# ASSESSMENT OF ALTERNATIVE MARINE FUELS FROM ENVIRONMENTAL, TECHNICAL, AND ECONOMIC PERSPECTIVES ONBOARD ULTRA LARGE CONTAINER SHIP

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**SUMMARY**

Ship emissions reduction targets are pushing the maritime industry towards more sustainable and cleaner energy solutions. Marine fuels play a major role in this because of the emissions resulting from the combustion process associated with the prime mover(s), therefore, one of the technical solutions is to replace conventional marine fuels with cleaner fuels. Hence the aim of this study is to undertake environmental, technical, and economic analysis of alternative fuels to reduce the environmental footprint and lifetime costs of the long-distance shipping sector. As a case study, an ultra large container ship operating on the East-West trade route has been considered, and the analysis focused on natural gas and methanol as alternative fuels. This study adopted three approaches: environmental, technical, and economic methods to compare the alternative fuels with the conventional ones. The results showed that a dual-fuel engine operated by natural gas will reduce $CO_2$, SOx, and NOx emissions by 28%, 98% and 85%, respectively, when compared with emission values for a diesel-powered engine. Furthermore, the reduction percentages reach 7%, 95% and 80% when using a dual-fuel engine operated by methanol, respectively. The proposed dual-fuel engines will improve the ship energy efficiency index by 26% and 7%, respectively. The study shows that methanol is the most economical alternative fuel for this container ship, replacing diesel with methanol, leads to a power system that is only 30% more expensive than the existing one. The analysis confirms that the cost of fuel has a major effect on the ship's life cycle cost and that by reducing the fuel costs, the costs of the power system become more acceptable.

## 1. INTRODUCTION

The exhaust gas released by fossil fuel combustion negatively affects the environment, and is comprised of carbon dioxide ($CO_2$), Sulphur oxides (SOx), and nitrogen oxides (NOx), whose increased concentration in the atmosphere causes global warming. Current research into air pollution caused by the shipping sector mainly focuses on seagoing vessels especially long-distance shipping sectors. Statistics indicate that the most three ship type that contribute by a valuable percent of carbon footprints are container, bulk carrier, and oil tanker ships (Elkafas et al., 2021a; Olmer et al., 2017).

Currently, there are several legislations in addition to many goals adopted by the International Maritime Organization (IMO) to reduce greenhouse gases (GHG) and achieve a blue economy (Psaraftis & Kontovas, 2021). One of those goals is to reach a 50 % reduction in the percentage of GHG emitted from ships by 2050 compared to 2008 (Joung et al., 2020). The decarbonization of the shipping sector can be achieved through technical and operational measures (Bouman et al., 2017; Xing et al., 2020). Balcombe et al. (Balcombe et al., 2019) performed a review to investigate the available decarbonization measures and showed that alternative fuels, new technologies, electrification and emission taxes can be applied to achieve the target of IMO. The replacement of conventional fossil fuel like heavy fuel oil (HFO) and marine diesel oil (MDO) which accounts for 79% of total fuel consumption in the international shipping with alternative and cleaner fuel with lower carbon content would reduce the carbon footprint of a ship power system (Hansson et al., 2019). The main alternative marine fuel types may be found in two forms: liquid and gaseous fuels. Liquid marine alternative fuels include Methanol, Ethanol, and Bio liquid fuel. On the other hand, the main alternative gasses fuels include Natural gas, Propane, Hydrogen, and Ammonia (Elkafas et al., 2021b).

Two alternative types will be considered throughout the present project, mainly: Natural gas (NG) and Methanol. Selection of the previous types is the matter of searching for alternative fuels that have less emissions to be applied on board ships in the short term. Methanol has been investigated as an alternative marine fuel in previous research projects such as Swedish EffShip (SSPA, 2013), and SPIRETH project (Ellis, 2014). Some studies by (Andersson et al., 2020; Dierickx et al., 2018) has been carried to evaluate the applicability of using methanol as an alternative marine fuel. Another research by (Ammar, 2019) shows that methanol reduce exhaust emissions by a considerable amount and reduce the fuel cost. Brynolf et al. (Brynolf et al., 2014) performed technical, environmental, and economic analysis between alternative fuels (natural gas and methanol) and the conventional fuel (HFO) onboard ro-ro vessel, this study indicated that implementation of alternative fuels increases the extracted energy and reduces exhaust emissions. Helgason et al. (Helgason et al., 2020) showed that methanol produced from natural gas is cost effectively when compared with HFO, but methanol produced from biomass is not a cost competitive.

The primary segment of natural gas is methane ($CH_4$), this fuel is the least carbon and sulfur content and consequently with the most promising option to decrease $CO_2$ and SOx emissions (Elgohary et al., 2015). Besides, the burning of natural gas in comparison with diesel is characteristically cleaner regarding NOx. Moreover, natural gas appears as a financially motivating measure for vessel types spending a long period of their cruising time like handy size tankers, RO-RO vessels, and container ships (Elkafas et al., 2021b). There is a study about application of lignified natural gas (LNG) onboard inland navigation ships (Fan et al., 2021) which assess the environmental and economic outputs and found that using LNG can lead to lower emissions and costs if operated in a hybrid power system. Meriden-Paul et al. (Merien-Paul et al., 2019) evaluated the emission reduction by using LNG instead of HFO onboard a bulk carrier for about 2.5 year, this study found that LNG reduce $CO_2$ emission by 35% and NOx by 40-93.7% when compared with HFO. Ammar and Seddiek (Ammar, 2017) analyzed many decarbonization measures to achieve the target of GHG reduction onboard ro-ro cargo ship, this study concluded that using LNG is the optimal solution over other technologies.

All the previous studies, whether research projects or research papers that dealt with the importance of alternative fuels usage onboard ships, confirm that the maritime industry has not benefited the most from alternative fuels. Moreover, it confirms the necessity of conducting many other studies to determine the potential benefits from alternative fuel onboard ships. Based on the above overview, a gap in the literature is evident: research into alternative fuels to reduce the carbon footprint is mainly directed at the long-distance shipping sectors, while the environmental and economic impact of their application in the container ships sector has not been adequately investigated. Alternative fuels are particularly important for high size container ships which operates between far east and northern Europe that need to meet emission reduction targets.

The contributions of this paper are summarized as follows: performing a techno-economic and environmental assessment of applying alternative fuels (natural gas and methanol) to reduce the carbon footprint of international shipping, where ultra large container ship is used as test case. This paper provides a model to calculate the ship emissions, identifies a set of alternative fuels that can be used, and, by performing a comparative study between alternative fuels and conventional diesel fuel, highlights the most economical and environmental potential of alternative fuels. Although the container ships type is taken as a test case, the models are more generally applicable if a set of input data for other types is known.

## 2. METHODOLOGICAL CONSIDERATIONS

This section aims to present the environmental, technical, and economic approaches applied in this paper to compare natural gas and methanol with conventional marine fuels.

### 2.1 ENVIRONMENTAL ASSESSMENT METHOD

The environmental assessment can be performed by calculating the exhaust emissions from ships in case of using the proposed alternative fuels compared with the conventional diesel fuel. The emissions from ships included many kinds of pollutants such as $CO_2$, SOx and NOx emissions. The quantity of exhaust emission during one trip ($M_{trip}$) can be calculated by using Eq. (1) which depending on the engine power.

$$M_{trip,i} = \sum_{i} MCR_i * L_i * T_s * E_p \qquad (1)$$

Where (MCR) is the maximum continuous rating power of engine in [kW], (i) is the type of engine (main engine or auxiliary engine), (L) is the load sfactor of engine and ($T_s$) is the operating time of ship in hour, and ($E_p$) is the pollutant emission factor in an energy based form [g pollutant/kWh] (Elkafas, 2022).

The individual emission energy-based rate in differs from type to another. In case of $CO_2$ emission, it is based on the conversion factor between fuel and $CO_2$ which depend on the carbon content in fuel, therefore, its value differs from fuel to another. Table 1 shows the conversion factor values for different fuels (Elkafas et al., 2021a).

Table 1: Conversion factors and carbon contents for marine fuels

| Fuel type | Carbon content | Conversion factor (g $CO_2$/g fuel) |
|---|---|---|
| MDO | 0.8744 | 3.206 |
| HFO | 0.8493 | 3.114 |
| LNG | 0.75 | 2.75 |
| Methanol | 0.37 | 1.375 |

The energy-based rate of $CO_2$ emission ($E_{co2}$) measured in g $CO_2$/kWh can be calculated using Eq. (2) based on specific fuel consumption (SFC) in g fuel/kWh and the conversion factor CF).

 

$$E_{co_2} = SFC \times CF \quad (2)$$

Regarding the air pollution emission inventory recommendation from IMO, NOx emission factor expressed in g/kWh for slow speed diesel engine depends on the ship construction date (Elkafas et al., 2021b). The first level of control (Tier I) applies for ships constructed on 1 January 2000 or after and can be calculated as shown in Eq. (3) which depends on the engine's rated speed (n).

$$E_{NOx} = 45 \times n^{-0.2} \quad (3)$$

A slow speed diesel engine (SSDE) that is installed on a ship constructed on 1 January 2011 or after (Tier II), a reduction equal to 15% should be fulfilled compared with Tier I NOx emission value. On the other hand, NOx emission factor for natural gas engine and methanol engine is 2.16 g/kWh and 2.47 g/kWh, respectively (Ammar, 2019; Elkafas et al., 2021a).

On the other hand, SOx is proportional to SFC and the content of Sulphur in the fuel (S) so that the $SO_X$ emission energy-based rate ($E_{SOx}$) can be calculated by Eq. (4) (EPA, 2000; ICF, 2009).

$$E_{SOx} = SFC \times 2.1 \times (S\%) \quad (4)$$

It is seen that lower the Sulphur content in fuel is led to reducing the specific emission rate of SOx, which is the reason why more and more strict demands towards lower Sulphur content in marine fuel.

In case of dual-fuel engine, the emission factor should be evaluated by considering the percentage of each fuel as shown in Eq. (5) (Elkafas et al., 2021a).

$$E_{p,DF} = x_{gas} \times E_{p,gas} + x_{P.F} \times E_{p,P.F} \quad (5)$$

Where, $x_{gas}$ and $x_{P.F}$ are the percentages of gas and pilot fuels in the dual-fuel engine (DF), $E_{gas}$ and $E_{P.F}$ are the pollutant (p) emission factors for gas and pilot fuels, respectively.

## 2.2 TECHNICAL ASSESSMENT METHOD

The technical performance can be assessed by using the procedure recommended from IMO through the calculation of Energy Efficiency Design Index (EEDI). EEDI has two indexes, a restrictive value ($EEDI_{req}$) and the actual value ($EEDI_{att}$) which should be lower than the restrictive value. The restrictive value depends on the ship type and its deadweight (DWT); therefore, Eq. (6) should be used for the calculation of $EEDI_{req}$ in case of container ship.

$$EEDI_{req} = \left(\frac{174.22}{DWT^{0.201}}\right) \times \left(1 - \frac{X}{100}\right) \quad (6)$$

Where (X) is the reduction rate of baseline value each five years as recommended from IMO; 10% in phase 1 (2015-2019), 20% in phase 2 (2020-2024) and 30% in phase 3 (2025-onwards) (El Gohary & Ammar, 2016; Elkafas et al., 2019).

On the other hand, the actual value is a measure of energy efficiency level for the specified ship and can be calculated as shown in Eq. (7). For the dual-fuel engine, the product of ($SFC_{ME} \times CF_{ME}$) can be calculated by using Eq. (8) depending on the SFC and CF of either gas fuel and pilot fuel (Elkafas et al., 2021b).

$$EEDI_{att} = \frac{(P_{ME} \times SFC_{ME} \times CF_{ME}) + ((0.025 \times MCR_{ME} + 250) \times SFC_{AE} \times CF_{AE})}{Capacity \times V_{ref}} \quad (7)$$

$$SFC_{ME} \times CF_{ME} = SFC_{gas} \times CF_{gas} + SFC_{P.F} \times CF_{P.F} \quad (8)$$

Where ($P_{ME}$) is 75% of MCR for each main engine (ME) in kW, ($V_{ref}$) is the operational ship speed in knots and (capacity) is 70% of the container ship deadweight. The auxiliary engine (AE) power necessary to operate the main engine and the crew accommodation is based on the MCR of the main engine in case of using an engine of more than 10,000 kW as shown in Eq. (7) (IMO, 2018).

## 2.3 ECONOMIC ASSESSMENT METHOD

The economic study of different power system can be done by using the Life-cycle cost assessment (LCCA) which considers the total costs of a power system configuration during the ship lifetime. These life-cycle costs refer to the investment cost and exploitation cost as shown in Figure 1. The investment cost represents Investment costs refer to the additional investment costs of the power system configuration since the diesel engine-powered ship already exists. The maintenance cost refers to the maintenance and replacement of some parts of the power system configuration, while the fuel cost relates to the life-cycle cost of a fuel that is used in the power system. The carbon credit cost refers to the cost of carbon allowance, which represents the right to emit 1 ton of $CO_2$.

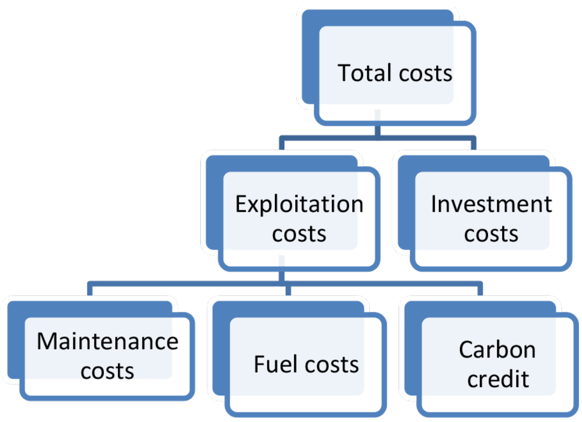


Figure 1. Total costs of a ship power system configuration

This paper investigates carbon credit implementation based on two different scenarios, Current policies (CP) scenario and Sustainable development (SD) scenario. Current policies (CP) scenario: considering the current policies that have been implemented in the energy sector, the Sustainable Development (SD) scenario refers to the strategic pathway to meet global climate, air quality and energy access goals (Trivyza et al., 2019). The forecast carbon allowance, ($C_A$) measured in (USD \$/tonne-$CO_2$) and its value for 2025 is 21.8 and 61 USD \$/tonne-$CO_2$ for CP and SD scenarios, respectively which obtained from (Agency, 2019). The life-cycle carbon credit cost, $C_{CC}$ (USD \$), for different scenarios can be calculated as shown in Eq. (9) (Perčić et al., 2021):

$$C_{CC} = \sum_{n=1}^{n} E_{CO2} * CA_n * ASD \tag{9}$$

where (n) refers to the ship lifetime, ($E_{CO2}$) denotes annual $CO_2$ emissions in tons/km, (ASD) is the annual sailing distance (km), while ($CA_n$) refers to the carbon allowance for year (n). A proper cost comparison of different power system options can be achieved by reducing their total costs to the Net Present Value (NPV), a measure that discounts the future costs to the present value. The NPV of each power system is calculated as shown in Eq. (10) (IMO, 2021):

$$NPV = C_I + C_{an} * \left[\frac{(1+r)^n - 1}{r * (1+r)^n}\right] \tag{10}$$

where ($C_I$) refers to the investment cost, ($C_{an}$) represents all annual costs in a year (including fuel cost, maintenance cost and carbon credit cost), (r) refers to the discount rate per year and (n) is the lifetime of a ship per years. The fuel cost can be calculated as shown in Eq. (11).

$$FC = P * T_s * SFC_i * fc_i * 10^{-6} \tag{11}$$

where (P) is the main engine power in kW, ($T_s$) is sailing time in hours, ($SFC_i$) specific fuel consumption in g/kWh of any fuel type (i) and ($fc_i$) is the fuel cost in USD \$/ton.

For comparative study between different power systems, the investment cost of a new diesel engine is calculated by multiplying the average power of the ship with the assumed conversion factor of 273 \$/kW. The cost of diesel fuel for shipping is 545 \$/ton (IMO, 2021; Jovanović et al., 2022). The maintenance cost of this power system is obtained from (Iannaccone et al., 2020) and it is 50 \$/kW.

The investment cost of a new-build LNG-powered system is calculated by multiplying the conversion rate (including the engine and all additional equipment costs) of 1264 \$/kW by the engine power. The life-cycle maintenance cost is calculated as for the diesel-powered vessel, where the conversion factor is equal to 57.6 \$/kW (Iannaccone et al., 2020). In this analysis, the LNG price is assumed to be 567 \$/ton (IMO, 2021).

Conversion from a diesel-powered system to a methanol-powered system results in a cost of 818 \$/kW for a new-build system which considers the purchase of a new engine and associated equipment. It is assumed that the life-cycle maintenance cost of a methanol-powered system is equal to the life-cycle maintenance cost of a diesel-powered system. The methanol price amounts to 382 \$/ton (IMO, 2021; Jovanović et al., 2022).

## 3. CASE STUDY DESCRIPTION

The case study for the assessment process of alternative fuels is selected to be ultra large container ship. The container ship (Al Jmeliyah) is owned to United Arab shipping company Dubai branch and operated by Hapag-Lloyd, Hamburg (DNV GL, 2021). The ship was built in 2017 and sailing under the flag of Marshall Islands. Table 2 shows the technical data of the ship (Hapag-LIoyd, 2021a).

Table 2: Main specifications of the case study

| Ship type | Ultra Large Container Ship |
|---|---|
| IMO number | 9732357 |
| Length overall, [m] | 368 |
| Breadth, [m] | 51 |
| Service speed, [knots] | 24 |
| Deadweight, [ton] | 149360 |
| Container capacity, TEU | 14993 |
| Main Engine type | 2× MAN B&W 9S90 |
| MCR power, [kW] | 2×37,620 kW at 72 RPM |

The vessel normally serves the Far East route from Asia to Northern Europe through the Suez Canal. The average time for each round of trip is 23 days from Busan in Asia to Hamburg in Northern Europa (Hapag-Lloyd, 2021b). The ship is currently powered by two SSDE (MAN 9S90 ME-C) with output of 37,620 kW at 72 rpm which operated with marine diesel oil (0.5% S).

Natural gas is competitive on the energy market for use as an alternative shipping fuel as it is an affordable, non-toxic, and non-corrosive fuel with lower carbon content than diesel. Natural gas is usually used in a dual-fuel diesel engine that provides high efficiency and offers a smooth switch between one fuel and the other during ship operation without loss of power or speed. Natural gas is originally in gaseous form. To make the handling process easier, natural gas is liquefied by cooling it at -163 ◦C. In this way, LNG has 600 times less volume than in its gaseous state (Attah & Bucknall, 2015). Therefore, the diesel-powered engine is proposed to be converted to 9G80ME-C10.5-GI dual-fuel engine (DFE) with the same power and speed operated by 98.5% natural gas and 1.5% MDO as a pilot fuel.

 

The second option to replace diesel fuel is methanol: a toxic, corrosive, but Sulphur-free and biodegradable fuel. The main raw material for its production is natural gas and, due to the low carbon content, it has been attracting wide attention. Its similarity to marine fuels (due to its liquid state) allows for methanol to be used in the current diesel infrastructure with only minor modifications (Ammar, 2019). It can be easily used in the commercially available MAN dual-fuel engine, which uses a small amount of pilot fuel to initiate combustion (MAN, 2022). In this paper, it is proposed to convert a diesel-powered engine to MAN B&W ME-LGI dual-fuel engine that can run on 95% methanol and 5% MDO as a pilot fuel.

The proposed engine's cylinder head is equipped with two valves for gas injection and two conventional valves for the pilot fuel oil. ME-GI has the same efficiency, power and dimensions of ME-C. Converting the main engine of a ship to run on natural gas or methanol will include some modifications, which include engine conversion fuel storage containers, piping, and related safety systems. For LNG-powered system, a membrane tank (GTT design Mark III) can be installed at the designated location in one of the holds, just in front of the engine room. The membrane tank for the case study must be capable of storing up to 6,700 cubic meters of gas, meaning the vessel will have to bunker twice per round trip, once in Asia, once in Europe. For the case study, around 290 container sites will be lost for the additional gas storage system. However, unlike LNG, methanol is a liquid at ambient temperature and pressure, meaning that it can be stored in ordinary tanks with few modifications.

## 4. RESULTS AND DISCUSSIONS

The environmental performance can be assessed by evaluating the exhaust emission rates per trip. The examined emission types are $CO_2$, SOx, and NOx, as these types are related with IMO regulations. The assessment process depends on the comparative study between the proposed dual-fuel engine operated with LNG or methanol and the conventional diesel engine operated with MDO (0.5%S). The first step in evaluating the environmental benefits of proposed dual-fuel engine is to calculate the energy-based emissions factors as discussed before. The different emissions rates per trip can be calculated based on the specified trip from Busan to Hamburg. The relative emissions rates of the proposed dual-fuel engine compared to diesel engine are shown in Figure 2.

For the current case study, the emissions rates of SSDE are 39.1 ton/hour, 2.13 kg/min and 20.4 kg/min for $CO_2$, SOx, and NOx, respectively. These rates are reduced after applying LNG-powered engine (98.5% NG and 1.5% MDO) to 28.2 ton/hour, 0.032 kg/min and 2.97 kg/min with reduction percentages of 28%, 98% and 85%, respectively. These rates are reduced after applying methanol-powered engine (95% Methanol and 5% MDO) to 36.25 ton/hour,

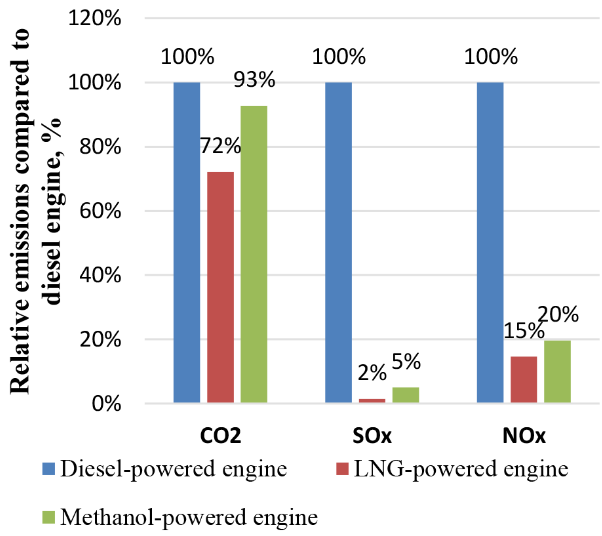


Figure 2. Relative emissions rates of the proposed dual-fuel engines compared to diesel engine

0.107 kg/min and 0.032 kg/min with reduction percentages of 7%, 95% and 80%, respectively.

NOx and SOx emission rates should be compared with the IMO 2016 and 2020 emission-limit rates, respectively. IMO 2020 SOx emission limit rate can be predicted based on fuel sulfur content (0.5%) which equals 2.133 kg/min. For the case study, SOx emission rates can be calculated for different pilot fuel percentage in dual-fuel engine to assess the effect of its value on emission rates as shown in Figure 3.

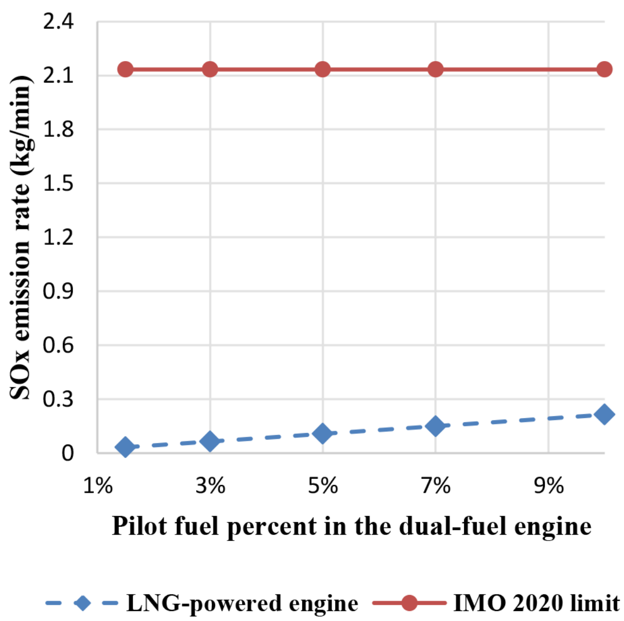


Figure 3. SOx rates at different pilot fuel percentages

It can be noticed that SOx emissions rates for dual-fuel engine are compliant with IMO 2020 limit at different pilot fuel percentage. IMO 2016 NOx emission limit rate can be predicted based on engine speed which equals 4.26

kg/min. For the dual-fuel engine operated by natural gas and pilot fuel, NOx rates can be calculated for different pilot fuel percentages to evaluate the impact of its value on emission rates as shown in Figure 4.

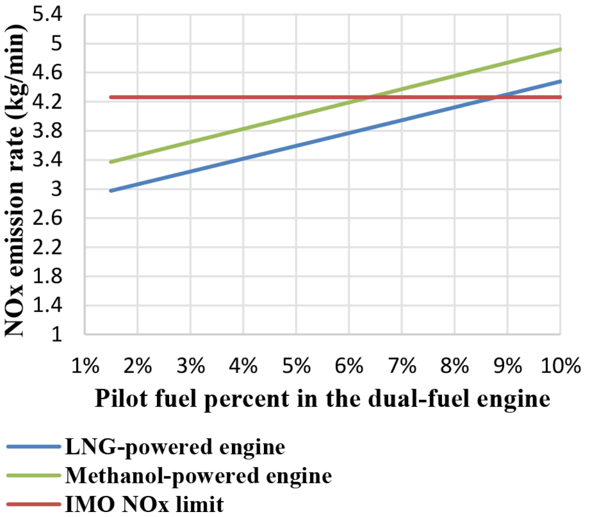


Figure 4. NOx rates at different pilot fuel percentages

As shown in Figure 4, the dual-fuel engine operated by natural gas and methanol will be compliant with the required IMO limit if the percentage of pilot fuel is lower than 8.8% and 6.4%, respectively. Furthermore, the energy efficiency can be assessed by the calculation of EEDI for the proposed dual-fuel engine as recommended by IMO. By conducting the reference EEDI procedure to the case study, it is shown that the reference EEDI and its value in the three phases can be calculated based on the deadweight of the container ship as investigated in Figure 5.

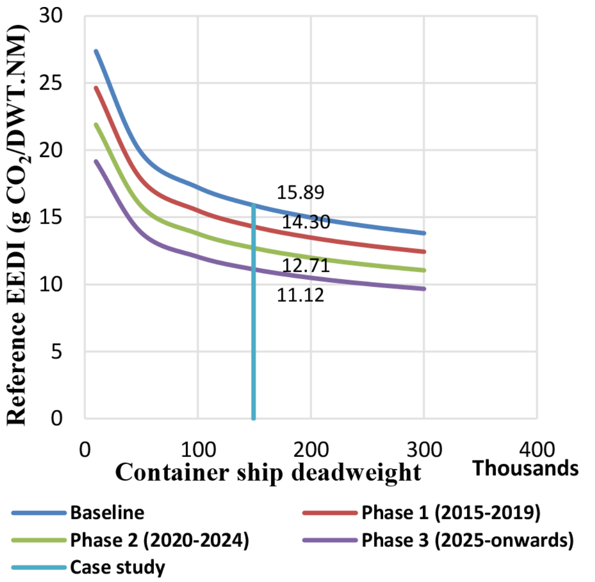


Figure 5. Reference EEDI values at different phases

This reference value will be compared with the actual attained EEDI for the case study powered by diesel which can be calculated by using Eq. (7) based on 24 knots service speed, 3.206 ton-$CO_2$/ton-fuel conversion factor of fuel to $CO_2$. The attained EEDI will be 11.91 g $CO_2$/DWT-NM. It is noticed that the current EEDI of diesel-powered engine is fulfilling the EEDI requirement until phase 2 but must be reduced to comply with EEDI phase 3.

To evaluate the energy efficiency benefits for the selected dual-fuel engine operated by either natural gas or methanol, attained EEDI should be calculated. Based on Eq. (7) and Eq. (8), the attained EEDI for dual-fuel engine (98.5% NG and 1.5% MDO) and (95% Methanol and 5% MDO) is 8.77 g $CO_2$/DWT-NM and 11.07 g $CO_2$/DWT-NM, respectively. To assess the results, it should be compared with the reference EEDI at different phases as shown in Figure 6.

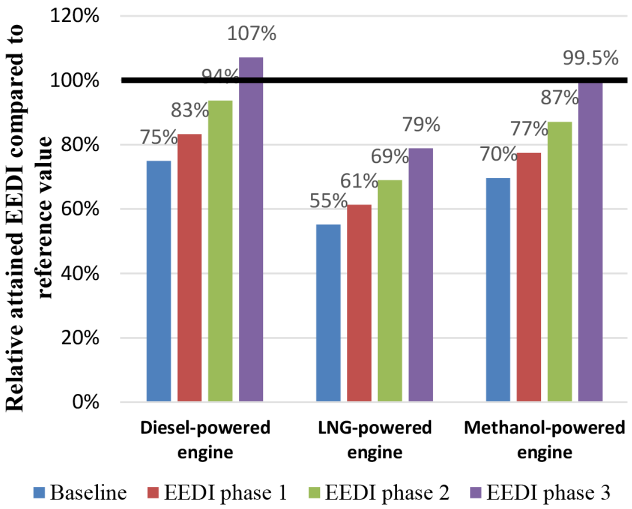


Figure 6. Relative attained EEDI compared to reference value at different phases

It is shown that, the proposed dual-fuel engine operated by (98.5% NG and 1.5% MDO) will comply with the required IMO phases now and in the future as the attained EEDI is about 61%, 69% and 79% of the reference EEDI at phase 1, phase 2 and phase 3, respectively. On the other hand, the proposed dual-fuel engine operated by (95% Methanol and 5% MDO) will comply with IMO phase 1 and phase 2 as it is about 77% and 87% of the reference EEDI value, respectively. While it will comply with the required IMO phase 3 by a small percentage, as the attained EEDI will reach 99.5% of the required EEDI.

The results of life cycle cost assessment for the case study are presented in Figure 7, in which the comparative study between different power systems is done. In the LCCA, the CP and SD scenarios as carbon credit implementation scenarios are consider.

The performed LCCAs resulted in revealing the most cost-effective power option for test case, this option is the conventional one (diesel-powered engine). However, following environmental trends, diesel-powered system will need to be replaced with some power system that has a lower carbon footprint which does not involve high total

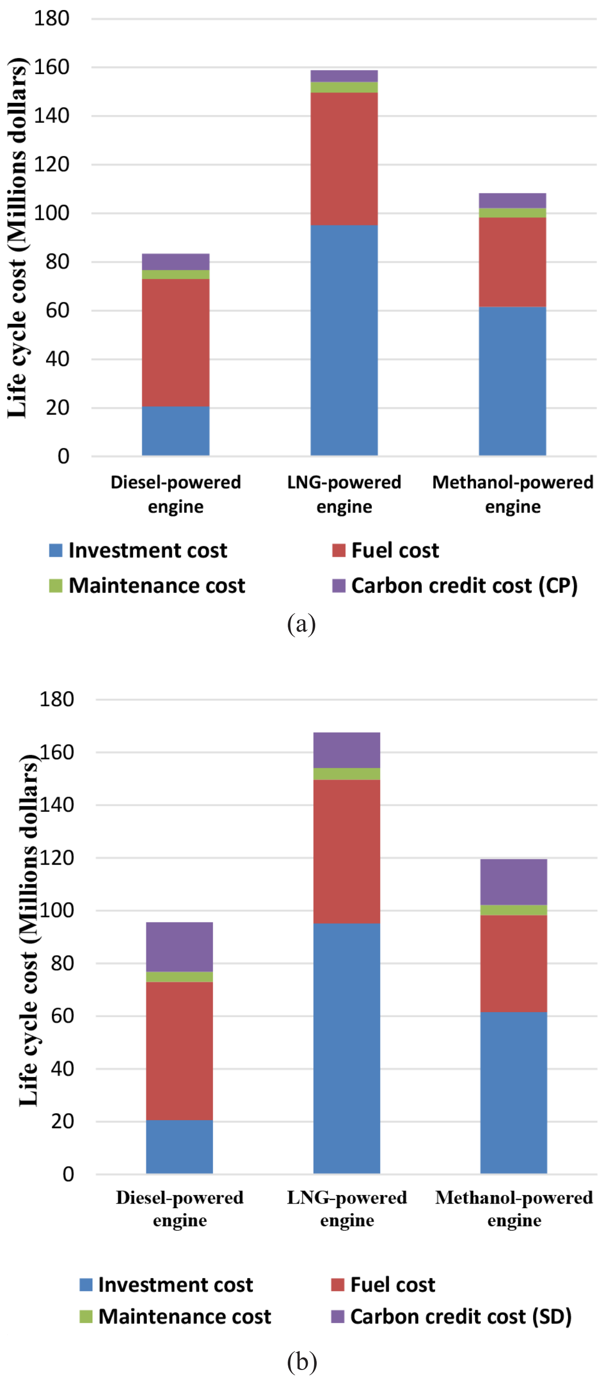


Figure 7. Comparative analysis of life cycle cost of different power system considering (a) CP carbon credit cost, (b) SD carbon credit cost

costs, this kind of option is hence a methanol-powered system. The analysis shows that the life cycle cost of a methanol-fueled system is lower than that of an LNG-fueled system. The analysis shows that the carbon credit cost for an LNG-powered system is the lowest among the other options, whilst the fuel cost of methanol is the lowest among studied options.

An insight into the impact of individual costs (investment, fuel, maintenance, and carbon credit costs) on the total NPV of each power system, with an assumed discount

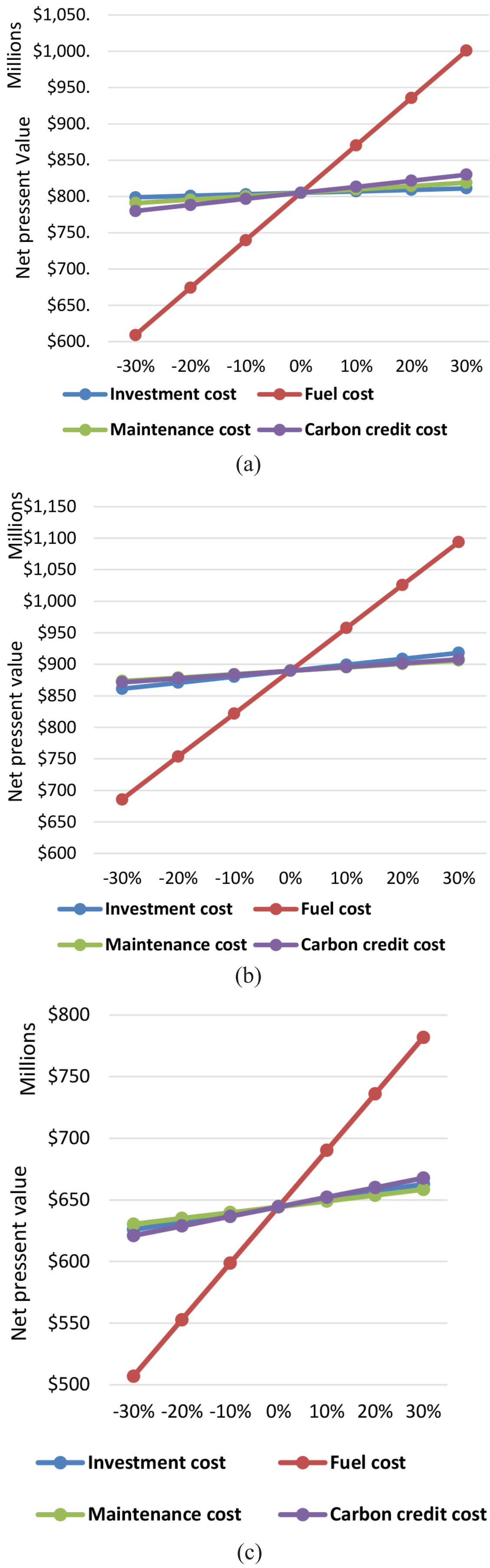


Figure 8. Impact of individual costs on the NPV for (a) diesel-powered system, (b) LNG-powered system, (c) methanol-powered system

rate of 5% (IMO, 2021), is performed and presented in Figure 8.

The analysis reveals that for most of the power systems, the cost of fuel has a major effect on the NPV and that by reducing the fuel costs, that is, with a fall in the price of fuel, the costs of the power system configurations become more acceptable. By varying the investment, maintenance, and carbon credit costs by ± 30%, with a step increment of 10%, the effect on the NPV is minor in comparison with the impact of fuel costs on the NPV for all power system options as shown in Figure 8.

## 5. CONCLUSIONS

The decarbonization of ship power systems through the use of alternative fuels is investigated in order to comply with ever stringent environmental regulations on the reduction of GHGs. The applicability of two alternative fuels (LNG, and methanol) is illustrated using the example of ultra large container ship. The main conclusions of this research are:

- From environmental point of view, using dual-fuel engine operated with 98.5% NG and 1.5% MDO will comply with the required IMO emissions regulations. This will lead to reductions in $CO_2$, SOx, and NOx emissions by 28%, 98% and 85%, respectively when compared with their values for SSDE operated by MDO (0.5%S). While the another proposed dual-fuel engine operated by 95% Methanol and 5% MDO will lead to reductions by 7%, 95% and 80%, respectively. Furthermore, the dual-fuel engine operated by natural gas and methanol will be compliant with the required IMO limit if the percentage of pilot fuel is lower than 8.8% and 6.4%, respectively.
- From energy efficiency point of view, the dual-fuel engine operated by (98.5% NG and 1.5% MDO) will comply with the required IMO EEDI phases now and in the future. On the other hand, the dual-fuel engine operated by (95% Methanol and 5% MDO) will comply with IMO EEDI phase 1, phase 2, and phase 3 by about 77%, 87%, and 99.5% of the reference EEDI value, respectively.
- The most cost-effective power system option is the one with the lowest total lifetime cost, which is a diesel-powered system for the case study. Even though methanol is shown as the most economical alternative fuel for the container ship, this study indicates that further development of the bunkering infrastructure and distribution chains of methanol are required. Since, the existing power system is the most cost-effective solution, replacing diesel with methanol, leads to a power system that is only 30% more expensive than the existing one.

Further investigation will focus on different hybrid power systems that can be applied onboard container ships. Their application, which depends on energy efficiency, i.e. environmental performance and cost-effectiveness, will be assessed. Finally, it should be mentioned that although this model has been applied in the case of container ship, it is generally applicable to other ship types if a relevant set of technical data, and information on operating conditions, of the considered type is available.

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