Environmental and economic performance investigation of natural gas and methanol as a marine alternative fuel.

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Abstract

Emissions from ships are a serious global issue due to their effects on environmental damage, particularly global warming of the atmosphere. As a result, the International Maritime Organization (IMO) places a high priority on environmental protection by reducing exhaust emissions by at least 50% by 2050. Among the IMO's proposed measures, using alternative marine fuels such as natural gas and methanol instead of conventional fuels has been prioritised. In this paper, a comparative study between convert diesel engine into dual fuel engine operated with alternative fuels such as methanol or natural gas is carried out. Environmental and economic assessment of the natural-dual fuel engine and methanol- dual fuel engine is conducted. A13-class container ship is investigated as a case study. The evaluation results show that using natural gas in a dual fuel engine with a percentage (95% NG and 5% MDO) reduces NOx, SOX, CO2, PM, and CO pollutions by 83%, 95%, 19.4%, 95%, and 32.6%, respectively, while the emissions percentage will be 81.2%, 95%, 57.1%, 95%, and 58.4%, in order, when using methanol as a dual fuel with percentage 95% Methanol. Moreover, the cost-effectiveness of using natural gas was 769.25 $/ton, 3304.1$/ton, 81.2 $/ton. 60082.64 $/ton, and 23782.84 $/ton for NOx, SOx, CO2, PM, and CO, in the order, while for methanol, was 850.67 $/ton, 3340.1$/ton, 45.588 $/ton, 55450.87 $/ton, and 13274.11 $/ton, respectively.

Introduction

Global environmental change compels us to alter our energy production and consumption practices. According to the findings of the world's air analysts, emission reductions are required to maintain a critical separation from fundamental changes in the planet's atmosphere, which have disastrous consequences for human well-being and the overall climate. According to recent International Maritime Organization IMO statistics, ships emit a significant amount of carbon dioxide (CO2), nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), and carbon monoxide (CO) (Elkafas et al., 2019). Furthermore, studies have demonstrated that ships produce annually approximately 1.1 Gt of carbon dioxide (CO2), accounting for 3% of global greenhouse gas (GHG) pollution, in addition to 2.3 Mt of sulfur dioxide (SOx), 3.2 Mt of nitrogen oxides (NOx), 1.4 Mt of particulate matter (PM), and 936 thousand tons of carbon monoxide (CO) (Ammar and Seddiek 2020a; IMO 2014b). IMO has established stringent targets to significantly reduce NOx, SOx, CO2, PM, and CO air-quality-related emissions. For NOx emission, regulation 14 is applied on marine diesel engines of over 130 kW output power, while to reduce SOx and PM pollutions, the sulfur content of the used fuel is limited (Yang et al., 2012). In terms of CO2 emission, the IMO introduced two ways to evaluate a ship's compliance with international regulations. These indicators are the Energy Efficiency Design Index (EDDI) and the Energy Efficiency Operation Index (EEOI) (Rehmatulla et al., 2017). Fig. 1, shows that there are approximately 54,743 merchant ships contributing to international shipping of goods and passengers. These ships account for 55% of total CO2 emissions (Olmer et al., 2017). Among of these ship types, container ships appear to be the type that contribute by the highest percent of CO2 emissions. Several methods that can be used to reduce GHG pollution from ships, according to mitigating measures, include propulsion systems, ship design, renewable energy, and alternative fuels (El Gohary et al., 2016; Sadek and Elgohary 2020). Searching for alternative marine fuels is considered the best solution method to solve the fossil fuel depletion problem. The primary alternative marine fuel types can be divided into two categories liquid fuels (methanol, biodiesel, and ethanol) and gaseous fuels (natural gas, hydrogen, and propane). Biodiesel is a type of green alternative fuel that emits less soot (PM), unburned hydrocarbons, carbon monoxide (CO), and sulfur dioxide (SO2). However, it performs poorly at low temperatures, and increased demand for its production has resulted in a food crisis, as well as an increase in NOx emissions (Kesieme et al., 2019). Studies have shown that ethanol can be used as an alternative fuel in marine applications, with combustion releasing only carbon dioxide and water, but with a poor start in cold weather. The main issue with hydrogen as an alternative fuel is its high cost of production and use, particularly when renewable energy is used to produce hydrogen fuel (Elgohary and Seddiek 2015). Methanol (ME) and liquid natural gas (LNG) are the best types of alternative fuels that can be used in marine engines. Natural gas (NG) is considered the most promising option for lowering GHG emissions. Methane (CH4) is the primary component of (NG); it contains the least amount of carbon and sulfur, which reduces CO2 and SOx emissions (Elgohary et al., 2015). Furthermore, when compared to diesel, natural gas combustion produces significantly less nitrogen oxide (NOx). Natural gas can be found in compressed form or in liquid form (Cheenkachorn et al., 2013). Liquid natural gas (LNG) is more efficient compared to compressed natural gas (CNG) in terms of safety, transportation, and storage (Li et al., 2015). LNG is preferred for long-term use, is more cost-effective in long-distance transportation systems, and is more environmentally friendly (Spoof et al., 2020; Arteconi et al., 2010). Methanol (ME) is another type of alternative marine fuel that can be used to reduce marine pollution and meet IMO 2020 requirements (Methanol 2018). Many research projects investigated methanol as a marine fuel such as Methaship, SPIRETH project, and Swedish EffShip, demonstrating methanol's ability to reduce NOx, SOx, CO2, PM, and CO emissions (Andresson et al., 2020; Dierickx et al., 2018). The aim of this research is to evaluate the environmental and technical benefits of using alternative fuels as a marine fuel. In addition to economic effects of using dual fuel engine with alternative fuel. This assessment is based on a comparative study between two alternative fuels, natural gas (NG) and methanol (ME) in terms of environmental and economic efficiency. A13-class container ship is investigated as a case study.

Environmental Analysis Methodology

Firstly, the total emission for ship during one travel per ton can be calculated by using Eq. The ship emission (EM) depends on the main engine power (P_w) in KW, the operation trip time (T) in h, the load factor (L_f) to take the consideration of maneuvering and standby during the trip, and fuel pollution factor (P_f) in g/kWh; (i) is the type of emission, (f) is the type of fuel (Ammar 2019; Ammar and Seddiek 2020).

$$EM_{trip,i,f} = \sum \left[T\left(P_w . L_f . P_{f,i}\right)\right]$$

1

The emission factor value is related to the type of exhaust. For CO2 emissions, the carbon content in a fuel, which varies from fuel to another, is the main parameter used to calculate the pollution factor for each fuel. Fig. 2 shows the carbon content for each fuel. CF is the conversation factor, and SFC is the specific fuel consumption (g/kwh) (Elkafas et al., 2021).

$$P_{co2} = SFC.CF$$

2

In terms of NOx emissions, the IMO has issued a new regulation that calculates the pollution factor for NOx based on the ship's construction date, and the speed engine (n), which can apply to ships built after January 1, 2000 (Mostafa et al., 2021).

$$P_{NOX} = 45.n^{-2}$$

3

Because sulfur is the main component of SOX, the pollution factor for SOx is determined by the specific fuel consumption (SFC) and the percentage of sulfur in the fuel (S %). The following equation can be used to calculate P_{sox} (ICF 2009).

$$P_{SOx} = SFC * (S\%) * 2.1$$

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For particulate matter (PM), previous studies have shown that PM emissions are related to sulfur content (S) and are based on the specific fuel consumption, which can be calculated by using the following Eq (Cooper and Gustafsson 2004; Kasper et al., 2007).

$$P_{PM} = SFC * (0.15729 * S\% - 0.000377) + 0.23$$

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In this study for a slow speed diesel engine (SSDE), the pollution factor such as P_{NOX}, P_{sox}, P_{CO2}, P_{PM}, P_{co}, and P_{HC} for marine diesel oil, natural gas and methanol was shown in Table 1, according to other studies (Ammar and seddiek 2017; Banawan et al., 2010; Seddiek and Elgohary 2014). Now, for a dual-fuel engine which is operated between two fuels, the total emission factor for each fuel is calculated with the effect of fuel percentage, as shown in the following Eq. Where, P_{total} is the total emission factor for dual fuel engine, P_D is the emission factor for pilot diesel fuel, and P_{gas} is the emission factor for alternative fuel.

$$P_{total} = (Diesel\%) * P_D + (New - fuel\%) * P_{gas}$$

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Table 1
Emission factors for slow speed diesel engines

Fuel type	P_{NOX} (g/kwh)	P_{sox} (g/kwh)	P_{CO2} (g/kwh)	P_{PM} (g/kwh)	P_{co} (g/kwh)	P_{HC} (g/kwh)
MDO	17	0.36	688.79	0.19	1.4	0.6
NG	2.16	0	548.2	0	0.92	1.4
ME	2.47	0	275	0	0.54	0.9205

NOx emission assessment: IMO provides a regulation to prevent pollution such as MARPOL Annex VI Regulation 13, which addresses the NOx Emission. This regulation is applied to engines with output power greater than 130 KW and for ships built on or after 1 Jan 2000. The reduction of NOx emission is passed through 3 levels: Tier I, Tier II and Tier III, which were implemented on 1 Jan 2000, 2011, and 2016, respectively, based on the engine speed (n), as shown in Fig 3. Tier III aims to reduce NOx by 80% compared with Tier I and is applied in the Emission Control Area (ECA). For SOx emissions, IMO adopted Regulation 14 in MARPOL ANNEX VI to eliminate the sulfur content in marine fuel, which is the main factor in creating SOx pollution. In 2020, IMO issued a new globally regulation to reduce the sulfur content in fuel from 3.5% to 0.5% m/m, while for ECAs, the highest restriction was applied to reduce SOx from 1% to 0.1% in 2015, as illustrates in Fig. 4 (Trozzi and Lauretis 2019; Ammar and Seddiek 2020b). For CO2 emissions, IMO adopted two methods: Energy Efficiency Design Index (EEDI) and Energy Efficiency Operational Indicator (EEOI) to evaluate the energy efficiency during operation and assessment for CO2 pollution. The EEDI is utilized to calculate the energy efficiency for vessels with 400 metric gross tonnages and higher, such as LNG and carriers, container ships, and tankers. The complex formula is executed to calculate EEDI based on a ship's emission, speed, and capacity (ABS 2013; Ančić and Šestan 2015). EEDI is computed according to IMO by using the following equation (Ammar and Seddiek 2020a; Ammar 2018): For IMO, two EEDI values are used to assess the energy efficiency of vessels: required EEDI and it is the EEDI's constrictive limit and calculated for all fully deadweight vessel types by using Eq (7). Attained EEDI is the actual value which can be evaluated by using Eq (8). $AECO_2emission$ is calculated in case of the MCR of the main engine is greater than 1000 KW (IMO 2013; IMO 2018). Table 2 shows the description of equation parameters

$$EEDI_{require} = \left(1 - \frac{X}{100}\right) * \frac{174.22}{DWT^{0.201}}$$

7

$$EEDI_{attained} = \frac{\left(ME\left(s\right) + AE\left(s\right) - innovativetechnology\right) CO_2emissions}{Transportwork}$$

8

$$MECO_2emissions = \left\{ \sum_{i=1}^{nME} P_{ME(i)}.\, C_{FME(i)}.\, SFC_{ME(i)} \right\}$$

9

$$AECO_2emission = \left\{ 0.025 * \left(\sum_{i=1}^{nME} MCR_{ME} + \frac{\sum_{i=1}^{nPTI} P_{PTI(x)}}{0.75} \right) + 250 \right\} * C_{FAE}.\, SFC_{AE}$$

10

$$ReductionCO_2frominnovativetechnology = \left\{ \sum_{i=1}^{neff} f_{eff(i)}.\, P_{eff(i)}.\, C_{FME}.\, SFC_{ME} \right\}$$

11

$$Transportwork = f_i.\, f_1.\, f_w.\, f_c.\, V_{ref}.\, Capacity$$

12

Both of specific fuel consumption (SFC) and conversion factor (CF) are related on fuel types, and for dual fuel engine, the term of SFC*CF can be evaluated by Eq:

$$SFC_{DF} * CF_{Df} = SFC_{PF} * CF_{Pf} + SFC_{Gas} * CF_{Gas}$$

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Energy Efficiency Operational Indicator (EEOI) assessment:

The Energy Efficiency Operational Indicator (EEOI) is another methodology used by IMO to calculate CO2 gas emissions to the environment per ton of transport work, described in Eq. (14): where i is the number of voyages, FC is the fuel consumption mass, CF is the conversion factor from fuel to CO2 emission, m is the cargo weight on board, and D is the is the distance of a voyage in nautical miles (Tran 2017; IMO 2009).

$$EEOI = \frac{\sum_i FC.\, C_f}{\sum_i m_{cargo}.\, D}$$

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Table 2 describe for EEDI Parameters

X	**The reduction percentage in EEDI based on IMO requirements, which increases from 10–20%, and 30% in 2015, 2020, and 2025, respectively.**
DWT	Dead Weight Tonnage
ME, AE	Main Engine, Auxiliary engine
$P_{ME(i)}, P_{AE}$	Power output from main engine, Power output from auxiliary engine
$SFC_{ME(i)}, SFC_{AE}$	Specific fuel consumption for engines
$C_{FME(i)}, C_{FAE}$	The fuel conversation factor from engines to$CO_2 emission$
MCR_{ME}	The maximum continuous rating for main engine(s)
$P_{PTI(x)}$	The shaft motor mechanical power divided by the generators weighted efficiency
$.P_{eff(i)}$	Power saving Because of innovative electrical energy efficient technology
V_{ref}	The reference speed of the ship
Capacity	For passenger ships, it is the gross tonnage, and for container ships, it is 70% of the DWT. The total DWT is used as capacity for other types.
$f_i, f_1, f_w, and f_c$	The correction factor for specific ship types. f_w is a non-dimensional factor that considers weather and environmental conditions and is calculated using Eq: $.f_w = 0.0208 * \ln(Capacity) + 0.633$

2. Economic analysis methodology

The economic analysis for using methanol or natural gas as a dual fuel evaluated by calculate the reduction of ship emissions annual cost-effectiveness E_{CE}. This includes the annual capital cost reduction (ACC) of using alternative fuels onboard and the conversion process in $/ton, the maintenance and operation costs (AMC), and the amount of emission reduction (RE) in tons/year, as shown in Eq (Ammar and Seddiek 2020b):

$$EAC_{CE} = \frac{ACC + AMC}{RE}$$

Case Study: Container Ship

In this study, A13-class container ship was selected to study the environmental and economic impacts assessment process from using alternative fuels instead of diesel fuel (Ammar and Seddiek 2020a). The container vessel AL RIFFA, which is owned by a United Arab shipping company and operated by Hapag-Lloyd, Hamburg, was built in 2017 with 13500 containers and sailing under Malta flag. Table 3 depicts the ship's critical data (Al Riffa 2022). The ship operated with a slow speed diesel engine that uses marine diesel (0.1S%) to move cargo between several ports in the United States of America, the Mediterranean and the Middle East region with a maximum continuous rating of 74255.5 kW. The relation between the specific fuel consumption and MCR can be used to calculate SFC (El Gohary and Abdou 2011). For 85%MCR, SFC is 169.1 (g/kwh). As shown in Table 3, for low-speed diesel engines, the emission factors are 17 g/kWh, 0.36 g/kWh, 688.79 g/kWh, 0.19 g/kWh, 1.4 g/kWh, and 0.6 g/kWh for NOx, SOx, CO2, PM, CO, and HC, respectively. Both NOx and SOx emissions are incompatible with current IMO limitation as IMO 2016 regulation reduced NOx emissions to less than 3.4 g/kWh and IMO 2020 regulation limited SOx to 0.5%. For this, the conversion process from using marine diesel fuel to dual fuel operated by alternative fuels (Methanol and natural gas) were evaluated to study its effect on marine pollution.

Table 3
The container ship case study's primary dimensions

Specifications	A 13
Ship’s Name	Al Riffa
Year built	2012
IMO No.	9525912
Flag	Malta
Length over all (m)	366
L.P.P, (m)	350
Breadth over all (m)	48
Speed (kn)	23
Power (kw)	71770
TEU	13470
Deadweight (tdw)	145528
Gross Tonnage (GRT)	141077
Displacement (ton)	187974.2
Main engine	MAN B&W 12K98ME
Waste Heat Recovery (KW)	1818 T/G
Shaft Generator [PTI/PTO] (KVA/KW)	3222/2578
Length of trip	20600 N.M

The ship is currently powered by MAN B&W 12K98ME engine with an output of 48,280 KW at 104 rpm, and operated with marine diesel oil MDO (0.1% S). The length and high of the engine are 29 m and 14.6 m; the bore is 980 mm, and the stroke is 2660 mm. For each trip, load factors for are 85% during cruise, 20% in maneuvering, and 5% at standby modes. The main engine provides with three auxiliary engines (AE), rated 4,250 kW for each engine. Additional shaft generator connects with engine shaft to produce 2,578 KW for the electricity power. The study aims to convert the main engine into a dual fuel engine by preparing the cylinder head with two conventional valves for the pilot fuel and alternative fuels. Table 4 illustrates the main properties of methanol and natural gas.

Table 4
Comparison between methanol, diesel, and natural gas properties

Properties	Diesel	Natural gas	Methanol
Boiling Point	320	-161.5 °C	83.189 °C
Freezing point	80	-182.6 °C	-97.8
Octane Number	-25	120 ~ 130	109 ~ 114
Flame speed (m/s)	0.867	0.38	0.445
Relative Density	0.8 ~ 0.84	0.72 ~ 0.8	0.787 ~ 0.792
Carbon content	86.64	73	37.5
Hydrogen content	13.01	24	12.5
Oxygen content	0	0.4	50
Latent Heat	250 kj/kg	510 kj/kg	1062.2 $kj.mol^{-1}$
Specific Gravity	0.85	0.43 ~ 0.47	0.896 ~ 0.91
Flammability limits	0.6 ~ 5.5	4 ~ 15	6 ~ 36
Ignition Temperature	355 °C	538 °C	470 ~ 500 °C

Results And Discussion

The current study is primarily concerned with compare between the effects of using natural gas and methanol as an alternative fuel in a dual-fuel engine on the container ship. Firstly, the emission rates (SOx, NOx, and CO2) per trip were evaluated to assess the environmental performance of using methanol and natural gas. The emissions rates are compared based on IMO limitation. Secondly, energy efficiency design index EEDI and energy efficiency operational indicator EEOI are calculated to evaluate the CO2 emission and compare with IMO requirements at different phases. Finally, the impact of using natural gas and methanol on cost-effectiveness is measured.

4.1 Emission assessment

To begin, the reduction effect of using natural gas and methanol as a dual fuel on emissions factors such as SOx, NOx, CO2, PM, CO, and HC was measured. Figure 5 illustrates the emission rates of using 95% dual fuel at (g/kwh). CO2 emission is reduced from 688.7 g/kwh to 555.23 g/kwh when using (95% NG and 5% MDO), and to 295.69 g/kwh when using (95% ME and 5% MDO). The methanol dual fuel decreased NOx emissions from 17 to 3.19 g/kwh, however, there was a slight increase compared to 2.902 for natural gas dual fuel. Both SOx and PM achieved maximum reduction for using dual fuel with ratios of 95% and 97.36%, respectively. HC emissions increased by using dual fuel from 0.6 g/kwh to 1.36 g/kwh and 0.9044 g/kwh for natural gas and methanol, in the order.

NOx emissions are assessed by comparing them with the IMO limitation. According to IMO 2016 limitations, the NOx emission rate is based on engine speed and equals 3.5549 g/kwh. Figure 6 describes the reduction effect of using methanol and natural gas as a dual fuel compared with diesel fuel on NOx emissions. Using diesel fuel is not matching with IMO 2016 regulation, and with increase the ratio of methanol dual fuel and natural gas dual fuel, the NOx emission reduced to 2.6153 g/kwh and 2.3084 g/kwh, respectively. According to Fig.6, using natural gas dual fuel with ratio above 91% NG or Methanol with ratio above 93% ME will be compliant with the new IMO requirements. For Sox emissions, IMO 2020 imposed new requirements for fuel oil used on board ships should not exceed 0.5% sulfur that equals 0.0857 ton/hr. There was a similarity for using dual fuel by natural gas or methanol, which reduced the SOx rate to 0.0001738 ton/hr with (99% NG and 99% ME), as shown in Fig.7. It is now necessary to calculate the total emission per trip and the annual emission for each emission factor. For this, a dual fuel engine with 98% natural gas and 98% methanol was used to evaluate the emission factor, as shown in Table 5. The load factor during maneuvering and standby mode was taken into consideration. It can be noticed the difference between emission factors during operation, maneuvering, and standby modes. Methanol dual fuel engine emits less SOx, CO2, and PM emissions better than natural gas; however, there is a slight increase in NOx emission. According to United Arab Shipping Company data, the Al Riffa container ship makes 6 trips per year at a rate of 49 days per trip. This equates to 295 days per year. By using Eq. (1), the total emission per trip and annual emission were calculated to assess the environmental effect from using a dual fuel engine. Table 6 illustrates the total reduction in emissions achieved by using a dual fuel engine. Using 98% natural gas dual fuel reduced the annual NOx, CO2, SOx, PM, and CO pollution by 85.55%, 20%, 98%, 98%, and 33.60%, respectively, while, using 98% methanol dual fuel recorded a reduction ratio by 83.76%, 58.87%, 98%, 98%, and 60.20%in the order. However, HC pollution increased for each dual fuel.

Table 5
the emission factor during, operation, maneuvering, and standby by using natural gas or methanol dual fuel

	type of emission	emission factor (g/kwh)	emission rate during operation (kg/hr.)	emission rate during maneuvering (kg/hr.)	emission rate during standby (kg/hr.)
98% Natural gas (NG) dual fuel	NOx	2.4568	132.8313	31.25443	7.813607
	Sox	0.0072	0.389281	0.091596	0.022899
	CO2	551.0118	29791.44	7009.752	1752.438
	PM	0.0038	0.205454	0.048342	0.012086
	CO	0.9296	50.2605	11.826	2.9565
	HC	1.384	74.82845	17.60669	4.401674
98% Methanol (ME) dual fuel	NOx	2.7606	149.2568	35.11925	8.779812
	Sox	0.0072	0.389281	0.091596	0.022899
	CO2	283.2758	15315.82	3603.721	900.9304
	PM	0.0038	0.20545384	0.04834208	0.01208552
	CO	0.5572	30.12602	7.088476	1.772119
	HC	0.91409	49.42192	11.62869	2.907172

Table 6
Environmental analysis of the Al Riffa container ship.

emission	Fuel type	Emission ton /trip	Emission ton /year	Reduction ton/year	% Of reduction / year
NOx	Diesel fuel	1408.680	8429.770		
	NG dual fuel	203.145	1218.251	7211.519	85.55%
	ME dual fuel	228.266	1368.896	7060.874	83.76%
Sox	Diesel fuel	29.767	178.510		
	NG dual fuel	0.595	3.570	174.940	98.00%
	ME dual fuel	0.595	3.570	174.940	98.00%
CO2	Diesel fuel	56954.000	341549.500		
	NG dual fuel	45561.529	273229.607	68319.893	20.00%
	ME dual fuel	23423.234	140467.655	201081.845	58.87%
PM	Diesel fuel	15.710	94.215		
	NG dual fuel	0.314	1.884	92.331	98.00%
	ME dual fuel	0.314	1.884	92.331	98.00%
CO	Diesel fuel	115.762	694.216		
	NG dual fuel	76.866	460.960	233.256	33.60%
	ME dual fuel	46.073	276.298	417.918	60.20%
HC	Diesel fuel	49.612	297.521		
	NG dual fuel	114.439	686.283	-388.762	-130.67%
	ME dual fuel	75.583	453.269	-155.748	-52.35%

4.2 Energy efficiency assessment

Based on IMO requirements, evaluated, the EEDI is the most effective way to assess the energy efficiency of a ship. As mentioned, there are two values of EEDI, required values that can be calculated by Eq. (7), where X is the reduction percentage and increased from 10% in 2015 to 30% in 2025, as shown in Fig. 8. The required EEDI for the Al-Riffa ship, which was built in 2012, is 15.971 gCO2/ton-nm at the DWT 145528 ton. According to IMO, this value should be reduced to 20% at phase 2 and equal 12.777 gCO2/ton-nm. Another value is the attained EEDI, which is calculated using Eq. 8, and then compare this value with required EEDI in phase 2. Based on IMO regulations, the service speed (23 kn) can be used as a reference velocity (V_{ref}), and 70% DWT is considered as a ship capacity. The actual EEDI is 14.83 gCO2/ton-NM; this value reduced from required EEDI with ratio 7.14%, which is lower than the required EEDI, but will be incompatible with phase 2 from 2020 to 2025, as shown in Fig. 9. The reduction effects from using natural gas and methanol as a dual fuel engine were evaluated for variable ratios (70%, 80%, 90%, and 95%) to find the best percentage of dual fuel that achieves the required EEDI. Fig. 10, illustrates the reduction values from using natural gas and methanol as a dual fuel. The actual EEDI reduced from 11.27 g.CO2/ton. NM at 70% NG dual fuel to 10.827 g.CO2/ton. NM at 95% NG dual fuel, while methanol dropped to 8.362 g.CO2/ton. NM at 95% ME dual fuel. Both of dual fuels complicated with IMO regulation.

Energy Efficiency Operational Indicator (EEOI) is another method adopted by IMO to measure the energy efficiency of the ships and carbon emissions during operations. According to Eq. (14), the EEOI is calculated based on the distance traveled, the transported TEU cargo, and the amount of fuel consumed per trip. For A13 class container ship, theTEU cargoes transported are 13500, over distance 20600 nautical miles. Figure 11 shows that the EEOI during operation is reduced from 0.00017 to CO2/TEU-NM when use MDO to 0.000146 tonCO2/TEU-NM and 0.000077 tonCO2/TEU-NM when use 95% NG and 95% ME, respectively. The calculations for maneuvering and standby were carried out based on 20% and 5% fuel consumption, in order.

4.3 Economic assessment

The economic impact of converting the diesel engine into a dual fuel engine was examined in this section, and the cost-effectiveness of reducing ship NOx, CO2, and CO emissions by using natural gas and methanol was assessed. In terms of capital cost, to calculate the annual fuel cost, it is important to evaluate the total fuel consumption in the case of using diesel fuel and dual fuel, as shown in Table 7. Because marine diesel fuel and alternative dual fuels are so similar, using natural gas or methanol requires only minor changes to diesel fuel infrastructure. As a result, the cost of bunkering facilities for diesel fuel and dual fuel is assumed to be the same in this study. The calculations are based on diesel, natural gas, and methanol fuel costs of 1320.8 \$/m3, 684.2 \$/m3, and 528.34 \$/m3, in addition to 8.0 \$/m3 for the bunkering prices (Afdc 2022). Table 8 illustrates the annual fuel cost for diesel fuel and dual fuel (natural gas or methanol)

Table 7
Al Riffa container ship main engine fuel consumptions.

Fuel consumption (m3)	**diesel engine**	**Dual fuel engine with 90% Natural gas**		**Dual fuel engine with 90% Methanol**	
	MDO	Natural gas	MDO	Methanol	MDO
per trip	17,280	20,753	1,900	30,226	1,900
per year	103,632	124,941	11,400	181,267	11,400

Table 8
Fuel consumption annual cost for diesel and dual-fuel engine

cost item	**Prices in (millions US$/year)**		
	diesel engine	NG-dual fuel engine	ME-dual fuel engine
Diesel fuel	136.877	15.057	15.057
Diesel bunkering	0.829	0.0912	0.0912
Natural gas	0	85.485	0
Natural gas bunkering	0	1	0
Methanol	0	0	95.771
Methanol bunkering	0	0	1.45
total fuel cost	137.706	101.6332	112.3692

For conversion cost from the main engine to a dual fuel engine, it is expected to be 10.72 million dollars with 285 $/kW conversation rate (Andersson and Salazar 2015; Stefenson 2014). For operation and maintenance costs, according to data collected, the total operation and maintenance cost is 714749 $/years (Banawan et al., 2010). Now, the total cost-effectiveness calculated for each emission type based on the added annual cost of the conversion process as discussed by using Eq. (15). Fig. 12, shows the annual cost-effectiveness of the proposed dual-fuel engine in reducing ship emissions for the container ship.

Conclusions

The International Maritime Organization (IMO) highlighted various methods for lowering ship exhaust emissions and improving marine energy savings from both operational and technical perspectives. One of the effective long-term measures for reducing emissions and improving energy efficiency which presented in this paper is converting from using fossil fuel in a conventional diesel engine to a dual fuel engine operating with alternative fuels. Natural gas and methanol are becoming more appealing as alternatives to traditional marine fuels. This study provided a comparative analysis of using methanol or natural gas to achieve the best solution in a dual fuel engine in terms of environmental performance. Furthermore, the economics of using alternative fuels instead of marine diesel oil are discussed. The analysis' findings revealed the following:

- From an environmental standpoint, the analysis results show that using natural dual fuel engines with ration (95%NG and 5% MDO) reduces NOx, SOx, CO_2, PM, CO emissions by 83%, 95%, 19.4%, 95%, and 32.6%, respectively. On the other hand, the emissions saved percentage by using 95% methanol as a dual fuel is 81.2%, 95%, 57.1%, 95%, and 58.4%, respectively. Moreover, converting a conventional diesel engine to a dual fuel engine powered by natural gas or methanol as an alternative fuel will comply with IMO 2016 and 2020 emission requirements for NOX and SOx with marine diesel oil percentages less than 10%.
- From energy efficiency point of view, according to energy efficiency design index EEDI techniques, the dual fuel engine powered by (95% NG and 5% MDO) or (95% ME and 5% MDO) will meet IMO requirements. The required EEDI value for the third phase was 11.81 gCO_2/ton-NM, and the attained EEDI value when using natural gas and methanol in a dual fuel engine was 10.827 g.CO_2/ton and 8.362 g.CO_2/ton-NM, respectively. Furthermore, using 95% natural gas or 95% methanol satisfies not only current IMO EEDI requirements but also future ones.
- In terms of cost-effectiveness, the suggested dual-fuel (95% NG + 5% MDO) engine will reduce NOx, SOx, CO_2, PM, and CO emissions while saving 769.25 $/ton, 3304.1$/ton, 81.2 $/ton. 60082.64 $/ton, and 23782.84 $/ton, respectively. in addition to 850.67 $/ton, 3340.1$/ton, 45.588 $/ton, 55450.87 $/ton, and 13274.11 $/ton, in the order, when using dual-fuel (95% ME + 5% MDO) engine.

Declarations

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Author Contributions: -

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mahmoud Abdel Nasser, Mohamed M. Elgohary, Mohamed Shouman and Majed Abdelnabi. The first draft of the manuscript was written by Mahmoud Abdel Nasser and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethical Approval

Not applicable.

Consent to Publish

The authors declare that they are approved to Publish the paper with title " Environmental and economic performance investigation of natural gas and methanol as a marine alternative fuel." to "Environmental Science and Pollution Research" journal.

Consent to Participate

The authors declare that they are agreeing to participate the scientific data of the paper with "Environmental Science and Pollution Research" journal

Availability of data and materials

The authors declare that they are approve to available any data and materials that relate with the paper.

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Figures

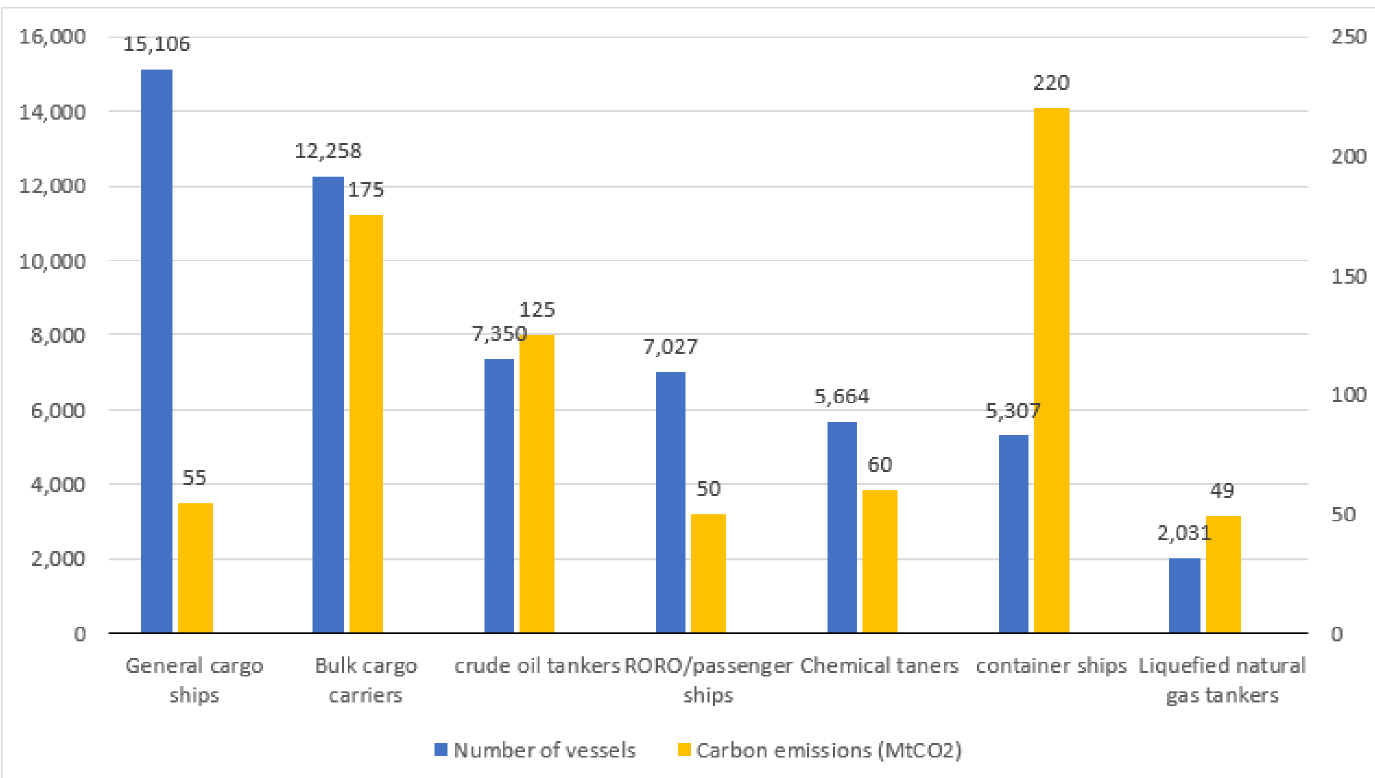

Figure 1

Number of merchant ships and their carbon emissions, by category in 2021. (Placek 2021).

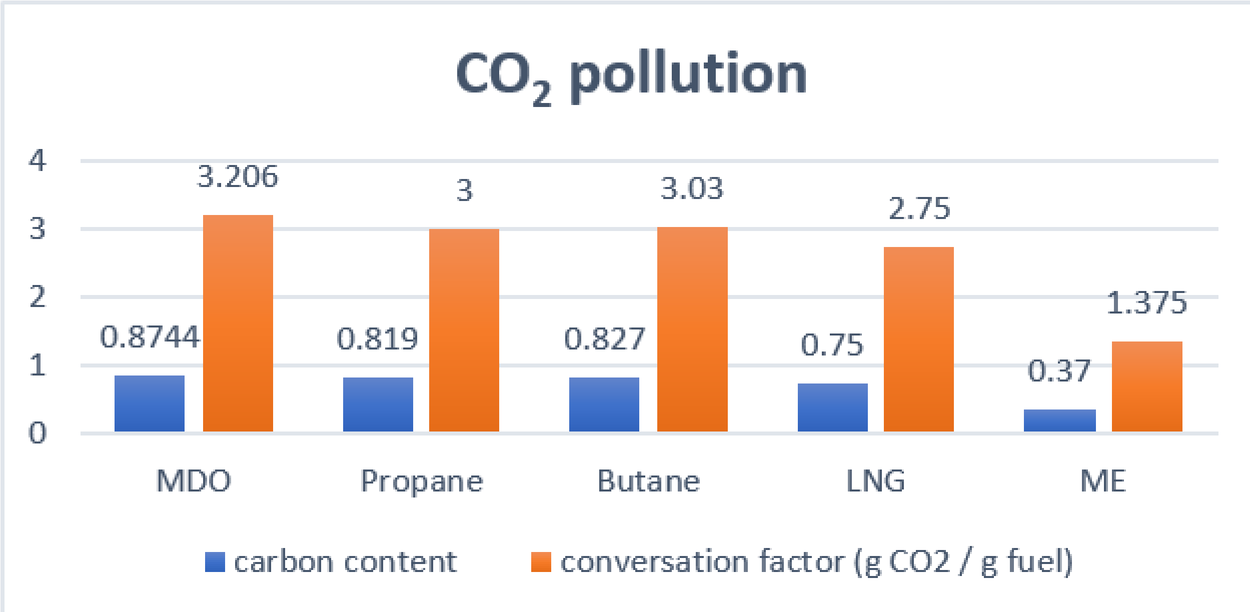

Figure 2

Carbon contents and conversion factors of different fuel types

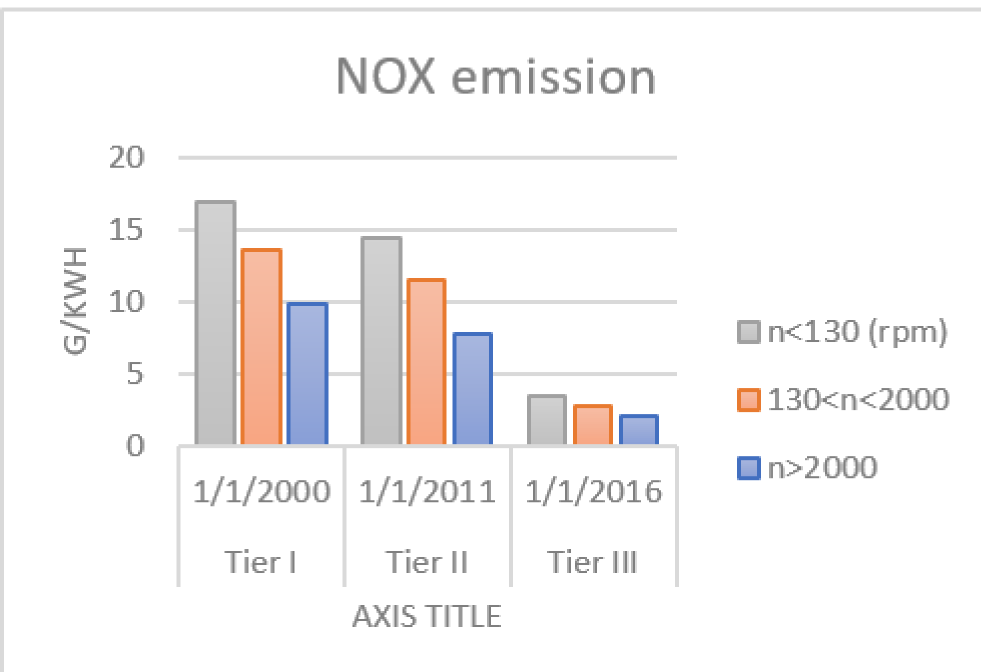

Figure 3

NOx emission limits for IMO regulation

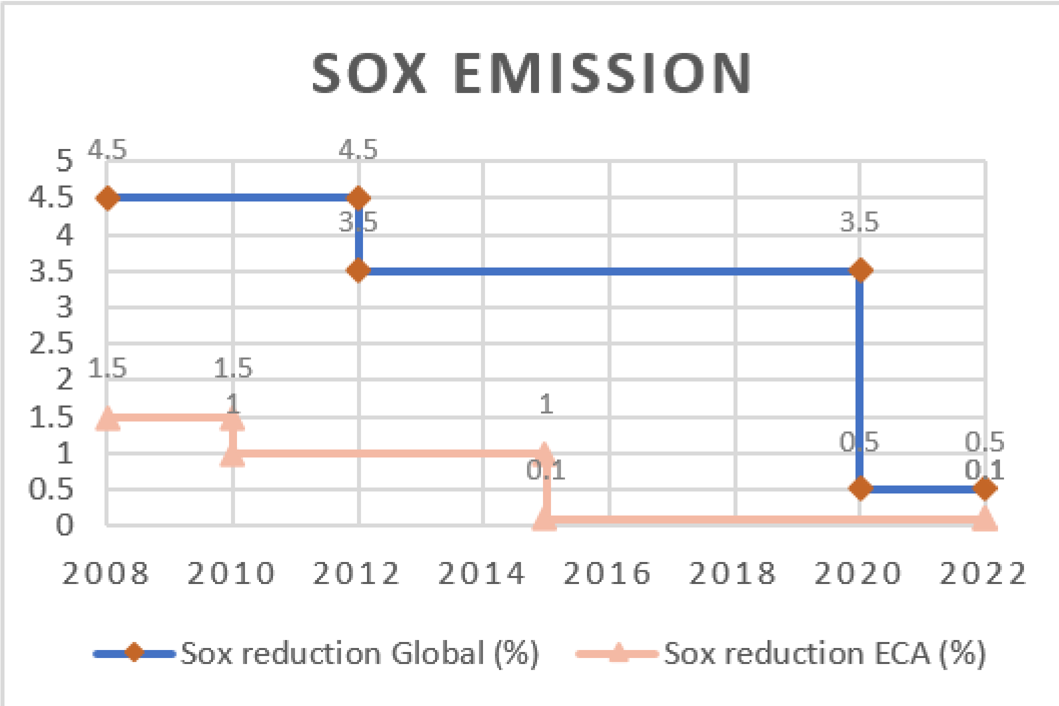

Figure 4

Sox emission limits for IMO regulation

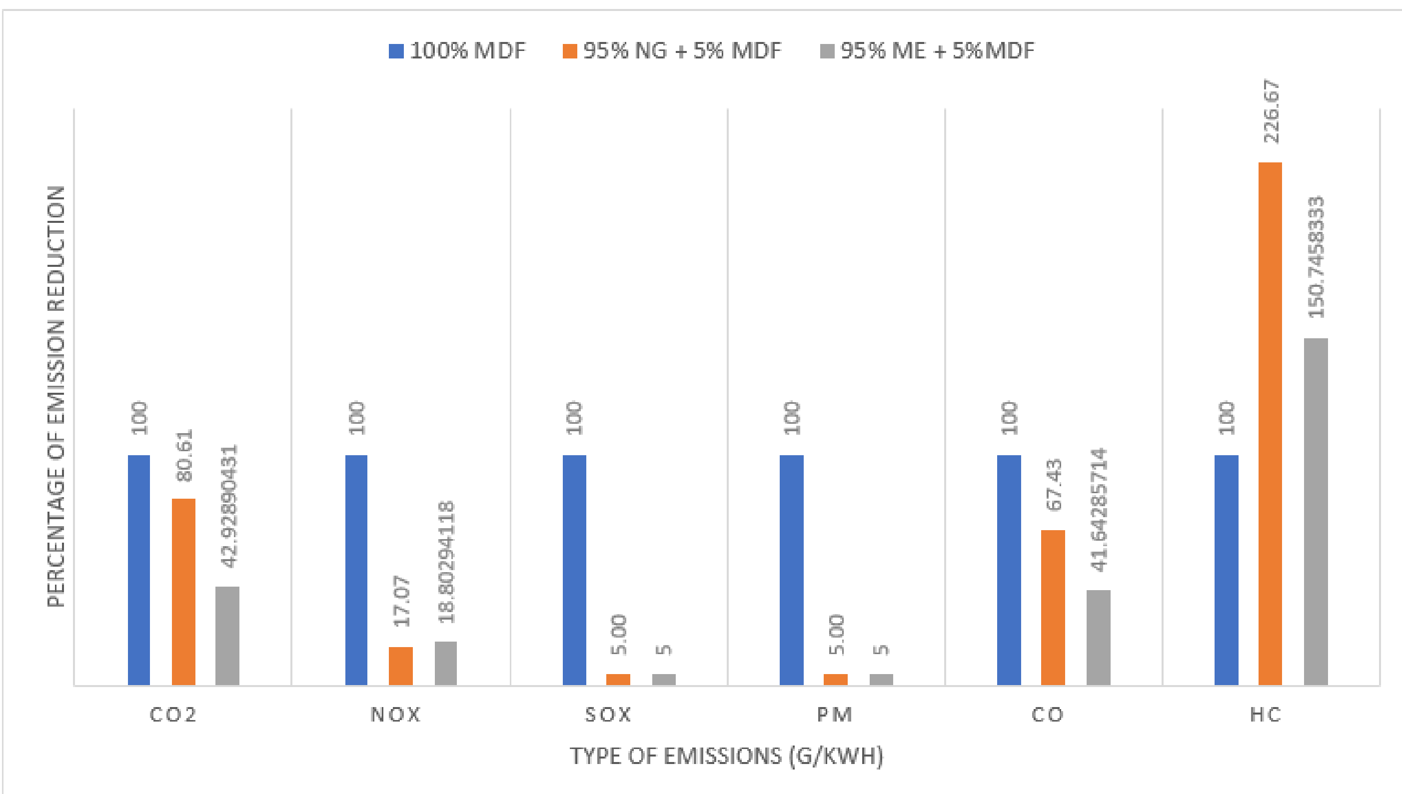

Figure 5

Emission rates of the proposed dual-fuel engine in comparison to diesel engines

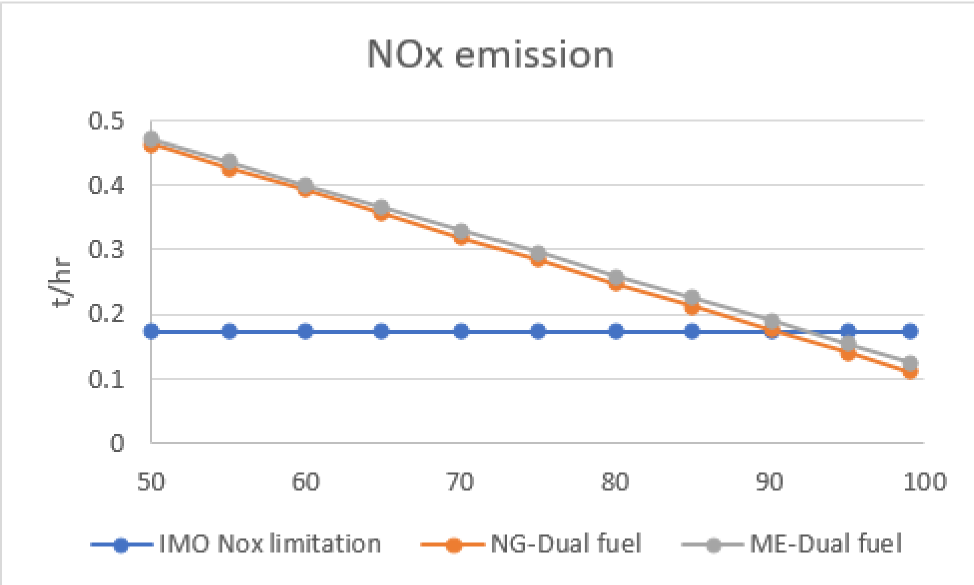

Figure 6

Rates of NOx emission at various pilot fuel percentages

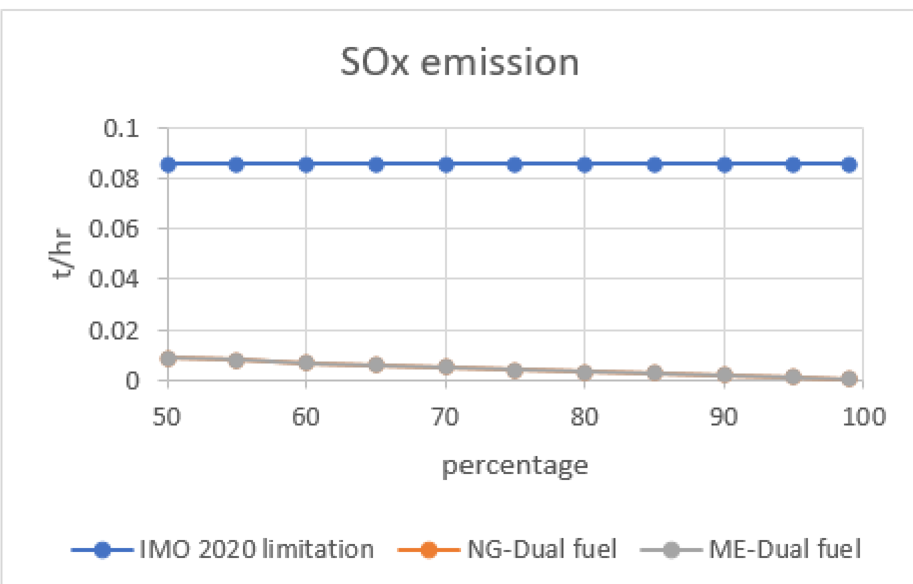

Figure 7

SOx emission levels at various pilot fuel percentages

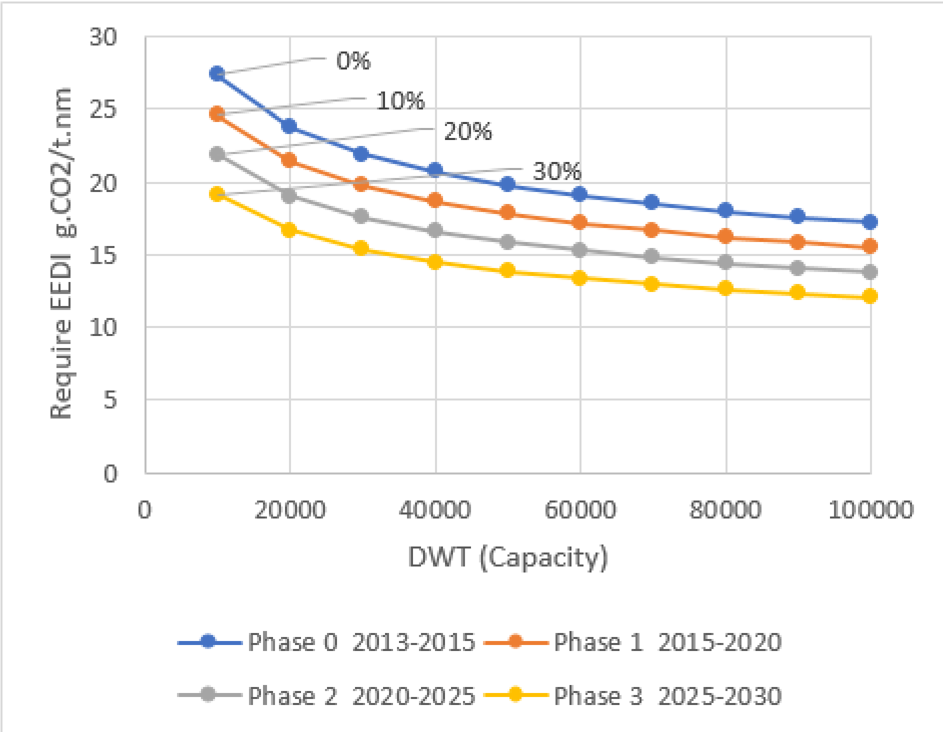

Figure 8

The required EEDI according to IMO regulation

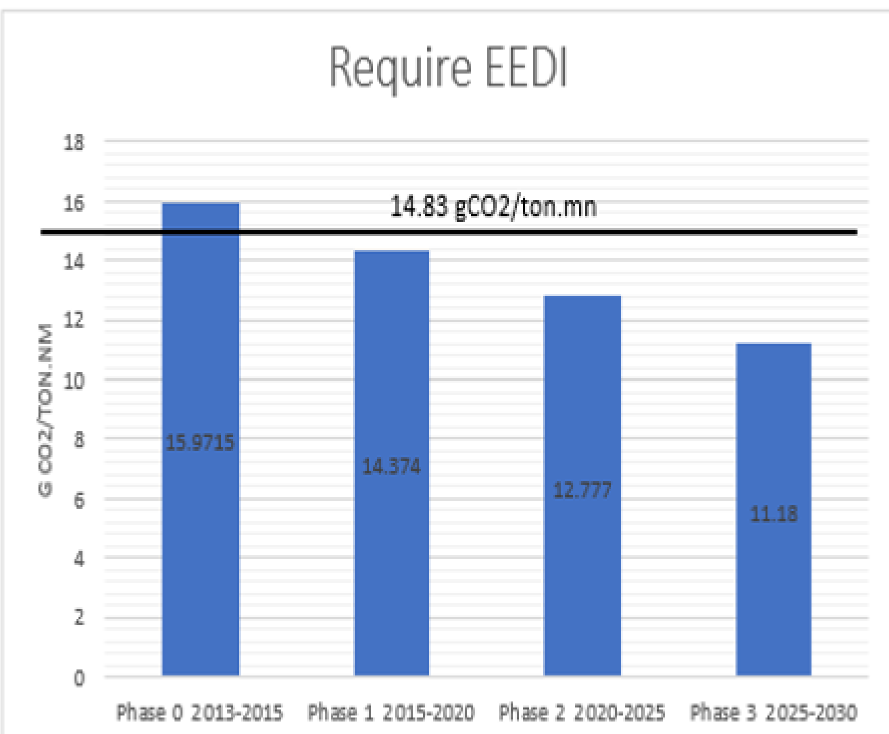

Figure 9

The required EEDI for the Al-Riffa ship

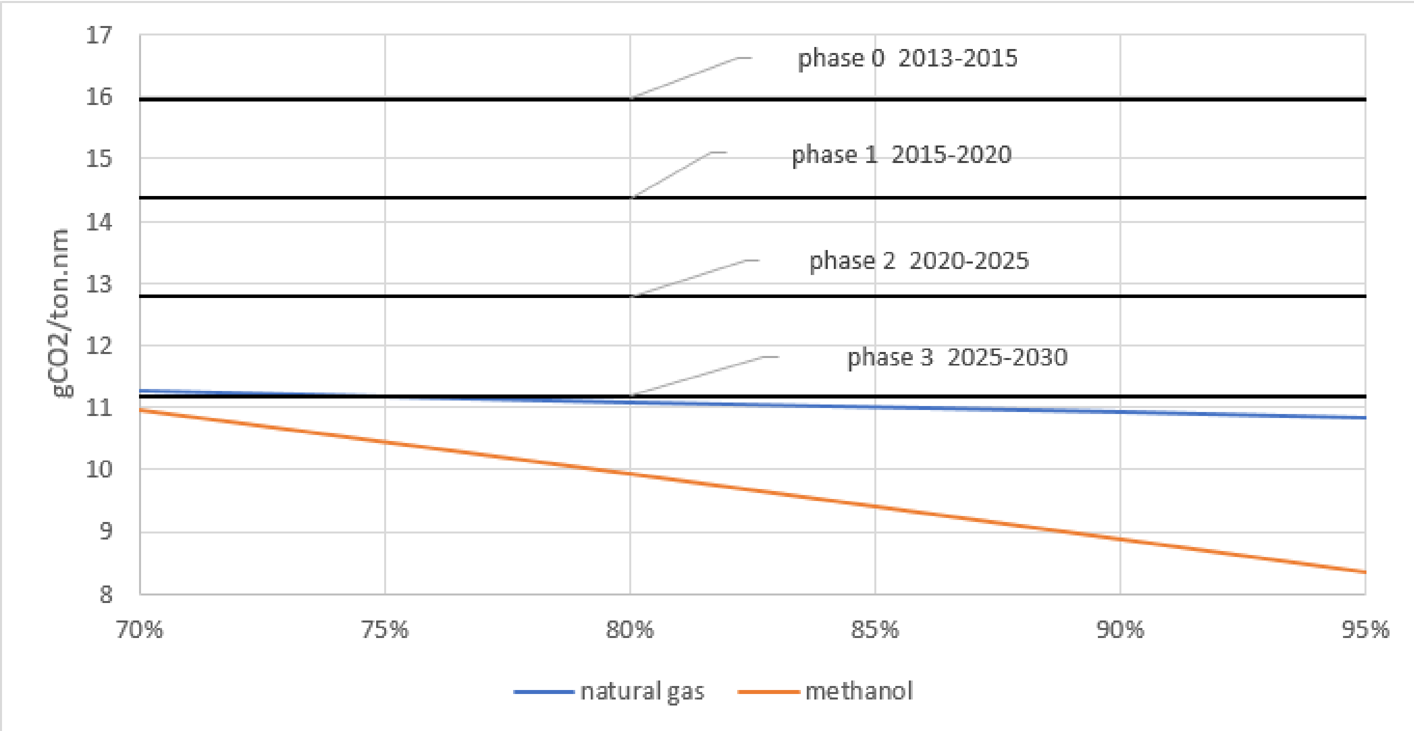

Figure 10

Relative attained EEDI compared to reference value at different phases

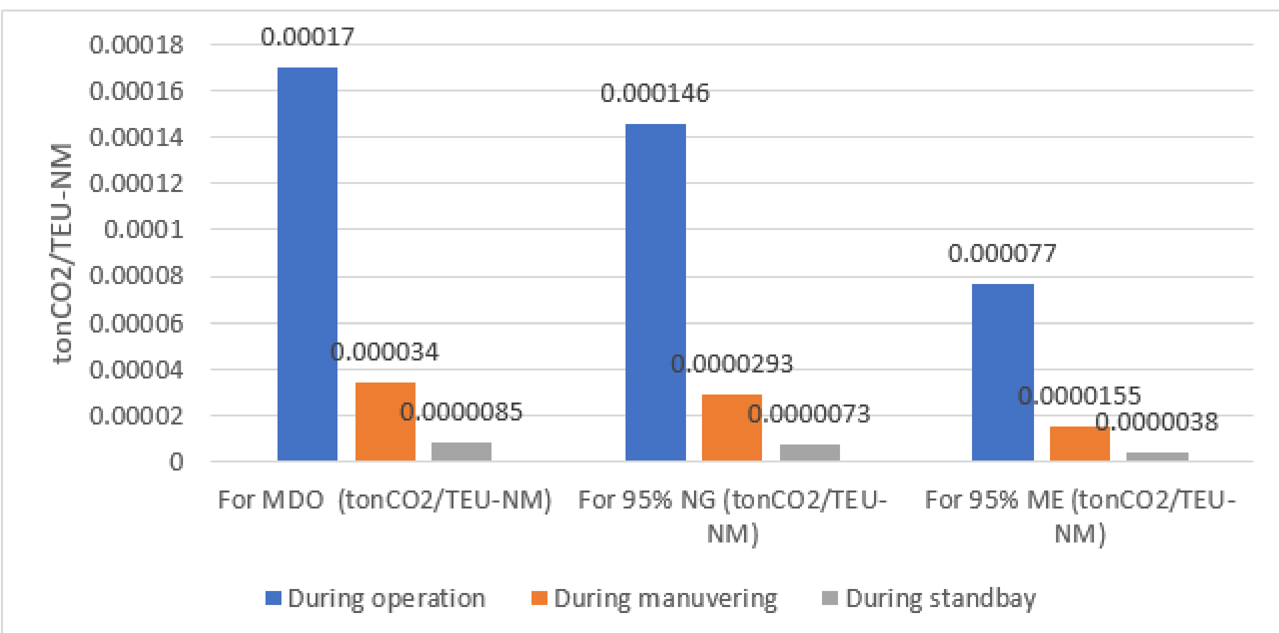

Figure 11

Calculated EEOI for the case studies at the operational ship speeds.

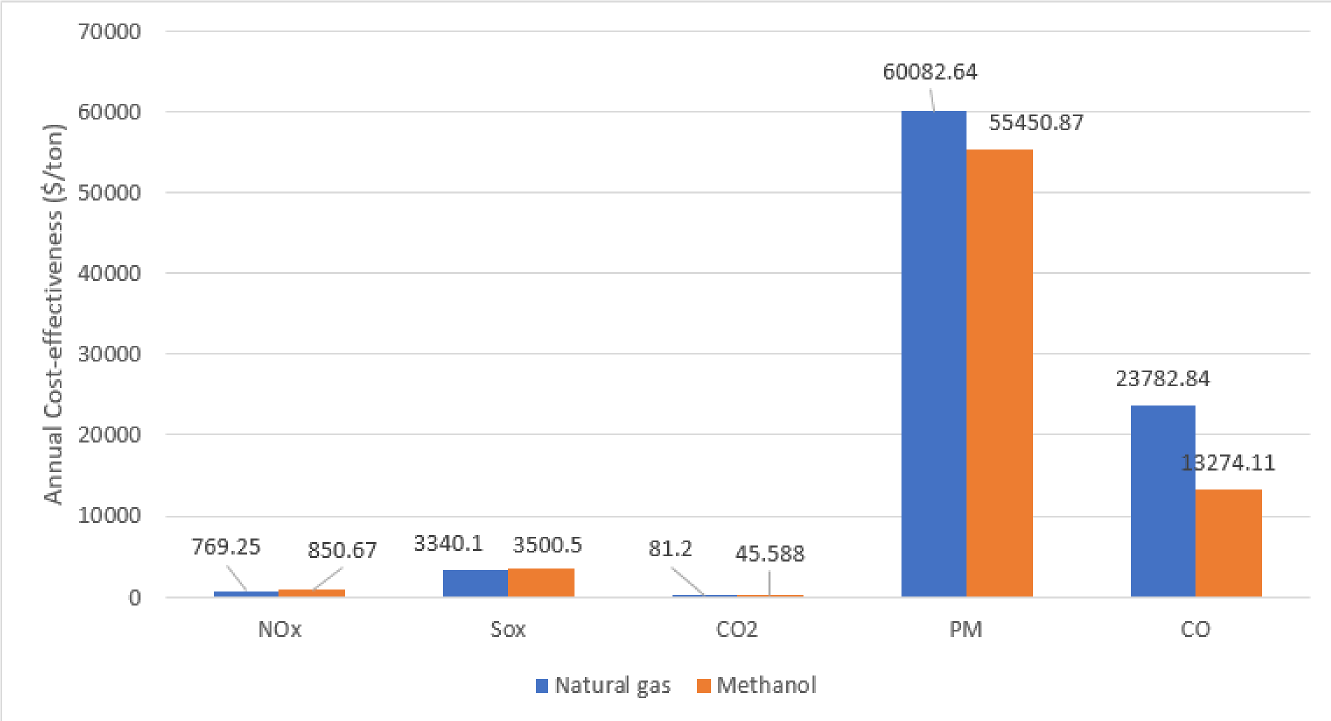

Figure 12

The annual cost-effectiveness of the proposed dual-fuel engine