Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-36809
www.engineeringscience.rs

Journal of Applied Engineering Science
Vol. 20, No. 4, 2022
Original Scientific Paper
Paper number: 20(2022)4, 1017, 1122-1132

ANALYSIS OF LNG CARRIER PROPULSION DEVELOPMENTS

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The LNG market has undergone major changes and significant development in recent years. With the increase in the number of ships and the increase in the amount of gas transported, the propulsion machinery of LNG ships has also changed. For many years, the steam turbine was the only propulsion engine on this type of cargo ship. A negligible number of vessels powered by a traditional, low-speed, heavy-duty diesel engines are increasingly being replaced by new technologies. Versions of dual-fuel internal combustion engines that burn evaporated natural gas are increasingly replacing steam turbine propulsion systems. This phenomenon has been particularly pronounced in the last few years, when orders for steam turbine-powered LNG vessels have ceased. This article examines and presents the main reasons for these changes, which fall into two categories. The first is financial, as the use of new technologies can lead to significant financial savings in fuel consumption. Fuel costs can be reduced by more than 35% in some cases. The reduction in fuel consumption leads to a significant reduction in overall exhaust emissions and thus a reduction in air pollution and CO_2 signature.

Keywords: LNG fleet, LNG ships, ship propulsion, air emission, fuel consumption

1 INTRODUCTION

More than a decade ago, Gkonis and Psaraftis pointed out: "The Liquefied Natural Gas (LNG) trade is one of the most promising sectors in energy shipping. It is expected that competition will increasingly develop in the shipping segment of the LNG chain" [1]. That research is one of the many studies conducted at that time on various aspects of the LNG trade [2, 3, 4]. Along with the research on LNG trade, LNG ship propulsion and future developments were also studied [5, 6]. Most of these analyses and predictions were not entirely reliable. The best commentary on these predictions came from Stanivuk et al. who wrote that "predictions of the LNG trade volume can be difficult; they depend on a multitude of factors and the market behaviour in the analyzed period" [7]. At the same time, the mentioned recent study analysed the LNG market growth in the past and made forecasts for the near future (Figure 1.).

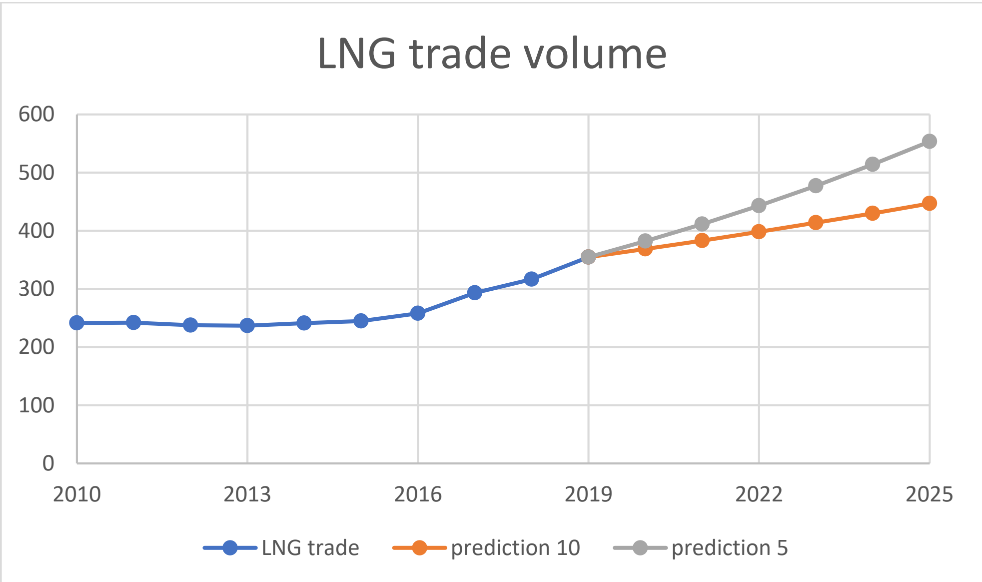
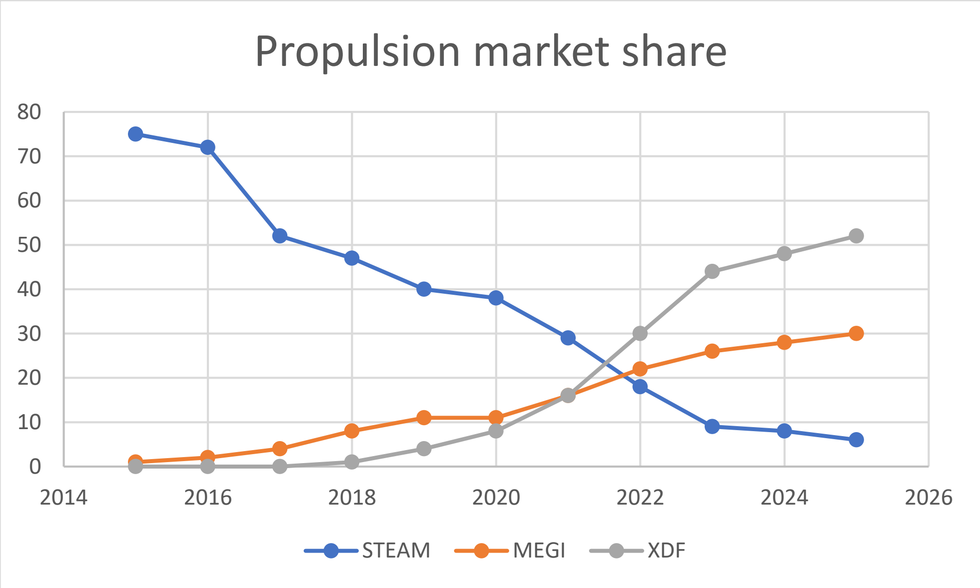


Fig. 1. LNG trade volume per annum in million tons [7]

One of the factors affecting LNG trade is the price of gas on the world market. According to many authors, this price is volatile [8, 9]. Trade itself is behaving erratically. During the period from 2010 to 2015, there was almost no increase in annual LNG trade while after this period there was a rapid expansion of the trade, averaging more than 8.2% annually [7].

Predictions for the future again vary, depending on the author and the methodology used. Ruszel [10] is very optimistic in his forecasts, predicting an average growth of 8% per year for the LNG trade. Meza et al. [11] gave a more conservative prediction of an increase of 3 to 4% per year. The majority of papers predict values that fall between these values, such as the work published by Liu et al [12] and Meza et al [11]. The growth of the LNG market is driving up costs, forcing both manufacturers and ship owners even more to optimize ship propulsion, as seen in Figure 2. [7].



STEAM - Steam turbine,
MEGI - M-type, Electronically Controlled Gas Injection engine,
XDF - Low-pressure gas injection engine.

Fig. 2. Comparison of most common LNG fleet propulsion systems [7]

The keyword and the technical process closely associated with the LNG carrier fleet are the so-called boil-off gases (BOG), gases produced during the evaporation of the liquefied gas stored in the cargo tanks. The imperfection of insulation layers attached to the boundaries of the cargo tanks is one of the reasons for commercial and technical issues in the selection of different types of propulsion. In addition to BOG gases, the driving force for the development of LNG propulsion engines are stricter NOx emission limits, the Energy Efficiency Design Index (EEDI), and the desire for flexible, efficient propulsion systems that meet various operating conditions [13, 14]. Table 1. shows the propulsion options and efficiency comparison of today's LNG fleet [13].

Table 1. Propulsion options and efficiency comparison on LNG fleet [13]

Propulsion options	ST		DFDE		SSDR		LSDF	
THERMAL EFFICIENCY OF ENGINES & TRANSMISSION EFFICIENCY OF COMPONENTS	Fuel/BOG	1.00	Fuel/BOG	1.00	Fuel/BOG	1.00	Fuel/BOG	1.00
	Boiler	0.88	DF engine	0.45	2-stroke engine	0.50	2-stroke DF engine (HP/LP)	0.50/ 0.49
	Steam turbine CST/UST	0.35/ 0.41	Alternators	0.97	Shafting	0.99	Shafting	0.99
			Convertors	0.98	Re-liquefaction			
	Gearbox	0.98	E-Motors	0.96				
	Shafting	0.99	Gearbox	0.98				
			Shafting	0.99				
TOTAL EFFICIENCY	CST 30% / UST 35%		40%		40%		HP 49% / LP 48%	

ST - Steam turbine,
DFDE - Dual fuel diesel-electric
SSDR - Slow speed diesel engine with reliquefaction unit
SSDR - Slow speed diesel engine with reliquefaction unit

The design of the propulsion system of LNG ships at the turn of the century was mainly a steam turbine at BOG [15]. The share of other types of propulsion was minimal [16].

The design of the LNG vessel propulsion system at the turn of the century was mostly a steam turbine at BOG. The share of other types of propulsion was minimal [16]. The dominance of steam turbine propulsion ended in the new LNG carrier fleet in the mid-2000s [17]. The cause of this change is attributed to the need to develop larger LNG carriers. As the volume of the ship's tanks increases, BOG also increases and the volume becomes too large for the actual energy demand (and consumption), so the remaining volume has to be directed back into the cargo tanks.

To decrease the fuel consumption of these larger LNG carriers (Table 1.), a slow-speed Diesel engine (SSD) was introduced as a more economical option than the steam turbine plant (the turbine plant has an efficiency of about

35% [18, 19]). SSD is starting to be a relevant propulsion option coupled with a reliquefaction plant intended for BOG to be reintroduced into cargo tanks [20]. SSD, which runs on either heavy fuel oil or diesel oil, is the engine without the ability to burn boil-off gases. This allowed LNG carriers to increase in size and led to the gradual replacement of the steam turbine plant as the main propulsion mode for LNG carriers in the beginning of the century [16, 17].

Further developments in this area are caused by the development of engines capable of burning both fuels, evaporated BOG gas and diesel oil, in the same engine package [17]. Modernization of dual-fuel engines or DFDE has been intensified in the late 2000th and especially since 2010. Today, dual-fuel diesel engines with high-pressure gas injection as a product of MAN B&W ME-GI (M-type, Electronically Controlled Gas Injection engine) and engines with low-pressure gas injection or X-DF engines developed by the manufacturer WinGD are the most widely used [21, 22, 23].

The propulsion of LNG carriers, fueled by economic and environmental reasons, has gradually changed to newer technologies, introducing better diesel engines and abandoning steam turbines, despite developments in this field [24, 25, 26]. Figure 3. shows the categorization of the propulsion systems of the modern LNG carrier fleet [13], i.e., the propulsion types we find today.

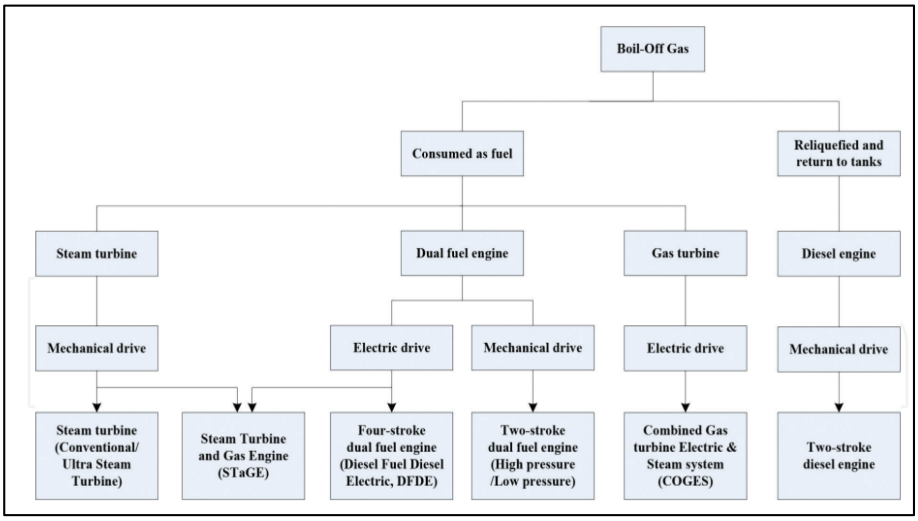


Fig. 3. Categorization tree of propulsion systems on LNG carriers [12]

There are six propulsion systems with their combinations, such as the optimized version of the steam turbine - ultra steam turbine, slow-speed diesel engines with MGO as fuel and installed reliquefaction plant - SSDR, and rare examples of installed hybrid propulsion systems such as combined gas and steam turbine engines - COGES or steam turbine and gas engines - STaGE. Contrary to the claim that the dominance of steam turbine propulsion has ceased in the new LNG carrier fleet built as of 2010, the market share of the different propulsion types in the existing fleet is as shown in Table 2. [7].

Table 2. LNG propulsion types in 2020. market share in percent [7]

Type of ship propulsion	World market share
STEAM	38.00%
MEGI	11.00%
XDF	6.00%
TFDE	14.00%
DFDE	19.00%
SSD	8.00%
S. REHEAT	3.00%
STaGE	1.00%

MEGI – high-pressure gas injected
XDF – low-pressure gas injected
TFDE – tree fuel diesel electric
DFDE – dual fuel diesel electric
SSD – slow-speed diesel engine
S. Reheat – steam thermal reheat
STaGE – hybrid propulsion system consists of steam turbine and electric motor

Despite much research in this area [7, 13, 16, 17, 28, 29], a simple quantification of the benefits of introducing newer technologies on LNG carriers has never been clearly formulated. Many studies and research in this area emphasize the environmental impact of newer technologies [6, 7, 14, 16, 17, 20, 26, 30] without quantifying the overall impact of these changes on the environment. The same situation is repeated when analyzing and comparing the amount of fuel consumed and the related difference in fuel costs.

This article aims to fill these two gaps by examining the differences in the amount of fuel consumed, NOx and CO_2, as well as the differences in associated fuel costs in a scenario where LNG vessels are operated for one year, with propulsion and voyage characteristics listed in Table 3.

Table 3. Calculation characteristics

Propulsion power	20 MW MCR
Fuel type	MGO and LNG
Steaming	250 days
Ports	30
Duration of each maneuvering	6 hrs

2 EMISSION METHODOLOGY ANALYSIS

For the comparison of the factor of exhaust emissions in the propulsion of the LNG fleet, the estimation method described by Trozzi & Vaccaro [31, 32, 33] is used. This method follows the EMEP/EEA air pollutant emission inventory guidebook [34], which provides guidance on estimating emissions from anthropogenic and natural emission sources. With reference to the Tier III standards of IMO Annex VI, this method calculates air pollutant emissions for the relevant propulsion types, taking into account the characteristics mentioned above. According to this method, there are different phases of ship activity, namely navigation, manoeuvring and hotelling. The amount of air pollutants (exhaust gases) emitted by ships is the sum of all three emission amounts. According to the methodology, each individual activity has a different load percentage of the main and auxiliary engines. The load percentages are shown in Table 4.

Table 4. ME and AE load percentages at different ship activity profiles [31]

PHASE	M/E MCR LOAD (%)	M/E OPERATING TIME (%)	A/E MCR LOAD (%)
Cruise	80	100	30
Manoeuvring	20	100	50

The calculation is based on the specific fuel consumption data for a given fuel and engine type given in Table 5.

According to the estimation method described by Trozzi & Vaccaro [31, 32, 33], the total quantity of exhaust gases emission per trip is:

$$E_{trip} = E_{at\ sea} + E_{maneuvering} + E_{hotelling} \tag{1}$$

Since this article is about LNG ship propulsion and exhaust emissions from propulsion engines, all activities in port are not considered in this calculation. Despite this note, it is important to emphasize that other benefits can also be achieved in port. New ships also use the same type of engine in port, which leads to a further decrease in consumption and pollution.

Since the fuel consumptions per phase are known, the emissions of the different pollutants are calculated as a sum for the complete trip according to Equation 2 [36]. In this task, it is assumed that the ship will bunker only MGO fuel that complies with the IMO 2020 Sulphur content regulations. The ships do not have a scrubber installed.

$$E_{trip\ i,j,m} = \Sigma_p \left(FC_{j,m,p} * EF_{i,j,m,p}\right) \tag{2}$$

where is:

E – emission per trip
FC – fuel consumption
EF – emission factor
p – phase/ship activity
i – pollutant
j – engine type
m – fuel type

Table 5. Emission factors and SFOC per activity and fuel type (based on [25, 31, 32, 33, 35, 36])

ENGINE	PHASE	ENGINE TYPE	FUEL TYPE	NOx (kg/tonne)	SFOC (gr/kWh)
Main	Cruise	Gas turbines (GT)	BFO	19.3	305.0
			MDO/MGO	19.0	290.0
		High speed	BFO	57.7	213.0

ENGINE	PHASE	ENGINE TYPE	FUEL TYPE	NOx (kg/tonne)	SFOC (gr/kWh)
		Diesel engine (HSD)	MDO/MGO	57.1	203.0
		Medium speed Diesel engine (MSD)	BFO	63.4	213.0
			MDO/MGO	63.1	203.0
		Slow speed Diesel engine (SSD)	BFO	89.7	195.0
			MDO/MGO	88.6	185.0
			LNG	4.71	136.0 - 140.0
		Steam turbine (ST)	BFO	6.6	305.0
			MDO/MGO	6.6	290.0
	Manoeuvring	Gas turbines	BFO	8.9	336.0
			MDO/MGO	8.8	319.0
		High speed Diesel engine	BFO	39.7	234.0
			MDO/MGO	44.3	223.0
		Medium speed Diesel engine	BFO	46.2	234.0
			MDO/MGO	45.7	223.0
		Slow speed Diesel engine	BFO	65.1	215.0
			MDO/MGO	64.2	204.0
			LNG	4.8	336.0
		Steam turbine	BFO	5.0	319.0
			MDO/MGO	8.9	336.0
Auxiliary	Cruise, Manoeuvring	High speed Diesel engine	BFO	49.4	227.0
			MDO/MGO	48.6	217.0
		Medium speed Diesel engine	BFO	62.5	227.0
			MDO/MGO	62.0	217.0

CO_2 emissions for the calculation are taken from Table 6. Fuel costs are calculated using prices listed by Ship & Bunker [37] at the time of writing this article (early 2022).

Table 6. CO_2 emission of the propulsion engines for different fuels [35]

PROPULSION TYPE	SSD			MSD		HSD		GT		ST	
Fuel type	LNG	MGO	BFO	MGO	BFO	MGO	BFO	MGO	BFO	MGO	BFO
CO_2 (gr/kWh)	435	588	620	645	677	645	677	922	970	922	970

The amount of nitrogen oxide emissions for the specified parameters is calculated using an equation similar to Equation 2.

$$E_{cruising\ i,j,m} = \left(FC_{j,m,} * \ EF_{i,j,m,}\right) \quad (3)$$

where is:

i – pollutant NOx
j – propulsion type SSDR
m – MGO

Fuel oil consumption in tonnes per annual trip is calculated using Equation 4:

$$FOC = c * \mathrm{P} * \mathrm{g} * \mathrm{l} \quad \text{[t/trip]} \quad (4)$$

where:

FOC – fuel oil consumption in tons
c – coefficient of % MCR of propulsion engine power in kW, according to Table 3.
g – specific fuel oil consumption in kg/kWh
l – sailing time in hours

3 PROPULSION OPTIONS ON LNG CARRIER FLEET

3.1 Steam turbine propulsion

Steam turbine propulsion (ST) is considered the basic propulsion option for the LNG carrier fleet. Even today, according to Figure 3, ST plants have a market share of up to 25% according to Figure 3. [7]. although with a strong downward trend due to the development and installation of advanced LSDF (low-speed dual-fuel) engines.

The propulsion plant usually consists of two high-pressure steam boilers as prime movers of two steam turbines with a pressure of 50-70 bar at 520°C of superheated steam, which drive two propeller shafts through the gearbox [38, 39].

Figure 4. shows a common steam propulsion system for LNG carriers, which consists of a steam boiler as the only propulsion engine. In addition to this, medium-speed diesel generators are used for power generation along with turbo generators. Diesel generators on this type of LNG carrier plant provide more redundancy in case the boilers fail.

The introduction of steam turbine plant as the first choice for LNG ship propulsion occurred for two reasons. Steam boiler burners can be easily operated with the excess LNG gases from cargo tanks, with a 0.15% boil off rate (BOR) of the daily cargo capacity with the isolation technology of the time. The second reason is that the HFO price was higher than that of LNG. Therefore, apart from low efficiency, steam turbine remained the main propulsion choice.

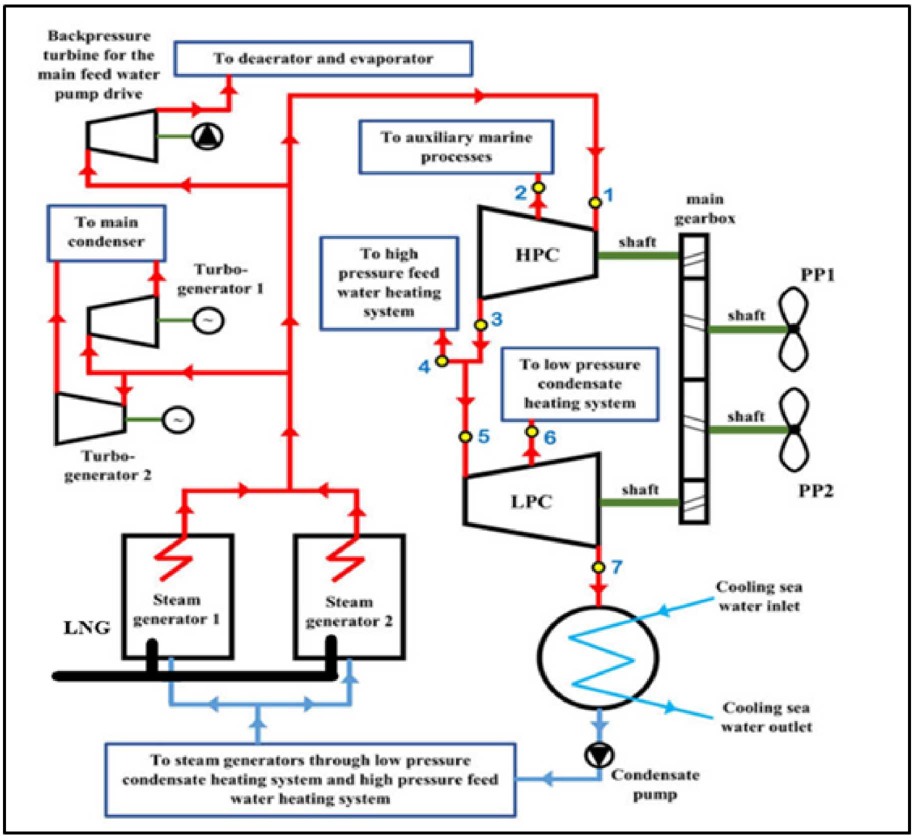


Fig. 4. Steam propulsion plant [38]

3.2 Slow speed two-stroke diesel engine

Figure 5 shows an example of an LNG carrier propulsion plant with two slow speed two-stroke engines for propulsion with a reliquefaction plant (SSDR). The reliquefaction unit, which is used to return BOG into a liquid that is then pumped to the cargo, has a power consumption of 3 - 8 MW. For this purpose, these vessels usually have four medium-speed diesel gensets located in the engine room.

This plant with diesel genset option has several advantages over a plant with ST. The Diesel generator responds excellently to load changes and has a better thermal efficiency of over 50% [22, 40, 41] compared to max 35% efficiency of a steam turbine [42, 43]. The downside of this design is the installation of BOG reliquefaction additional power need to be covered and difficulty in reaching Tier III standard [41].

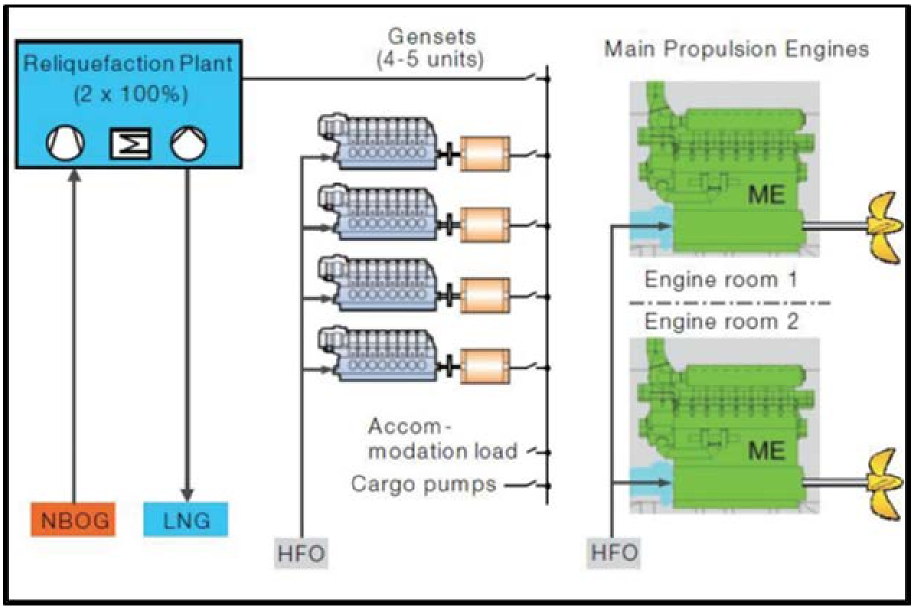


Fig. 5. SSDR propulsion plant with reliquefaction unit [13]

4 MODERN PROPULSION OPTIONS FOR THE LNG FLEET

In the early 2000s, the diesel-electric propulsion solution for the LNG carrier fleet became mainstream in engine development with dual-fuel medium-stroke diesel engines or DFDEs. The first orders for slow-speed two-stroke dual-fuel engines were signed in December 2012 [13]. The timing of the orders coincided with the resolution of the uncontrolled cylinder knocking problem in gas combustion. Both LSDF factories (MAN and Wartsila) have ensured dynamic response regardless of load changes and achieved the highest thermal efficiency with IMO Tier III or at least II emissions standard (Table 7.).

Table 7. Comparison between ME-GI and X-DF engines [13]

	LOW-PRESSURE (WinGD X-DF)	HIGH-PRESSURE (MAN ME-GI)
Power performance	BMEP: 17.3 bar Output approx. 17% lower than the diesel engine equivalent. Dynamic response poorer than a diesel engine	BMEP: 21 bar Output comparable with the diesel engine counterpart Dynamic response comparable with diesel engine
Thermal efficiency	Approx. 47%	Approx. 50%
NOx emission	IMO Tier III	IMO Tier II
CH_4 slip	3 gr/kWh	0.2 gr/kWh
Methane number MN	MN ≥ 65DCC technology	Adapt to various MN
Gas consumption	140 - 142 gr/kWh @ 100%MCR	136 - 138 gr/kWh @100%MCR
Pilot fuel consumption	0.8 gr/kWh @ 100%MCR 2.7 gr/kWh @ 30%MCR	Approx. 50%
Fuel gas supply system	LNG pump: centrifugal pump, with simple structure and low maintenance requirement. Low-pressure gas compressor: a large variety of products, small size and weight, low energy consumption. Low-pressure vaporizer: low cost and mature technology	Low-pressure vaporizer: low cost and mature technology. High-pressure gas compressor: few products, large size and heavyweight, high energy consumption

The most common new engine room design today consists of two LSDF engines driving two propeller shafts independently and 4 DFDE auxiliary 4 cycle engines generating power for the ship's electrical grid.

4.1 ME-GI LSDF propulsion

The solution for an LNG ship propulsion system with ME-GI engines [44] is shown in Figure 6. This is a solution from the largest manufacturer of marine propulsion systems, MAN B&W. The abbreviation ME-GI stands for **M**-type **E**lectronically Controlled **G**as **I**njected engine. These engines are characterized by the fact that the fuel, in this case gas, is injected into the cylinder at a high pressure of 250 - 300 bar together with a minimum quantity of pilot fuel at an injection angle close to the top dead center. This provides a dynamic response similar to the MGO combustion of the slow speed MAN ME -C engine series with Tier II emission standards.

To achieve the Tier III standard, due to difficulties [45], it is necessary to install one of the additional emission treatment solutions such as EGR, exhaust gas recirculation, or SCR (selective catalytic reduction). Accordingly, MAN has recently developed a low-pressure engine ME-GA a gas admission engine that solves these problems and approaches the performance of the main rival X-DF engine.

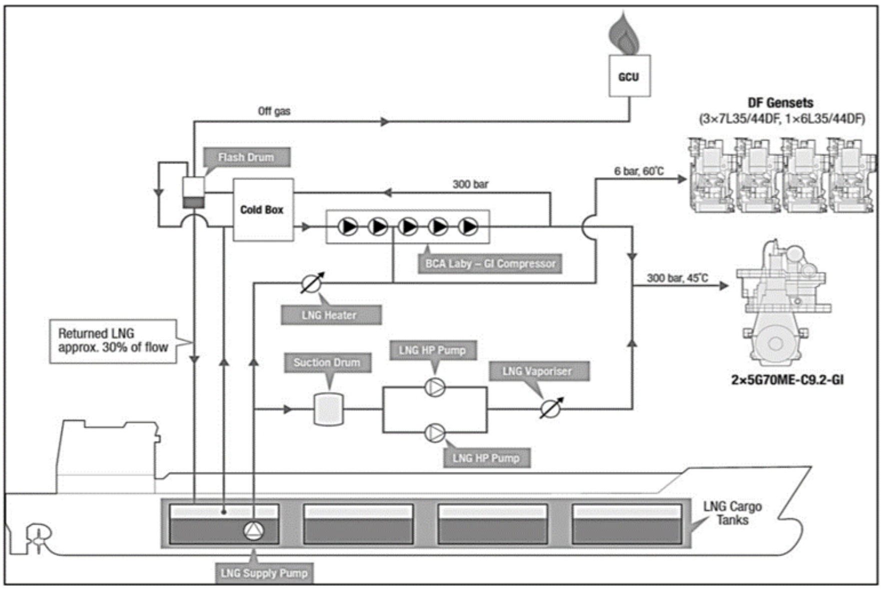


Fig. 6. LNG ship propulsion plant with ME-GI engines solution [44]

4.2 X - DF LSDF propulsion

Due to the increasing demand for low-speed dual-fuel engines [27], the WinGD factory developed a low-pressure injection with a high air-fuel ratio fuel in the cylinder. They used a well-proven ex-Sulzer slow-speed engine design, further improved with Wartsila's dual-fuel technology, which burns a lean air-gas mixture in the Otto cycle, injected mid-stroke in gas mode, with a small amount of diesel pilot fuel injected in the cylinder for ignition at TDC. WinGD delivered its first X-DF engine in 2017. Figure 7. shows the design of the X-DF engine propulsion system.

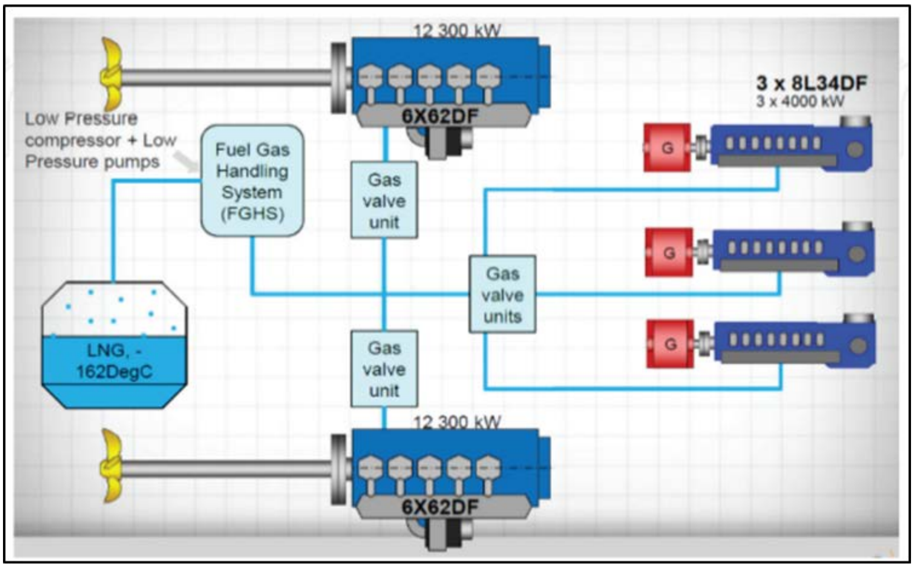


Fig. 7. LNG ship propulsion plant with X-DF engines solution [13]

Thanks to advanced technology, X-DF is Tier III compliant without the need for an expensive emission control process [45, 46] such as a scrubber or SCR system, as shown in Table 7.

5 CALCULATION RESULTS

Financial gain is certainly the most important incentive for any change. The changes that are taking place in LNG carrier propulsion engines and the introduction of other fuel types also depend on the same reasons [13. 47, 48]. Table 8. shows the financial benefits of introducing the new technologies, calculated according to Equation 4 and the data from Tables 3 and 4. Fuel and gas prices are taken from Ship & Bunker [37] at the beginning of 2022. When analyzing the results in Table 8, it is important to note that due to the new conditions on the market (caused by the war in Ukraine), all prices have increased, resulting in even greater savings.

Table 8. Yearly fuel consumption and financial incentive calculation

	ST	SSDR	LSDF ME-GI	LSDF X-DF
FOC (ton)	27 850	17 760	13 050	13 450
FO cost ($)	24 675 100	15 735 360	11 562 300	11 916 700
Savings	**-**	**8 939 740**	**13 112 800**	**12 758 400**

Next in line are environmental reasons as an incentive to purchase more technologically advanced engines. Calculations of the estimated air emissions of the propulsion engines, carried out according to the methodology developed by Trozzi and Vaccaro [31, 32, 33], clearly confirm this assertion. The results were calculated for the ship with the characteristics given in Table 3. The results are presented in Table 9.

Table 9. Yearly air pollutant emission calculation

	ST	SSDR	LSDF ME-GI	LSDF X-DF
NOx (ton)	183.8	1573.5	61.5	63.8
CO_2 (ton)	88 512	56 448	41 773	43 047
Difference	-	32 064	46 739	45 465

The comparison of propulsion solutions shows that the ST propulsion system has 13 times lower NOx emissions compared to SSDR. At the same time, it lags significantly in the economic criteria, as the thermal efficiency is much lower. Despite the simplicity and reliability of the ST system, fuel oil consumption and associated costs have caused the demise of the steam turbine as a propulsion option for LNG vessels. On the other hand, according to Table 2. the steam turbine is still the most common propulsion device, found on 38% of the ships, even if they are older.

Environmental concerns and economic advantages have led to the latest developments and the switch to the ME-GI or X-DF concept, which has a better NOx signature than the steam turbine and lower fuel costs than SSDR.

6 CONCLUSION

The analysis presented in this article and, in particular, the results of the calculations in Table 8. define precisely the reasons why the steam turbine is being used less and less as a propulsion engine on LNG ships. The advantages are obvious and can be expressed in financial terms and in the reduction of environmental impact. The initial switch from steam turbine to diesel engine was clearly due to financial benefits. The fuel cost for the slow-speed diesel engine with reliquefaction unit was 36.2% lower than the cost for the steam turbine, resulting in very large savings, calculated to an amount of almost 9 000 000 $ annually. It is important to emphasize that the calculation was done for a propulsion system of 20,000 kW, which until recently was considered an average size. As the size of LNG carriers continues to increase, as does the propulsion power, the annual savings will consequently increase.

Although this analysis ignored some of the advantages of steam turbine propulsion systems (such as purchase and maintenance costs and easier adaptation to fuel use with the right specifications, etc.), the financial advantage of switching propulsion systems is too great compared to the benefits. These developments reduced the CO2 signature of the prime movers (due to lower FO consumption), but at the same time caused an 850% increase in NOx emissions.

Despite the enormous financial benefits and the widespread belief that money makes the world go round, environmental common sense has emerged in recent years as the most important aspect of marine fleet management and the main driving force behind recent innovations in the field. New engines produced by WinGD and MAN B&W as leading manufacturers create only 4% of NOx compared to SSDR. Comparing the NOx emissions of these engines to those of a steam turbine, there is a large reduction of about 66%. Financial benefits, although also very large (up to 25% compared to SSDR), are a close second as an incentive for improvement.

As the first newly developed engines, those from MAN ME-GI with advanced cryogenic gas processing technology, providing fuel at pressures up to 300 bar, are currently leading the market for new propulsion solutions. The later-developed WinGD X-DF has a combined diesel and Otto cycle with a lean fuel mixture injected at low pressure. Due to the high air to fuel ratio and lower combustion temperatures, the X-DF engines achieve Tier III emissions standards and do not require exhaust aftertreatment with additional SCR or scrubbers.

Despite the very large improvements that have been achieved, the use of LNG as a fuel should be considered as a transitional phase from high carbon fuels to future fuels that will meet the UN 2015 Paris Agreement of a net zero strategy by 2050.

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Paper submitted: 06.03.2022.

Paper accepted: 23.05.2022.