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Research Article

Keywords: Energy Efficiency, Environmental Protection, Alternative fuel, Liquefied Natural gas, ship emissions, Container ship

Posted Date: February 9th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-194729/v1

Version of Record: A version of this preprint was published on June 23rd, 2021. See the published version at https://doi.org/10.1007/s11356-021-14859-6.

Environmental Protection and Energy Efficiency Improvement by using Marine Alternative fuels in Maritime Transportation

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Abstract

Emissions from vessels are a major environmental concern because of their impacts on the deterioration of the environment, especially global warming of the atmosphere. Therefore, the International Maritime Organization (IMO) concern significant care to environmental protection through the reduction of exhaust emission and improvement of energy efficiency through technical and operational measures. Among the suggested measures from IMO, the alternative fuel such as Liquefied Natural Gas (LNG) has the priority to be used instead of fossil fuels. The present paper calculates the effect of using LNG in a dual fuel engine from Environmental and Energy efficiency perspectives. As a case study, a Container Ship has been investigated. The results of the analysis show that percent of CO_2, NOx and SOx emissions reduction corresponding to using a dual-fuel engine operating by LNG instead of a diesel engine operating by Heavy Fuel Oil is about 30.1%,81.44%, and 96.94%, respectively. Also, the attained Energy Efficiency Index Value in the case of using the dual-fuel engine is lower than its value by using diesel engine by about 30% and this value will be 77.18%, 86.84%, and 99.27% of the required value of the first, second and third phases, respectively as recommended by IMO.

Keywords: Energy Efficiency; Environmental Protection; Alternative fuel; Liquefied Natural gas; ship emissions; Container ship.

Abbreviations

CFD	Computational Fluid Dynamics
CSR	Continuous Service Rating
CO_2	Carbon Dioxide
DF	Dual Fuel
DWT	Deadweight
EEDI	Energy Efficiency Design Index
CEAS	Computerized Engine Application System
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IACS	International Association of Classification Societies
IGF	International Code of Safety for Gas Fuelled Ships
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

ITTC	International Towing Tank Conference
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
ME-GI	Main Engine Gas Injection
NG	Natural Gas
NOx	Nitrogen Oxides
PM	Particulates Matter
SFC	Specific Fuel Consumption
SG	Shaft Generator
SOx	Sulfur Oxides
TEU	Twenty-Foot Equivalent Unit

1. Introduction

Worldwide environmental change moves us to change the way we produce and use energy. In view of the detections of the world's air analysts, emissions decreases are essential to keep an essential separation from basic changes on the planet's atmosphere with outrageous ramifications for human wellbeing and the overall climate (Bouman et al. 2017; IPCC 2018a). Maritime transport is the primary mean of transport utilized worldwide and utilized for the improvement of the worldwide economy. In this manner, discharges from vessels are a huge ecological worry because of their impact on the debilitating of the climate, especially a worldwide temperature alteration of the environment. Thusly, the International Maritime Organization (IMO) which is the United Nations explicit office subject for protected and proficient transportation and the shirking of contamination from ships has made and embraced dynamically severe guidelines expected to basically decrease outflows from vessels. The Third IMO GHG study (Smith 2015) shows that global sea transportation created 796 million tons of CO_2 in 2012, speaking to around 2.2% of the complete overall CO_2 outflows for that year and that releases from worldwide sea transportation could grow someplace in the scope of 50% and 250% by 2050 primarily due to the improvement of the world maritime exchange. In this investigation, worldwide sea transportation is evaluated to make around 18.6 million and 10.6 million tons of NOx and SOx, Annually. Global NOx and SOx emanations are around 13% and 12% of overall NOx and SOx from anthropogenic sources itemized in the IPCC Fifth Assessment Report (IPCC 2018b), separately. In such a manner, IMO has been successfully busy with an overall way to deal with further improve marine energy proficiency and take measures to lessen outflows from ships. IMO's Marine Environment Protection Committee (MEPC) has given a wide idea to control of emanations from ships and received in 2011 a heap of specialized measures for new ships and operational decrease measures for all vessels. This pack incorporated another Chapter 4 of the International Convention for the prevention of pollution from ships (MARPOL) Annex VI which called " Regulations on energy efficiency for ships" and went into power on 1 January 2013 and applies to all vessels of 400 gross weights or more

(IMO 2011). These rules expect to improve marine energy proficiency and decrease outflows by lessening the measure of fuel devoured.

The bundle of technical and operational measures, that apply to ships more than 400 gross tonnages, requires new ships to be built to a compulsory design index, the Energy Efficiency Design Index (EEDI), which sets a base energy efficiency level for the work attempted (for example, CO_2 emissions per ton-mile) for various vessel types and sizes and gives a benchmark to compare the energy efficiency of vessels while setting a base required degree of efficiency for various vessel types and size. The EEDI has been created for the biggest and most energy serious sections of the world merchant fleet. The EEDI intends to expand the energy efficiency of new ships after some time. Mandatory execution of EEDI quickens the procedure of energy saving and emission reduction in maritime transportation, and higher prerequisites are proposed for the improvement of green vessels (Elkafas et al. 2020).

Measures for improving the marine efficiency from energy and environment perspective are relied upon to be implemented through EEDI application incorporate design and operational measures. Design measures fundamentally demonstrate various technical arrangements during design or construction steps for new ships and a few might be fitting for retrofitting existing vessels like improvement of hull design, hull coatings, weight reduction, air lubrication, ideal propulsion systems, waste heat recovery, fuel cells for auxiliary power, wind propulsion and utilizing an alternative fuel (Elgohary et al. 2015). Operational measures relate with methods that might be applicable on ships, for the most part without specialized modification like speed reduction, climate routing and voyage optimization, engine observation, auxiliary power reduction, trim/draft optimization, hull/propeller cleaning and skin friction reduction by air lubrication system.

The fundamental alternative marine fuel types might be found in two structures - liquid and gaseous fuels. Biodiesel, Ethanol, and Methanol are the liquid types that could be used as an alternative fuel in the marine application (Kolwzan et al. 2012). On the other hand, the fundamental alternative gasses fuels include Hydrogen, Propane, and natural gas. Among the previous sorts, Hydrogen and natural gas demonstrated numerous challenges to be applied onboard ships (Seddiek and Elgohary 2014). Hydrogen is demonstrated to be effective and environmentally friendly fuel. It has high specific energy, low start energy prerequisite, astounding flame speed, and wide flammability range. However, engines run distinctly with hydrogen require costly hydrogen generation, which constrains its utilization. Consequently, the cost of vessel powering by hydrogen fuel is high compared to natural gas (Bellaby et al. 2016; Mansor et al. 2017). To consent to IMO rules, Liquefied Natural Gas (LNG) is turning into a motivating choice for merchant vessels (Burel et al. 2013). LNG is a competitive fuel from both environmental and technical advantages over other fuels especially liquid ones (Banawan et al. 2010a; Seddiek et al. 2013; Elma et al. 2014).The combustion of natural gas discharges modest quantities of sulfur dioxide because of the diminished sulfur content in natural gas. Besides, the burning of natural gas in comparison with diesel is characteristically cleaner regarding pollutant emissions (NOx and particulate matter specifically). The burning of LNG is possibly connected with lower CO_2 emissions contrasted with diesel due to the lower proportion of carbon per energy content (Bengtsson et al. 2011). Moreover, LNG alternative fuel 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.

The present research aims at evaluating the potential environmental and energy efficiency benefits of using one of the technical long-term measures. The proposed long-term measure is the utilization of alternative fuel (LNG) as the main fuel in a dual-fuel engine. As a case study, a Container ship is investigated. The results are analyzed to show the impacts of conversion process on the environment and energy efficiency.

2. Energy-Environmental modeling for the assessment of LNG impact

This section aims to present the environmental and energy efficiency models with emphasis on the calculation of Energy Efficiency Design Index (EEDI) which applied to analyze the effect of LNG as an alternative marine fuel on ship emissions and energy efficiency.

2.1 Energy Efficiency Design Index calculation procedure

The IMO has approved vital energy efficiency rules for international ships underneath the Energy Efficiency Design Index (EEDI). EEDI is utilized to check associate degree energy-efficient design for explicit vessels. MARPOL Annex VI concern their regard for unique kind of vessels which have 400 metric gross tonnages and higher, for example, container ships, tankers, gas carriers, LNG carriers, bulk carriers, and passenger ships. EEDI Index is considered also for existing ships in service. The impact of maritime transportation on the environment can be shown in EEDI value. (American Bureau of Shipping 2014; Ančić and Šestan 2015; Bøckmann and Steen 2016).

2.1.1 Required EEDI

Required EEDI is the restrictive limit for EEDI. It is determined for all vessel types utilizing 100 % of the deadweight (DWT) at summer load draft, except for passenger ships where gross tonnage is utilized. The required EEDI value can be calculated as presented in Eq. (1) (Polakis et al. 2019; Elkafas et al. 2020).

$$EEDI_{required} = Baseline(1 - \frac{x}{100}) \quad (1)$$

The baseline is characterized as a curve indicating a mean value corresponded to a group of values for vessels from the same type. The baseline is created according to IMO guidelines using a group of ships from the same type with the corresponding capacity then a regression analysis is done to obtain the final form of the base line as shown in Eq. (2) (IMO 2013).

$$Baseline = a \times Capacity^{-c} \quad (2)$$

Where a and c are constraints vary from vessel type to another, their values are 174.22 and 0.201, respectively, for container ships. Capacity is the deadweight tonnage (DWT) (IMO 2013).

The reduction rate of the EEDI reference line value is determined by the fabricated year. It is between 10%, 20% and 30% in phase 1(1 Jan 2015-31 Dec 2019), phase 2 (1 Jan 2020-31 Dec 2024) and phase 3 (1 Jan 2025 and onwards), respectively (Germanischer-Lloyd 2013).

2.1.2 Attained EEDI

Attained EEDI is the actual value for the case study and its value should be lower than required EEDI to be satisfied by IMO (IMO 2018). Attained EEDI is a measure of energy efficiency for a ship and evaluated as presented in Eq. (3) (Polakis et al. 2019).

$$EEDI_{attained} = \frac{\prod_{j=1}^{M} f_j \left(\sum_{x=1}^{nME} P_{ME(x)} \times SFC_{ME(x)} \times C_{FME(x)}\right) + SFC_{AE} \times C_{FAE} \times P_{AE} + SG_e - ME_{er}}{f_i \times f_1 \times f_w \times f_c \times Capacity \times V_{ref}} \quad (3)$$

Where f_j is the ship-specific design elements correction factor, if elements aren't introduced, the factor is set to be 1. The power of the main engine (P_{ME}) is taken for EEDI procedure at 75% of Maximum Continuous Rating (MCR) for each main engine (x) in kilowatts. P_{AE} is the auxiliary power that is theoretically necessary to operate the main engine periphery and accommodation of the crew. Its value is a function of MCR of the main engine as presented in Eq. (4) in which P_{PTI} is 75% of the rated mechanical power of the shaft motor divided by the weighted efficiency of the generators (Ammar 2018; IMO 2018).

$$P_{AE(MCR_{(ME)}>10000KW)} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME} + \frac{\sum_{i=1}^{nPTI} P_{PTI(x)}}{0.75}\right)\right] + 250 \quad (4)$$

SFC is the specific fuel consumption measured in gram/ kilowatt hour and C_F is a conversion factor between tons of fuel burned and tons of CO_2 produced for each main engine (ME) and Auxiliary engine (AE). The conversion factors of fuels used in the marine field are introduced in **Fig. 1** (Rehmatulla et al. 2017; Tran 2017).

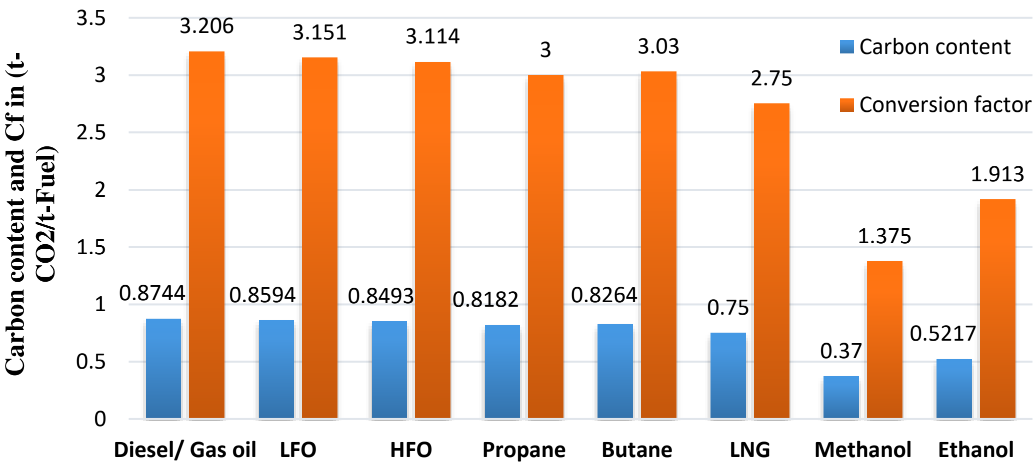

Fig. 1 Conversion factors and carbon contents for marine fuels

For the dual-fuel engine, Eq. (5) is utilized to calculate the term of C_F×SFC for dual fuel (DF) case study depending on the value of each one for gas fuel and pilot fuel at the related load point.

$$C_{F(DF)} \times SFC_{DF} = C_{F,pilotfuel} \times SFC_{pilotfuel} + C_{F,Gas} \times SFC_{Gas} \quad (5)$$

CO_2 emissions from Shaft generators (SG_e) and CO_2 emission reduction due to innovative technologies (ME_{er}) can be evaluated based on the power of the main engine as introduced in (Polakis et al. 2019). f_i is the capacity factor for any specialized limitation on capacity, and ought to be equal (1.0) if no need of the factor, f_l is a correction factor for general cargo ships outfitted with cranes, f_w is a non-dimensional coefficient demonstrating the reduction in speed due to wave and wind conditions (Liu et al. 2011) and f_c is the cubic capacity correction factor for special types of ships and ought to be equivalent to one if no need of this correction exists.

The term called Capacity depends on the ship type, for all ship types except passenger ships and container ships, the deadweight should be used as capacity while gross tonnage should be used for passenger ships and 70 % of the deadweight should be used for container ships.

The reference speed in EEDI conditions (V_{ref}) is calculated by assuming that the weather is calm with no wind or waves and measured according to the ITTC recommended procedure. The reference speed used in the calculation of attained EEDI must be estimated at 75% MCR (Germanischer-Lloyd 2013).

2.2 Calculation of exhaust emissions rates

The emissions from ships included many kinds of pollutants such as CO_2, SOx, NOx and PM emissions. The individual emission energy-based rate in g/kWh differs from type to another. When looking based on g CO_2 per kilowatt-hour, it is found that it is proportional to the specific fuel consumption and also the conversion factor between fuel and CO_2 as discussed in **Fig. 1** which concluded that the quantity of CO_2 emission depends on the fuel type (Elkafas et al. 2020). On the other hand, SOx is proportional to the specific fuel consumption (SFC) and the content of sulfur in the fuel (S) so that the SO_X emission energy-based rate (E_{SOx}) in g/kWh can be calculated by Eq. (6) (EPA 2000; ICF 2009).

$$E_{SOx} = SFC \times 2.1 \times (S\%) \quad (6)$$

Where S is the percentage mass sulfur content in the fuel and SFC is in g/kWh. It is seen that lower the sulfur content in fuel is lead to reduce the specific emission rate of SOx, which is the reason why more and more strict demands towards lower sulfur content are imposed on oil for marine diesel engines at the current time.

The emission of particulates (PM) has been seen as especially influenced by the sulfur content contingent upon the outcomes from various investigations which can be found in (Cooper and Gustafsson 2004; Pedersen et al. 2010). Based on these outcomes the following Eq. (7) has been derived for the particulate emission factor (E_{PM}) in g/kWh in which S is the sulfur content in % (Kasper et al. 2007; Agrawal et al. 2008).

$$E_{PM} = 0.26 + 0.081 \times S + 0.103 \times S^2 \quad (7)$$

The emission rate of Nitrogen oxide (NOx) relays with the type of engine and fuel the Tier which depends on the year of installation as the recommendations of the air pollutant emission inventory (Trozzi and Lauretis 2019), and illustrated in **Fig. 2**. As can be seen, the highest allowable specific NO_X emission rate (IMO Tier I level for engines manufactured before 2011) is 17 g NO_X/kWh for low-speed engines, while the rate for medium-speed engines (750 RPM) is approximately 12 g NO_X /kWh. For high-speed engines, at about 1100 RPM the allowable NO_X emission rate according to Tier I is approximately 11 g/kWh. IMO Tier II and III levels have to be fulfilled corresponding to 15 % and 80 % NO_X reduction respectively, compared with the Tier I level (Ammar and Seddiek 2020).

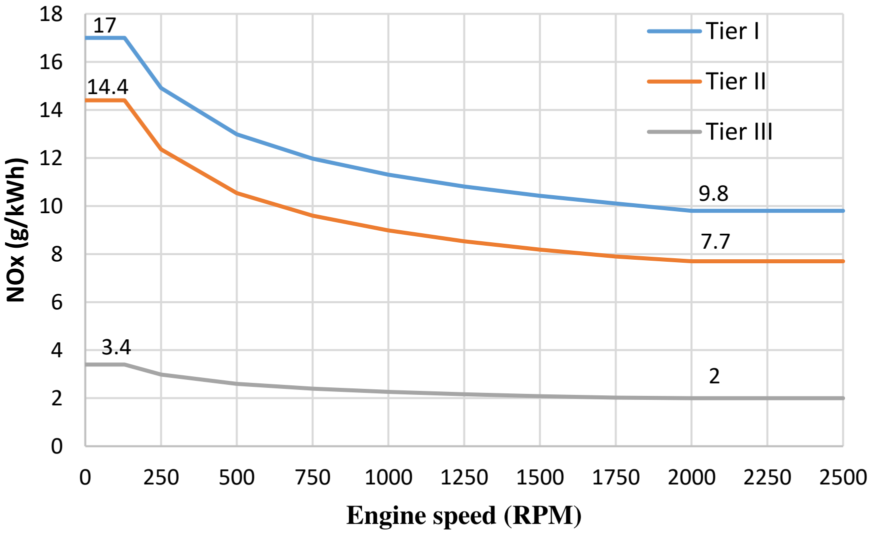

Fig. 2 NOx limits in MARPOL Annex VI

The conversion factor of each emission type between fuel and pollutant type can be determined in g (pollutant)/g (fuel) through divided the energy-based rate by the specific fuel consumption value at the actual service condition. The important rate factor for emission is the rate of emission per hour which can be calculated as presented in Eq. (8).

$$F_i = \mathrm{FC} \cdot C_{F(i)} \quad (8)$$

Where F is the emission rate factor for each pollutant type (i) on t /hr, FC is the fuel consumption in t/hr however, C_F is the conversion factor for every emission type (i). The emission rate can be modified to be based on the ship deadweight and the transported nautical miles (g/dwt.nm) by dividing emission factor (F) by the speed and deadweight of ship.

In sum, the method which can be used to apply LNG as a marine fuel is by using a dual-fuel engine such as ME-GI engine (MAN 2019). From an environmental perspective, the impacts of using a dual-fuel engine can be analysed by evaluating the emissions factor rate and then converts it to be independent of transport work. Dual fuel engine's emission factors can be calculated from that of pilot fuel and natural gas by taking the percent of each one inconsiderable. From an energy efficiency point of view, the process of the attained EEDI calculation will be identical in conventional and dual-fuel engines except for the calculation of specific fuel consumption and conversion factor. As presented in Eq. (5), the product of specific fuel consumption and conversion factor in the dual fuel mode can be calculated. Therefore, the attained EEDI in dual-fuel engine can be determined.

3. Container ship Case Study

The case study for the assessment process of energy efficiency and environmental impacts is selected to be a Cellular Container ship. The ship is operated by Hapag-Lloyd which have a total of 235 container ships and its fleet total Twenty-foot equivalent unit (TEU) capacity amounts to 1.7 million TEU (Hapag-Lloyd 2019). The container ship (RIO GRANDE EXPRESS) has a capacity of 4250 TEU. The ship was built in 2006 (15 years ago) by Samsung Heavy Industries Co. Ltd. Currently sailing under the flag of USA. Principal dimensions of the ship are given in **Table 1** (Fleetmoon 2020; Vesseltracking 2020).

Table 1 Principal dimensions of the container ship case study

Particular	Value
Ship name	RIO GRANDE EXPRESS
IMO NO.	9301823
Flag	USA
Built Year	2006
Container capacity, TEU	4250
LOA, m	260
Breadth, m	32
Depth, m	19.3
Draft (Summer), m	12.6
Service Speed, knots	23.7
Main engine type	MAN B&W 8K90MC-C
MCR power, kW	42504

The container ship is propelled by a low speed marine diesel engine (MAN B&W 8K90MC-C) with a MCR of 42504 kW which operated by HFO (MAN Diesel & Turbo 2012). Currently, the emission factors for the slow speed diesel engine operated by HFO can be calculated depending on the mentioned methodology in the previous section. The NOx emission factor depends on the installation year of engine, which is before 2010, therefore, NOx emission factor is 17 g/kWh. The selected condition is EEDI condition which uses 75 % MCR so SFC is equal to 166.4 g/kWh. The emission factors are 518.1 g/kWh, 17 g/kWh, 3.49 g/kWh, 0.44 g/kWh and 0.35 g/kWh for CO_2, NOx, SOx, PM, and CO, respectively (Elkafas et al. 2020).

It can be noticed that NOx and SOx emissions rates for the current engine are not compliant with the IMO 2016 and 2020 emission limits as IMO NOx 2016 limit for slow speed diesel engine is defined to be 3.4 g/kWh and the sulfur content is limited to be 0.5%. Referring to the calculated MCR, the proposed main engine for the conversion process from diesel engine operated by HFO to a dual-fuel engine operated by natural gas is chosen to be MAN 8S90ME-C-GI which is a verified dual-fuel engine that satisfies the rules of emissions and the safety requirements. The main specification of the main engine are shown in **Table 2** (MAN Diesel & Turbo 2012).

Table 2 Main specifications of the selected main engine (MAN Diesel & Turbo 2012)

Data description	Value
Engine type	8S90ME-C-GI
Max continuous power (kW)	42504
Max continuous speed (r/min)	84
Mean effective pressure (bar)	18.3
Cylinder bore (cm)	90
Stroke (mm)	3260

Data description	Value
Number of cylinders	8

Using the Computerized Engine Application System (CEAS) online calculation tool, the specific consumption of gas and pilot fuel can be determined in different power load by specifying a mixture of 97 % natural and 3% diesel fuel as shown in **Fig. 3** (MAN Diesel & Turbo).

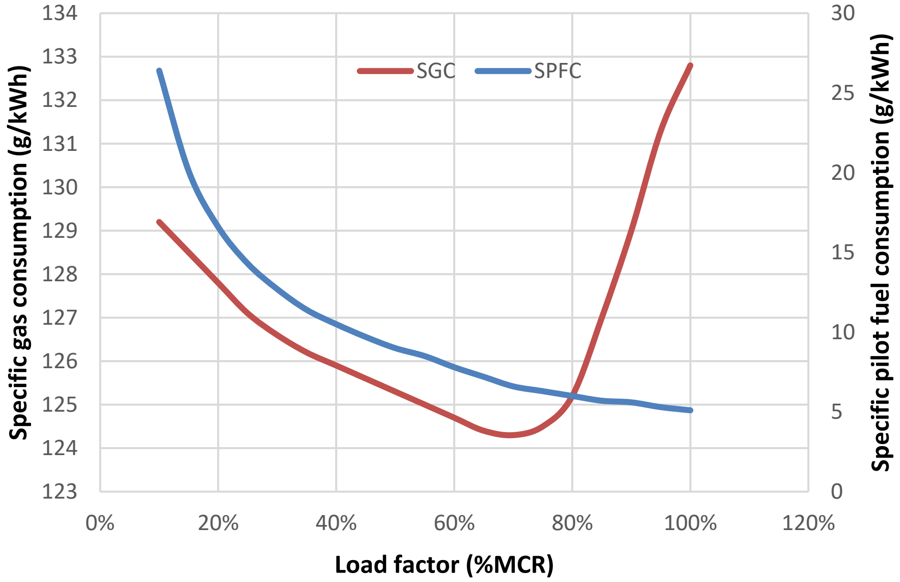

Fig. 3 Specific gas and pilot fuel consumption for different power factor

The lowest gas consumption occurs at approximately 70-75% MCR (EEDI power condition) for a normal engine tuning, while the specific gas consumption increases for higher and lower engine ratings, depending on the engine tuning.

4. Results and discussions

The energy and environmental impacts of using LNG as an alternative fuel in a dual fuel engine on the container ship case study are discussed. Firstly, the environmental effects of using LNG and the rate of exhaust emissions are discussed. Secondly, calculation of the required EEDI values at the baseline and the three phases according to IMO rules then the comparison of these values with the attained EEDI value at the operational speed of the case study operated by LNG in a dual-fuel engine.

4.1 Environmental Impact of using LNG

For the actual condition of the case study, the engine is assumed to be normally tuned and the ship is assumed to be loaded at the actual draught of 10.33 m corresponds to 70% maximum deadweight (EEDI capacity condition). By using the same service speed (23.7 knots) to be in the actual service condition, the necessary main engine power at this condition is 32744 kW so that Continuous Service Rating (CSR) can be calculated now by dividing the necessary power to the Maximum Continuous Rating of the main engine. The specific gas and pilot fuel consumption at actual condition can be calculated from **Fig. 3** corresponds to the CSR (%MCR). Finally, the data corresponding to the actual condition can be shown in **Table 3**.

Table 3 Gas and Pilot fuel consumption at actual condition

Parameter	Value
Engine rating in actual condition (CSR)	77%
Specific Gas consumption at CSR (g/kWh)	124.9
Specific Pilot Fuel Consumption at CSR (g/kWh)	6.1

Gas consumption (t/hr.)	4.1
Pilot fuel consumption (t/hr.)	0.19

The values of emissions factors of CO_2, NOx, SO_X, PM and CO for two-stroke diesel engine operated by Marine Diesel oil (MDO) are 545 g/kWh, 13.6 g/kWh, 3.57 g/kWh, 0.44 g/ kWh and 0.35 g/kWh, respectively. While Emission factors of CO_2, NOx, SOx, PM and CO for the natural gas engine are 355 g/kWh, 2.16 g/kWh, 0 g/kWh, 0.03 g/ kWh and 0.3 g/kWh, respectively (Banawan et al. 2010b; Seddiek and Elgohary 2014; Speirs et al. 2020). Dual fuel engine's emission factors can be calculated from that of marine diesel oil and natural gas engines by taking the percent of each one into account. **Table 4** presents the average emission factors for the selected dual-fuel engine operated at actual condition by using 97% natural gas and 3% marine diesel oil (Ammar and Seddiek 2017; Elkafas et al. 2020).

Table 4 the emission factors of dual fuel main engine

Fuel type	**Emission factor g/kWh**	**CO_2**	**NO_X**	**SO_X**	**CO**	**PM**
97% (NG)+ 3% (MDO)	Main Engine	360.7	2.5	0.107	0.302	0.042

The exhaust gas emissions rates in (g/dwt.nm) can be calculated when multiplying the fuel consumption to the corresponded specific emission factor as discussed in section 2.2 and the results are presented in **Table 5**.

Table 5 Exhaust emission rates by using dual fuel engine

Emission Type	**CO_2**	**NO_X**	**SO_X**	**CO**	**PM**
Emission Factor (g/dwt.nm)	14.48	0.099	0.004	0.0122	0.00167

Exhaust Emission rates in (t/hr) using a dual-fuel engine operated by 97% natural gas and 3% Marine diesel oil (MDO) can be obtained from emission factors in **Table 4**. These values can be compared with that of emission rates using the diesel engine operated by Heavy Fuel oil (HFO) as a main fuel. For the container ship, CO_2 emission rates are 12.42 t/hr and 17.76 t/hr for dual fuel engine and HFO diesel engine, respectively so that the percent of CO_2 emissions saving corresponding to using the dual-fuel engine is 30.1%.

NO_X emission rates are 85.04 kg/hr. and 458.07 kg/hr. for dual-fuel engine and HFO diesel engine respectively so that NO_X saving percent corresponding to using the dual-fuel engine is 81.44%. On the other hand, SO_X emission rates are 3.67 kg/hr. and 119.68 kg/hr. for dual fuel engine and HFO diesel engine respectively so that SO_X saving percent corresponding to using the dual-fuel engine is 96.94%. So, converting diesel engines to dual-fuel engines will reduce the emissions rates and comply with not only the current IMO emission rates but also with the future ones.

Environmental benefits of the dual-fuel engine by using natural gas as the main fuel and marine diesel oil as a pilot fuel are clear when compared with those of the diesel engine using HFO as the main fuel as shown in **Fig. 4** which shows that the dual-fuel engine has lowered the emissions rates of CO_2, NO_X, SO_X, CO, and PM by 30.1%, 81.44%, 96.94%, 13.11%, and 90.49%, respectively.

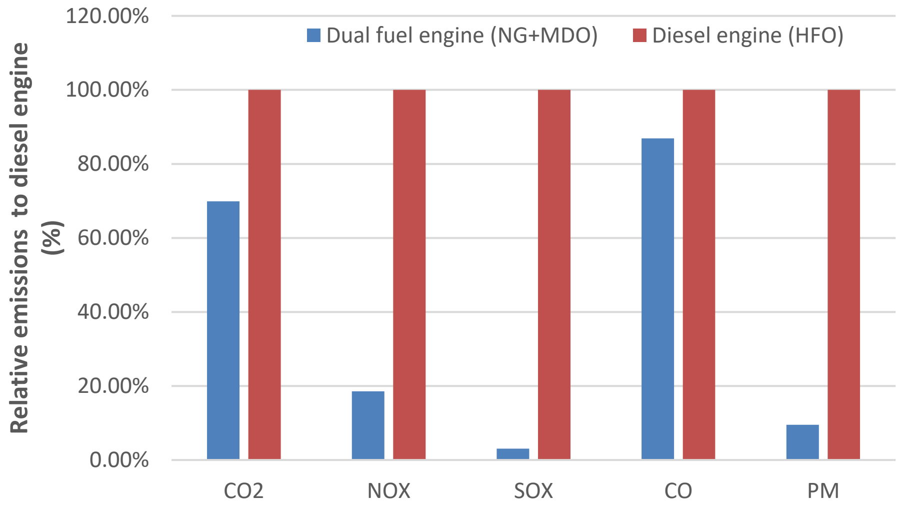

Fig. 4 Relative emissions of dual fuel engine and diesel engine for the case study

4.2 LNG effect on Marine Energy Efficiency

IMO has introduced an index to measure the marine energy efficiency EEDI. The EEDI assesses marine energy efficiency. The required EEDI is the greatest suitable limit for the Index and can be determined by utilizing Eq. (1) and Eq. (2). For the case study, the maximum Deadweight is 51741 tons. The reduction factor (x) is determined by the fabricated year, it is about 10%, 20%, and 30% in 2015, 2020 and 2025 at Phase 1, 2 and 3 respectively for the case study.

Fig. 5 shows the restrictive limit of EEDI for the container ship type for various deadweight values. For the case study at the Maximum deadweight, the baseline value of required EEDI is reduced from 19.66 gCO_2/ton-NM to 17.7, 15.73 and 13.76 gCO_2/ton-NM at the three phases respectively.

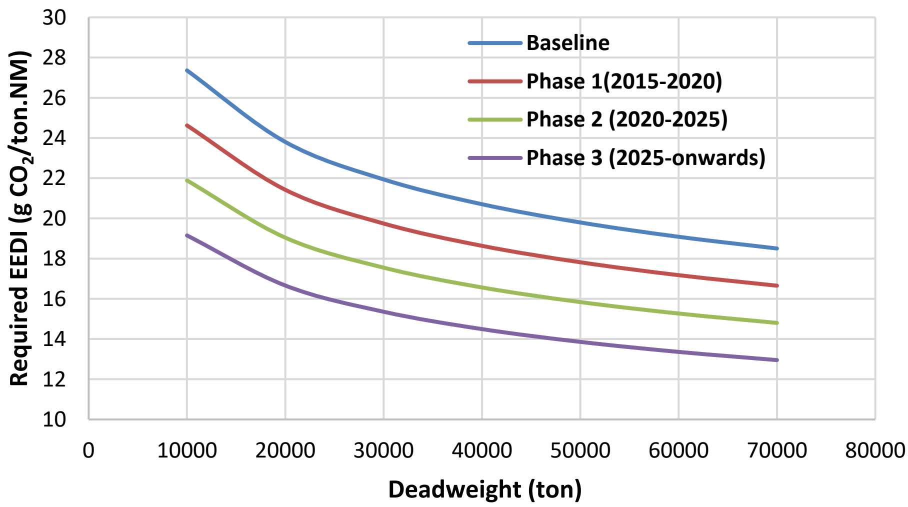

Fig. 5 the restrictive limit of EEDI based on IMO regulations for container ship type

The attained EEDI at design service speed can be determined according to IMO regulations based on the technical data of the case study. As discussed in section 2.1 and according to Eq. (3), (f_j, f_i, and f_c) for the case study are set to be 1.0. The ship is propelled by one main engine and only one generator is usually connected during normal seagoing conditions to supply the required electric power. The ship uses natural gas as the main fuel and marine diesel oil as the pilot fuel for main engine and auxiliary engines so that by using Eq. (5) the parameter ($SFC_{DF} \times CF_{DF}$) for both the main engine and auxiliary engine can be determined. The specific gas consumption and specific pilot fuel consumption of the main engine are determined at 75% MCR as recommended by IMO guidelines which can be determined from **Fig. 3**. The other parameters of attained EEDI are calculated as discussed in section 2.1 and presented in **Table 6**.

Table 6 Attained EEDI parameters for dual fuel engine

Parameter	Values	Units
Main engine power (75%MCR)	31878	kW
Auxiliary power	1313	kW
Specific fuel consumption (Natural gas)	124.5	g/kWh
Specific fuel consumption (Pilot fuel)	6.1	g/kWh
Conversion factor (Natural gas)	2.75	gCO_2/g fuel
Conversion factor (Pilot fuel)	3.206	gCO_2/g fuel
Capacity (70% DWT)	36219	tons
Reference speed	24.46	knots

The result of applying Eq. (3) for the attained EEDI is set to be 13.66 gCO_2/ton-nm at the design service speed. **Fig. 6** shows a comparison between the attained EEDI value by using a dual-fuel engine and the required EEDI values for the case study. it shows that attained EEDI value by using dual-fuel engine will be 77.18%, 86.84% and 99.27% of the required EEDI value of the first, second and third phases, respectively so that dual-fuel engine by using 97% NG and 3% MDO will comply with not only the current IMO EEDI requirement but also with the future ones.

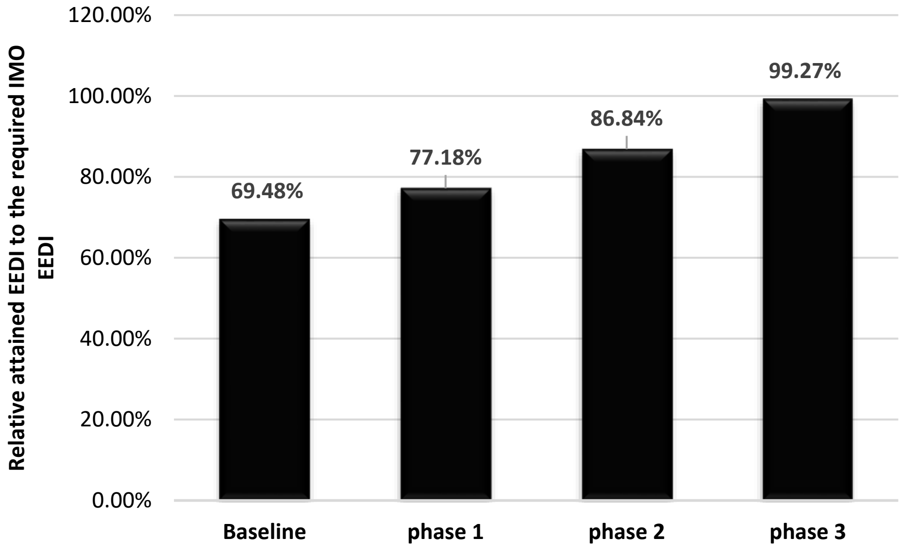

Fig. 6 Comparison of attained and required EEDI values for dual-fuel engine

By comparing the value of attained EEDI at the condition when using a dual-fuel engine with the condition when using diesel engine (HFO), it shows that attained EEDI value at the dual-fuel engine is lower than that at diesel engine by about 30% so that, converting diesel engine to dual-fuel engine operated by 97% NG and 3% MDO will improve marine energy efficiency.

5. Conclusions

The International Maritime Organization (IMO) identified many measures for the reduction of exhaust emission from ships and the improvement of marine energy efficiency through technical and operational viewpoints. One of the effective long-term measures for reducing emissions and improving Energy Efficiency is presented in the current paper. Liquefied Natural Gas (LNG) in a dual fuel engine which is a competitive fuel from both environmental and technical benefits over other fossil fuels. The dual-fuel engine requires the injection of pilot fuel to start the combustion and then gas fuel into the combustion chamber. The proposed dual-fuel engine in the research is operated with a mixture of 97% Liquefied Natural Gas and 3% Marine Diesel Oil in seagoing operations. The main conclusions from this paper can be summarized as follows:

- From an environmental point of view, the results of the analysis show that CO_2, NOx, SOx and PM emissions saving percent corresponding to using a dual fuel engine operated by LNG instead of diesel engine operated by HFO is about 30.1%,81.44%, 96.94%, and 90.5%, respectively. So, converting diesel engines to dual-fuel engines operating by LNG will reduce the emissions rates and comply with not only the current IMO emission rates but also with the future ones.
- From an energy efficiency point of view, the attained EEDI value at the case of using LNG in a dual fuel engine is set to be 13.66 gCO_2/ton-nm at the design service speed. This value is lower than that at diesel engine operated by HFO by about 30%. The attained EEDI value by using a dual-fuel engine will be 77.18%, 86.84% and 99.27% of the required EEDI value of the first, second and third phases, respectively. So that the dual-fuel engine by using 97% LNG and 3% MDO will comply with not only the current IMO EEDI requirement but also with the future ones.

Declarations

Consent to Participate

Not applicable

Conflict of interest

The authors declare that they have no conflict of interest.

Ethics approval

Not applicable

Consent for publication

Not applicable

Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Funding

Not applicable

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ahmed G. Elkafas. The first draft of the manuscript was written by Ahmed G. Elkafas. Mohamed Khalil, Mohamed R. Shouman and Mohamed M. Elgohary were commented and reviewed previous versions of the manuscript. Supervision of the research: Mohamed Khalil and Mohamed M. Elgohary. All authors read and approved the final manuscript.

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Figures

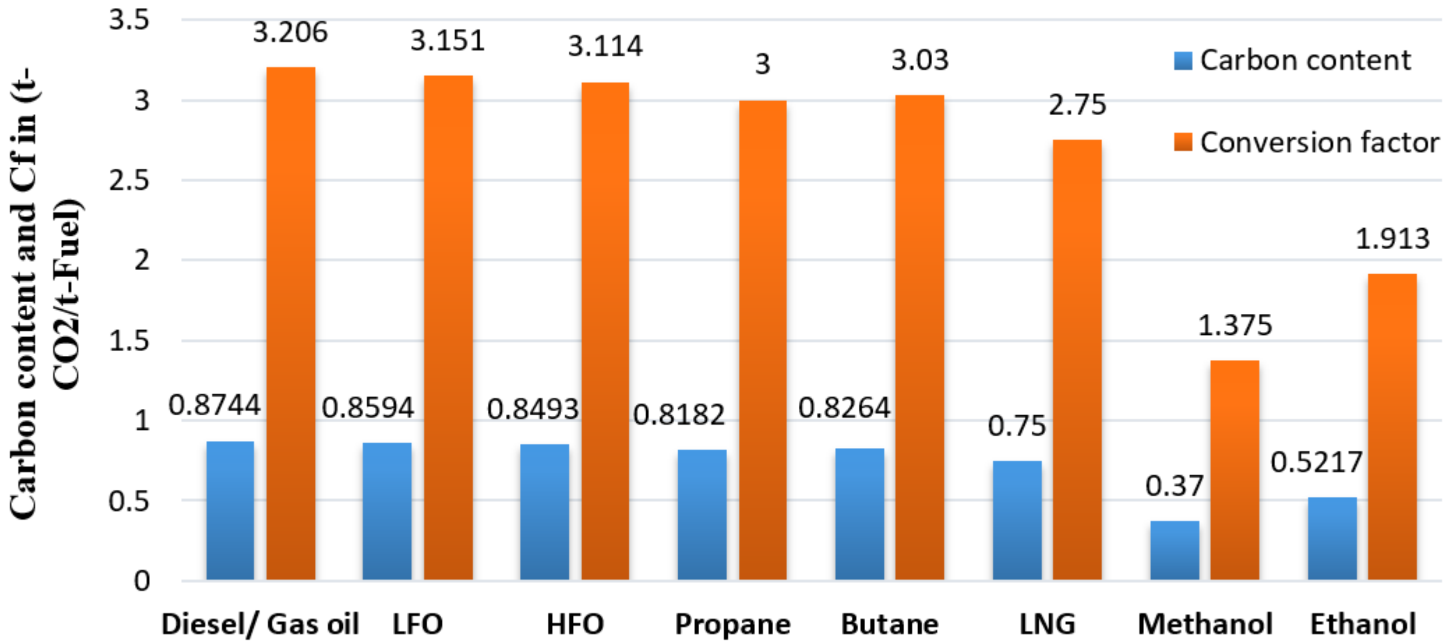

Figure 1

Conversion factors and carbon contents for marine fuels

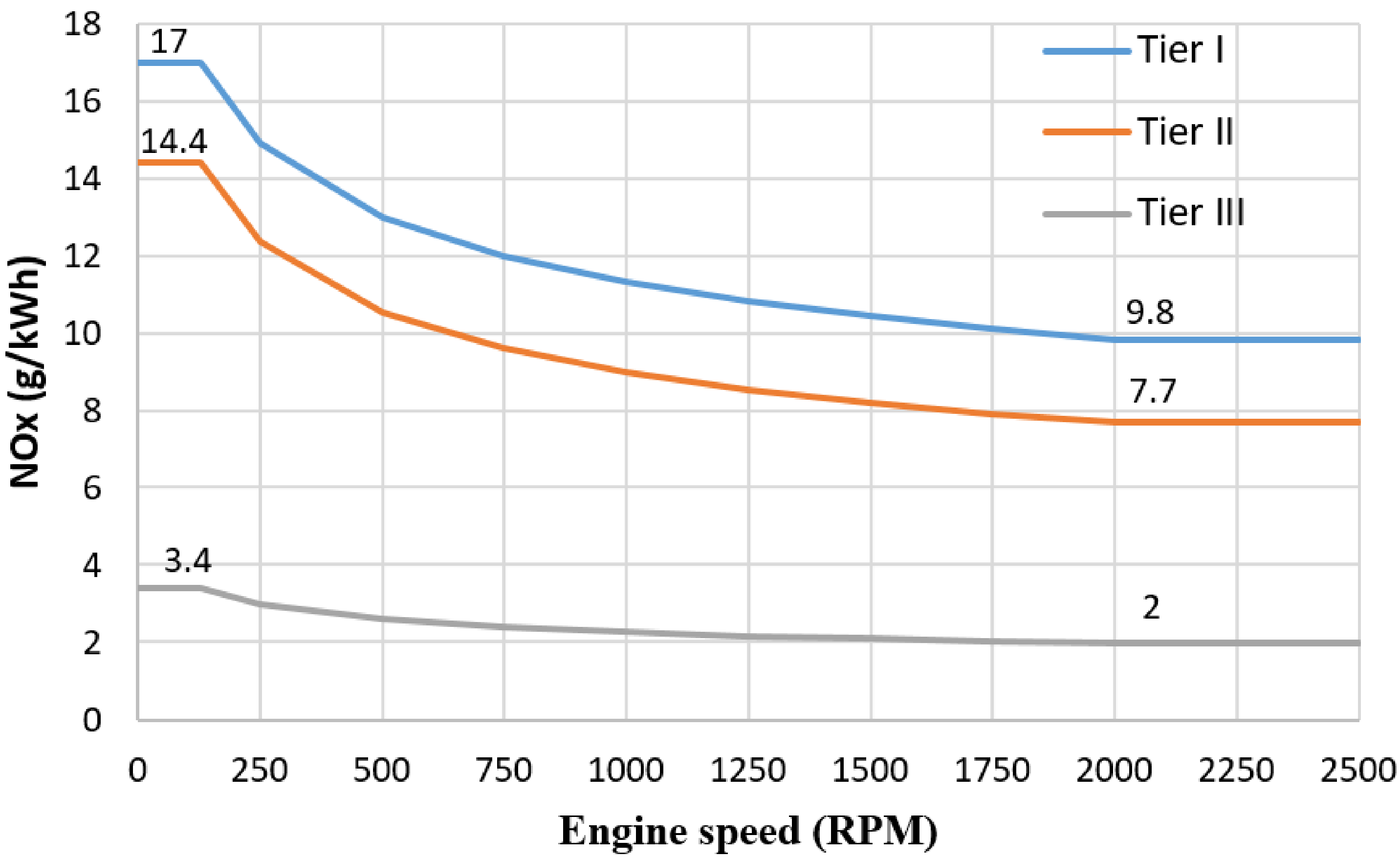

Figure 2

NOx limits in MARPOL Annex VI

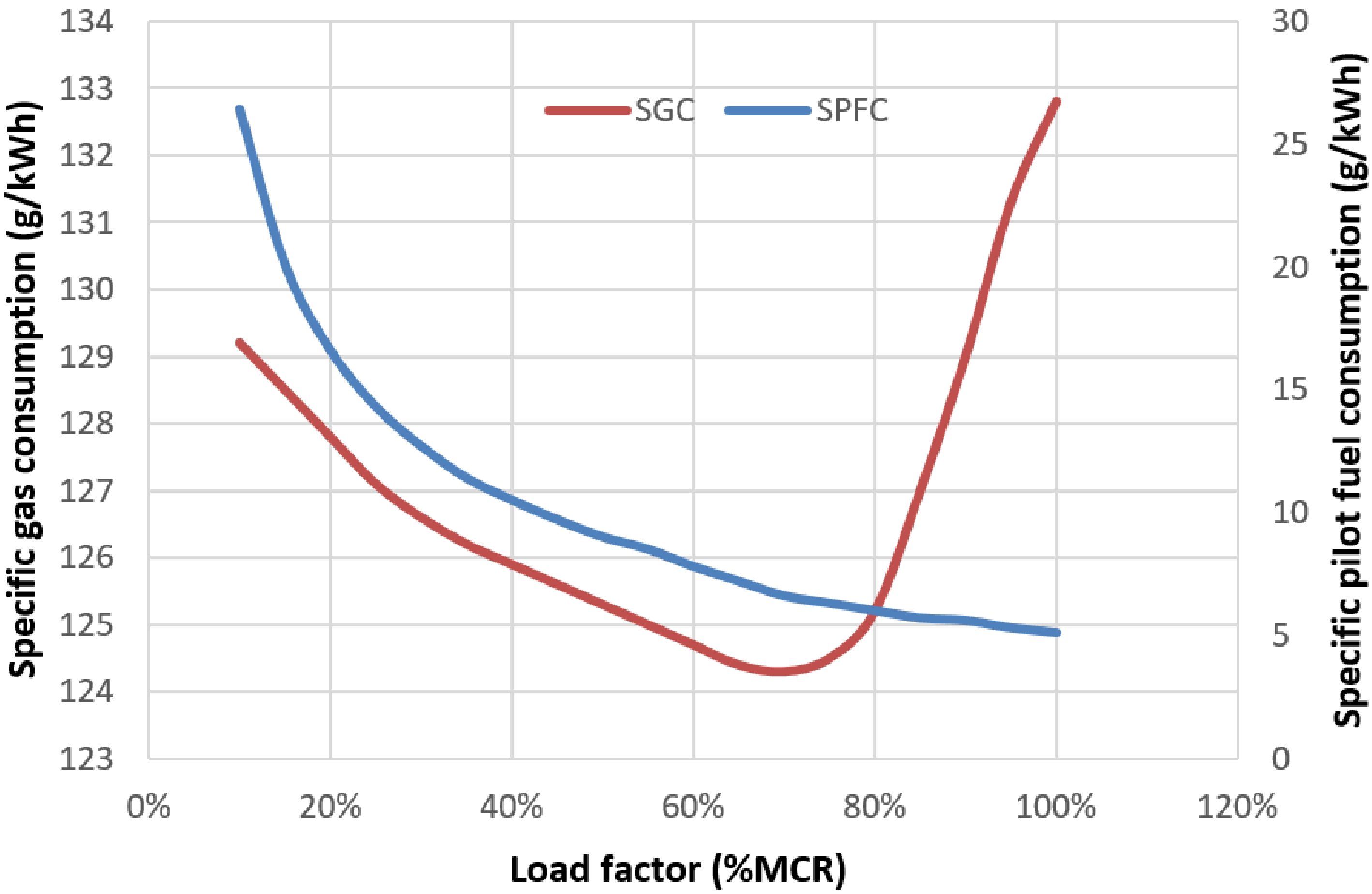

Figure 3

Specific gas and pilot fuel consumption for different power factor

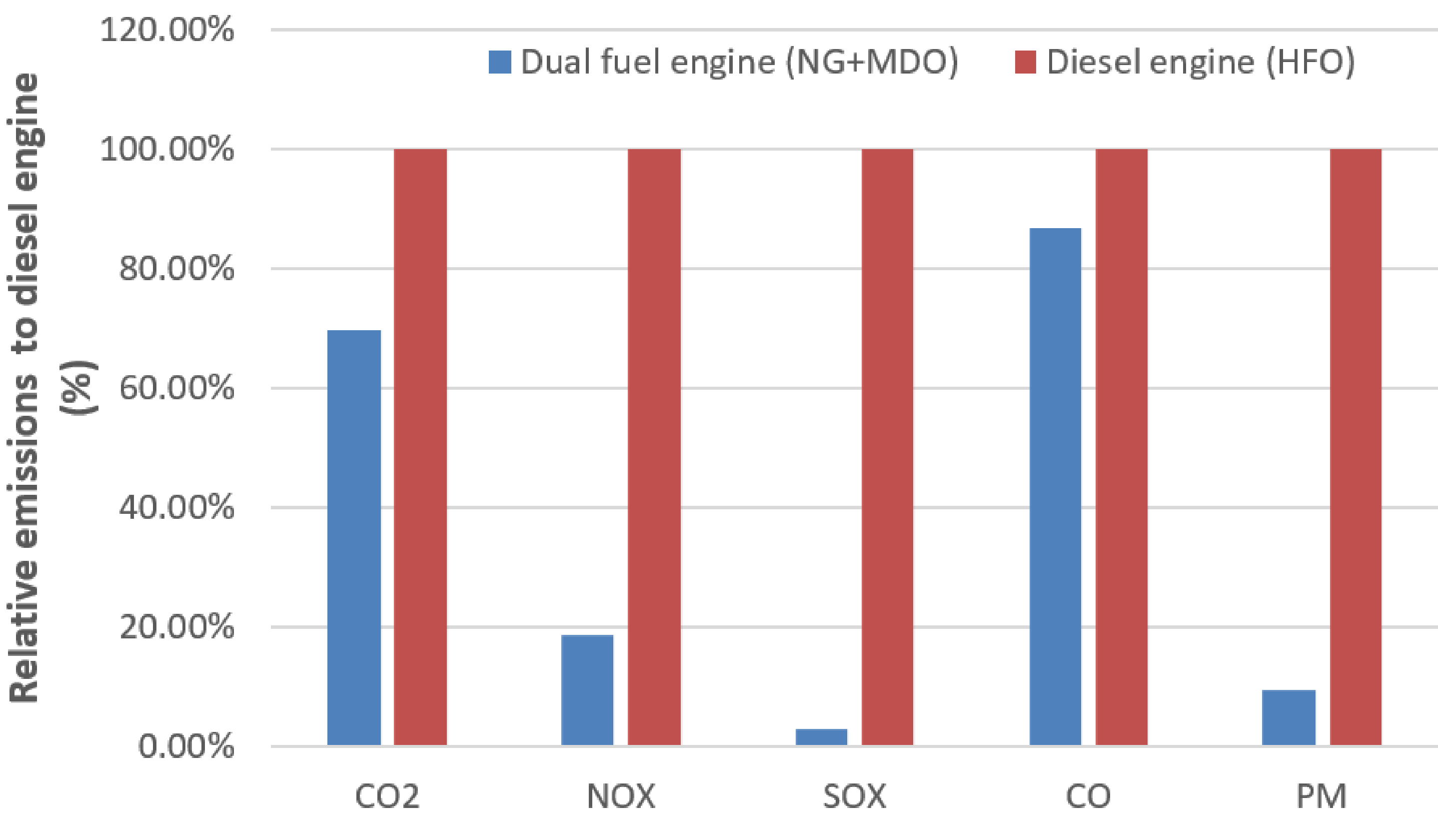

Figure 4

Relative emissions of dual fuel engine and diesel engine for the case study

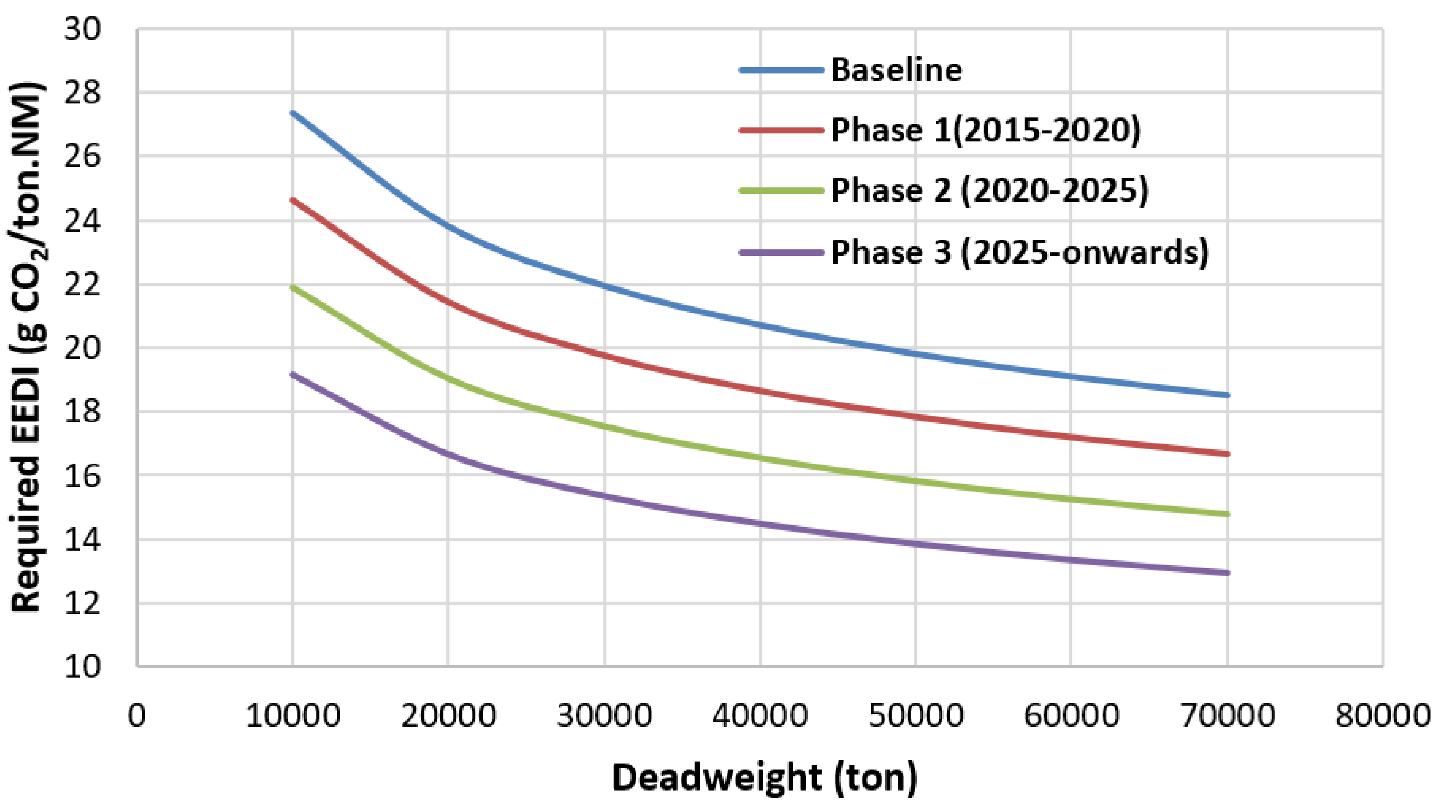

Figure 5

the restrictive limit of EEDI based on IMO regulations for container ship type

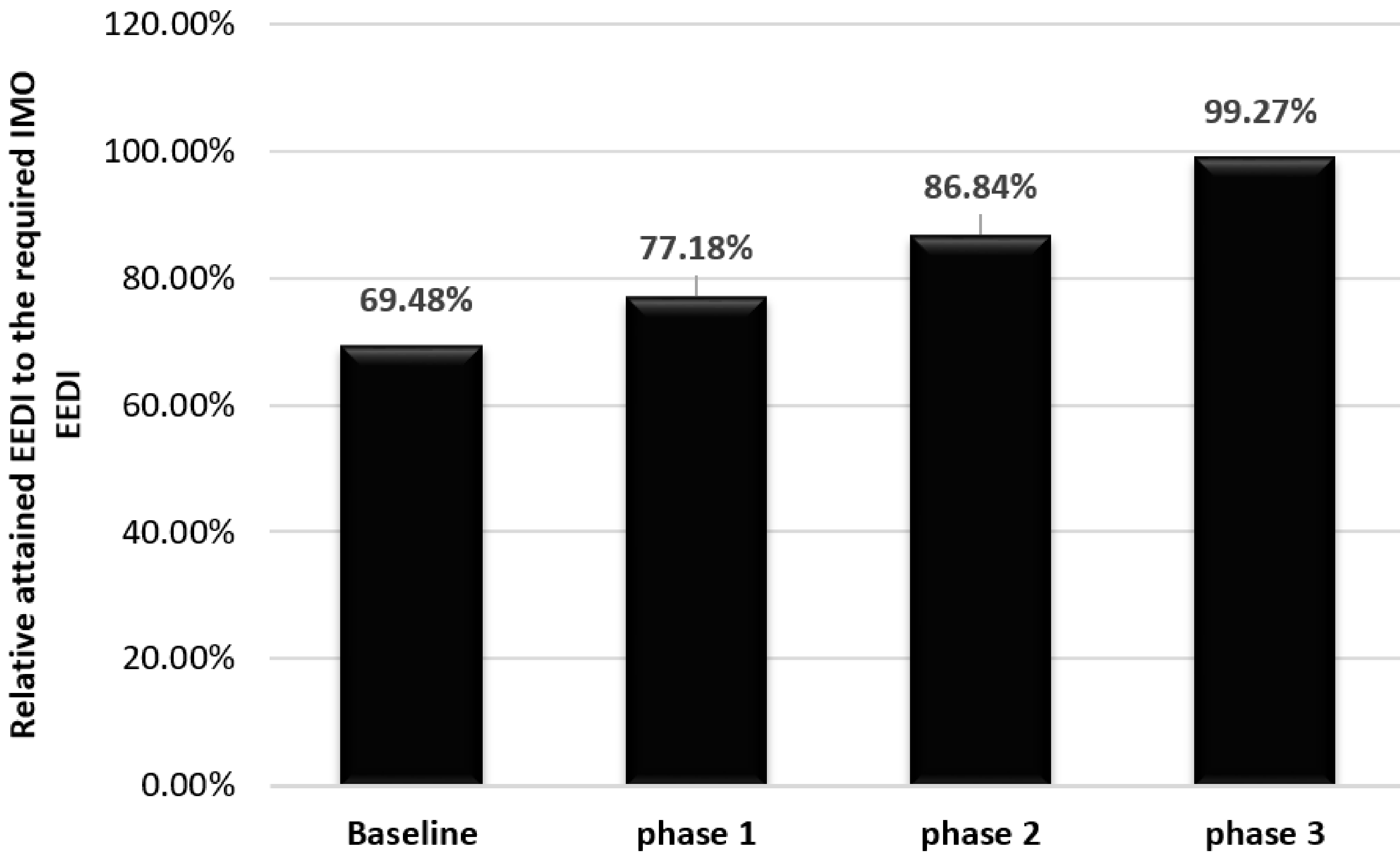

Figure 6

Comparison of attained and required EEDI values for dual-fuel engine