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DFDE and Steam Turbine Propulsion System, Energy Efficiency Operational Index comparison on board LNG Carrier

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ABSTRACT

The strong world demand for energy has increased the need for Floating Storage Re-gasification Unit (FSRU) and terminals. Due to geopolitical tensions, it is predicted that large volumes of liquefied natural gas (LNG) will be transported during the coming years, which leads to an increase in the number and size of LNG Carriers. In that context, the fourth GHG of IMO made an emphasis on environmental issues with respect to air emissions. Traditionally for LNG Carriers, the propulsion efficiency of the steam turbine propulsion system can only achieve 30%, the DFDE propulsion system exceeds 42% for an LNG Carrier; this represents a reduction of 1/3 of fuel consumption impacting the overall energy efficiency. In addition, the flexibility of electric propulsion increases the reserved volume to the cargo. The present paper provides the case study of an Algerian maritime company first Dual Fuel Diesel Electric LNG Carrier. To demonstrate the energy efficiency of the DFDE Propulsion system, a comparison between two LNG Carriers with approximately the same principal dimensions are carried out. The study reveals that the DFDE propulsion system for LNG Carrier reached an optimized Energy Efficiency Operator Index (EEOI), compared to LNG Carrier fitted with steam turbine propulsion system over the same voyage profile.

1. Introduction.

The LNG carriers are under scrutiny as they resume the rapid and profound change in novel propulsion systems and larger size, in order to fulfill the market trends of the LNG shipping industry in particular and energy demand in general.

To respond to emissions restrictions from ship's, in 2010, the two-stroke dual fuel technology has been introduced in LNG carriers [1], with both the high pressure and low pressure gas injection technology, but considering the methane slip condition occurred in low pressure configuration [2], the DFDE became a popular propulsion system choice for LNG carriers.

The number of LNG carriers has considerably increased in the last twenty years, these vessels have been propelled by installations based on boilers and steam turbines. The phase out of the steam turbine begins in 2010, for a more efficient propulsion system based on diesel engines. The Algerian Shipping Company proceeds to the transition to the Dual Fuel Diesel Electric on its vessels at the beginning of 2016.

Is noted that Gazoecan is the initial operator of the first three DFDE LNG carriers delivered from 2006 to 2007 [3]. In November 2008, the first DFDE Japan LNG tanker flinched its gas trial test and it is delivered in January 2009, built by Mitsubishi Shipbuilding Co. Ltd for MISC Berhad [4]. It should be noted that among 539 existing LNG carriers, there are 258 equipped with steam turbine propulsion system (47%) and 174 equipped with a DFDE propulsion system (32.28%) [5]. Not all

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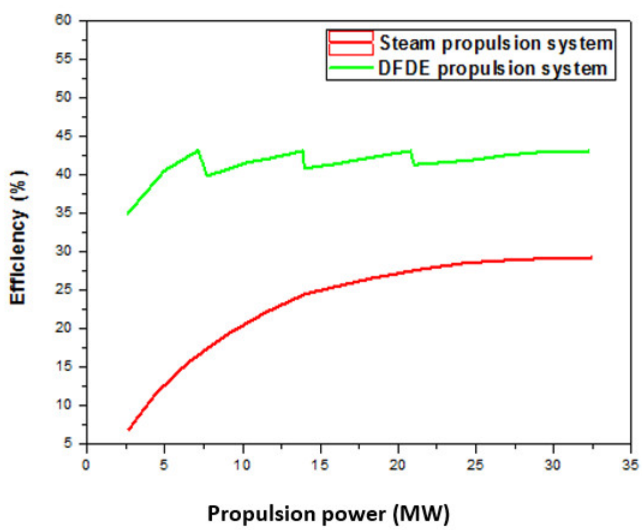
LNG Carriers are fitted with the DFDE propulsion system; for example, some LNG carriers of 260 000 m3 capacity, which is the case of Qatar gas Company are equipped with a two-stroke diesel engine propulsion system and reliquefication plants.

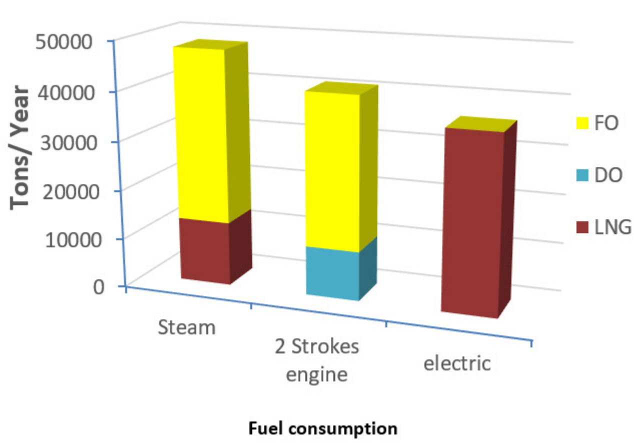
Figures 1 and 2 show, respectively the efficiency of both DFDE and steam turbine propulsion systems and the fuel consumption per year of the three propulsion system types [6].

Figure 1: Efficiency of DFDE and steam turbine propulsion systems.



Source: Authors.

Figure 2: Fuel consumption per year of the three propulsion systems.



Source: Authors.

Emissions produced by ships are regulated by Annex VI to the MARPOL Convention [7]. July 2011 was an important day, in which comes into force from then international maritime organization (IMO) MEPC 213(63) [8] and amended by MEPC 245(66) [9], where the Ship energy efficiency management plan (SEEMP) was mandatory by the introduction of EEDI for newly built ships and EEOI for existing vessels in order to reduce CO_2 emissions, this requirement applies to ships of 400 gross tonnages and above. The purpose of a SEEMP is a management tool that will establish a mechanism for ships to improve their energy efficiency.

Representing 80% of world global trade volumes [10, 11], the international ship transport is an active and growing economic sector over the last year's impact of the shipping industry on the environment, is the main concern of various stakeholders directly linked to this sector.

A number of initiatives have emerged from institutions, different shipping companies to establish strategies in order to quantify and consider this impact. The IMO established a global framework for assessing and estimate ship's emission, we will focus on the last report, The Fourth IMO GHG Study [12] which is a result of the Initial IMO Strategy on reduction of greenhouse gas (GHG) emissions [13] from ships2018 under which IMO Member States have pledged to cut emissions from international shipping and to phase them out as soon as possible.

The new study estimates that total shipping emitted 1,076 million tons of CO_2 in 2018 [12], accounting for about 2.89% of the total global anthropogenic CO_2 emissions for that year. Total shipping emissions in 2018 increased from 977 million tons seen in 2012.

Despite this low impact if compared with other industrial sectors, the shipping industry frequently comes under fire for its greenhouse gas contributions, the changes and milestones already achieved by companies and organizations in reducing its impact should be noted. IMO has been actively engaged in a global approach to further enhance ship's energy efficiency and develop measures to reduce GHG emissions from ships, as well as provide technical cooperation and capacity-building activities.

IMO strategy in line with the Paris climate agreement COP 21 [14], shifted towards the option of green shipping based on the concept of sustainable development applied to the shipping sector, incorporating environmental and social responsibility, The objective is that, in the coming years, vessels are greener and shipping carbon footprint is zero.

From different experts' point of view, when discussing short-term measures, the figure over the next 10 years will bring the shipping carbon intensity reduction in 2030 to more than 40%, below the year 2008. This is a remarkable achievement by a sector that is, and will remain, the most efficient mode of transportation. The decarbonization of this sector in the short term would be possible by 2030.

The first inventory of possible solutions already adopted is as follows:

1. Primary techniques, which modify the combustion process, such as water injection, slide valves, slow steaming.
2. New propulsion systems, or switch the fuel, commonly bunker fuel oil, for distillate fuels, LNG or alternative fuels (methanol, biofuels, ammonia, hydrogen, etc.).
3. Secondary measures, which are exhaust gas treatment systems such as exhaust gas recirculation, waste heat recovery, selective catalytic reduction systems, scrubbers or

diesel particle filters.

4. Measures applicable in ports, such as shore-power supply system or shore-based exhaust cleaning systems.
5. Scrubbers and switches to lower Sulphur fuels such as marine distillate fuels (diesel or gas oil), LNG or methanol are efficient techniques to tackle SO2 emissions.
6. A switch to LNG and the implementation of SCR are effective means to reduce NOx emissions, followed by EGR.
7. Improving energy efficiency and moving to alternative non-fossil fuels and new emerging propulsion systems would also effectively reduce both air pollutant and greenhouse gas emissions.
8. On-shore power supply system at berth can reduce significantly the emissions of pollutants and GHG from ships during hoteling. Shore- or barge-based exhaust gas cleaning systems also provide.

Each solution goes through a strict assessment process, in our case; we will consider different scenarios for alternative fuels. The large spectrum of this alternative fuels which include Electricity, Hydrogen, natural gas and bio-methane, Bio-based fuels, Synthetic and paraffinic fuels, including HVO, bio-LPG, bio-methanol, ammonia, some are available others are pending technological evolution.

For the use of alternative fuel, the industry is actively exploring liquid natural gas (LNG), hydrogen and ammonia due to their reduced environmental impact.

Fuels such as LNG offer a very strong option as a positive transition marine fuel. This is due to the fact that they can offer significant reductions in carbon dioxide emissions while still being able to be supplied to the existing infrastructure and burned in current engine setups."

The GHG emissions considered are: CO_2, CH_4, and NO_2 (with Intergovernmental Panel on Climate Change (IPCC) [15] adopted global warming potentials (GWPs)), expressed as CO_2 eq.

The situation for the time being is based on the fact that most fleets have traditionally been powered by the cheaper high-Sulphur heavy fuel oil (HFO). To meet the more stringent Sulphur limits, (low-Sulphur) marine gas oil (LS MGO) and ultra-low Sulphur fuel oil (ULSFO) which are available.

In view of the regulated Sulphur limits, we expects MGO to become the most successful alternative to HFO, for the very short term.

For the vessels with an on-board exhaust, cleaning system (scrubber) installed or on order, with most of them being open loop retrofits. Notwithstanding, Reuters, 2019 recently reported that European ports have started to restrict or ban open loop scrubbers. Beyond fuel-switching and retrofitting strategies, vessel technologies based on alternative fuels are considered as the best option to meet 2030 and 2050 GHG emissions requirements.

Another two aspects to be taken into account while dealing with projections and assessments of GHG emissions, first is the fact that this emissions could be higher than projected when economic growth rates are higher than assumed here or when the reduction in GHG emissions from land-based sectors is less than would be required to limit the global temperature increase to well below 2 degrees centigrade second although it is too early to assess the impact of COVID-19 on emission projections quantitatively, it is clear that emissions in 2020 and 2021 will be significantly lower.

Depending on the recovery trajectory, emissions over the next decades maybe a few percent lower than projected, as in normal conditions and according to a range of plausible long-term economic and energy business-as-usual scenarios, shipping emissions could represent an increase of 90-130% of 2008 emissions by 2050.

In that context, it should be noted that many authors have studied the effect of the SEEMP implementation in the reduction of CO_2 emissions for example:

Hannes et al. [16] have discussed the impact of the application of the SEEMP compared with ISO 50001 and ISM Code for the reduction of the consumption of energy on board vessels' which leads the decrease of CO_2 emissions.

Also, it should be noted that vessels which keels laid after 30 June 2013 or delivered after 30 June 2015 must have EEDI technical file; this document must be elaborated by shipyard and approved by ship classification society in accordance with MEPC.245(66) (guidelines for the calculation of EEDI). 2017 is a very important date with the entering in force of the MRV regulation EU (2016/2017) [17].

Many authors carried out investigations about propulsion system for LNG carrier; R.P. Sinha et al. [18] made a comparison between steam turbine, DFDE and 2 strokes diesel engine as propulsion system for LNG carriers in terms of fuel consumption, gas emission, maintenance coast and spare parts, authors conclude its difficult for ship owner to choose which propulsion system is efficient for LNG carriers due to nature of chart supplier and gas receiver, for example spot voyage or long term chart (more than 20 years).Tu Huan et al. [19] investigated the difference between several propulsion systems of LNG carriers; steam turbine, DFDE, slow speed DFDE propulsion system, and combined gas turbine & steam system. In this study a comparison was carried out in terms of fuel consumption, emission standard compliance and BOG treatment. Authors conclude that the choice of the propulsion plant for LNG carrier is directly influenced by vessel size, trade made (spot, time charter. . .), type of fuel and BOG (natural or forced), maintenance coast and regulation compliance in term of CO_2 emissions (MARPOL Annex XI). The vessels emissions include greenhouse gas, CO_2, NOx and SOx. It is very important to notify that the two last mentioned gases depend on fuel and engine types. These gases have a local impact and their control depends on specific areas (ECA zones) [20].

S. Grzesiak [21] conducted a comparison study of propulsion plants for LNG tanker with a capacity exceeding 65 000 m3 in terms of efficiency, environmental effect and rehabilitee. In this paper the author, choose three propulsion systems among which DFDE/TFDE, Steam and two-stroke diesel engine, the author concludes that DFDE/TFDE propulsion system is the favorite for operators and ship owners. K. Dedes et al. [22] studied the influence of the implementation of hybrid battery diesel electric as propulsion system for dry bulk carriers on the ship emissions (SOx, NOx and CO_2); the research is based on operating record for fleet, which contain all bulk carrier categories. The purpose is to reduce gas emissions by minimizing fuel oil consumption using hybrid battery diesel propulsion system. The results show that gas emissions were reduced by 14% for bulk carriers and 1.8% for all world vessel emissions.

In that aspect and for environmental consideration, the need to reduce the EEOI became very important. In this paper, we will make a comparison between two existing ships with different propulsion systems (DFDE & Steam Turbine) and see which of them is a performance in terms of energy efficiency.

Why Dual Fuel Diesel Electric Propulsion system on LNG Carriers ?:

This type of propulsion provides more advantages such as:

- Reducing the size of the engine room;
- Increasing cargo capacity;
- Reducing fuel consumption by 30%;
- Optimum adaptation to all mode of speeds;
- Opening to the spot markets;
- Redundancy superior to steam turbine propulsion system (4 diesel motors instead of 2 boilers);
- Modern technology;
- Pollution divided at least by two;
- Opening up to pods LNG Carriers.

However, there are also a few disadvantages:

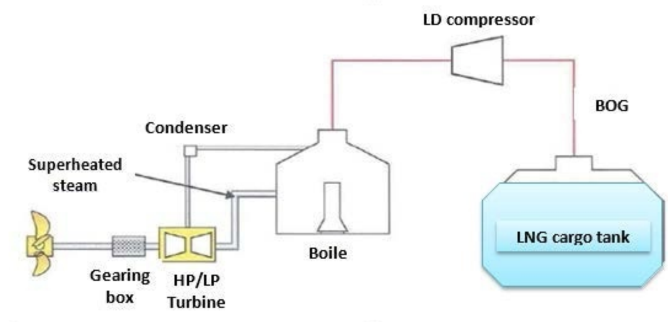
- Steam turbines have proven to be very reliable over time, more reliable than diesel engines;
- Steam turbine plants need less maintenance than diesel;
- Diesel engines have higher lube oil consumption than steam turbines;
- Electric driven vessels need additional equipment to handle excess boil-off gas;
- Steam turbines are very flexible in terms of fuel types and fuel mixing ratios, whereas dual fuel diesel engines operate either in gas mode or in diesel mode.

2. Steam turbine propulsion system.

Traditional steam turbine propulsion plants operate at 60 to 70 bar pressure and 520°C superheat steam temperature. A typical installation includes two main boilers, both of which can burn fuel oil and BOG to generate superheated steam fed to HP (high pressure) and LP (low-pressure) turbines for propulsion, and two steam turbo-generators for electrical power generation. One conventional 4-stroke diesel generator is normally installed as a standby.

A single-stage centrifugal type low duty (LD) gas compressor is used to supply BOG from the cargo tanks to the boilers. The plant is capable of burning fuel in any combination, such as fuel only, gas only, and any combined ratio of fuel and gas. The installation of two boilers and the steam dump system allows for proper management of tank pressures under the IGC Code [23]. Steam turbine propulsion plants handle excess cargo BOG by dumping surplus steam to the seawater-cooled condenser in the engine room. Any shortfall of natural BOG can be replaced by forced gas (through a vaporizer) or fuel oil [24].

Figure 3: Simplified steam turbine propulsion plant overview.



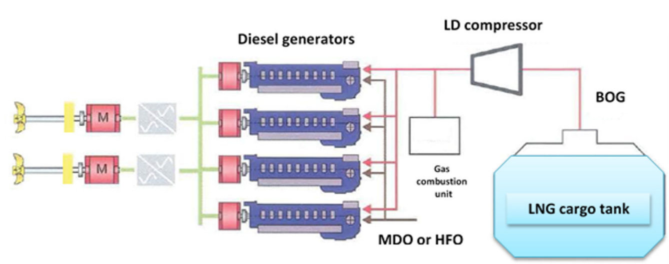
Source: Authors.

3. DFDE ship propulsion system.

DFDE propulsion used multiple engines of the same type, usually four engines, coupled to electrical generators to supply power to the entire vessel including the main propulsion, which is driven by two electric motors.

DFDE vessels can operate on the BOG, MDO, and HFO. When operating on Gas, MDO is required as pilot fuel. If excess BOG available than the power required for the propulsion or electric load, then this excess BOG is sent to the gas combustion unit (GCU).

Figure 4: Simplified dual fuel propulsion plant overview.



Source: Authors.

4. Sea trial of the dual fuel and Steam turbine LNG Carriers.

The target vessels equipped with the two different propulsion systems mentioned above have approximately the same characteristics. First; she is 171866.50 m3 LNG Carrier, where the dual-fuel propulsion system is adopted dealing with the requirements of the ship owner and the second is 145000.00 m3

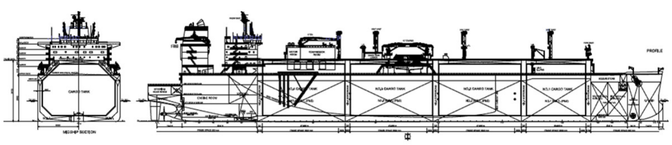
LNG Carrier. The main particular and general arrangement plans are listed below:

Table 1: Main particulars of LNG carrier with DFDE Propulsion system.

Ship speed	21.000 knots	**Class**	Lloyd's Register
L_{OA}	291.400 m	**Max Displacement**	128 534.5 t
L_{BP}	284.000 m	**Lightship**	33 959.5 t
Max Height from keel	63.800 m	**Deadweight (Summer)**	93 634.0 t
BREADTH MLD	46.400 m	**Gross tonnage // Net tonnage**	112 867 t // 35 325 t
DEPTH MLD	26.400 m	**Suez GRT/Suez NRT**	119 051.58 t // 104 612.87 t
DEPTH (TRUNK)	34.700 m	**Max Propulsion Power**	2×13890 Kw × 72.9 rpm
DRAUGHT (Design)	11.770 m	**Main Engine**	2 Wartsila-Hyundai 12V50DF
Max DRAUGHT	12.621 m		2 Wartsila-Hyundai 8L50DF

Source: Authors.

Figure 5: LNG Carrier with DFDE Propulsion system.



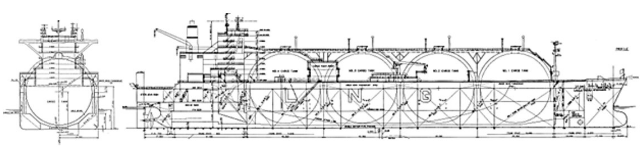
Source: Authors.

Table 2: Main particulars of LNG Carrier with steam turbine.

Ship speed	20.31 knots	**Class**	Bureau Veritas
L_{OA}	289.500 m	**Max Displacement**	110 447.0 t
L_{BP}	277.00 m	**Lightship**	33 100.00 t
Max Height from keel	68.150 m	**Deadweight (Summer)**	77 349 t
BREADTH MLD	49.00 m	**Gross tonnage // Net tonnage**	118 363 t // 35 508 t
DEPTH MLD	27.00 m	**Suez GRT/Suez NRT**	130 681.33 t // 119 273.83 t
DEPTH (TRUNK)	49.00 m	**Max Propulsion Power**	26 900 Kw × 102 rpm
DRAUGHT (Design)	11.900 m	**Main Engine**	2 Boilers
Max DRAUGHT	11.929 m		

Source: Authors.

Figure 6: LNG Carrier with steam turbine.



Source: Authors.

The trial speed curves for both vessels are shown respectively in figure 7 and 8 in accordance with ISO Standard 15016: 2015 [25].

5. Energy Efficiency Operational Index.

The EEOI developed by the IMO provides a tool to calculate CO_2 gas emission to the environment over the useful work done, It can be applied to all ships; new and existing that perform transport work. The unit of EEOI are presented in grams of CO_2 per capacity mile.

It is calculated using the following formula performed in compliance with IMO guidelines (MEPC.1/Circ.684) [26]:

$$\boldsymbol{EEOI = \frac{\sum_J FC_J . C_{Fj}}{m_{cargo} . D}\ [g\ (CO_2)/t.Nm]}$$

Where:

j : Fuel type used;

C_{Fj} **:** Fuel mass to CO_2 mass conversion factor with fuel j ;

FC_j : Mass of consumed fuel j ;

m_{cargo} : Weight of cargo carried (tons) on ship or work done (number of TEU or passengers) or gross tonnes for passengers' ships;

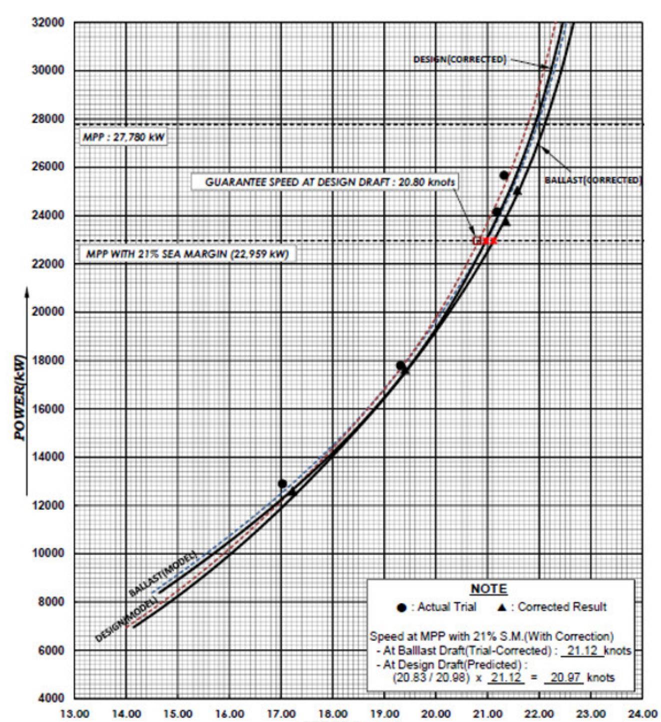
D : Distance of voyage (nautical miles) corresponding to the cargo carried or the work done.

The values of C_Fj are illustrated on the table below:

N°	Fuel type	ISO standard reference	$C_F[t.(CO_2)/t.(fuel)]$
01	MGO/MDO	ISO 8217 Grades DMX through DMC [27]	3.206
02	HFO	ISO 8217 Grades RME through RMK [27]	3.114
03	LNG	Methane MSDS	2.750

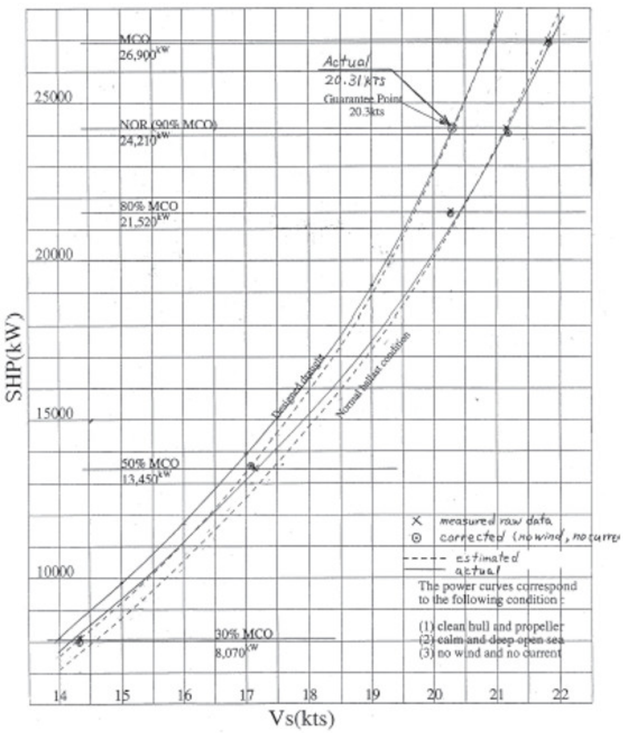
Source: Authors.

Figure 7: Speed trial curve for DFDE.



Source: Authors.

Figure 8: Speed trial curve for steam turbine.



Source: Authors.

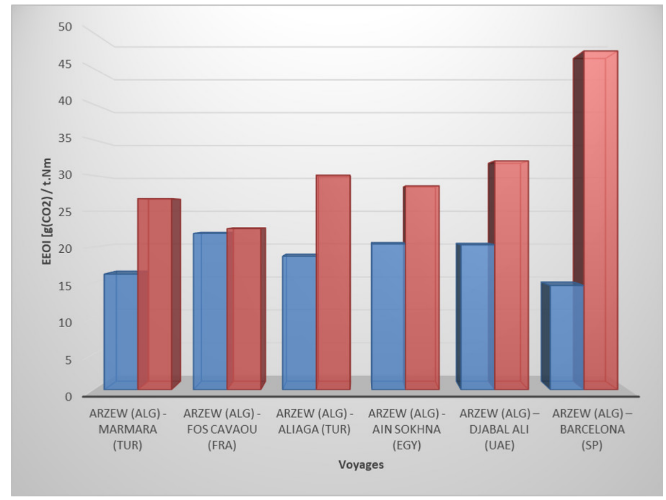
6. Comparison between steam turbine and DFDE propulsion in terms of Energy Efficiency Operational Index EEOI.

The comparison between the LNG carrier with DFDE propulsion system and LNG carrier with a steam turbine in terms of EEOI is shown below (Table 3 & Figure 9) for different voyages. It is clearly shown the value of EEOI for the DFDE propulsion system is less than that of an LNG carrier with a steam turbine.

Voyage profile	EEOI LNG Carrier with DFDE Propulsion system	EEOI LNG Carrier with steam turbine
Arzew (Algeria) - Marmara (Turkey)	16.2	26.77
Arzew (Algeria) - Fos cavaou (France)	21.9	22.56
Arzew (Algeria) - Aliaga (Turkey)	18.7	30.06
Arzew (Algeria) - Ain Sokhna (Egypt)	20.4	28.56
Arzew (Algeria) –Djabal Ali (UAE)	20.3	32.05
Arzew (Algeria) – Barcelona (Spain)	14.6	29.74

Source: Authors.

Figure 9: EEOI for steam and DFDE propulsion system.



Source: Authors.

7. Comparison between steam turbine and DFDE propulsion in terms of estimated index value EIV.

The estimate index value EIV which is a simplified from the EEDI is calculated using IMO resolution ref. MEPC.308(73) **[28]**.

LNG carrier with DFDE propulsion system:
$MPP = 27\ 780\ kW$ (see figure 7)

$$\boldsymbol{EIV = 3,1144 \frac{190.\sum_{i=1}^{NME} P_{MEi} + 215.P_{AE}}{DWT.V_{ref}}}$$

As for LNG Carriers having diesel electric or steam turbine propulsion systems, V_{ref} is the relevant speed at 83% of MPP.
At 83% of MPP=23 057,4 kW

$$V_{ref} = 21,15\ knots$$

$$\boldsymbol{PME = 0,83.\left(\frac{MPP}{\eta}\right)}$$

$$PME = 0,83.\left(\frac{27\ 780}{0,913}\right) = 25\ 254,55\ kW$$

$$for\ vessels\ having\ power\ greater\ than\ 10\ 000\ kW$$

$$\boldsymbol{PAE = \left(0,025\ .\left(\sum_{i=1}^{NME} MCR_{MEi} + \frac{\sum_{i=1}^{NME} P_{PTi}}{0,75}\right)\right) + 250}$$

$$PAE = (0,025.\ (27\ 780 + 0)) + 250 = 944,5\ kW$$

$$DWT = 93\ 634\ t$$

$$\boldsymbol{EIV = 7,88\ g\ CO_2/ton\ \ NM}$$

LNG carrier with steam turbine propulsion system:
Power (kW) of mean engine at 100 % MCR is 26 900 kW :

$$\boldsymbol{EIV = 3,1144 \frac{190.\sum_{i=1}^{NME} P_{MEi} + 215.P_{AE}}{DWT.V_{ref}}}$$

As for LNG carries steam turbine propulsion systems, V_{ref} is the relevant speed at 83% of MCR (see figure 6).

At 83% of MCR= 22 327 kW

$V_{ref} = 20,7\ knots$ (see figure 8)

Steam turbine:

$$\boldsymbol{PME = 0,83.\ MCR}$$

$$PME = 0,83.\ MCR = 22\ 327\ \text{kW}$$

$$\boldsymbol{PAE = \left(0,025\ .\left(\sum_{i=1}^{NME} MCR_{MEi} + \frac{\sum_{i=1}^{NME} P_{PTi}}{0,75}\right)\right) + 250}$$

$$PAE = (0,025.\ (26\ 900 + 0)) + 250 = 922,5\ kW$$

$$DWT = 77\ 349\ t$$

$$\boldsymbol{EIV = 8,64\ g\ CO_2/ton\ \ NM}$$

EIV:

Table 3: Comparison between EIV for both DFDE & Steam turbine.

Propulsion type	EIV $[g\ CO_2/ton\ NM]$
LNG carrier with steam turbine propulsion system	8,64
LNG carrier with DFDE propulsion system	7,88

Source: Authors.

Conclusion.

The results found, demonstrates that the DFDE option in terms of energy efficiency in operational mode are well better than those provided by the steam turbine configuration. As explained for the same voyage profile the average EEOI of DFDE is 18.66 %, those of steam turbine is 28.9%.

In terms of Estimated Index Value (EIV) linked to the design index, it is clear that the DFDE Option will be online with the required values as stated in EEDI Technical file.

Another aspect to consider is the cargo capacity, as when using a DFDE propulsion system, the size of the room machinery is optimized leading to an increase in cargo, for our case study 21%.

Some LNG carrier companies, maintain the use of Steam turbine due to the consequences when steeping towards DFDE engines, lack of training of their crew members, fear of new technology, they consider treatment of the exhaust gas at the exit (scrubber), which can be considered as a temporary solution, regarding the IMO restrictions, retrofitting solutions are available subject to a detailed CAPEX and OPEX studies.

If considering the extension of the LNG option as a fuel bunker for all other commercial vessels, we must consider the availability of Infrastructure for LNG bunkering, procedures for bunkering and other technical aspects; this will be done through an assessment process, taking into consideration the following points:

- Market development.
- LNG production maturity and availability.
- Assessment of results.
- Policy issues waterborne transport.
- Research and innovation.
- Standardization.
- Well-to-tank greenhouse gas (GHG) emissions assessment (life cycle analysis).
- Well-to-tank energy performance maturity of LNG production.
- Well-to-tank costs potential capacity and actual production.

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