Analysis types of small ships in use for conversion to LNG usage

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Introduction

Established on seas Emission Control Areas (ECA) are regulated by international conventions, limiting the amount of pollutants emitted to the environment by vessels during their operation.

The Emission Control Area established are: [1]

- Baltic Sea area – as defined in Annex I of MARPOL (SO_x only),
- North Sea area – as defined in Annex V of MARPOL (SO_x only);
- North American area – as defined in Appendix VII of Annex VI of MARPOL (SO_x, NOx and PM);
- United States Caribbean Sea area – as defined in Appendix VII of Annex VI of MARPOL (SO_x, NO_x and PM) [2].

The distribution of ECA zones in northern Europe is shown in Figure 1.

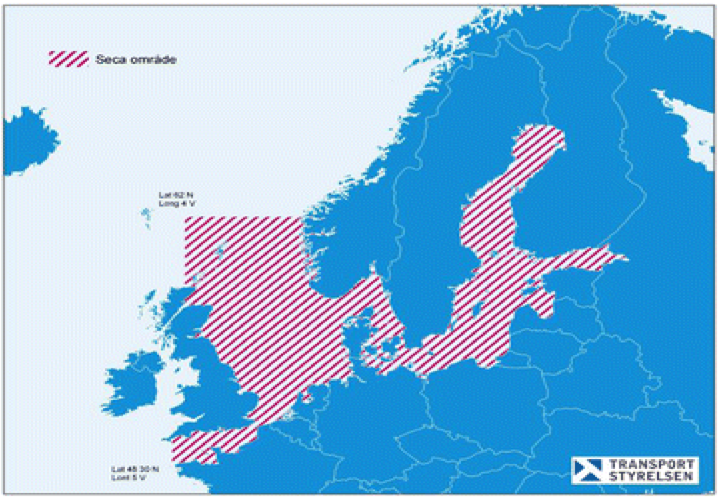

Fig 1 North Europe ECA location [3]

As you can see, the entire Baltic Sea is covered by the ECA zone. All ships activities are responsible of air pollutants emissions and particularly: ships steaming, movement in port, hoteling, loading and unloading. Exhaust emissions are caused by burning of fuel onboard the vessel. From the self-ignition engines NO_x, SO_x, HC, CO, PM and CO_2 is the most dominant.
Emissions of harmful substances in the exhaust gas depend largely on both the structure and the main propulsion engine power. The emission controls divide between those applicable inside Emission Control Areas (ECA) established to limit the emission of SO_x and particulate

matter and those applicable outside such areas and are primarily achieved by limiting the maximum sulphur content of the fuel oils as loaded, bunkered, and subsequently used on board. These fuel oil sulphur limits (expressed in terms of % m/m – that is by weight) are subject to a series of step changes over the years as shown onFig ure 2.

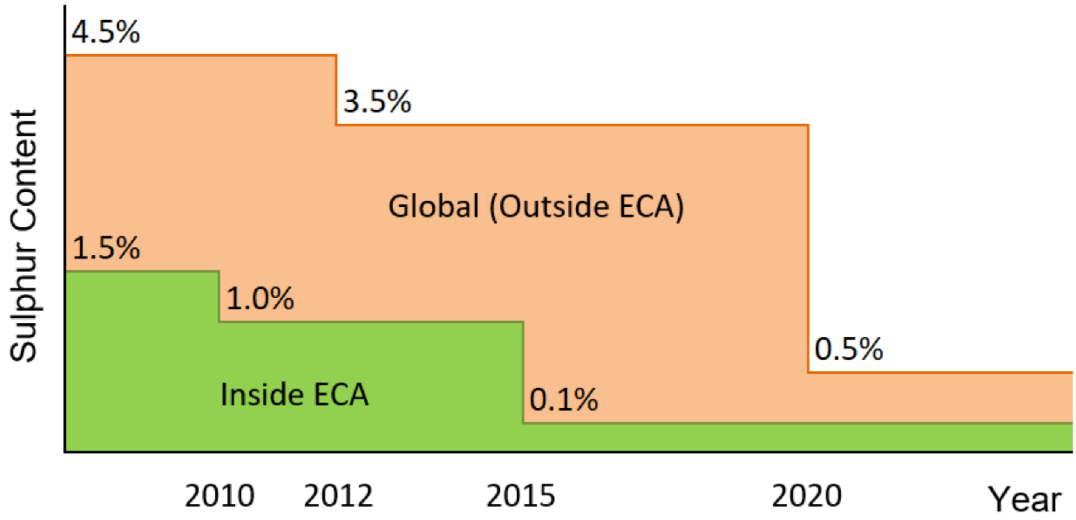

Fig 2. The MARPOL Annex VI fuel oil sulfur limits [4]

SO_x Reduced Emissions Areas (SECAs) are included in the ECA zones shown in Figure 2. The operation of ships using liquid fuels in SECA means that expensive fuels with a sulphur content of 0.1% (Fig 2) or the installation of equally expensive SO_x aftertreatment systems on board ships are required.

OnFig ure 3 is shown share in emissions of different types of ships, including small vessels, pointed as the "small unidentified" operating in Baltic Sea basin, equipped with various constructions of self-ignition engines installed on board.

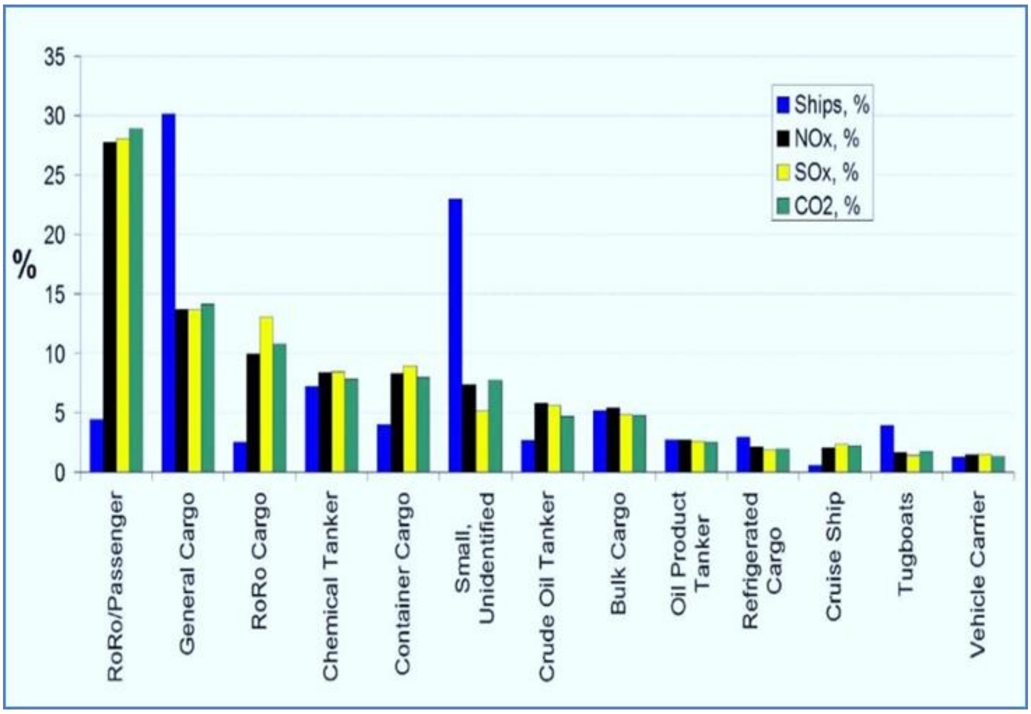

Fig 3 Share of pollutants emitted to the environment by vessels during their operation. [5]

Small vessels make up a significant share of about 23% of the number of ships operating in the Baltic Sea basin and are responsible for about 8% of total harmful emissions of exhaust gases (Fig 3).

The group of small vessels includes: tugs, fishing vessels, dredgers, passenger ships, ferries, work boats, port cleaning ships, fire-fighting vessels, research vessels, patrol vessels and may others.

The way to reduce harmful emissions from marine engines is to use LNG or bio-gas as fuel. Comparative emissions of individual components in relation to the emissions from the combustion of petroleum-based fuel are shown in Figure 4.

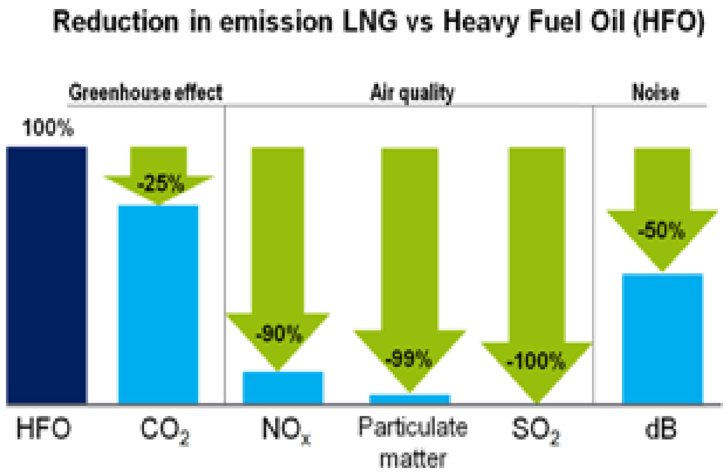

Fig 4. Reduction of emissions and noise after use as LNG fuel in relation to HFO fuel [6]

Considering the gaseous form of LNG and bio-fuels, the lack of sulfur in gaseous fuels and the different combustion conditions, a significant reduction in emissions is achieved: NOx by 90%, PM by 99% and no SO_x emissions. Only because of the hydrocarbon content of both types of fuel, CO_2 emissions from the combustion of gaseous fuels decrease by 25%. Moreover, when burning gaseous fuels, the noise emission decreases by 50% (Fig 4).

In this respect, there are clear benefits of using natural gas as a fuel. This is the main advantage compared to liquid petroleum-based fuels, however, it should be remembered that the level of emissions depends to a large extent on the design of the engine, its combustion chamber, the characteristics of the power supply system, regulatory parameters and its general technical condition.

Taking into account the physico-chemical properties of liquid petroleum-based fuels and gas fuels, their state of aggregation and calorific values, different volumes of fuel tanks are required to travel along the same route, as shown in Fig 5.

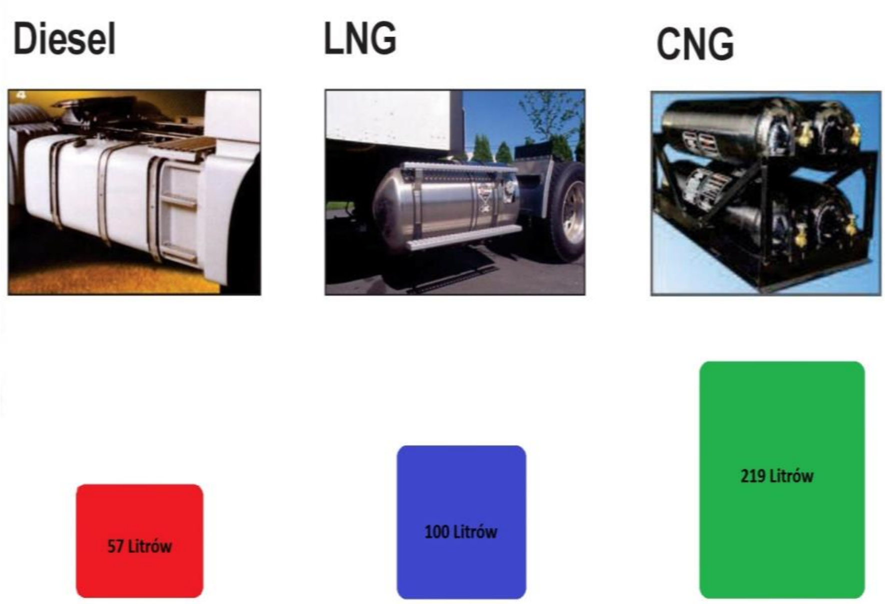

Fig 5. Tank size difference for selected fuels [7]

As shown in the Figure 5, the changes in the volume of gaseous fuel tanks for oil-derived fuel change approximately in the following proportions: LNG twice the volume, CNG four times the volume.

Marine LNG fuel systems

Diagram of the ship's LNG fuel system and its components is defined by the ISO standard (Figure 6).

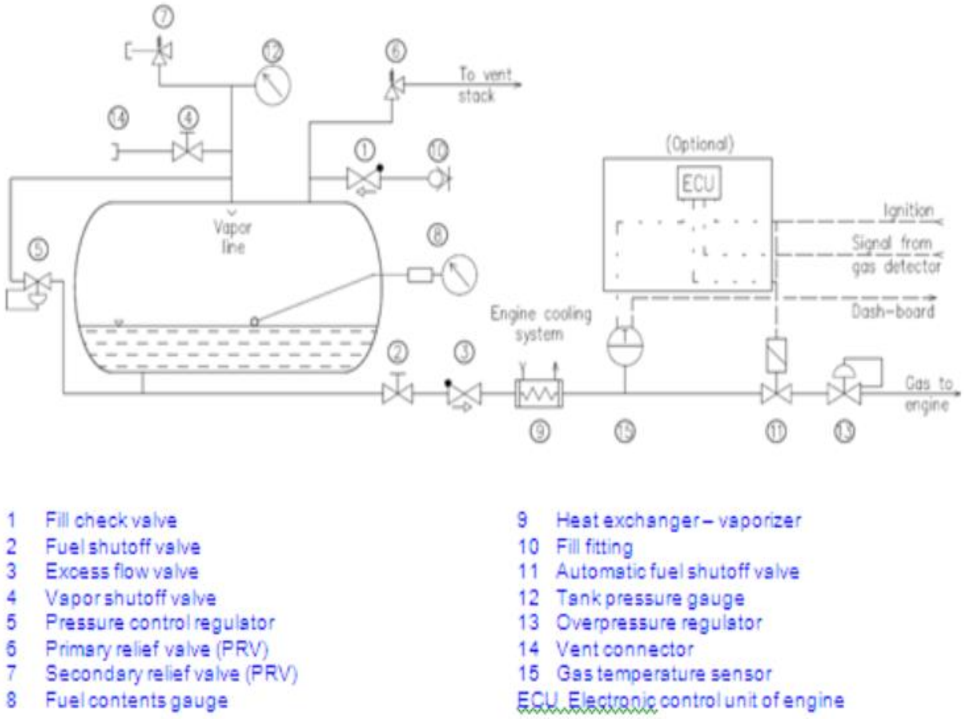

Fig 6. Marine LNG fueling system construction and assembly [8]

Based on the requirements of the ISO standard, LNG fuel systems for ships, including small vessels, shall be designed. An exemplary diagram of such a system for small vessels is presented in Figure 7.

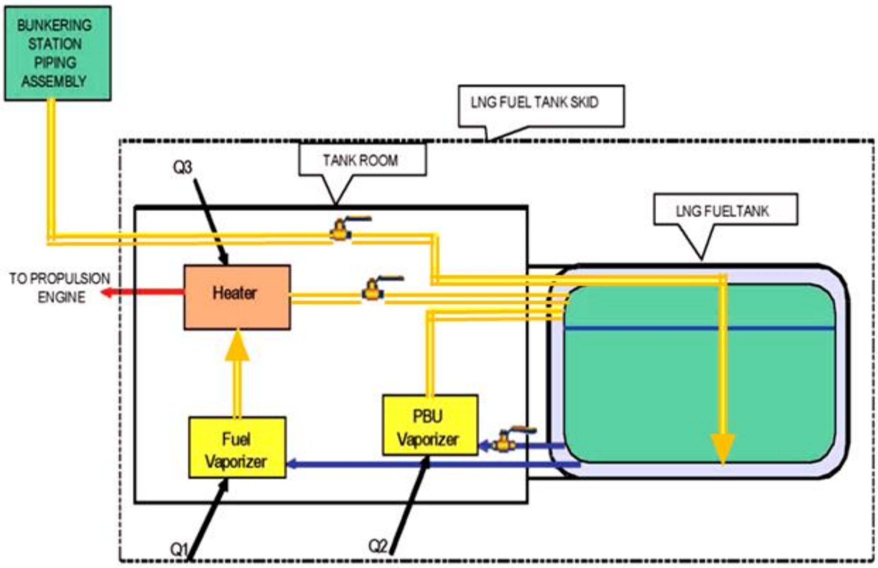

Fig 7. Idea of the LNG fuel system for small ships [9]

The most important element of the LNG fuel system is the fuel block, the diagram of which is presented in Figure 8.

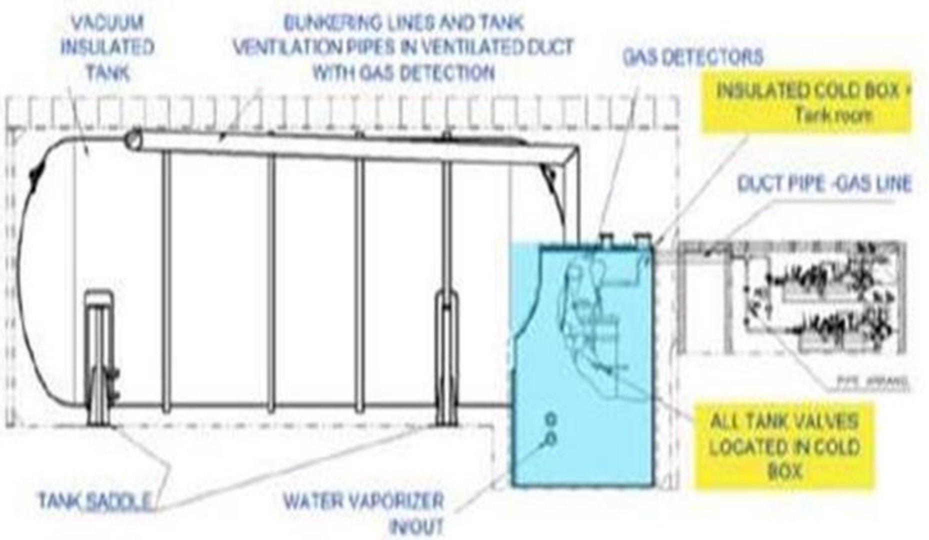

Fig 8. Idea of the marine LNG fuel block [10]

The fuel block shall consist of (Fig 6,7,8):

- Cryogenic fuel tank LNG;
- Bunkering station - enables delivery of LNG from the bunkering station to the tank;

- Tank connection space - in which the gas is vaporized using a heat exchanger supplied with the engine cooling water, hot water, steam or exhaust gases, and then directed to the engine.

The fuel block is mounted on the fundamental frame and delivered to the ship (Figure 9,10).

Fig 9. Marine LNG fuel block [11]

Fig 10. Container with marine LNG fuel block [11]

Cryogenic fuel tanks LNG

According to the current IMO IGC Code of Regulations, the LNG tanks on board ships using LNG as fuel must be independent tanks type A, B or C. These tanks are self-supporting and are not part of the ship's hull structure. Type C tanks are the preferred solution for LNG-powered ships. The tanks have proven to be reliable and safe, are easy to manufacture and install. The maximum filling level of this type LNG tanks is 95%. Type C tanks can be installed in a horizontal or vertical position.

Basic data on type C LNG fuel tanks:

- Double insulated stainless steel tank (inner vessel, insulation and vacuumed, outer vessel). Expanded perlite is the most commonly used insulating material;
- Temperature inside -163°C;
- Pressure inside the tank is depending on system (between atmospheric and 1.8MPa currently);
- Automatic valve;
- Pressure relief valve’s (primary and secondary):
- primary is used for venting,
- secondary is used in case of emergency.

Depending on the engine power, type C gas tanks are built with volumes from 1 to 350 m^3.

Tank cross-section of 1.5 m^3 is shown in Figure 11.

Fig 11. LNG tank cross-section (volume 1,5 m^3) [12]

The LNG fuel block installed in the truck is shown in Fig 12.

Fig 12. LNG truck fuel block [12]

The use of fuel blocks for land transport (Fig12) is worth considering for use on small vessels with engines up to 400 kW.

Gas-powered engines for use on small vessels

Small ships use mainly four-stroke, medium and highspeed engines with supplied almost exclusively by the distillate fuels.

The use of gas supply for engines requires an analysis of the supply methods and operating conditions. There are three basic technologies used in natural gas engines – lean burn spark-ignition pure gas, dual fuel with diesel pilot and direct injection with diesel pilot. The engine technology can also be divided into which thermodynamic cycle is used by the engine, either the Otto cycle or the Diesel cycle.

The basic characteristics of these two cycles are defined in the table 1.

Table1 Ignition technologies used in gas fuel engines [13]

Combustion cycle	**Fuel injection**	**Ignition**
Otto	The fuel is mixed with air and admitted to the cylinder before the compression starts	The Otto cycle combustion is started by an ignition source, typically an electric spark or injection of pilot fuel.
Diesel	The fuel is admitted to the cylinder first at the end of the compression stroke.	Combustion is usually started by self-ignition of the fuel, also called compression ignition.
Combined cycle dual fuel	In gas mode – the above Otto cycle process is used. In diesel mode – the above diesel cycle process is used.	In gas mode – usually started by injection of pilot fuel oil into the compressed mixture of air/natural gas. Normal diesel cycle ignition in diesel fuel only mode.
Diesel cycle dual fuel	In both gas and diesel modes – the fuel is admitted to the cylinder first at the end of the compression stroke.	In gas mode – pilot fuel is injected and self-ignites; gas is then injected into the flame from the pilot oil fuel

The gaseous-fuel engine fuel systems may be subdivided according to the information in Table 1, taking into account:

Method of ignition:

- mono-fuel, allowing engines to run only on gaseous fuel;
- independent bi-fuel (.Bi-fuel" or "Bipower") providing alternatives to petroleum-based fuels or natural gas;

- dual-fuel mixed ("dual-fuel" or FFV Flexible-fuel vehicle), allowing diesel engines to run on gas fuel with a reduced dose of petroleum-based fuels or on petroleum-based fuels alone.

Depending on where the gaseous fuel enters the engine:

- in front of the air damper;
- behind the air damper;
- before the turbocharger (compressor) directly into the combustion chamber;
- behind the turbocharger (compressor);
- directly into the combustion chamber.

Mono-fuel power system for supercharged engine.

This way of power supply only allows the engine to run on natural gas. Undoubtedly, it is a great nuisance for the users of such transport, because the operation is dependent on the gas distribution network. It is now recommended to use mono-fuel systems developed for reconstructed self-ignition engines with reduced compression and spark ignition.

Dual-fuel engine power system

In view of the limited availability of compressed or liquefied gas, a dual-fuel system has long been a priority, giving spark-ignition engines complete freedom of fuel choice. The adaptation of the spark ignition engine to the combustion of natural gas consists in the installation of an additional supply system for this fuel. An example of a design solution for a fuel system of this type of engine is shown in Figure 13.

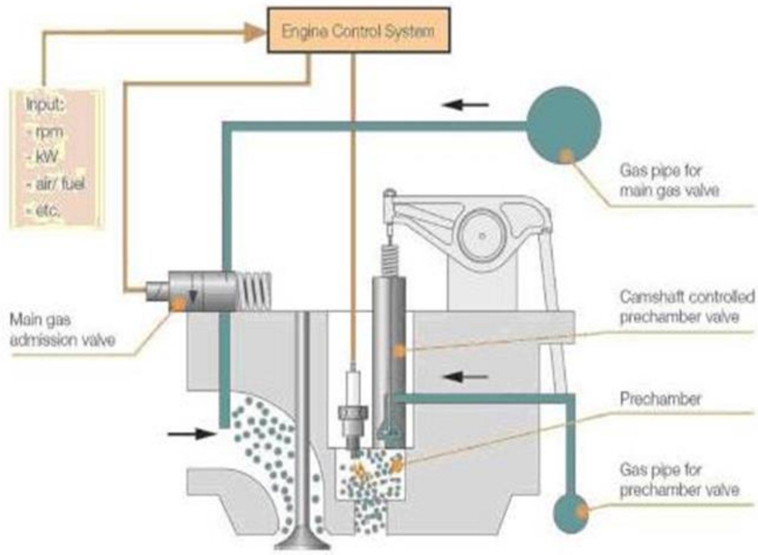

Fig 13. Wärtsilä 20V34SG spark ignition gas engine head with pre-chamber and gas supply system [14]

When using dual fuel spark-ignition engines, complex head designs with pre-chamber (Fig 14) are most often used. The necessary element for ignition is a spark plug of appropriate design as well as the use of a dual-fuel system (DF) with pilot injection of liquid fuel, ensuring the appropriate ignition energy of the gas mixture as well as the preservation of the typical combustion chamber.

Two-fuel mixed engine power system

Dual-fuel engine power supply system is a solution designed for use in a self-ignition engine that burns a fuel mixture consisting of air and fuel containing natural gas and petroleum-based fuels. The task of petroleum-based fuel is to initiate the process of self-ignition of the mixture. The implementation of such a supply can be carried out in both naturally aspirated and supercharged engines.

A diagram of the fuel system for the dual fuel engine is shown in Figure 14.

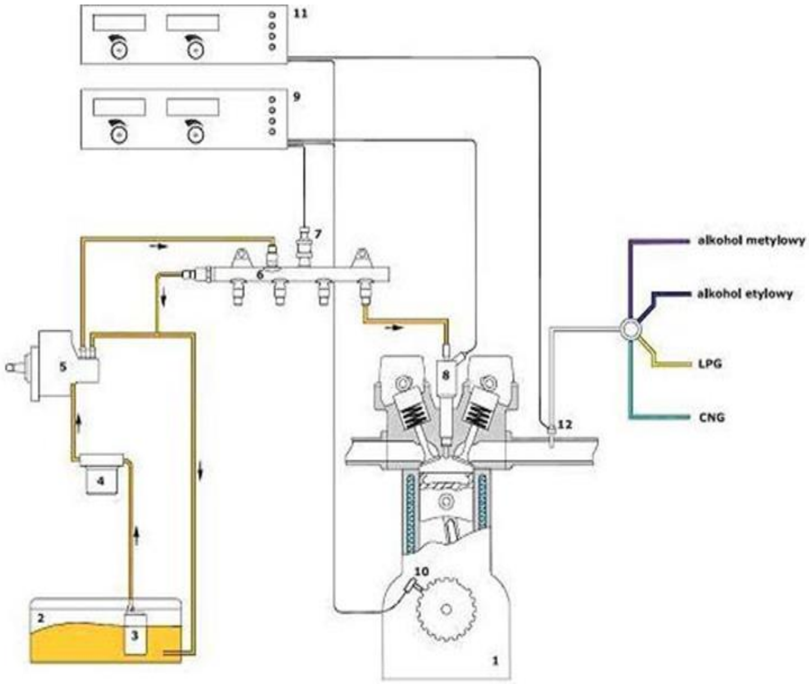

Fig 14. Diagram of a mixed-fuel self-ignition engine feed system [15]
1-engine, 2- tank of petroleum-based fuels,3-fuel pump, 4-fuel filter, 5-high pressure fuel pump, 6-fuel tray, 7-fuel pressure sensor, 8-fuel injector,9-CR controller, 10- crankshaft position sensor, 11-gas fuel controller, 12- gas fuel injector

According to the concept of the power supply system presented in the Figure 14, one of the most important issues is the selection of the value initiating ignition of the dose of petroleum-based fuels as well as the angle of injection advancement of a given dose of fuel. Together these values have a significant impact on the performance of the engine, its efficiency as well as the level of components in the exhaust gas. Most of the solutions for engine power regulation are realized by changing the value of the gas fuel dose, which leads to a variation in the composition of the fuel-air mixture as the engine load changes.

Modernization engines to gas supply

Small ships use mainly four-stroke, medium and high speed engines with supplied almost exclusively by the distillate fuels.

Gas as a fuel, can be used for all spark-ignition and diesel engines after appropriate design changes.

In the case of dual-fuel diesel engines, the application of gas supply requires a small range of modifications to the base engine consisting in the installation of a gas supply system to the intake manifold without the need to interfere with the construction of basic base engine units.

There are also negative phenomena resulting from the dual-fuel diesel engine.

These are among them:

- The possibility of uncontrolled self-ignition of the gaseous fuel-air mixture at the end of the compression stroke, especially at higher engine loads, when the compressed air-fuel mixture becomes richer. The idea to put aside the danger of this phenomenon is to reduce the share of gaseous fuel or to reduce the compression ratio;
- Possibility to burn a knockout mixture of air and gaseous fuel - outside the combustion area, the initial dose is initiated as a result of a sudden increase in pressure after the start of combustion. A way to reduce this phenomenon is to identify it using the knock sensor and delay the injection start moment of the initiating dose of diesel fuel or reduce the compression ratio.

Dual-fuel engines, powered by liquid or gaseous fuel, or both at the same time, are increasingly used in shipbuilding. They can be designed as low pressure four-stroke engines or high pressure two-stroke engines. Most dual fuel engines are equipped with a low pressure system, where the fuel supply in the form of gas is carried out immediately at the beginning of the compression stroke at a pressure of 3 to 5 bar, at 20°C.

In four-stroke medium-speed engines, gas is fed through a separate pipe and a controlled gas valve located in the head. A safety valve must be installed in the gas supply line to prevent backflow of gas together with a fire damper to ensure fire safety.

Small gas-fueled vessels

The largest group of gas-powered ships are the ferries, whose exemplary constructions and basic technical data are presented in Figures 15 – 19.

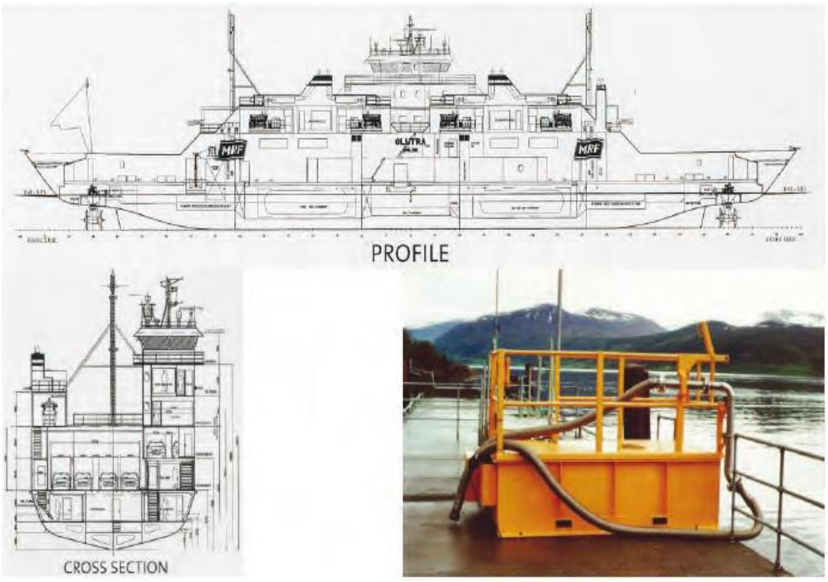

Fig 15. The LNG fuelled ferry **GLUTRA (**Profile and section, engine room top left and refuelling bridge) [16].

Length - 95 m, Passengers – 300, LNG tank /capacity 2 × 27 m^3 vacuum/perlite C-type, LNG Bunkering rate/time 2 hours, every 6 day

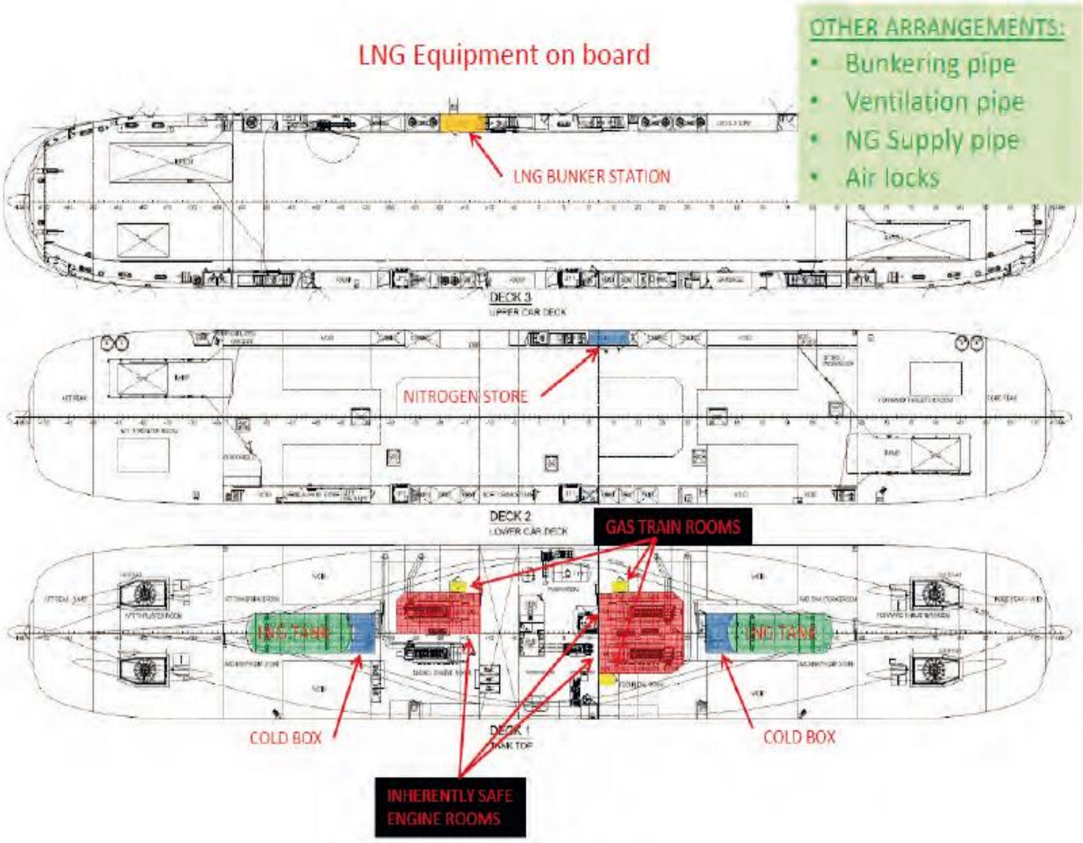

Fig 16. LNG fuelled ferries **Fjord1**, (LNG equipment on board and inherently safe engine rooms) [16]

Length - 130 m, LNG tank type/capacity 2×125 m^3 vacuum/perlite C-tanks, LNG Bunkering rate/time 3 hours, once a week

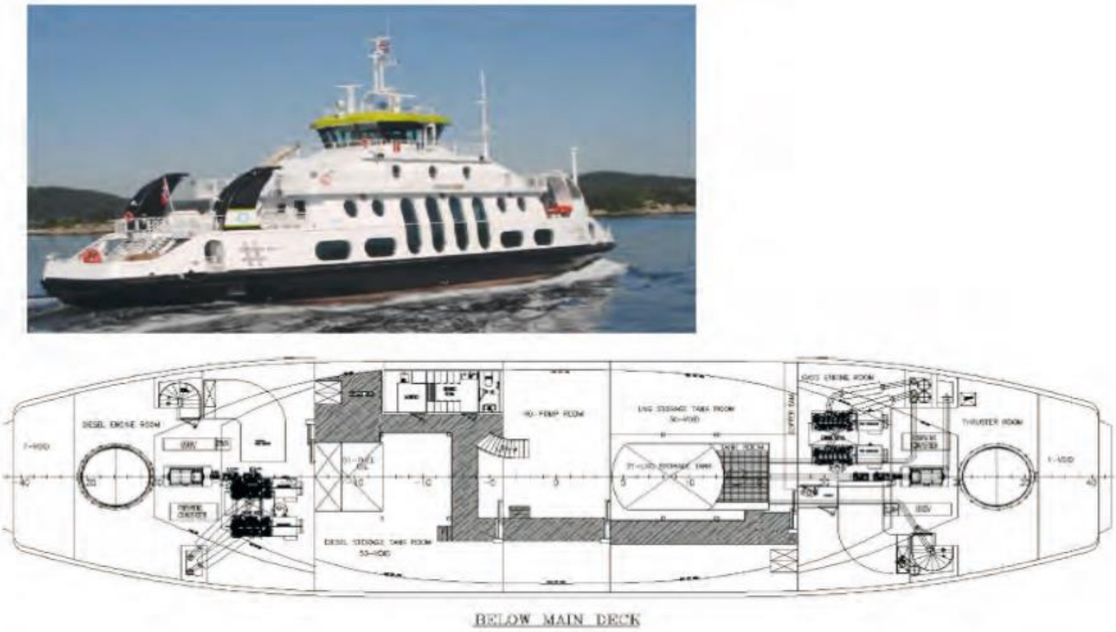

Fig 17. The LNG fuelled ferry **TIDEKONGEN** (tank and engine arrangement) [17]
Length - 95 m, LNG tank capacity - 50 m^3, LNG Bunkering rate/time: Twice a week, 1–2 h,

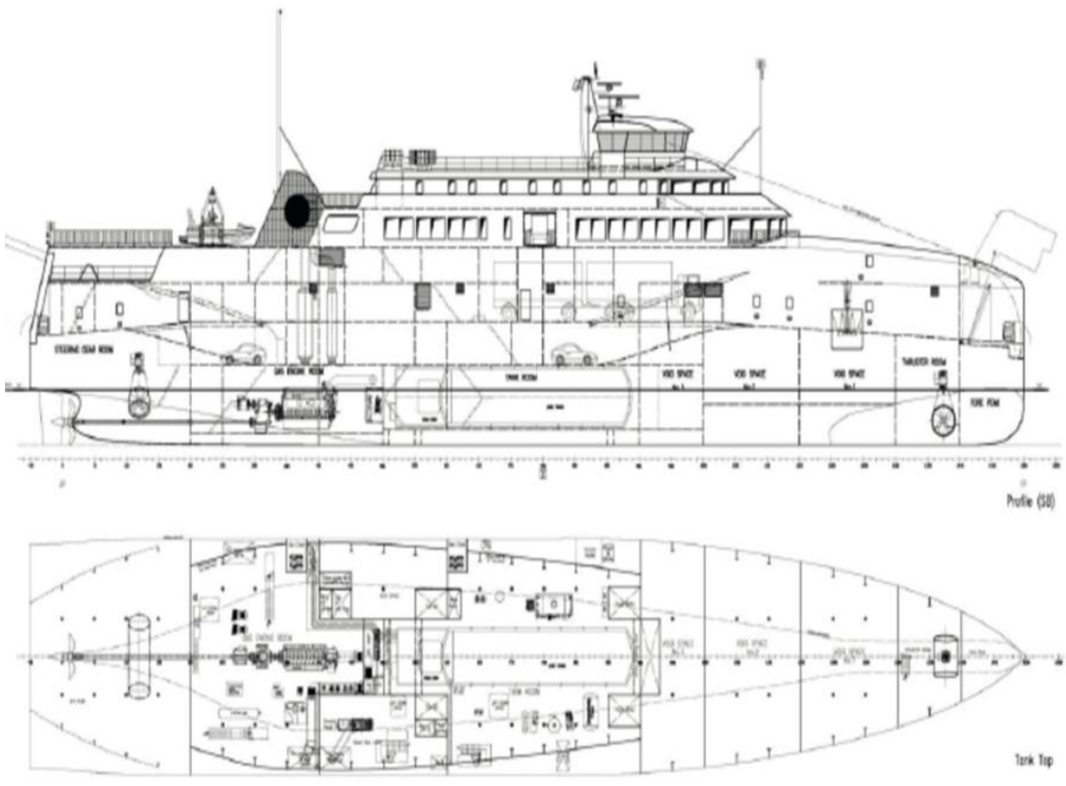

Fig 18. The LNG fuelled ferry **TORGHATTEN** (profile, tank and engine arrangement) [17]
Length - 93 m, LNG tank capacity - 150 m^3**,** LNG Bunkering rate/time 150 m^3/h /1h

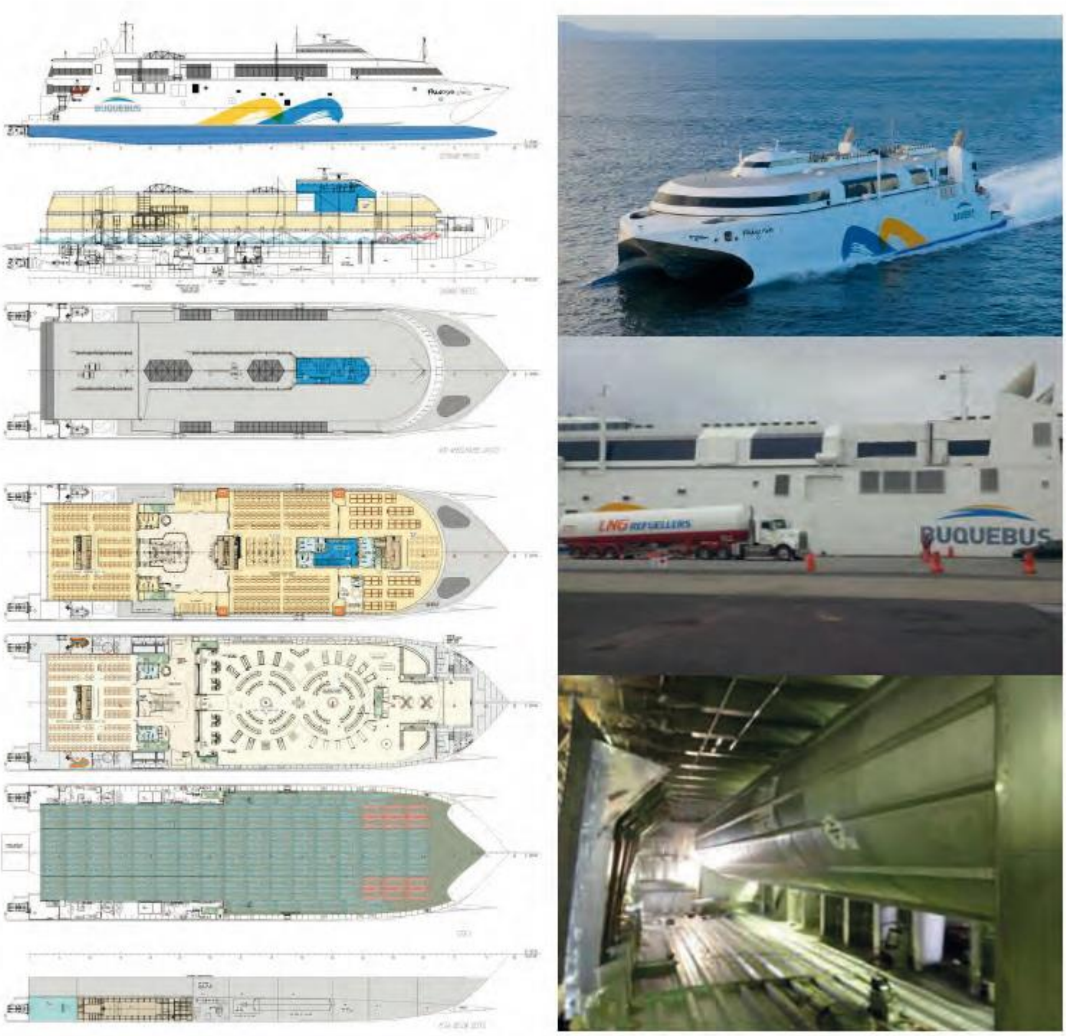

Fig 19. The dual fuelled high speed ferry (profile, ferry arrangement) [18]
tank capacity: 2×40 m^3 LNG, 2×70 m^3 fuel oil

Other types of small LNG-powered ships are shown in Figures 20-26

Fig 20. An illustration of LNG powered OSVs (offshore supply vessel) [19]

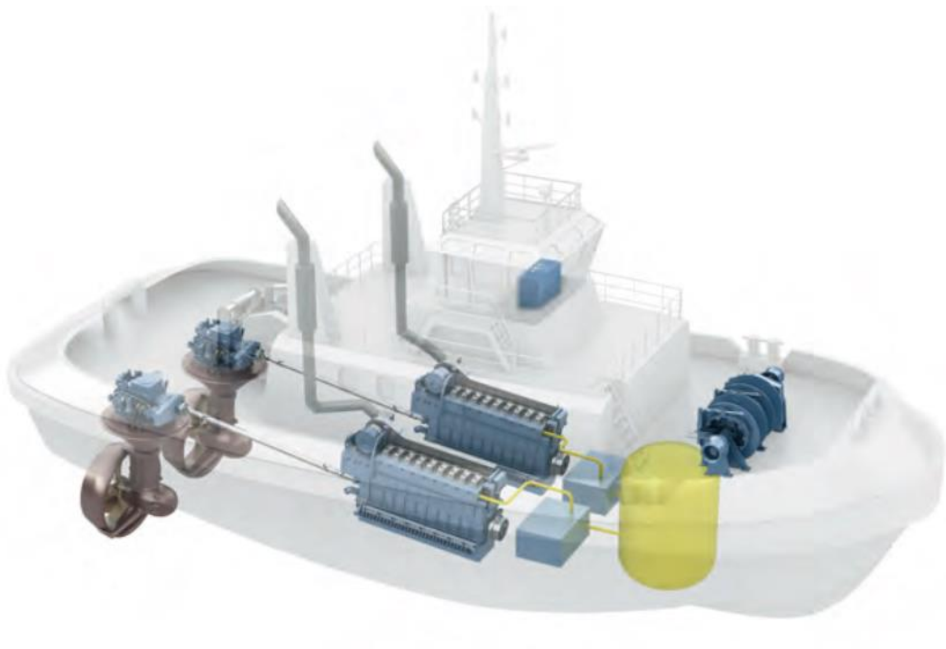

Fig 21. LNG fuelled tug [19]

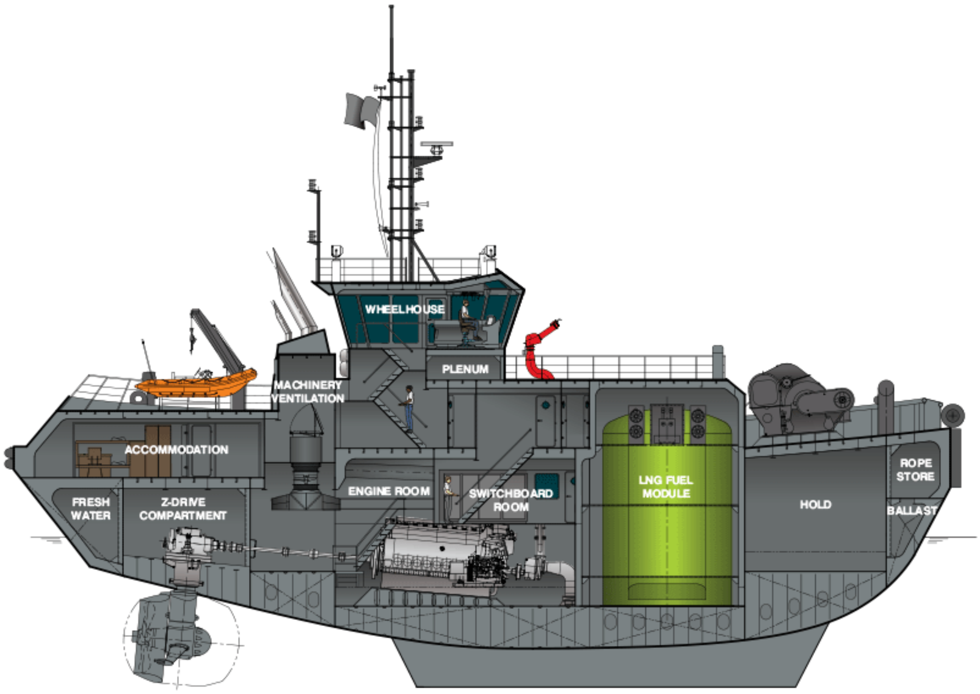

Fig 22. LNG fuelled tug (cross section) [20]

length – 36,5 m, installed power – 2x 2430 kW, LNG tank capacity – 80 m^3

Fig 23. LNG fueled port cleaning ship [21]

Fig 24. LNG-powered dredging vessel [22]

Fig 25. LNG-Fueled Fishing Trawler [23]

length – 35 m, LNG tank capacity - 350 m^3

Fig 26. LNG-Fueled Fishing Cutter [24]

Wide application of LNG as a fuel found on inland waterway vessels. Examples of construction of gas-powered inland waterway vessels are presented in Figures 28-32

Fig 27. LNG powered tank barge [25]

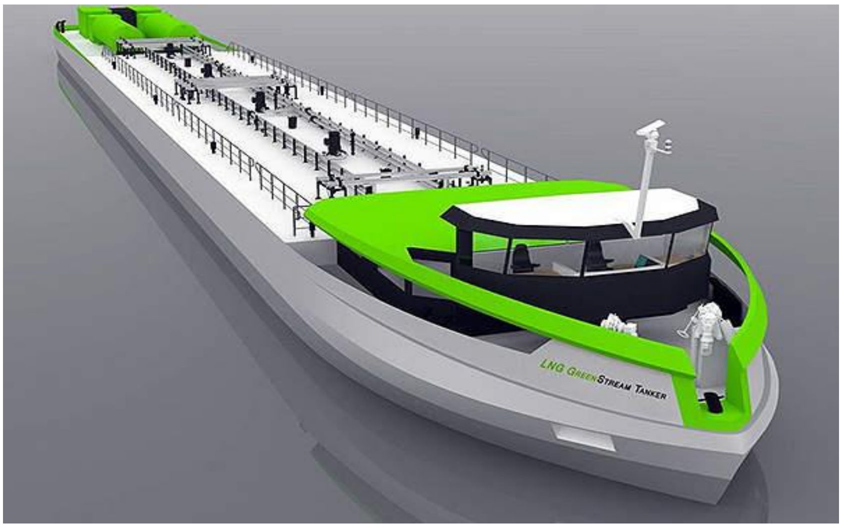

Fig 28. LNG powered inland tanker [25]

Fig 29. LNG powered inland barge [26]

Fig 30. LNG fueled shallow draft pushboat [27]

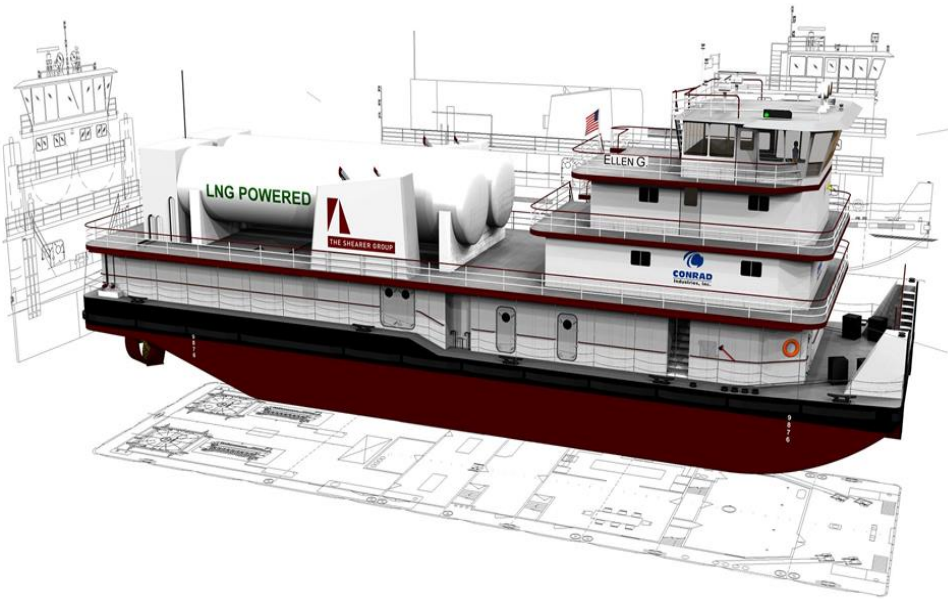

Fig 31. LNG fueled pushboat [28]

Small vessels modernized for gas fuelled

In addition to the design and construction of gas-fuelled ships, their frequent modernization enabling the use of gaseous fuel. Examples of modernized ships are presented in Figure 32-34.

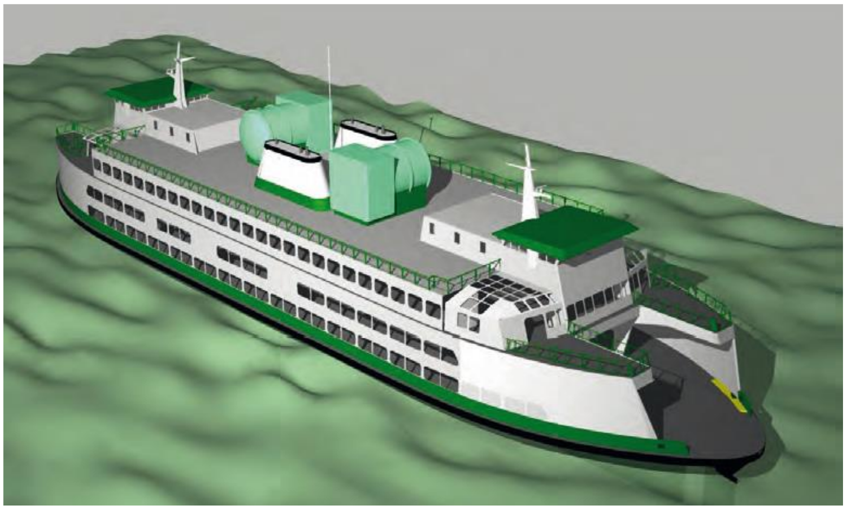

Fig 32. Ferry modernized to LNG fueled [29]

3D View of the 32m LNG Fuelled (DF) Harbour Tugboat.

Principal Particulars of LNG Fuelled (DF) Harbour Tug.

Length Overall	32.00 m
Moulded Breadth	12.48 m
Moulded Depth	5.30 m
Design Draft	4.00 m
Extreme Draft (With Skeg)	5.40 m
Service Speed	13 knots
Bollard Pull (Astern)	65 Tons
Main Propulsion Engine	2 x 1920kW @ 800 RPM
Thruster (ASD)	2.7 m diameter
LNG Tank Capacity	2 x 20 m^3
LNG System	LNG Vaporizer, Buffer tank
Classification	ABS +A1, + AMS, E, Towing Vessel, Fire Fighting Vessel Class 1, BP ( ), GFS (DFD), UWILD.

Fig 33. Tug modernized to LNG fueled [30]

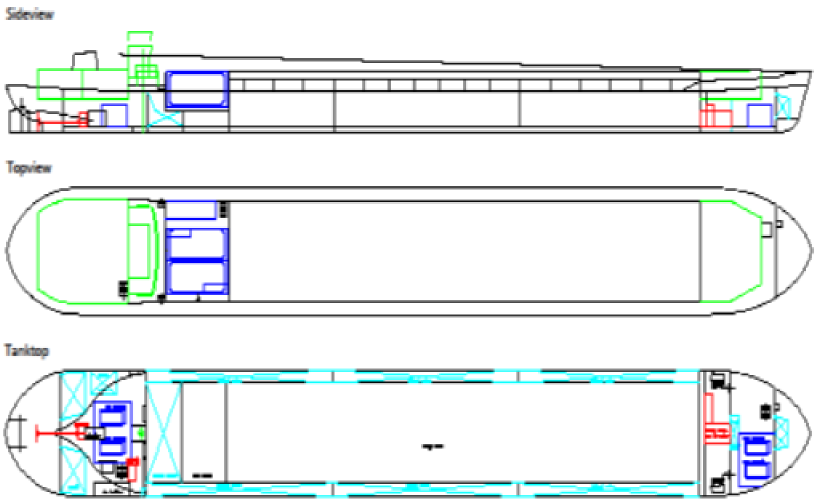

Fig 34. Barge modernized to LNG fueled (LNG system in blue) [31]

As can be seen in Figures 32-34, during the modernization of ships for propulsion with the use of LNG as a fuel, the location of the gas tank poses the biggest problems.

In particular types of analyzed ships, the LNG tanks were located in the following locations:

- Ferry – on the navigation deck (Fig. 33);
- Tug – on the main deck (Fig. 34);
- Barge - in the hold (Fig. 35).

Factors, to be taken into account when upgrading vessels to gas-fuelled, are presented in Table 2.

Tab.2 Comparing the alternatives fuels using at ships: LNG, MGO and HFO [32]

	Environmental features compared to the traditional HFO alternative				**Factors influencing viability compared to the traditional HFO alternative**		
Fuel type	Gas emission				Cargo capacity	Capital investments	Operating costs
	SO_x	NO_x	CO_2	PM			
LNG/BNG	very low	very low	low	very low	restricted	very high	low
MGO	low	high	high	high	not restricted	low	very high
HFO+ scrubber	low	very high	high	low	slightly restricted	high	medium

The use of gas as a fuel will ensure the lowest emission of harmful components of exhaust gases and operating costs (mainly costs of fuel purchase).

Unit fuel costs depending on engine type, power system configuration and drive power are shown in Figure 35.

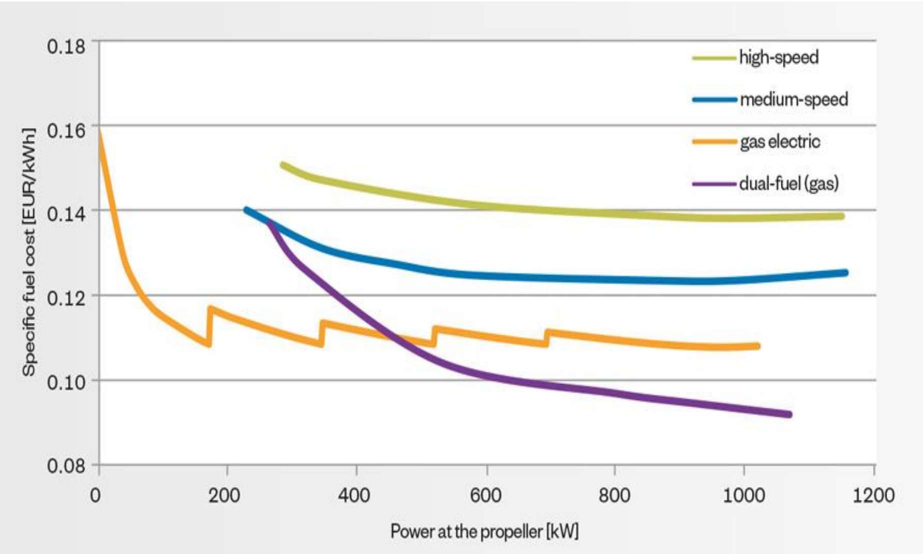

Fig 35. Specific fuel cost as a function of power at the propeller [33]

The lowest fuel costs will be incurred with the use of gaseous fuel in the configuration of the gas electric power system and direct propulsion of the propeller by a dual-fuel engine. It should be noted that in the case of direct propulsion of the propeller by a dual-fuel engine, fuel costs decrease as the engine power increases (Fig 35).

Configurations of power systems of gas-fuelled vessels

Examples of basic configurations of energetic systems used on ships are presented in Figure 36.

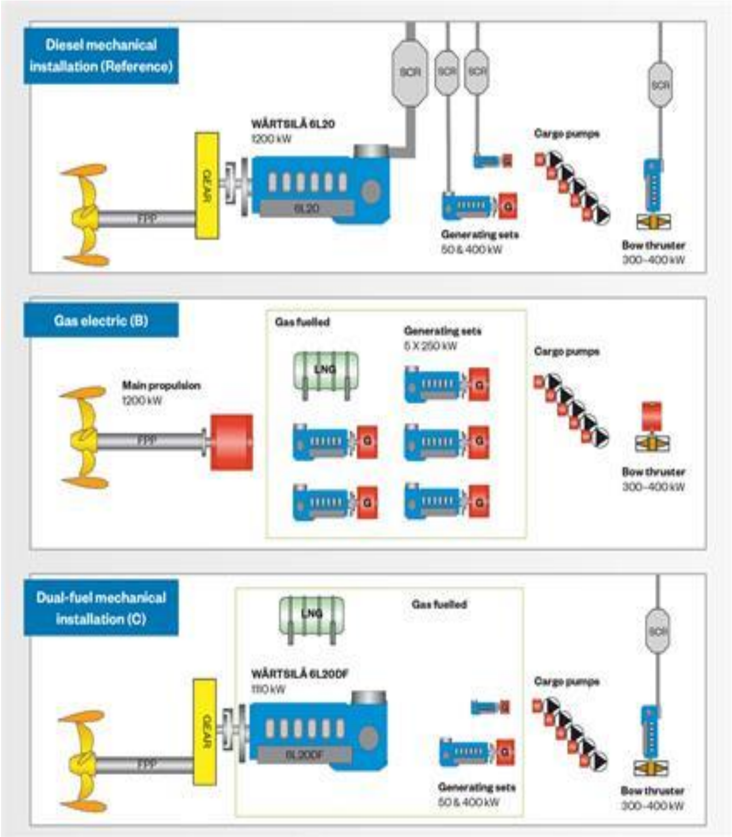

Fig 36. Basic configurations ship's energetic systems [33]

The most commonly used power system is the one in which a combustion engine sowed with petroleum-based fuels directly drives the ship's propeller (Fig 36 at the top). Low-sulphur fuels and SCR systems are used to reduce emissions of harmful exhaust components. (SCR-selective catalytic reduction technology used, among others, in diesel engines, whose main principle is the reduction of particulate matter (PM) emissions in the exhaust gases and the reduction of nitrogen oxides (NO_x)).

The use of gas as a fuel allowed to use the energetic systems with direct propulsion of the ship's propeller by a two-fuel engine (Fig 36 below). With this solution, no SCR system is required.

An increasingly common solution is the gas-electric energetic system shown in Figure 36 (center). In this solution, gas-powered internal combustion engines drive generators, called diesel generators, to generate electricity. Electricity is transferred to the electric motors that are drives of the ship's propeller. The use of several diesel generators enables the operation of any number of them, depending on the required drive power.

Energy system selection for Magda vessel

One of the objectives of the project titled *Liquefied (bio-)gas as a driving force for development and use of green energy technology* is to rebuild the Magda unit for gas supply.

Current technical characteristics of the Magda vessel

Side view of the vessel is shown on the Figure 37.

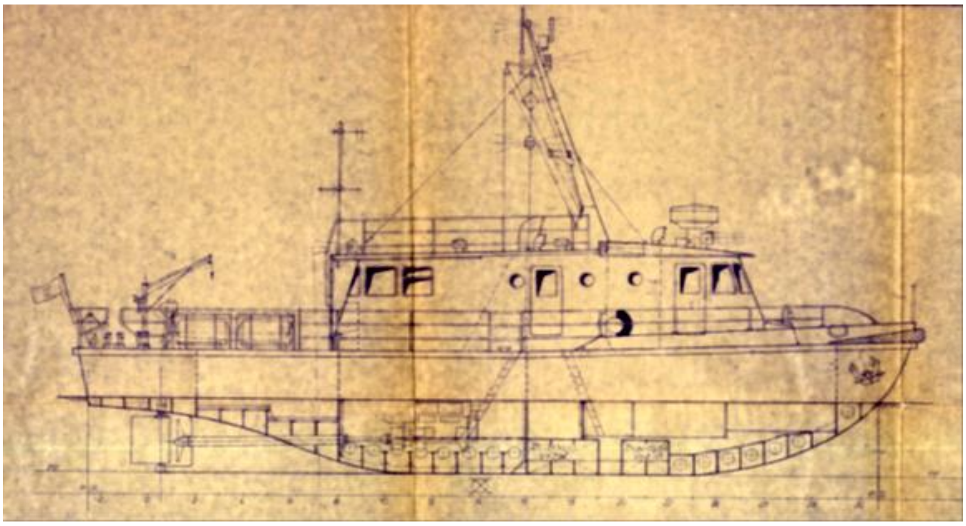

Fig 37. Side view of the vessel Magda [34]

Technical characteristics of the vessel:

Overall lenght:	Lc = 18,00 m
Lenght between perpendiculars:	Lpp = 15,25 m
Beam:	B = 4,50 m
Moulded depth:	H = 2,60 m
Deadweight:	5,5 t
Total weight:	42,74 t

Main engine:

Type:	Delfin SW 680, four stroke, overhead valve engine, aspiration engine
Number of cylinders	6 in a vertical position
Power:	121 kW at 2000 rev/min

Maximum torque:	743 Nm at 1200 rev/min
Cylinder diameter:	127 mm
Piston stroke:	146 mm

<u>Cargo spaces:</u>

Height:	135 cm
Width:	320 cm
Length:	360 cm

The unit uses an energetic system in which the internal combustion engine directly drives the ship's propeller through reduction gear. At present, the vessel uses petroleum-based fuel type MDO, which consumes 23 l/h at power 100 kW.

In order to adapt the vessel to gaseous fuel supply, the energetic systems presented in the Figures were developed and analyzed.

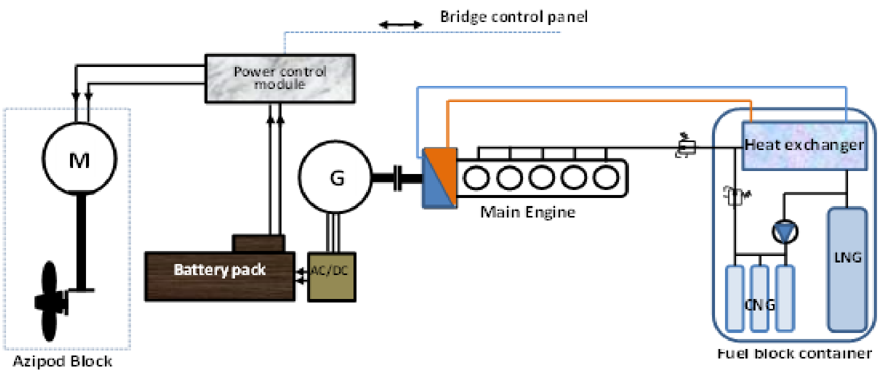

Fig 38. Gas-electric energetic system with Azipod propeller module [35]

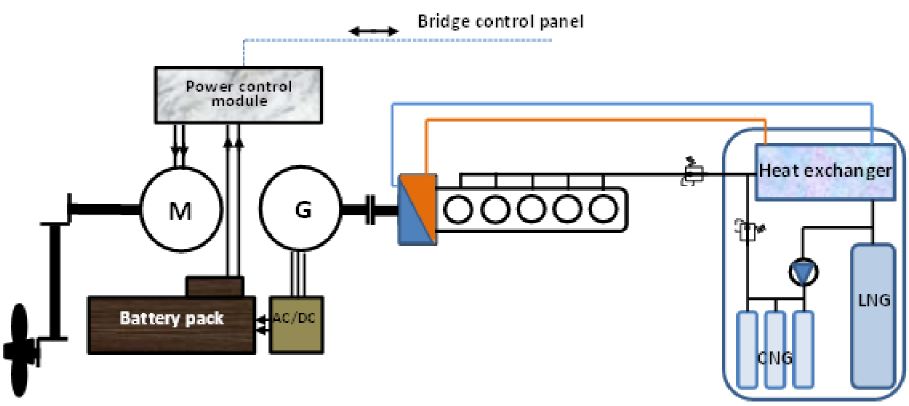

Fig 39. Gas-electric energetic system with Z-type propeller module [35]

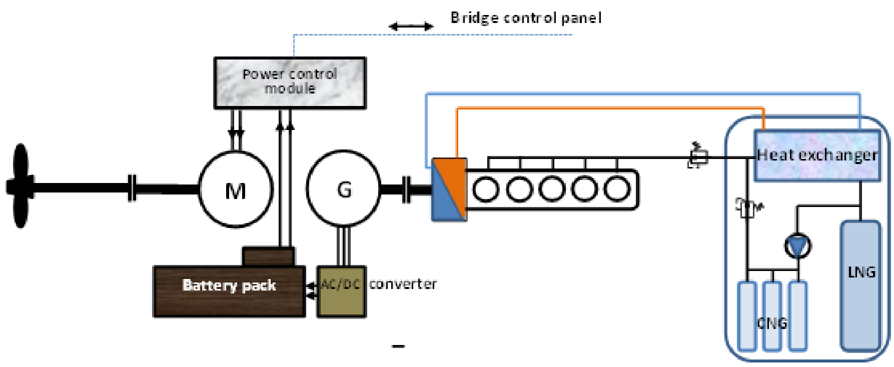

Fig 40. Gas-electric energetic system [35]

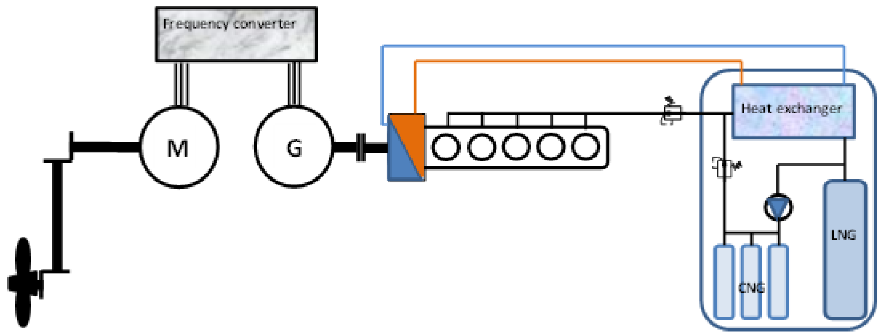

Fig 41. Diesel-electric energetic system with Z-type propeller module [35]

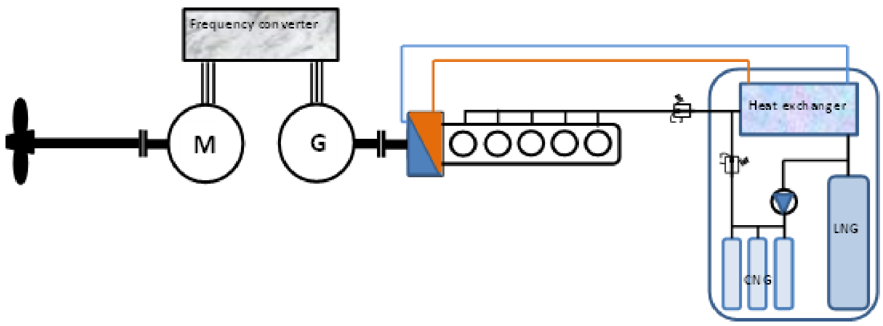

Fig 42. Diesel-electric energetic system [35]

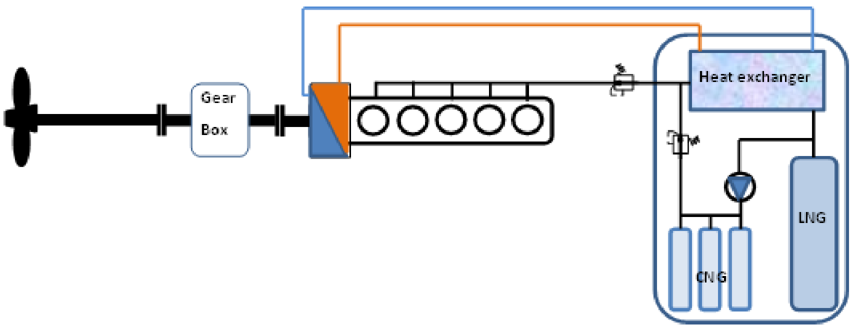

Fig 43. Gas engine energetic system [35]

The latest construction solution in the shipbuilding industry is the gas-electric energetic system shown in Figures 38-40. In the gas-electric energetic system, a combustion engine powered by gas fuel drives a generator. The generated electricity is transferred to the battery pack, from which the electric motors of the ship propeller drive are powered.

The gas-electric energetic systems shown in Figures 38-40 differ in the type of propeller module:

- Azipod propeller module - allows to resign from the rudder due to 360° rotation. Is used on ships which require high maneuverability e.g. tugs;
- Z-type propeller module - it can be installed above the waterline, e.g. on the main deck. Often used on barges and dredgers.

When using gas-electric and diesel-electric energetic systems, it is possible not to install a reduction gear in propulsion system. Each gas-electric and diesel-electric energetic system requires the installation of new modules and equipment (current converters, generators, power management system, electric motors, accumulator batteries), which increases investment costs. In addition, the use of the Azipod and Z-type propeller module requires a cost-intensive conversion of the vessel's hull in the stern region caused by the removal of the rudder. In each analyzed energetic system it is necessary to install a liquefied gas tank and a gas fuel block.

Taking into account the above requirements and the funds available in the project, it was decided to modernize the Magda vessel's energetic system to the gas engine system shown in Figure 43, in which the internal combustion engine powered by gas, through a reduction gear drives the ship's propeller.

Required basic conversion range for Magda vessel:

- Due to the age and technical condition of the Delfin's engine, it is required to replace it with a new one or an engine with similar power and technical parameters, upgraded for gas supply. The engine will be connected to the existing SR 19.5 gearbox of Puck Mechanical Works. It will be powered by a power take-off shaft from the engine with 2 x 12 (24V) alternators of 3 kW each, and will drive an outboard water pump, engine cooling water pump, and engine lubricant oil pump;

- The cargo hold will be equipped with a LNG and CNG gas tank and a gas fuel module.

Taking into account the size of the cargo hold, it will be possible to use a LNG tank with a maximum capacity of 1000 l, which is sufficient for about 12 hours of engine operation. In order to prevent excessive pressure increase from the LNG tank, a CNG tank with a total volume of 180 l and a maximum working pressure of 20 MPa will be installed, to which the gas evaporated from the LNG tank will be pumped with a compressor.

7. Selected vessels to be upgraded for gas-fuelled operation

Selected types of small ships of the polish fleet adapted to be modernized for gas-fuelled operation are presented in Table 3.

Table 3 Selected type of small vessels indicated for gas fueling

[Inland ships table based on data from https://www.prs.pl/wydawnictwa/rejestry-statkow-jachtow-lodzi (access 15.06.2023)]

No.	Vessel Name	Vessel Type	Year of const./recon	Owner	Port of registry	L [m] B [m] T [m]	Engine producent/ Engine type	Power [kW]	Generators [kW]
1	ANDRZEJ	ice-breaker/tug	1965	Regionalny Zarząd Gospodarki Wodne w Szczecinie	Szczecin	30,34 8,09 5,73	Wartsila Finland Oy W4L20	784,0	2x135 kVA 400V p
2	ANIA	tank barge	1967 / 2003	Oktan Energy & V/L Service Sp. z o.o	Szczecin	56,50 7,50 2,00	PZM Puck 2, SW 680/195	242,0	242,0
3	BASIOR	ice-breaker	1969	REVERS sp. z o.o.	Płock	15,26 5,60 2,00	VEB SKL, Magdeburg 1, 8NVD48-2U	770,0	1x18,5 380V p
4	BLUE SHADOW	passenger vessel	2015	Princess Cruise Line	Cairo	70,11 14,40 3,60	Caterpillar 3, C18	1071,0	-
5	BORSUK	ice-breaker	1989	PBH "ODRA 3" Sp. z o.o.	Szczecin	28,05 6,96 1,70	VEB SKL-Magdeburg 1, 8VD36/24A-1U	441,0	2x45 400V p
6	BUTLONOS	tug	1984	(1)	Kołobrzeg	10,25 4,04 2,27	WSK Mielec 1, SW 680/195/1	121,0	-
7	BYK-06	pusher	1978	(1)	Kędzierzyn-Koźle	46,94 8,60 1,70	PZM Puck 2, SW 680/196	242,0	2x1.5 24
8	CONRAD GOLIATH	floating crane	1962	Marine Projects Ltd. Sp. z o.o.	Gdańsk	16,94 5,36 2,68	Baudouin SMB 1, 8P15E	211,0	-
9	CZARNA PERŁA	passenger vessel	1974 / 2008	(1)	Gdynia	25,62 6,60 3,00	WSK Mielec 2, SW680/195	242,0	2x37 380V p
10	CZELIN	inspection vessel	2012	Regionalny Zarząd Gospodarki Wodnej w Szczecinie	Szczecin	17,00 4,30 1,31	Volvo Penta 2, D5A-B TA	236,0	1x40 380V p
11	DP WUŻGda 15	floating crane	1988	WUŻ Port and Maritime Services Ltd Sp. z o.o.	Gdańsk	40,86 19,98 3,69	H. Cegielski – Poznań 2, 6AL25/30	687,0	2x640 400V p
12	DRAGON	passenger vessel	1963 / 2007	(1)	Gdynia	31,54 8,40 4,37	DOOSAN DAEWOO 1, V222TI	530,0	-
13	DZIK	ice-breaker	1988	PGW Wody Polskie RZGW w Szczecinie	Szczecin	33,13 7,84 2,54	ZPM H. Cegielski, Poznań 1, 6AL25D	780,0	2x28.0 400
14	FLIS	tug	1986	(1)	Wiąg	15,90 4,00 1,50	WSK – Mielec 1, SW 680/195	121,0	1x1.68 28

15	FW-3	pusher	1985	(1)	Kozienice	19,11 4,40 1,30	ZM PZL Wola 1, 57H6Aa	210,0	3x0.9 28
16	GALAKTYKA	hydrographic vessel	1974	Urząd Morski w Szczecinie	Szczecin	27,83 6,82 2,53	ZM PZL Wola 1, 135V12 TC	440,0	2x48.0 380
17	GENERAŁ KUTRZEBA	passenger vessel	2005	(1)	Gdynia	14,42 4,70 1,15	Volvo Penta 1, AD 41 P-A	147,0	-
18	GEPARD	pusher	1979	PBH "ODRA 3" Sp. z o.o.	Szczecin	20,17 8,17 1,99	ZM PZL Wola 2, 57H6Aa	310,0	1x36.0,1x7.2 400
19	GOZDOWICE	pusher	2013	Regionalny Zarząd Gospodarki Wodnej w Szczecin	Szczecin	16,70 4,50 1,43	AB Volvo Penta 2, D5A BTA	236,0	-
20	GRYF	passenger vessel	1963 / 2005/2010	(1)	Ustka	20,53 5,82 2,45	PZL Mielec 1, SW 680	147,2	1x33.0 400
21	HELENKA	motor boat	1968	(1)	Gdańsk	15,72 4,20 1,65	PZM Puck 1, SW 680/195	121,0	1x1.5 24
22	HETMAN	pusher-tug	1973 / 2011	(1)	Gdańsk	22,15 5,60 1,55	SCANIA 2, DS1144	290,0	-
23	HYDROBUD 1	pusher	1985	P.H.U. HYDROBUD Adam Dzik	Kołobrzeg	27,00 8,50 2,20	Volvo Penta 2, TAMD162C-B868416	750,0	-
24	JANKO	pusher	1978	(1)	Szczecin	20,22 8,20 2,00	ZM PZL Wola 2, 57H6Aa	310,0	-
25	KALMAR	tug	2015	Urząd Morski w Szczecinie	Mrzeżyno	11,39 4,46 1,64	Volvo Penta 2, D5A-BTA	190,0	-
26	KANGUR	ice-breaker	1970	REVERS sp. z o.o.	Płock	35,30 8,00 2,50	VEB SKL-Magdeburg 1, 8NVD48-2U	770,0	1x14.8 380
27	KASIA	tug	2008	MPWiK w m.st. Warszawie S.A.	Warszawa	13,00 4,00 0,90	SHIEDAM 1, DT66422E	125,0	-
28	KOBUZ	techanical vessel	2014	RZGW w Warszawie, Zarząd Zlewni w Giżycku	Giżycko	17,45 4,20 1,40	John Deere 2, 6068TFM75	266,0	-
29	KOS	motor boat	1985	Regionalny Zarząd Gospodarki Wodnej w Gliwicach	Kędzierzyn-Koźle	15,85 4,00 1,56	PZM Puck 1, SW 680/195	121,0	-
30	KRAKÓW	inland vessel	1988 / 2011	Miejskie Przedsiębiorstwo Wodociągów i Kanalizacji S.A	Dobczyce	22,28 5,20 1,00	Volvo Penta 2, D5A-BTA	204,0	1x17,5 kVA 400V p

31	KFig TYNA	passenger vessel	1968	(1)	Elbląg	16,14 4,29 2,80	PZM Puck 1, SW 680/195	121	2x2.38 28
32	LEMUR	ice-breaker	1969	REVERS sp. z o.o.	Płock	28,057,06 2,40	Kaliningrad, Rosja 1, M400-1. GOST 10150-8812CZNS	736,0	-
33	LIDMANN & MEGGER I	pusher	1968 / 1981	(1)	Szczecin	8,90 4,33 1,35	DEUTZ AG 1, BF 12L 714	186,0	-
34	LIS	ice-breaker	1988	PGW Wody Polskie RZGW w Szczecinie	Szczecin	27,77 6,82 2,40	VEB SKL-Magdeburg 1, 8VD36/24A-1U	441,0	2x45.0 400
35	ŁOSOŚ	tug	1964	Regionalny Zarząd Gospodarki Wodnej w Poznaniu	Poznań	18,82 3,70 1,30	PZM Puck 1, SW 680/195	121,0	1x0.9 28
36	ŁOŚ-02	pusher-tug	1975	PBH "ODRA 3" Sp. z o.o.	Szczecin	19,35 4,40 1,30	ZM PZL Wola 1, 57H6Aa	148,0	2x2.0,1x1.68 24
37	MACIEK	pusher-tug	1965	SPELWAR HYDROTECHNIKA Sp. z o.o.	Gdańsk	20,36 5,80 1,60	PZM Puck 2, DELFIN	242,0	2x1,5 2x0,3
38	MAGDALENA	passenger vessel	1965 / 2017	(1)	Jastarnia	16,78 5,20 2,60	Caterpillar s. sp, 4s, 3176	448,0	1x1,1 1x0,3 24V s
39	MONIKA	passenger vessel	1965	(1)	Płock	36,10 6,56 3,10	CZMN Skoda 2, 6L-160 PNS	280,0	1x15.0,1x3,5 220
40	MORŚWIN	tug	1983	(1)	Darłowo	10,25 4,06 2,26	PZM Puck 1, SW 680/195	121,0	-
41	NAVIGAR-2	pusher	1978 / 1999	NAVIGAR Sp. z o.o. Sp. komandytowa	Szczecin	24,93 5,20 1,60	IVECO, Włochy 1, 8281 SRM 50	368,0	-
42	NAVIGAR-3	pusher	1978	NAVIGAR Sp. z o.o. Sp. komandytowa	Szczecin	24,76 5,20 1,60	KMD 1, S14 - IIV - 500PK	370,0	1x20.0 220
43	NIEGOCIN	pusher	1970	RZGW w Warszawie, Zarząd Zlewni w Giżycku	Giżycko	19,31 4,38 1,30	ZM PZL Wola 1, H6A	147,0	1x2.0,1x0.6 24
44	NOSOROŻEC-G-01	pusher	1970	Żegluga HTŚ Sp. z o.o.	Gdańsk	19,30 8,57 3,00	MAN Truck & Bus AG 2, MAN, D2842 LE419	880,0	2x48.0 400
45	NOSOROŻEC-G-02	pusher	1970	Żegluga HTŚ Sp. z o.o.	Gdańsk	20,74 8,57 3,00	AB Volvo Penta 2, D16C-A MH 550	808,0	2x48 400
46	NOSOROŻEC-S-05	pusher	1978	Port-Żegluga Szczecińska Sp. z o.o.	Szczecin	20,17 8,82 3,00	ZM PZL Wola 2, 54H12A	560,0	2 x 44.1 400

47	ODRA QUEEN	passenger vessel	1990	Unity Line Limited Sp. z o.o. Oddział w Polsce	Szczecin	37,485,50 1,70	John Deere Power Systems 2, 6068TFM75	300,0	1x45 kVA 380V p
48	ODYNIEC	ice-breaker	1988	PGW Wody Polskie RZGW w Szczecinie	Szczecin	33,37 8,11 2,01	ZPM H.Cegielski – Poznań 1, 6AL25D	780,0	2 x 28.0 400
49	OGAR	ice-breaker	1970	PGW Wody Polskie RZGW w Szczecinie	Szczecin	35,38 8,38 2,51	VEB SKL-Magdeburg 1, 8NVD48-2U	566,0	1x15.0 380
50	OGNICA	inspection vessel	2012	Regionalny Zarząd Gospodarki Wodnej w Szczecinie	Szczecin	17,00 4,30 1,31	Volvo Penta 2, D5A-B TA	236,0	1x40 400V p
51	OKEANOS	tug	1978	Stocznia Remontowa NAUTA S.A.	Gdynia	23,67 6,81 3,55	ZPM Poznań 1, 6AL25/30	688,0	2x48 400V p
52	ORKA	ice-breaker	1991	Regionalny Zarząd Gospodarki Wodnej w Gdańsku	Tczew	27,60 6,81 2,40	VEB SKL-Magdeburg 8VD 36/24A-1U	442,0	2x36.0 400
53	OSKAR	pusher	1983	Przedsiębiorstwo Robót Czerpalnych i Podwodnych Sp. z o.o.	Szczecin	20,22 8,43 1,60	PZM Puck 2, UE 680/193/1	242,0	2x36.0 380
54	OSTRÓW-1	train ferry	1978	Stocznia Gdańsk S.A.	Gdańsk	57,00 11,52 4,00	ZM PZL Wola 2, 31H12A	618,0	2x48.0 380
55	PANTERA	ice-breaker	1988	(1)	Płock	33,13 7,85 2,55	ZPM H.Cegielski – Poznań 1, 6AL25D	780,0	2x28.0 400
56	PODJUCHY	pusher	2013	PGW Wody Polskie RZGW w Szczecinie	Szczecin	16,70 4,50 1,42	AB Volvo Penta 2, D5A BTA	236,0	-
57	PYTON	tug	1973	Morska Stocznia Remontowa GRYFIA S.A.	Świnoujście	25,20 8,31 4,30	Ruskij Disel b. Leningrad 2, 6D30/50-4-2	882,0	2x25.0 230
58	ROZA WENEDA	passenger vessel	1961	(1)	Dziwnów	34,21 6,55 3,10	PZM Puck 2, SW 680/195	242,0	1 x 16.0 28
59	STANISŁAW	ice-breaker/tug	2014	PGW Wody Polskie RZGW w Szczecinie	Szczecin	35,38 8,22 2,51	Wartsila Finland Oy 1, W6L20	1176,0	-
60	STRAŻAK-24	fireboat	1977	Zarząd Morskich Portów Szczecin i Świnoujście S.A.	Świnoujście	31,13 6,82 2,60	ZM PZL Wola 2, 36H12Aa	734,0	2 x 48.0 400
61	STRAŻAK-4	fireboat	1976	Straż Ochrony Portu Gdańsk Sp. z o.o.	Gdańsk	31,01 6,81 2,60	ZM PZL Wola 2, 36H12Aa	734,0	2 x 48.0 400

62	STRAŻAK-6	fireboat	1971	Straż Ochrony Portu Gdańsk Sp. z o.o.	Gdańsk	20,16 5,80 2,93	BOLNES 1, 5NL	257,0	-
63	SYRENKA	passenger vessel	1990	(1)	Sandomierz	37,90 5,30 1,70	John Deere 2, 6068TFM75	300,0	1x31 kVA 400V p
64	ŚWISTAK	ice-breaker	1969	Regionalny Zarząd Gospodarki Wodnej w Szczecinie	Szczecin	28,06 7,06 2,40	VEB SKL-Magdeburg 1, 8NVD36-1U	300,0	-
65	TUR-W-01	tug-pusher	1963	(1)	Warszawa	20,76 5,72 1,60	Volvo Penta 2, TD163ES-958; TD162F-950	194,0	-
66	WEZYR-1	pusher	1983	Fairplay Towage Polska Sp. z o.o. Sp.k.	Szczecin	22,37 8,90 2,03	ZM PZL Wola 2, 48H12Aa	566,0	-
67	WEZYR-2	pusher	1983	Fairplay Towage Polska Sp. z o.o. Sp.k.	Szczecin	22,37 8,90 2,03	ZM PZL Wola 2, 48H12Aa	566,0	-
68	WIDUCHOWA	pusher	2013	PGW Wody Polskie RZGW w Szczecinie	Szczecin	16,71 4,50 1,43	AB Volvo Penta 2, D5A BTA	236,0	-
69	WILK	ice-breaker	1968	PBH "ODRA 3" Sp. z o.o.	Szczecin	35,50 8,32 2,50	VEB SKL-Magdeburg 1, 8NVD48-2U	566,0	1x14.8 400
70	WYDRA	ice-breaker	1969	(1)	Płock	28,08 7,06 2,40	Kaliningrad, Rosja M400-1, GOST 10150-88-12CZNS	736,0	3x2.0 24
71	ZDROJE	inspection vessel	2012	Regionalny Zarząd Gospodarki Wodnej w Szczecinie	Szczecin	17,00 4,31 1,30	Volvo Penta 2, D5A-B TA	236,0	1x40 400V p
72	ŻBIK	ice-breaker	1987	PGW Wody Polskie RZGW w Szczecinie	Szczecin	27,72 6,82 2,40	VEB SKL-Magdeburg 1, 8VD 36/24A-1U	441,0	2x36.0 400
73	ŻUBR	pusher	1962	PBH "ODRA 3" Sp. z o.o.	Szczecin	20,54 5,85 1,67	ZM PZL Wola 2, 04H6	214,0	2x0.9 28
74	ŻUBR	Pusher	1973	Przedsiębiorstwo COMAL Sp. z o.o.	Gdańsk	20,27 8,62 3,00	ZM PZL Wola 2, 54H12Aa	624,0	2x48 400

(1) Data protected in accordance with the Personal Data Protection Act of 10 May 2018 and Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016

Figures 44-52 show the most numerous types of barges and pushers on which the upgrade to gas fueling can be carried out. Technical data of these vessels can be found in Table 3

Fig 44. B-500 type barge [36]

Fig 45. B-600 type barge [36]

Fig 46. Pushboat Renifer[36]

Fig 47. Bison type pushboat [36]

Fig 48. Ice breaker Dzik

Fig 49. Ice breaker Lis

Fig 50. Inspection vessel Kontroler 15

Fig 51. Passenger vessel Odra Queen

Fig 52. Pilot ship Pilot 63

Bibliography

1. Buchholz B., Harndorf H, Fink C,: IMO TIER 3:Strategies and challenges, Green shipping, Ship & Offshore | 2010 | No 4,
2. Hombravella A., Kılıçaslan A., Péralès J., Rüs C.: Study of Exhaust Gas Cleaning Systems for vessels to fulfill IMO III in 2016. Study of Exhaust Gas Cleaning Systems European Project Semester 2011
3. https://link.springer.com/article/10.1007/s12544-015-0161-9/figures/2
4. Sangsoo H , Byongug J , Kwanghyo J, Mingyu K ,Peilin Z.: Life Cycle Assessment of LNG Fueled Vessel in Domestic Services. Mar. Sci. Eng. 2019, 7(10), 359; https://doi.org/10.3390/jmse7100359
5. Jalkanen J.P., Johansson L., Kiukkonen J., A Comprehensive Inventory of the Ship Traffic Exhaust Emissions in the Baltic Sea from 2006 to 2009, AMBIO A Journal of the Human Environment, 43(3), pp.311–324, 2014
6. https://www.globalsuzuki.com/corporate/environment/environment/design.html
7. Economic Commission for Europe, Inland Transport Committee „ LNG: a safe fuel for trucks"
8. Source: ISO12614-1
9. www.hamworthy.com/.../LNGFuelGas
10. https://www.greencarcongress.com/2018/09/20150945-skygo.html
11. Photograph reproduced courtesy of Marine Service GmbH
12. 002 LNG Study pdf
13. https://www.nap.edu/read/25342/chapter/6
14. Sutkowski M., Latvasalo T.: The 20V23SG – a high-efficiency Lean-burn gas engine for highly efficient Wartsila gas power plants. Combustion Engines, 2007, No SC1
15. http://marengine.com/home
16. Petrov, 2013 Ref (Stokholm & Roaldsřy, 2000)
17. Grimstad Osberg, 2013
18. https://www.lngindustry.com/small-scale-lng/27022015/tallink-and-meyer-turku-ink-lng-fuelled-ferry-contract-333/
19. Image reproduced courtesy of Harvey Gulf
20. https://ral.ca/2014/11/21/rangler-new-angle-lng-fuelled-tugs/
21. https://www.iims.org.uk/wp-content/uploads/2018/05/LPV-LNG-Fuel-tank.jpg

22. https://www.portofrotterdam.com/en/news-and-press-releases/new-lng-powered-vessel-to-start-dredging-in-port-of-rotterdam
23. https://www.marinelink.com/news/world-first-lngfueled-fishing-trawler-437871
24. https://www.tersanshipyard.com/haberler
25. https://www.ship-technology.com/projects/lng-greenstream-tanker/
26. https://www.damen.com/en/news/2015/03/lng_powered_ecoliner_delivers_dramatic_fuel_savings
27. https://www.workboat.com/news/coastal-inland-waterways/robert-allan-mtu-develop-lng-pushboat-design
28. https://www.google.com/search?q=LNG-Fueled+Tugboat&tbm=isch&source=iu&ictx=1&fir=73pNfagCKT8iOM%252C8FYcNdvu7ILaDM%252C_&vet=1&usg=AI4_-kTibB5vLr4iBmHO6Hor7-
29. Image reproduced courtesy of WSF
30. https://www.slideshare.net/KelvinXu3/portable-fuel-tank-the-application-of-a-new-method-of-bunkering-for-small-scale-gas-fuelled-vesselscompressed-68451051
31. https://www.theseus.fi/bitstream/handle/10024/54840/Markus_Bergfast.pdf?sequence=1&isAllowed=y
32. https://www.lek.com/insights/ei/imo-2020
33. https://www.wartsila.com/twentyfour7/in-detail/the-path-to-cleaner-inland-waterway-shipping
34. Own photo
35. Own draft
36. https://www.zegluga-rzeczna.pl/articles.php?article_id=242