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Current Trends in Oceanography and Marine Science

Review Article Curr Trends Oceanogr Mar Sci: CTOMS-104.
DOI: 10.29011/ CTOMS-104. 100004

Review Article

Environmental Comparison and Review of the Alternative Propulsion Options for LNG Carriers

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Citation: Ammar NR (2018) Environmental Comparison and Review of the Alternative Propulsion Options for LNG Carriers. Curr Trends Oceanogr Mar Sci: CTOMS-104. DOI: 10.29011/ CTOMS-104. 100004

Received Date: 25 June, 2018; **Accepted Date:** 04 July, 2018; **Published Date:** 11 July, 2018

Abstract

The current paper reviews the different propulsion options which can be used for LNG carriers. A variety of propulsion derivatives can be used such as gas and steam turbines, combined cycles, 2 and 4 stroke internal combustion engines, as well as liquefaction plants, while encompassing mechanical, electric and Dual Fuel (DF) technology systems. The selection of the suitable propulsion system is the major concern of the LNG carrier shipping industry because of the importance of the propulsion system for the ship capital and life cycle cost. The propulsion systems implemented have undergone continual alteration in order to adjust to market needs, which were always governed by both efficiency and the possibility of consuming Boil-Off Gas (BOG), always in compliance with the strict air pollution regulations. The current direction of LNG vessel propulsion systems is the installation of 2-stroke DF low pressure engines due to their high efficiency and their possibility of installing a BOG re-liquefaction plant. Another great advantage of this propulsion system is its compliance with the IMO TIER III emission regulations, without the need to install any supplementary gas treatment system.

Keywords: Boil-Off Gas; Dual-Fuel Engine; Electric Propulsion; Emission; LNG Carriers; Turbine

Abbreviations

BOG : Boil Off Gas

CODAG: Combined Diesel Engine and Gas Turbine Propulsion

COGAG: Combined Cruising Gas Turbine with Booster Gas Turbine Propulsion

DO : Diesel Oil

HFO : Heavy Fuel Oil

DFDE : Dual Fuel Diesel Electric Engines

GCU : Gas Combustion Unit

LNG : Liquefied Natural Gas

MARPOL: Marine Pollution Prevention Convention

NG : Natural Gas

UST : Ultra Steam Turbine

Introduction

The trend in power generation of shifting away from coal to reduce the adverse effects of CO_2 and other gas emissions on the environment has made steep demand on the supply of natural gas. Because of these developments, natural gas is now the fastest growing energy source and in the last five years, the growth rate in LNG production has been about 60% with the current annual output now touching 260 million tons [1-2].

Liquefied Natural Gas (LNG) commerce is under constant growth owing to its vast demand worldwide [3-5]. Such demand is provided for mainly by maritime transport, which is the main stay of bulk material transportation. To meet current demand, the number of LNG vessels has increased considerably in recent years, both on international markets as well as short-haul sea shipping. The design of LNG vessels is determined by the characteristics of the load, since it is transported in a liquefied state at cryogenic conditions of-163°C, and with a pressure slightly above atmospheric [6-7]. LNG reduces the gas volume by 600 times and has a density of approx. 450 kg/m^3. The LNG is always being refrigerated by means of its boil-off gas and, therefore, the LNG tanks will normally not be completely emptied because some of the LNG still has to cool down the tanks. The classification of this vessel type is carried out according to its design, with the integration of the re-liquefaction plant being the main characteristic, given that the availability of boil-off to be burned in the systems of power generation and propulsion depends on this .Technological developments implemented on LNG vessel propulsion systems is conditioned by factors that are both economic as well as environmental, interlinked by the MARPOL Convention, since the restriction of emissions implies the use of higher quality fuels and hence, an increase in costs [9].There is no standard propulsion system for LNG vessels [10]. After an exhaustive review of works related to LNG vessel propulsion systems, an extensive variety of systems installed on board has been found, ranging from turbines to internal combustion engines with endless variants. There is, however, no work that carries out a comparison of all systems installed. Therefore, the purpose of this review is to study of LNG vessel propulsion systems with environmental comparison, taking into account the latest technological developments in this field.

LNG Carriers and Boil-Off Gas

All liquefied gases carried in bulk must be carried on a gas carrier in accordance with the Gas Code rules of IMO (International Maritime Organization). The gas tankers are constructed according to the double-hull concept, including the bottom areas as a protection against ship grounding incidents. Furthermore, the gas must be carried according to the so-called **"**cargo containment system**"** principle, i.e. the cargo tanks are installed separately in the ship's holds, and are not a part of the ship's structure. The gas tanks (fully refrigerated at atmospheric pressure) used today in LNG carriers as shown in (Figure 1). are normally of the spherical (Moss) type, introduced in 1971, and membrane type, introduced in 1969, and in some few cases of the structural prismatic design. The spherical tanks and tanks of the structural prismatic design are self-supporting and are tied to the main hull structure. The tanks with the membrane wall system are rectangular and fully integrated into the hull and rely on the strength of the ship's hull. The membrane system is based on a very thin primary steel barrier (0.7-1.5 mm membrane of stainless steel alloy) supported through the insulation [11]. Such tanks, therefore, are not self-supporting, but only a relatively small amount of steel has to be cooled. Heat transfer to the LNG from the environment through insulated spaces and holding tanks results in the boiling of the load, with the consequent formation of steam, referred to as Boil-Off Gas (BOG). The greatest production of BOG is generated during cargo transportation [12-15].

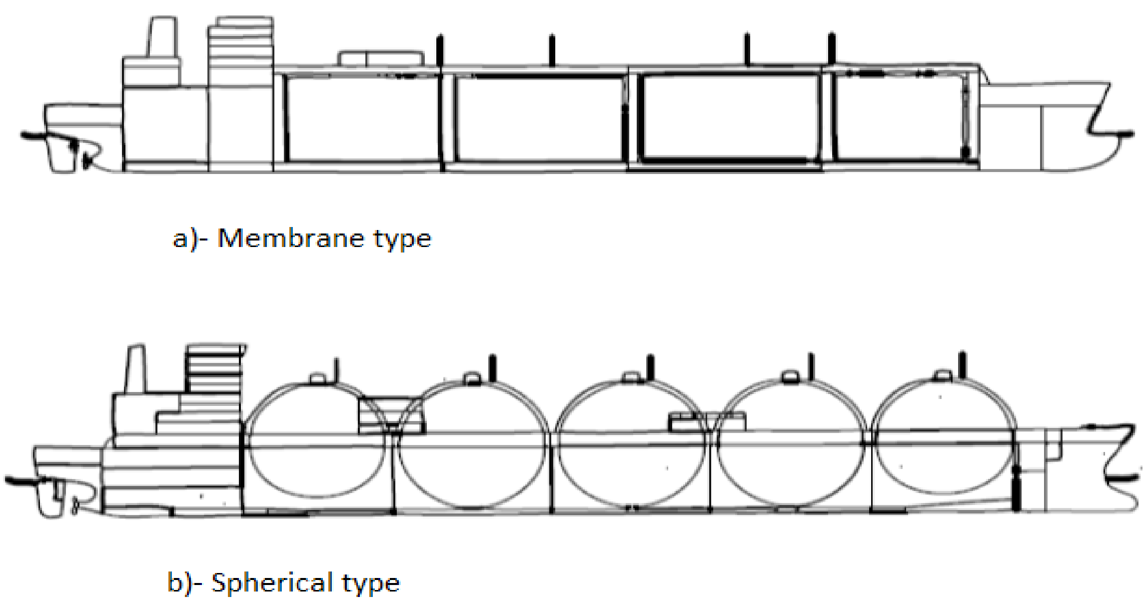

Figure 1: Examples of Equal-Sized Membrane and Spherical LNG Carriers.

The application of natural gas in marine engines depends on its properties. Natural gas is lighter than air, and in the event of leakage it disperses upwards to the atmosphere. Evaporating Liquefied Natural Gas (LNG) floats away, in contrast to other liquid fuel vapors, which linger near the engine and the bilge. The flammability of LNG is only possible within a tight mixture with air ranging (5%:15 %). The properties of NG and conventional marine fuel oil are summarized in (Table 1) [15-17].

Property	Marine Fuel Oil	Natural gas
Ignition temperature,˚C	250	600
Density, kg/m^3@ 1 bar	850	0.74
Lower calorific value, MJ/kg	42	50
Carbon contents (%)	84.7	70
Hydrogen contents (%)	12	42

Table 1: Comparison between LNG and Marine Fuel Oil Properties.

Propulsion Options for LNG Carriers

The propulsion system for LNG vessels is closely related with the generation and consumption of the cargo boil-off One way of classifying LNG vessel propulsion systems is according to the purpose appointed for the BOG produced in the cargo spaces. Both the fuels used as well as the emissions regulations are factors that influence the direction of LNG vessel propulsion system [18]. Another propulsion system classification is based on the fuel to be used allowing the possibility of selecting the propulsion system based on future lines of development. Steam Turbine (ST) based propulsion has been the main system implemented on LNG vessels since 1960, as this system allows the simultaneous burning in boilers of heavy fuel-oil together with the BOG generated during transportation, which in turn feed the propulsion turbines and electric turbo generators. Since 2003, LNG vessel propulsion systems have been at a turning point. STs are being replaced by internal combustion engines due to improvements in the efficiency of the latter and because, as above mentioned, these permit the burning of both heavy fuel oil as well as BOG from the cargo [19]. In addition, the Dual Fuel Diesel Electric Engine (DFDE) is one of the promising propulsion systems for LNG carriers. The DF engine adopted the lean-burn concept from the Otto-cycle, and a small amount of diesel as the pilot fuel, approximately 1 to 8%, which is used for ignition in the combustion chamber in its operation with gas as fuel (gas mode). DFDE engines developed around the year 2003 are 4- stroke (4S). At present, however, owing to technological advances which enable the use of NG in 2 - stroke engines (2S), a new change in propulsion systems to be implemented on LNG vessels is occurring to follow, a description of the main LNG vessel propulsion systems is discussed.

Steam Turbine Propulsion

Steam turbine has been the main propulsion system for LNG ships from very early days of gas transportation by sea primarily because of the ease with which the natural BOG can be burned in the boilers. A suitable marine steam power plant employs two boilers each of around 80-90 tons per hour steaming capacity at 60-70 bar pressure and 520˚C super heat steam temperature [20]. Propulsion system will comprise of a high pressure, an intermediate pressure and a low pressure turbine with total power output of 35-45 MW. The low pressure turbine also carries an astern turbine on the same rotor shaft for speed reversal. The auxiliary electrical power of about 10 MW will be provided by two steam turbines generators and one medium speed diesel generator of 3 MW power ratings. Overall thermal efficiency of a typical 30 MW conventional marine steam power plant, Mitsubishi, used for propulsion of 157000 m^3 LNG tanker has been estimated to 35% [21]. Now the improved versions of these steam plants designed on UST technology are able to offer nearly 15% fuel saving which amounts to an increase in the overall fuel efficiency to about 41% and is thus comparable to the fuel consumption of DFDE [22].

In order to enhance plant efficiency of steam turbine propulsion system, the newly developed concept has been introduced in the market, so called as Ultra Steam Turbine as shown in (Figure 2). Comparing with the existing steam system, the reheating cycle was added to improve thermodynamic efficiency and the intermediate pressure turbine section is incorporated in addition to HP (High Pressure) and LP (Low Pressure) turbines. It is expected that this development will enhance the efficiency of steam ship by about 15%, but still lower than other solutions with diesel engines [23].

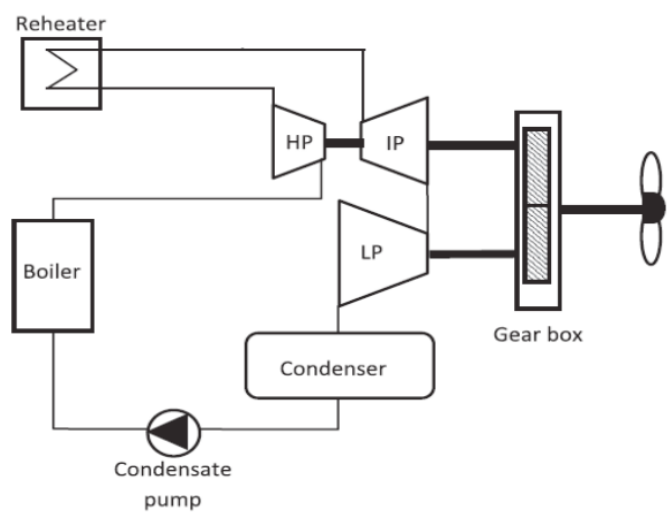

Figure 2: Ultra Steam Turbine System Propulsion System.

Dual Fuel Four Stroke Diesel Engines (DFDE)

In the early stage of LNG transportation diesel engines lost to steam turbines mainly because they could not handle natural BOG from the cargo tanks. But now the new diesel engines particularly the 4-stroke medium speed design can alternatively burn both liquid as well as gas fuels and because of that they have been considered potential alternative to less fuel-efficient steam turbines. A look at the new orders of LNG ships shows a good number of these contracts have been signed with 4 stroke medium speed diesel engines as prime mover in electrical propulsion modes. In gas mode when BOG is the fuel the engine operates with lean air/fuel ratio on the principle of Otto cycle with a small amount of diesel oil injection in the combustion chamber as pilot fuel for ignition. However, when the BOG is insufficient then the engine is operated on liquid fuel such as Diesel Oil (DO) or Heavy Fuel Oil (HFO). In this situation the BOG has to be disposed of by burning in the GCU with consequent penalty on energy loss. Therefore, loss of BOG together with losses in associated electrical components of the propulsion system (6-8%) must be taken into account while comparing DFDE with its competitors. In the DFDE design, as shown in (Figure 3), because electrical power for propulsion and cargo handling are in different operating time phase the net power requirement of the ship is considerably reduced unlike in other mechanical coupled propulsion systems which is a distinct advantage. However, the loss from BOG disposal during liquid fuel mode of operation will more than offset this advantage. Another serious shortcoming of DFDE is the high risk of detonation and misfiring as load increases. The DFDE have very narrow range of air/fuel ratio for detonation free operation which calls for a complex control system as each cylinder requires dedicated air to fuel ratio controller [24].

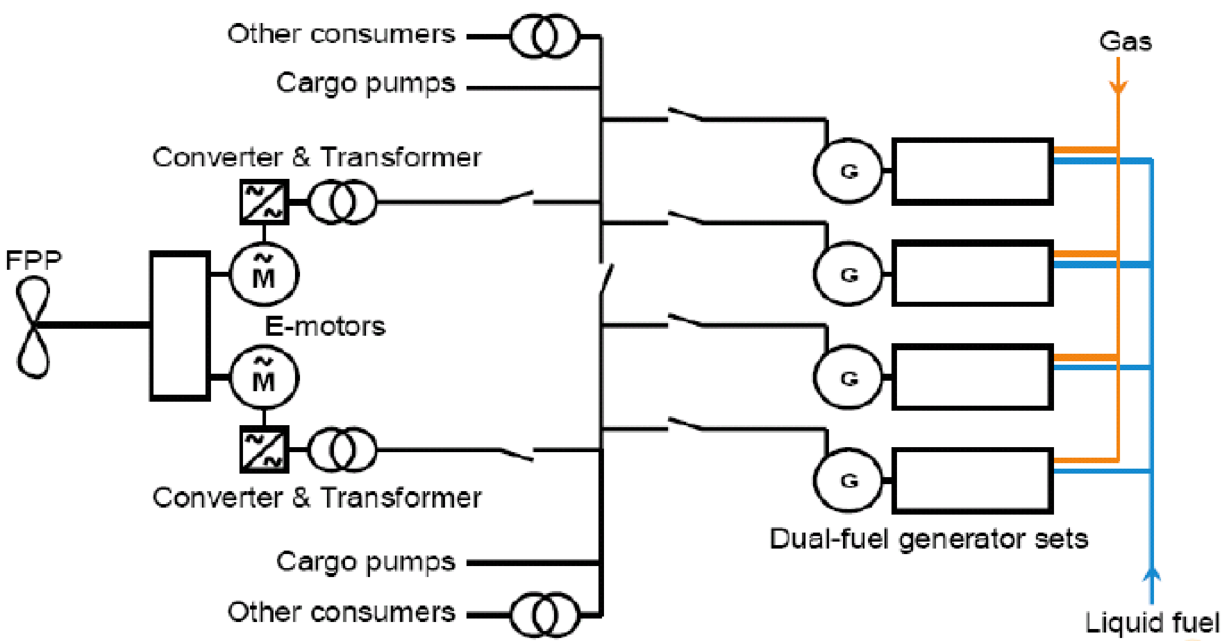

Figure 3: Dual Fuel Four Stroke Diesel Engines Propulsion Option.

Slow Speed Diesel Engines

It is another majority in propulsion systems for LNG carriers nowadays, especially for the LNG carriers of very large capacity and the long-distance trading vessels, which are the factors coming simultaneously in general. It has been a little controversial which one is more efficient system between DF diesel electric propulsion system and this conventional slow diesel application, which have been main trends of LNG carrier propulsion recently. Usually the designers carry out economic evaluation on their own, but the final conclusion is on the operators who evaluate operation cost on the basis of their input data about values of fuel oil, LNG cargo, natural BOG and forced BOG, initial investment, maintenance cost, etc. under the given trading & operating profile. This propulsion system is identical to those used in most of the merchant ships. 2- Stroke diesel engine is installed on the tank top in engine room and a shaft line is directly coupled to the engine for propulsion. No doubt this is the most efficient ship propulsion machinery at the moment in marine field. 4- Stroke diesel auxiliary generators are provided for electric power supply. Sometimes shaft disconnecting devices are provided for each shaft line in case of twin skew vessels, in order to disconnect the failed engine from propulsion shaft line as soon as possible and keep on voyage [25-26].

Two strokes slow speed engines were used as the main propulsion system in merchant shipping because of its low maintenance costs, high efficiency and the option of burning low-quality fuels. This system is used on LNG carriers of over 200,000 m3 on long distance crossings but with the peculiarity of integrating a re-liquefaction plant and a Gas Combustion Unit (GCU), as shown in (Figure 4). The re-liquefaction plant has the task of re-liquefying the BOG generated in cargo tanks and returning it to into a liquid state inside, avoiding any wastage of the LNG being transported. On the other hand, the Gas Combustion Unit (GCU) is designed to burn the BOG generated which, if there were a breakdown in the re-liquefaction plant, would be impossible to treat, avoiding the pressure increase in the tanks and could cause great damage.

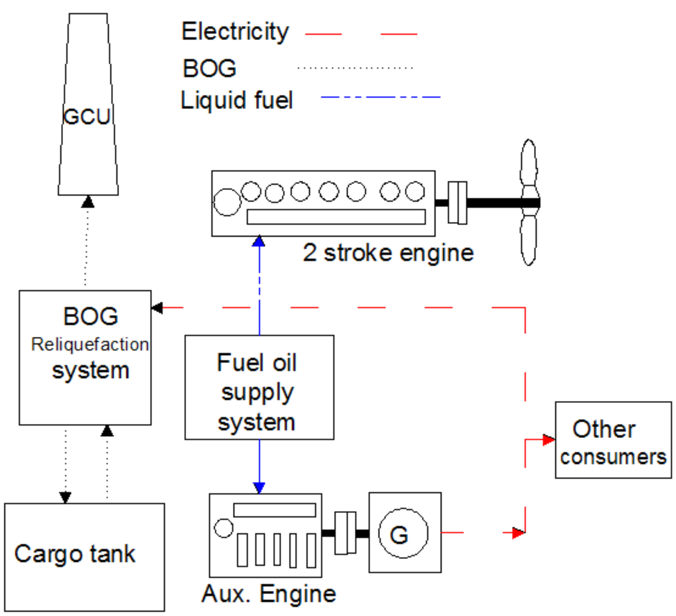

Figure 4: Propulsion System using 2- Stroke Diesel Engines and Re-Liquefaction Plant.

Gas Turbines in Combined Cycle

Gas turbines despite their many good features such as compact size, light weight, excellent reliability, and high power to weight ratio and quick response to sudden power demand have not found favors with ship owners mainly because of low fuel efficiency. In marine field, gas turbines have found applications mostly in naval ships propulsion and to some extent in offshore industry. In naval applications the gas turbines are used in either Combined Diesel or Gas Turbine (CODOG) or Combined Cruising Gas Turbine with Booster Gas Turbine (COGAG) configurations in which the base cruising power is provided by a low powered diesel engine or gas turbine. The high-power demand for the short sprint combat action comes from the large power gas turbine which makes overall power plant operation reasonably fuel efficient but still less economical. However, gas turbines in land-based application have been used in combined cycle with steam turbines and achieved very favorable fuel efficiency often superior to all other prime movers [26-27] (Figure 5). illustrates a power driven combined cycle arrangement. The system comprises a GT of around 36 MW which is responsible for supplying the required torque through a reducer, to rotate the ship's propeller. The exhaust gases generated in the GT are sent to the recovery boiler where they provide the heat input required to generate steam that is sent to a turbine of around 10 MW, coupled to a generator that supplies power to the vessel during navigation. The plant also includes three auxiliary generators with a combined capacity of between 6 and 12 MW used for power generation at port, when both turbines are stopped [28].

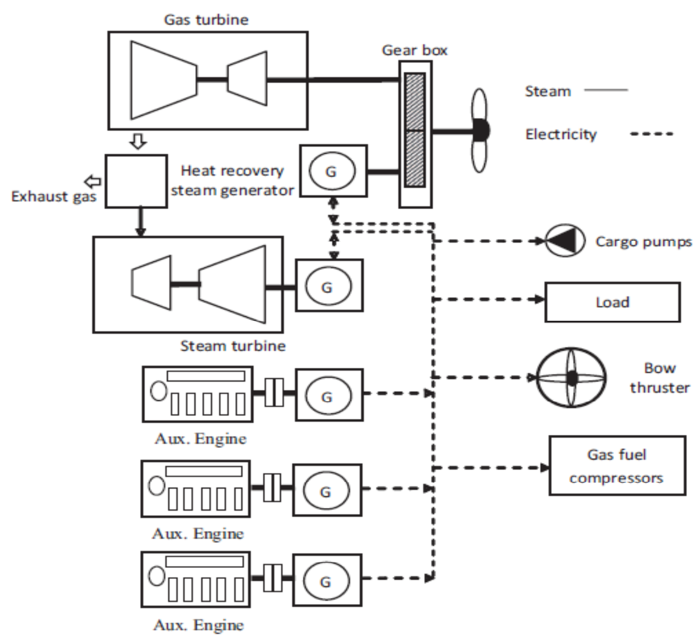

Figure 5: Combined Gases and Steam Propulsion System for LNG Carriers.

Environmental Comparative Study

Fuel efficiency is the most significant performance index of a propulsion system as it not only affects the operating cost of the ship but also hugely contributes to gas emissions. Steam power plants have lower fuel efficiency in comparison to internal combustion engines but recent developments in UST technology with increased pressure and temperature followed by steam re-heating the fuel efficiency of marine steam plants has been raised almost to the level of marine diesel engines. Similarly, operating gas turbines in combined cycle with a steam turbine gives much improved fuel efficiency often higher than conventional diesel engines. Fuel efficiency of a typical conventional steam turbine propulsion plant of a 157000 m^3 LNG tanker has been calculated from the heat balance data obtained during sea trials. The estimated fuel efficiency of this plant works out to 35% and if additional 15% fuel saving from UST design is also taken into account then the overall fuel efficiency of steam plant comes to 42% which is very close to the DFDE. Fuel efficiency of different propulsion options is shown in (Table 2) [29-30].

LNG propulsion option	Thermal efficiency	Specific fuel consumption (g/kWhr)
Steam turbine	35%	286
Ultra-Steam Turbine	41%	243
2-stroke diesel engines and re-liquefaction plant	40%	230
Dual Fuel four Stroke Diesel Engines	42%	243
Gas Turbines in Combined Cycle	50%	245

Table 2: Comparison between Thermal Efficiency of Different LNG Propulsion Options.

On the other hand, gas emission is now a major environmental concern because of its impact on global warming and to address the issue, strict time bound emission control levels for ships have been imposed by the IMO through appropriate MARPOL regulations. Because of MARPOL restrictions gas emission will constitute a major parameter of comparison for alternate propulsion systems. It is therefore important to understand the chemistry of gas emissions and their Cost-Sulphur essentially enters fuel in the refinery with crude oil and converts into SO_2 or higher oxides when burns in combustion chamber. Since Sulphur is present in fuel as impurity nothing can be really done in the combustion chamber to minimize its emission and the only option to prevent excess SO_2 release is to limit Sulphur content in the fuel [31].

In order to calculate exhaust gas emissions from ships, Emissions Factors (EF) were developed by third GHG study 2014 [32]. This can be used directly with Specific Fuel Consumption (SFC) for emission calculations as expressed in Equation (1). For example, the baseline or reference CO_2 emission values for the different fuel types used in marine engines can be expressed as in Equations (2, 3, 4). In addition, (Table 3). shows CO_2 emissions factor for all the different fuels which can be used in the marine field [33].

$$\text{Emission}, EF_{baseline}\left(\frac{\text{g pollutant}}{\text{gfuel}}\right) = \frac{EF_{baseline}\left(\frac{\text{g pollutant}}{\text{kWh}}\right)}{SFC_{baseline}\left(\frac{\text{g fuel}}{\text{kWh}}\right)} \quad (1)$$

$$\text{HFO}, EF_{baseline}(CO_2) = 3.114\,\frac{\text{kg } CO_2}{\text{ton fuel}} \quad (2)$$

$$\text{MDO}, EF_{baseline}(CO_2) = 3.206\,\frac{\text{kg } CO_2}{\text{ton fuel}} \quad (3)$$

$$\text{LNG}, EF_{baseline}(CO_2) = 2.750\,\frac{\text{kg } CO_2}{\text{ton fuel}} \quad (4)$$

Type of fuel	Reference	Carbon Content	CF ($t\text{-}CO_2/t\text{-}Fuel$)
1. Diesel/Gas oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
4. Liquefied Petroleum Gas	Propane/Butane	0.8182 / 0.8264	3.000 / 3.030
5. Liquefied Natural Gas (LNG)		0.7500	2.750
6. Methanol		0.3750	1.375
7. Ethanol		0.5217	1.913

Table 3: CO_2 Emission Factors for Different Types of Fuels.

Due to the trend of environmental-friendly design and the regulations that limit emissions worldwide, it becomes an important factor to be considered during ship design. Use of boil-off gas as a fuel is a big advantage to reduce emissions from ships and the additional equipment's for flue gas treatment could be considered case by case upon the selected propulsion system and the applicable regulations. Please refer to the comparison of emissions between some of the alternatives as shown in (Table 4) [34-38].

Marine power plant	NO_x (g/kWh)	SO_x (g/kWh)	CO_2 (g/kWh)	Particulates (g/kWh)
2-stroke marine diesel engine	17	12.9	5.5	0.5
4-stroke marine diesel engine	12	13.6	6.16	0.4
Dual fuel diesel electric	1.3	0.05	5	0.05
Steam Turbine	1	11	9.3	2.5
Gas turbine	2.5	0	5.9	0.01

Table 4: Emissions from Different LNG Propulsion Power Plants.

Lowering of exhaust gas emissions is obligatory on Emission Control Areas (ECA) set by the International Maritime Organization (IMO) according to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI requirements and in the future worldwide in all sea areas. The levels of tier II and tier III may be fulfilled on LNG carriers depending of propulsion plant and use of fuel type [39-40].

Conclusions

Selection of the LNG ship propulsion option can be based on comprehensive comparison between the available propulsion systems. Many more factors play key roles in the selection of propulsion system for large LNG ships. Based on the current review of LNG carrier propulsion systems, it possible to formulate the following conclusions:

- Steam turbine has been adapted to most LNG carriers because it has been burnt all Boil-Off Gas (BOG) or vaporized gas from cargo tanks in boilers as a fuel without the re-liquefaction plant. Its reliability is high because both BOG and Heavy Fuel Oil (HFO) are combustible as fuel for main boilers.
- In the dual fuel diesel engine, the dual fuel burning of BOG and HFO is possible and fuel efficiency is better but the high-pressure injection is required when the BOG is introduced to the engine. There is also a disadvantage of needed MDO fuel for pilot burning. Flexibility is inferior because exclusive BOG combustion is impossible and moreover in the diesel engine a large quantity of NO_x is discharged due to the high combustion temperature.
- In the diesel engine with re-liquefaction plant, the propulsion engine and BOG handling are perfectly separated. In this case more emissions are discharged due to the HFO fired diesel engine.
- In the gas combined cycle, the BOG is fired in the gas turbine. The steam turbine is driven by steam generated by the exhaust gas energy from gas turbine. There is needed a high-quality fuel MDO or MGO (expensive fuels) so the emission is lowering and is like the same from the steam turbine plant. This system is a proposition with an electric propulsion plant for the largest LNG carriers.

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