



## Liquefied Natural Gas – The Future Fuel for Shipping or Cul-de-sac

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**Abstract:** The paper analyses the reasons for the interest in natural gas as a potential marine fuel to replace the existing fuels derived from crude oil. The increase in environmental awareness and the effects of human activity caused the process of searching for more environmentally friendly fuels. Naturally, interest has been shifted to a well-known energy source commonly found on Earth in quantities much more considerable than crude oil. This fuel, in the form of liquefied natural gas, seems to be an attractive substitute for the currently dominant types of marine fuels. The technologies of its extraction, liquefaction, storage and transport were mastered, and marine engines were adopted for its combustion as dual-fuel engines. The regulations introduced by the International Maritime Organization and the European Parliament, forcing the reduction of emissions of harmful substances into the atmosphere from the combustion of marine fuels, require taking action to meet them. The proposals for individual next 30 years are given. Due to the introduction of regulations to reduce carbon dioxide emissions, it is necessary to switch to fuels with a lower or zero carbon content or biofuels recognised as more environmentally friendly. Due to only 25% lower carbon content in methane with its higher lower heating value, it is possible to reduce the direct emission from this gas by about 30%. However, methane leaks occur in the processes from natural gas extraction to the energy effect in engines as a fuel, significantly worsening its image as an ecological fuel. Researches indicate that with current technologies, natural gas should not be recognised as an ecological fuel until gas leaks are significantly reduced. The article justifies why LNG should be considered a transient marine fuel, with the need to switch to other synthetic fuels, ammonia, and hydrogen.

**Keywords:** fuel for shipping; liquefied natural gas; marine fuel of the future; fuel leakage; green-house effect; atmosphere contamination

### 1. Introduction

Liquefied Natural Gas (LNG) consist mainly of methane (87-97%) and other higher hydrocarbons. The concentration of non-condensing gases is limited (mainly nitrogen) due to the problem of increasing the compression pressure during re-liquefaction processes (SIGGTO 2016, Liquefied Natural Gas).

Natural gas reserves are much larger than other fossil fuels (BP 2021, US EIA 2020). LNG has many advantages higher Lower Heating Value (about 48-



54 MJ/kg) than other marine fuels (about 39-43 MJ/kg), lower carbon concentration in the fuel (75%) and consequently lower carbon dioxide emission in the combustion process, lower emission of other toxic gases due to the better cleanliness of fuel (Thomson et al. 2015). The disadvantages are as follows: very low temperature of liquefying at ambient pressure ( $-161.5^{\circ}\text{C}$ ), needs cryogenic fuel tanks with required thermal isolation, and finally, the energetic equivalent volume of fuel tanks is 2-3 times more than for traditional marine fuels (heavy fuel oil and marine diesel oil) (Herdzik 2012, Herdzik 2013), the LNG-air mixture is flammable (5-15%, for pure methane 5.3-14% v/v) and such fuel system requires additional safety precautions. Two primary parameters of methane in a state of gas are essential:  $-187^{\circ}\text{C}$  is a flash point (risk of fire from naked flame and static electricity), and  $530^{\circ}\text{C}$  is an auto-ignition temperature (means that methane is not ignited from hot surfaces – lower risk of fire in the engine room).

In the early phase of using LNG as a marine fuel, independent, type-C tanks were the best suited to dual-fuel or gas-fueled vessels. Now, the GTT (in cooperation with Wartsila) offers membrane-type LNG storage tanks of different capacities for all sizes of vessels.

The rate of boil-off gas (BOG) from LNG tanks is determined by the kind of thermal insulation and the level of the temperature outside the fuel tank (mainly the outboard seawater temperature) and reaches the level of 0.1-0.3% of tank volume per day (Herdzik 2018a). The rate may be increased using the LNG vaporisers or other heat exchangers which use the waste heat of engine cooling water if the demand for gas fuel is increased (increased demand for power). In the case of deficient demand for gas, the pressure of gasses inside the fuel tank may increase over the level of opening the safety relief valves, and the discharge system will release the gasses to a mast riser into the atmosphere (Corres 2017). The varying demand for BOG in the different operating states of the ship must be close to the natural rate of BOG evaporation in fuel tanks. Furthermore, mainly so that it is possible to consume BOG in the operating state with the lowest total energy (power) demand. Using BOG re-liquefaction systems would significantly complicate the fuel system and, due to additional electric energy consumption, would impair the efficiency of using LNG as a whole.

## 2. Solutions of LNG fuel systems for marine diesel engines

There are three concepts for LNG fuel systems for marine diesel engines:

- LNG system with pump – it is a simple system with a lower pressure tank and forced additional evaporation in a vaporiser and gas heater for gas engines require a pressure of 2-3 bar(g);
- LNG system with pressure build-up – there is a pressure build-up system which brings the entire tank up to the pressure required by the engines. This is the simplest and cheapest system but has a significant disadvantage. When

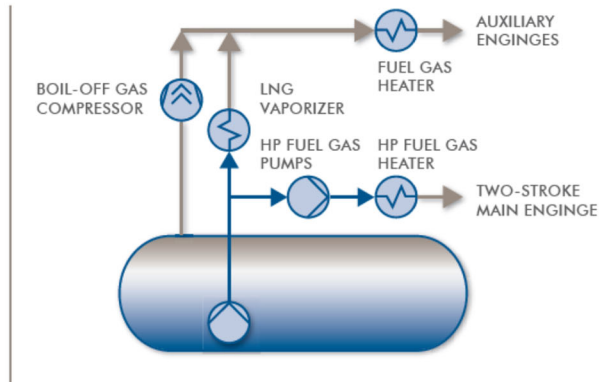
no fuel is used (the engine stopped), the tank pressure will slowly creep up until it must be blown off. The blown-off gas should be burned in the incinerator;

- LNG fuel system with compressor – BOG compressor can be used to bring the gas to the engine. This is the most flexible solution but has another critical disadvantage – compressors are expensive and less efficient than a pump system. Additionally, the natural gas during compression should be cooled in an intercooler and aftercooler.

TGE proposed an LNG fuel system presented in Fig. 1 with a tank design pressure of 4 bar(g) and different gas pressures for auxiliary engines (about 4 bar(g)) and a two-stroke main engine (about 350 bar(g)).

#### Type High Pressure Fuel Gas System

- Foam insulated type C tank
- No bottom outlet
- Submerged fuel gas pump, high pressure pump, and BOG compressor
- Tank design pressure 4 bar g for easy BOG handling
- Gas to main engine: 350 bar g



**Fig. 1.** LNG fuel system – proposition of two systems with two different gas pressures (TGE 2019)

Examples of shipbuilding with such systems have been indicated in (TGE 2019, IGC Code 2016).

It should be noted that “natural boil-off gas” comes from the top of LNG tank and contains a higher amount of methane than the liquid from which it comes and they are fewer problems with the operation of compression ignition marine engines. On the other hand, the “forced boil-off gas” type is coming from deep down in the tank (a place of pump well) and should be well mixed before extraction to the evaporator (better homogeneity) to ensure constant gas quality supply (Kuczyński et al. 2020). This impacts knocking stability during the natural gas burning process and the risk of possible methane slipping into the atmosphere due to misfire (Herdzik 2018b).

There are two basic systems for feeding methane as a gaseous fuel to diesel engines: high-pressure injection into the combustion chamber at the end of the compression stroke (Diesel cycle) or low-pressure (Otto cycle) and low-pressure injection into the intake manifold in the suction stroke. The first two options are preferred for two-stroke engines (ME-GI engines), and the third for smaller four-stroke engines with a spark-ignition (LBSI, gas only) type. For engine manufacturers, the target is to minimise the methane slip (only from the engines during the combustion process) from 1-2 g/kWh (current state) to a level of 0.2-0.3 g/kWh.

### **3. Fuel consumption by marine diesel engines and carbon dioxide emission from different types of marine fuels in 2000-2050**

The highest fuel consumption occurs in marine main propulsion engines due to the demand for mechanical energy to drive the ship in an amount constituting 70-90% of the total (the others are electricity and heat). In the process of burning hydrocarbon fuels (heavy marine fuels, marine diesel fuels etc.), about 3.12 tons of carbon dioxide are emitted from a ton of burned fuel (fuel coefficient  $c_F$  is about 3.12). Between 1990 and 2020, the weight of goods transported by sea tripled and continues to increase. As a result, carbon dioxide emissions from maritime transport account for 2.5-3% of total global emissions. For example, in 2021, it was 0.92 Gt, which accounted for 2.4% of 38.4 Gt worldwide.

In ocean shipping, slow-speed two-stroke engines are most often used to drive a ship. These are currently engines with the highest thermal efficiency (48-51%), operating on the cheapest fuels in gearless drive systems with fixed-pitch propellers, ensuring the highest value of the so-called total propulsion efficiency. This makes it possible to achieve the lowest CO<sub>2</sub> emissions per transport effect [g CO<sub>2</sub>/ton · nautical mile].

Typical emission level from the two-stroke marine diesel engines before introducing the limitations in 2000, 2020 and later as prognosis has been presented in Table 1 (MAN 2013, IMO 2018).

**Table 1.** Typical main diesel engine (low-speed two-stroke) fuel consumption and emission before 2000, in 2020 (Tier 3) and as prognosis in 2035 and 2050 per 1000 kWh produced mechanical energy (own elaboration)

Year of consideration	Specific fuel consumption	Lubricating oil consumption	Carbon dioxide emission	Nitrogen oxides emission	Sulfur oxides emission	Hydrocarbons emission
Before 2000	170 kg*	1.5 kg	530 kg	17-20 kg	15.3 kg**	0.15-0.2 kg
2020	165 kg*	0.7 kg	515 kg	2 kg	1.6 kg***	0.15-2 kg****
2030	140 kg****	0.5 kg	350 kg	0.2 kg	0.05 kg****	0.2 kg****
2050	350 kg****	0.5 kg	25 kg	0.2 kg	0.05 kg****	0.01 kg****
2050	52 kg*****	0.5 kg	kg (trace)	unknown	trace	zero

\* for fuels of LHV equal to 42.7 MJ/kg (ISO standard),

\*\* for 4.5% sulfur content in the heavy fuel oil (HFO),

\*\*\* for 0.5% sulfur content in the heavy fuel oil,

\*\*\*\* for LNG (LHV = 50 MJ/kg),

\*\*\*\*\* for ammonia and 5% pilot dose of marine diesel oil (MDO),

\*\*\*\*\* for hydrogen (liquefied) as fuel (LHV = 120 MJ/kg).

#### 4. IMO regulations on CO<sub>2</sub> emissions from marine diesel engines

International Maritime Organization (IMO) is an agency of the United Nations (UN). That worldwide organisation deals with international shipping matters. It had (at the end of 2021) 175 members (States). Many organisations (about 50) work with IMO as advisory members. One of IMO ideas is “zero carbon” in shipping in 2050. It has prepared a document (IMO Action 2018, IMO 2019) presenting the timetable for greenhouse gases (GHG) emissions reduction from ships, as follows:

- 2020 – EEDI phase 2: up to 20% reduction in the carbon intensity of the ship for newly built vessels in the design phase – it has been done;
- 2023-2030 – up to 30% reduction in the carbon intensity of the ship. This requirement is up to a 50% reduction from 2022 for the largest container-ships;
- 2030-2050 – long term measures to reduce the carbon intensity of the fleet by at least 70%;
- 2050 – at least 50% reduction of total annual GHG emissions. It requires approximately 85% CO<sub>2</sub> reduction per ship, considering the carbon dioxide equivalent factors.

These intentions concern the reduction of emissions expressed in the coefficient as the quotient of the amount of carbon dioxide emitted for the transport effect achieved, i.e. the mass of cargo and the distance of sailing. Units [ $\text{g CO}_2/\text{ton} \cdot \text{nautical-mile}$ ] are commonly used.

Many factors influence the value of this coefficient. A wide variety of solutions has been presented in Fig. 2 (IMO Action 2018). They are related to the process of optimising the shape of the hull (reducing the resistance of the hull immersed in water and protruding parts of the hull and superstructures above the draft line), optimising the ship's path, its speed, using fuels with lower carbon content, biofuels or synthetic fuels recognised as ecological.

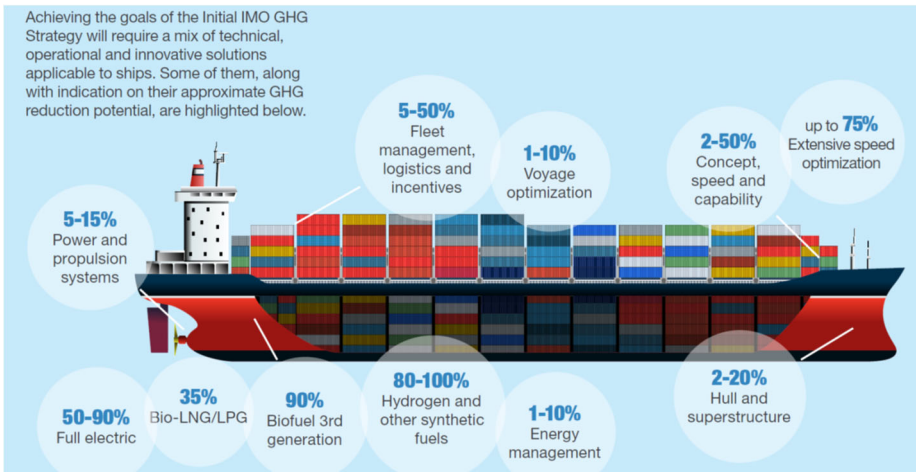


Fig. 2. A wide variety of design, operational and economic solutions (IMO Action 2018)

## 5. EMSA regulations on carbon dioxide emission decreasing from marine diesel engines. EU action “Fit for 55” for marine transport

Carbon dioxide emission from marine transport has been monitored due to (Directive 2015, and Directive 2018). On 14 July 2021, the European Commission adopted the EU’s “Fit for 55” package. In order to achieve climate neutrality by 2050, a 90% reduction in overall transport emissions is needed. Four of the ten proposals of that package are directly related to maritime. Two of the four are as follows:

- Revision of *the EU’s Emission Trading System* (ETS) which the European Commission proposes to gradually extend to the maritime sector over the period 2023-2025;
- *FuelEU Maritime* aims to stimulate the production and use of low or zero-carbon, sustainable fuels.

The target reflects the fleet GHG emission and energy used onboard by ships in 2020 and reduced by the following percentages: 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045 and 75% by 2050.

The other proposals (plans) are:

- A proposition of tax on bunker fuels (a minimum 0.9€ per GJ from 1 January 2023) for intra-European maritime voyages with the exemption of ammonia and advanced biofuels;
- Support the use of clean fuels at birth, requires to ensure a shore-side electricity supply for sea-going container and passenger vessels in maritime ports by 1 January 2030;
- Member States are required to ensure that an appropriate number of refuelling points for LNG are put in place at TEN-T core maritime ports by 1 January 2025.

The last requirement poses financial severe risks related to investments in the LNG bunkering network in ports in the context of the possible recognition of LNG as transient fuel with the possibility of its use as a marine fuel for only 10-20 years.

## **6. Environment effect of liquefied natural gas as a marine fuel. Is LNG a transient fuel?**

More than 100,000 ships are in service in international shipping. In 2020, alternative fuels were used on 169 LNG-fueled, ten methanol-fueled, 12 LPG-fueled and two ethane-fueled vessels in operation worldwide, which is about 0.2% of the world's fleet.

For this reason, changes in the emission of harmful substances into the atmosphere from maritime transport are negligibly small.

Fuels carry energy in a condensed, safe, ready-to-use form. In 2020, the demand for marine fuels (heavy fuel oil HFO and marine diesel oil MDO) was about 370 million tons. With the same demand for the energy contained in marine fuels as in 2020 (Herdzik 2021), it would be necessary to have as equivalent: 324 million tons of LNG, 338 million tons of LPG, 777 million tons of methanol, 600 million tons of ethanol and 835 million tons of ammonia. Global ammonia production in 2020 was about 144 million tons (38 million tons in China). It is produced mainly from natural gas. Carbon dioxide emission from ammonia production accounts for about 1% of global emissions!

Liquefied natural gas seems to be an attractive marine fuel which decreases carbon dioxide emission by up to 30%, counting only the direct emission from an engine (MAN 2013, PRS 2021, Stenersen & Thonstad 2017). Even if methane leaks (slip) in engines are significantly reduced, this gas will still leak into the atmosphere from its extraction, processing, storage and transport (Ocktaeck &

Sangijn 2021). It is possible to reduce these leaks, but it requires new technologies and financial outlays that will have to be incurred in the event of the introduction of international regulations in this matter. An estimate of the current situation is given in Table 2. It presents the variation in emissions of individual pollutants (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, black carbon – BC) expressed in grams per gram of fuel burned.

**Table 2.** Well-to-wake emission factors for each pollutant (EF<sub>WTW</sub>) and associated carbon dioxide equivalent factors (CEF<sub>WTW</sub>) (elaborated on a base: Comer & Osipova 2021)

Fuel type	Engine type	Well-to-wake [g/g fuel]					
		EF <sub>WTW</sub>				CEF <sub>WTW</sub>	
		CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	BC	CO <sub>2e100</sub>	CO <sub>2e20</sub>
HFO	Slow speed DE	3.545	0.00404	0.00018	0.00019	3.915	4.553
	Medium speed DE	3.545	0.00404	0.00017	0.00049	4.182	5.510
MDO/ MGO	Slow speed DE	3.734	0.00453	0.00019	0.00019	4.124	4.787
	Medium speed DE	3.734	0.00453	0.00018	0.00049	4.391	5.744
LNG	Otto-SS DE	3.280	0.05336	0.00014	0.00002	5.259	8.023
	Otto-SS DE – crankcase	3.280	0.05977	0.00014	0.00002	5.490	8.580
	Otto-MS DE	3.280	0.03499	0.00014	0.00002	4.600	6.427
	Otto-MS DE – crankcase	3.280	0.04175	0.00014	0.00002	4.844	7.015
	Diesel	3.280	0.01958	0.00023	0.00001	4.063	5.077
	LBSI*	3.280	0.04438	0.00014	0.00002	4.936	7.242
	LBSI* – crankcase	3.280	0.05079	0.00014	0.00002	5.167	7.799

\* LBSI – low burn spark engine;

DE – diesel engine.

It appears from Table 2 that the best environmental marine fuels (the lowest factor CEF<sub>WTW</sub>) are currently used. For new types of marine fuels, new technologies that reduce emissions to the environment (atmosphere) in their extraction, processing, storage and transport can significantly improve this condition. This goal should be achieved to justify the reasonableness of introducing new regulations. They cannot be concerned only with the direct combustion of fuel in engines.



Biofuels should be considered very prudently during the assessment of how ecological the fuels are (earlier mentioned a proposal of exemption from emission tax) because they come from various sources and a significant amount of energy is consumed in the production process of the final product, which in current conditions means emissions into the atmosphere, which should be taken into account when assessing the environmental performance of fuels (Biernat et al. 2021, DNV GL 2018).

Due to the carbon dioxide emission reduction targets (over 30%), LNG will be a transient fuel in maritime transport. Therefore, the reasonableness of building port infrastructure in terms of LNG bunkering on ships is being called into question. As a result, attempts are being made to design the LNG distribution network for other purposes: fueling a power plant or combined power and heat plant, for port infrastructure demand, supplying methane for chemical processes etc. (ECOFYS 2019, Hamelinck et al. 2019).

This article does not analyse the use of hydrogen as a marine fuel (only emission factors are given in Table 1). However, it seems to be the fuel of the future (beyond 2050). Therefore, it will be of great importance to which processes hydrogen is obtained and the impact on the environment until the final product is delivered to the fuel tank on the ship.

## **6. Final remarks**

Reducing the harmful substances emission into the atmosphere forced the search for greener marine fuels. Thirty years ago, it seemed that the era of natural gas would come. It is coming with a long delay, and as a result, it will not happen.

It seems that liquefied natural gas will be a marine fuel of significant importance, with a share, in the fuel market, at the level of 30-50% over the next twenty years. In the coming years, many fuels will be used, and the share of one fuel in the market will not dominate. There will be a move away from fuels derived from crude oil and other fossil fuels. It will be of great importance to what extent the electricity used in creating new fuels will be green. Regulations on the reduction of carbon dioxide emissions must lead to the process of its slow withdrawal after 2035. LNG as a marine fuel is temporary, and it is a typical *cul-de-sac*. LNG will continue to be used, but its share in the marine fuel market will decrease.

We have to wait for the hydrogen era.

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