.e. with LNG after its regasification at the station) or in liquid form by means of land transport. It is also possible to deliver LNG to the final recipient directly from the import terminal, bypassing island stations, e.g. supplying LNG refueling stations or large industrial plants with the appropriate infrastructure. Another gas supply plan foresees only LNG transport by barges equipped with a regasification installation (FSRU units). LNG undergoes regasification on the barge, from which the gas is delivered to the recipient via the gas pipeline.

The choice of the solution depends primarily on the gas demand volume, its seasonality, and the available infrastructure and technology. Each of the proposed solutions has its advantages and disadvantages. In the first of the considered variants, it is necessary to build LNG storage island stations equipped with a regasification system. On one hand, such a solution causes an increase in investment costs, but on the other hand, it creates the possibility of local use of waste cold from regasification. When

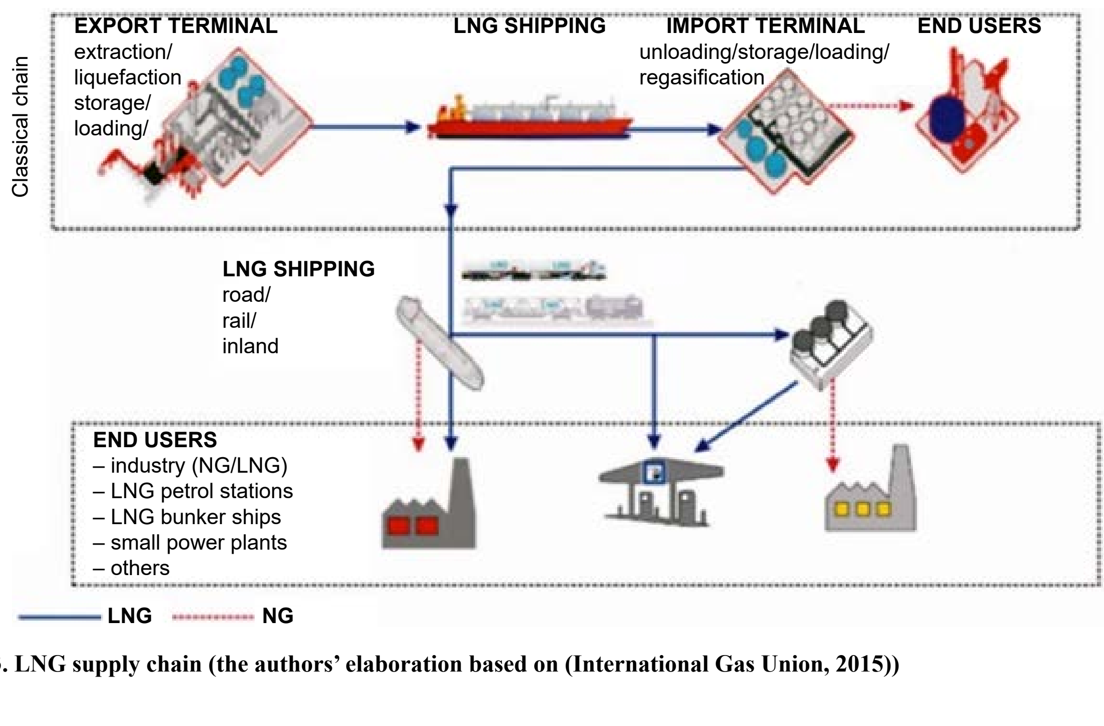

Figure 3. LNG supply chain (the authors' elaboration based on (International Gas Union, 2015))

designing the LNG supply chain, its continuity must also be ensured, so it is required to have an appropriate transport fleet. An interesting alternative to common road transport is inland transport. As shown in many studies, LNG transport via river barges is much more effective than road transport, a possible combination of these two transport systems is beneficial (Lopez Alvarez et al., 2020). At the same time, in order to implement the LNG supply chain based on inland transport, there must be access to waterways of the appropriate class. Moreover, these roads should be located close to potential gas consumers. This issue, however, does not fall within the scope of this work, but it will be described in more detail in other works by the present authors.

As already mentioned, LNG is increasingly more often considered as a fuel for powering truck engines, which is dictated by both environmental protection and economic reasons. Taking into account the needs of the market, there is undoubtedly a need to build and expand a network of LNG refueling stations on the main transport routes.

Methodology

This article presents a consideration on the LNG fuel supply chain for truck refueling stations located on the A2 motorway (as shown in Figure 4). This road was chosen because, alongside the A4 motorway, it is the most heavily loaded and, at the same time, it is the key transport route in Poland. The average daily annual traffic of motor vehicles

Figure 4. Network of existing and planned superhighways and expressways (the authors' elaboration based on (GDDKiA, 2019))

(SDRR) on the A2 motorway is 24,031 vehicles/day, of which 20.9% are trucks with trailers, 11.3% light trucks (e.g. delivery trucks), and 2.6% trucks without trailers (Zieliński et al., 2021). Figure 4 shows the network of existing and planned motorways in Poland (GDDKiA, 2019). Currently, the length of the A2 motorway is 486 km; however, it ultimately will be 657 km.

Currently, there is no detailed data on the number of LNG-powered cars on our roads. Only information on the number of registered cars is available. According to PZPM data, in March 2020, 2935 natural gas-powered passenger cars (mainly CNG) as well as 1724 vans and 2848 trucks were registered in Poland. The number of these cars is increasing systematically. Hence, this analysis is purely theoretical, based on various predictions on the increasing demand for LNG-powered cars, especially in the truck sector. The number of LNG-powered cars was determined on the basis of the assumption that 5% of the total number of heavy goods vehicles, traveling on the A2 motorway daily, are LNG-powered vehicles, i.e. 202 vehicles/day. The average LNG consumption by trucks equipped with engines, powered by liquefied natural gas, ranges from 23.6 kg to 24.5 kg of LNG per 100 km (Volvo Trucks Polska, 2019). To travel the A2 motorway, i.e. approximately 500 km, cars will consume an average of 120 kg of LNG. The capacity of the liquefied natural gas tank ranges from 105 kg to 210 kg. In some solutions, double tanks are used to increase the range of the car. For the purposes of this analysis, the average LNG tank capacity was assumed to be 120 kg, which allows for a distance of about 500 km. Thus, in line with the presented assumptions, virtually every LNG-powered truck driving on the A2 will be refueled at least once.

Discussion and results

Ultimately, at least six LNG refueling stations (3 on each side) should be built on the A2 motorway. The map (Figure 4) shows the proposed locations of the LNG refueling stations along the A2. Stations are separated from each other by an average of approximately 300 km, which results directly from the range of LNG-powered trucks, which is between 500 km and 1000 km (Volvo Trucks Polska, 2019).

The LNG supply chain to the refueling stations is as follows: LNG from the Świnoujście import terminal is transported by barges along the Odra River to the island stations. Next, from this station, gas is transported by tankers to the refueling station.

At the same time, the island station can be used as an LNG warehouse for both the transport sector and other sectors of the economy. An alternative solution may be the direct loading of LNG tankers from the barge, thanks to which losses related to the multiple reloading of gas, and its storage and the costs of building the island station, can be avoided. Then the barges would constitute a mobile LNG storage facility. An island station may be built at the existing river ports. In this analysis, it has been assumed that the station will be located near Krosno Odrzanskie.

The factor determining the size of the island station is the demand for LNG and its seasonality. Nevertheless, the phenomenon known as “aging” of LNG is also of great importance. Due to its properties, liquefied gas can only be stored for a few weeks. Hence, in case of longer storage periods, it is necessary to have appropriate technical equipment that enable the gas to be re-liquefied.

In the analyzed case, the size of the island station is directly related to the demand for the LNG by trucks traveling on the A2 motorway. Total daily demand for gas, for the above-mentioned assumptions, amounts to 24,222 kg/day, i.e. about 58 m^3/ day, 1507 m^3 per month, and 18,080 m^3 per year. Assuming that there are 3 LNG refueling stations along each side of the A2 motorway, the average daily LNG consumption at a single station is 20 m^3, 520 m^3 per month, and 6240 m^3/year. The size of tanks at refueling stations should be 150–200 m^3, assuming three gas deliveries per week. The size of the island station should be selected to ensure a capability of monthly LNG deliveries to refueling points at the level of 1500 m^3/month. Hence, for the adopted assumptions, the storage capacity of the island station should be at least 2000 m^3. The presented figures are estimates and constitute only a starting point for an examination of the possibilities of organizing the supply of liquefied gas, for refueling stations, and other industries in the interior of the country.

The LNG terminal with a capacity of 100 to 10,000 m^3 is referred to in the literature as a small island station (or a satellite station). As in the case of large LNG import terminals, also in the case of small island stations, it is extremely important that gas transport and its storage are carried out at the lowest possible costs. Hence, island stations should be located (if possible) in the vicinity of waterways that allow access to ships and barges. As shown in many analyzes, river transport by barges is much more economically effective and, above all, has a smaller negative impact on the natural environment than road or rail transport. Figure 5 shows the concept of

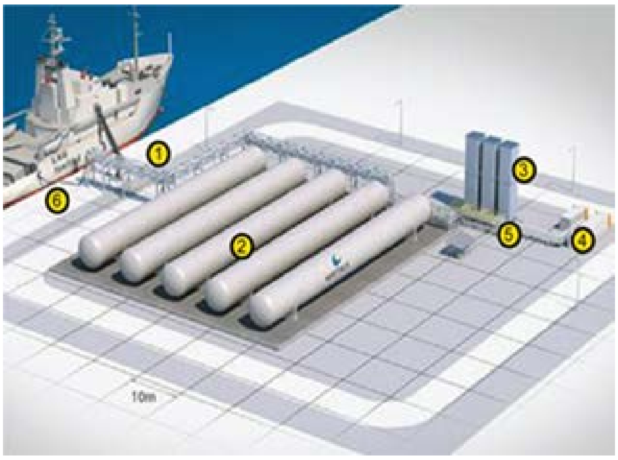

Figure 5. Small island station: 1 – loading/unloading, 2 – LNG tanks, 3 – LNG regasification unit, 4 – measuring station, 5 – connection to the gas pipeline, and 6 – connection to bunkering (filling tanks etc.) (Wärtsilä Corporation, 2018)

a small island station developed by Wartsil (Wärtsilä Corporation, 2018).

This type of station can be used as a back-up facility for onshore liquid gas distribution, as well as it being equipped with a regasification system and connected to the gas network. The LNG storage at small island stations consist of cylindrical pressure vessels. These tanks are made of stainless steel or aluminum with perlite (ceramic) or multi-layer thermal insulation. The pressure on them is maintained at the level of 0.5–8 bar. These tanks can be vertical with a maximum capacity of 300 m^3 and horizontal tanks with a maximum volume of 1200 m^3 (Chart Industries, 2016; Wärtsilä Corporation, 2018). During LNG storage, a major operational problem is the evaporation of LNG, which is the so-called boil-off gas (BOG), leading to an increase in the pressure in the tank. The average amount of BOG varies from 0.05 to 0.1% of the tank volume per day. LNG can be stored in a pressure vessel for a maximum of 1 month without the need for re-liquefaction. It should be remembered that the BOG phenomenon occurs at every link of the supply chain, which partially determines its shape and applied solutions.

According to the adopted assumptions, it is tank trucks that deliver LNG from the island station to the refueling points located on the A2 motorway. Three deliveries of 50 m^3 each are planned per week. In turn, gas is delivered to the island station from the Świnoujście terminal via river barges. To ensure the continuity of the LNG supplies to the refueling points on A2, the island station with a capacity of 2000 m^3 should be supplied with gas once a month. Hence, the capacity of the LNG transport barge should be at least 2000 m^3.

Generally speaking, LNG carriers can be classified, depending on their size, into large units with a cargo capacity of 100,000–270,000 m^3, medium-sized units with a cargo capacity of 10,000–100,000 m^3, and small units with a cargo capacity of ≤ 10,000 m^3. The range of small units includes barges with a cargo capacity ranging from 200 to 4000 m^3. These barges are often equipped with an LNG regasification system (Wärtsilä Corporation, 2018), such a solution may be an alternative to the small land LNG terminals (island stations). Table 2 presents a list of selected small units for the LNG transport, storage, and bunkering. Some of them are already in operation, some remain in the area of the projects and research. On small LNG vessels, IMO type-C tanks prevail; they are most often spherical or cylindrical pressure vessels.

As already mentioned, one of the problems encountered during the transport and storage of LNG is its evaporation, which leads to an increase in pressure in the tanks. To prevent an excessive increase of this pressure and to maintain safety during LNG storage and transport, the generated gases (BOG) must be continuously removed from the storage space. Here, the question arises: how should we effectively manage the resulting gas? In the case of large LNG transport units, it is used as a main propulsion fuel (Fernández et al., 2017). In some other solutions, BOG is re-liquefied. At the same time, re-liquefying LNG is associated not only with high operating costs, but also with large investment costs. Another solution found in inland terminals is the use of BOG in the regasification process. In the case of LNG stored at a vehicle refueling station, there are several options for using the resulting BOG. One of them is its compression to a high pressure, which results in CNG fuels or the production of electricity. Electricity production may also take place at the island station.

When analyzing the current state of the fuel market, we can see that, apart from the LNG-powered cars (also CNG-powered cars), it is of relatively high interest. Hence, one of the BOG development options is to use it in the production of CNG fuel. CNG fuel pressure for engine fueling should be between 18 and 25 MPa. It can be assumed that the pressure of the gas stored at the station will be 5 MPa higher. The theoretical power N_t that must be supplied to the compressor, to obtain the gas at the required pressure, can be determined on the basis of the change in the enthalpy Δh of the working medium and the mass flux of the substance $\dot{m}$ involved in the process, which is described by the equation:

$$N_t = \dot{m} \cdot \Delta h \tag{1}$$

Dividing both sides of this expression by the amount of substance, we obtain the specific work:

$$l_t = \Delta h \tag{2}$$

The following assumptions were made for the analysis of the discussed variant:

- BOG pressure is also the pressure in the tank;
- LNG is treated as pure CH_4 (methane);
- methane is considered an ideal gas;
- BOG is in a dry saturated vapor state, i.e. $x = 1$;
- the isentropic efficiency of the compression process is 85%.

Figure 6 shows the effect of the initial BOG gas pressure on the unit compression work.

As can be seen from the presented plot, the higher the initial gas pressure, i.e. the higher the LNG storage pressure, the less work l_t has to be done during the compression. This decrease is logarithmic, and the higher the BOG pressure, the flatter the curve. By increasing the storage pressure of the LNG from 1.5 bar to 2 bar, the unit conversion work is reduced by 7%; by increasing this pressure from 3.5 bar to 4 bar, the compression work is reduced by 3%. Thus,

Table 2. List of selected small ships for LNG transport, storage, and bunkering. The authors' elaboration based on Houlder Limited, 2019; LNG America, 2019; Seatech Engineering, 2019, Conrad Shipyards, 2021

Company / Vessel	Tanks Capacity [m^3]	Vessel Dimensions [m]		
		Total Length	Width	Draught
Seatech / SE – 605	2×1000	74.90	11.40	2.5
LNG America / Gemini Class	3000	lack of data	lack of data	lack of data
LNG America /Mercury Class	1000	lack of data	lack of data	lack of data
Houlder LNG Technology & Solutions	1500	62	16	2.5
Conrad Shipyard / LNG Bunker Barge	2200	70	14.87	4.77
Conrad Shipyard / LNG Bunker/ Transport Barge	2×2100 (membranous)	91.44	18.9	5.94
Conrad Shipyard / LNG Bunker / Transport Barge	4×750 (IMO type-C)	91.44	18.9	5.64

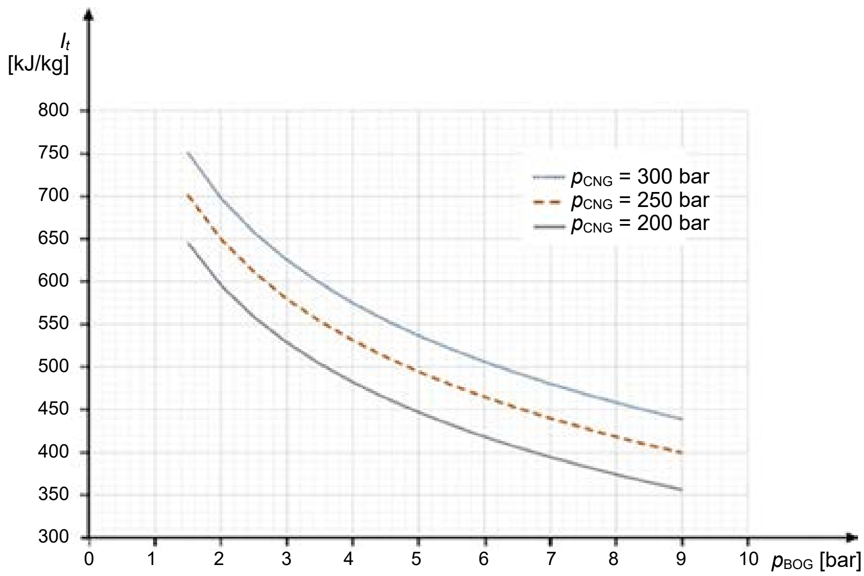

Figure 6. Change in the specific work of compression, l_t, depending on the BOG pressure, p_{BOG}

it can be expected that there is some optimal BOG initial pressure value for which the CNG production process is the most economically and energetically efficient. The presented results include three values of the final CNG gas pressure: 200 bar, 250 bar, and 300 bar. The higher the compression end pressure, the more work needs to be done. Thus, to compress the BOG from an initial pressure of 9 bar to a final pressure of 300 bar, a work of 438.7 kJ/kg has to be performed. To lower the BOG temperature to –161°C and re-liquefy it for the same initial conditions, it is necessary to collect 550 kJ/kg of heat. According to data from the literature, the efficiency of the condensation process ranges from 0.05 to 0.362 kJ/kJ (Zhang et al., 2020). Assuming the most favorable conditions, the work of the sprinkling process will be 1519 kJ/kg, which is almost 4 times more than with the compression. Therefore, it is a favorable solution, which is one of the possibilities of using BOG for the production of CNG fuel.

Conclusions

Statistics show that the number of LNG-powered vehicles is growing yearly, especially in the truck sector. Therefore, it is necessary to build and expand the network of LNG refueling stations. This article considers the possibilities of supplying LNG to the refueling stations located along the A2 motorway. This particular road was chosen because it is a key transit route through Poland, with the highest traffic intensity. Świnoujście terminal was indicated as a source of the LNG storage. It has been shown that it is possible to organize an LNG supply chain to refueling stations using an inland waterway transport. The possible construction details of barges, necessary for LNG hauling, were also pointed out. Undoubtedly, this form of transport is effective, but it is associated with a need to build the so-called island station. This, despite an investment costs increase, allows development of the LNG supply chain for other industries. Krosno Odrzanskie was indicated as a possible position for the construction of a large island station.

One of the main problems that occur during the storage and transport of LNG is its aging. This phenomenon is associated with continuous evaporation of the LNG (so-called BOG), which causes an increase in the energy costs of the LNG supply chain. This article presents an effective use of BOG that produces CNG fuel. The theoretical analysis showed that the higher the initial pressure of the BOG, the less work has to be done to obtain the CNG. Therefore, it is advantageous to use pressure tanks at refueling stations. The study described here is an introduction to further research and analysis, related to the distribution and effective use of LNG.

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