



Environmental protection and energy efficiency improvement by using natural gas fuel in maritime transportation

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Received: 23 January 2021 / Accepted: 8 June 2021 / Published online: 23 June 2021
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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) concerns 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 natural gas has the priority to be used instead of fossil fuels. The present paper calculates the effect of using natural gas 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 the percent of CO₂, NO_x, and SO_x emission reduction corresponding to using a dual-fuel engine operated by natural gas instead of a diesel engine operated by heavy fuel oil is about 30.4%, 85.3%, and 97%, respectively. Moreover, it found that NO_x and SO_x emission rates of the dual-fuel engine comply with the IMO 2016 and 2020 limits, respectively. Furthermore, the Energy Efficiency Design Index value in the case of using dual-fuel engine is lower than the value by using diesel engine by about 30%, and this value will be 77.18%, 86.84%, and 99.27% of the required value for the first, second, and third phases, respectively, as recommended by IMO.

Keywords Energy efficiency · Environmental protection · Alternative fuel · Natural gas · Ship emissions · Container ship

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, emission decreases are essential to keep an essential separation from basic changes on the planet's atmosphere with outrageous ramifications for human well-being and the overall climate (Bouman et al. 2017; IPCC

2018a; Elkafas et al. 2019). Maritime transport is the primary means of transport utilized worldwide and for the improvement of the worldwide economy. In this manner, discharges from vessels are a huge ecological worry because of their impact on debilitating the climate, especially a worldwide temperature alteration of the environment (Ammar et al. 2019). 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 dynamicaly 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 CO₂ in 2012, speaking to around 2.2% of the complete overall CO₂ 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 NO_x and SO_x, annually. Global NO_x and SO_x emanations are around 13% and 12% of overall NO_x and SO_x from anthropogenic sources itemized in the IPCC Fifth

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Assessment Report (IPCC 2018b), separately. In such a manner, IMO has been successfully busy all the way to deal with further improving marine energy proficiency and take measures to lessen outflows from ships. IMO's Marine Environment Protection Committee (MEPC) has given extensive attention to controlling emissions from ships and adopted in 2011 a bundle of specialized measures for new ships and operational reduction measures for all vessels. This bundle incorporated in a new part 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 force on 1 January 2013 and applies to all vessels of 400 gross tonnages or more (IMO 2011). These rules expect to improve marine energy efficiency and decrease emissions by lessening the amount of fuel consumed.

The bundle of technical and operational measures, which 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 (e.g., CO₂ 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 sizes. 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. 2021).

Energy efficiency improvement measures can be implemented through EEDI application, whether design or 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, improved 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, weather routing and voyage optimization, engine observation, auxiliary power reduction, trim/draft optimization, hull/propeller cleaning, and hull 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). Biodiesel is a renewable fuel which

could be used to reduce dependence on fossil fuel onboard ships (Kesime et al. 2019), but it has bad starting at cold weather, has storage instability, and causes increase in NO_x emissions (+ 2: + 5%). Recent studies (Ammar 2019; Paulauskiene et al. 2019) showed the possibility of using methanol as an alternative fuel in marine applications. The problems associated with the use of methanol or its blends are the emission of aldehyde, phase separation, vapor lock, cold starting, and cost-effectiveness (Elgohary et al. 2015). On the other hand, the fundamental alternative gaseous 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 an effective and environmentally friendly fuel. El Gohary et al. (2015) and van Biert et al. (2016) showed the possibility of using hydrogen as a fuel for marine applications especially in fuel cell systems. It has high specific energy, low start energy prerequisite, astounding flame speed, and wide flammability range. However, hydrogen powered engines require a high cost, which constrains their 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; 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 (NO_x and particulate matter specifically). The burning of LNG is possibly connected with lower CO₂ 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 (natural gas) as the main fuel in a dual-fuel engine. The study aims to compare the environmental results from using conventional fuel in diesel engine and natural gas with a pilot 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. The energy efficiency is investigated by calculating the effect of conversion process on EEDI and EEOI as recommended from IMO. Moreover, the annual cost-effectiveness will be calculated for the conversion process to a dual-fuel engine.

Assessment methodology of energy, environmental, and cost-effectiveness

This section aims to present the environmental and energy efficiency models with emphasis on the calculation of Energy Efficiency Design Index (EEDI) and Energy Efficiency Operational Indicator (EEOI) which are applied to analyze the effect of natural gas as an alternative marine fuel on ship emissions and energy efficiency. Moreover, the last section describes the methodology to assess the cost-effectiveness of the conversion process.

Energy Efficiency Design Index calculation methodology

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).

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. 2021).

$$EEDI_{required} = Baseline \left(1 - \frac{x}{100} \right) \tag{1}$$

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).

$$Baseline = a \times Capacity^{-c} \tag{2}$$

where a and c are constraints that 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 ship building 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 2013).

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).

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

where f_j is the ship-specific design element correction factor; if elements are not 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).

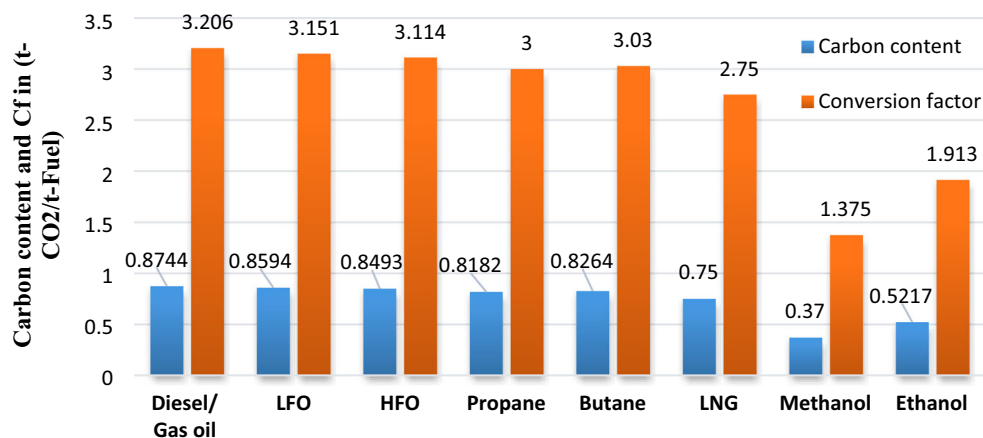
$$P_{AE(MCR_{(ME)} > 10000KW)} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME} + \frac{\sum_{i=1}^{nPTI} P_{PTI(x)}}{0.75} \right) \right] + 250 \tag{4}$$

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 CO₂ 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).

For the dual-fuel engine, Eq. (5) is utilized to calculate the term of $C_F \times SFC$ for dual fuel (DF) case study depending on the value of each one for gas fuel and pilot fuel at the related load point (Elkafas et al. 2021).

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

Fig. 1 Conversion factors and carbon contents for marine fuels



CO₂ emissions from shaft generators (SG_e) and CO₂ 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_1 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 2013).

Energy Efficiency Operational Indicator calculation methodology

Energy Efficiency Operational Indicator (EEOI) is established by IMO following the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Annex VI for prevention of air pollution from ships. The calculation of EEOI value is a fundamental work to determine this value at ship in research process. EEOI, which is formerly called operational CO₂ index, is a tool for measuring the CO₂ gas emission to the environment per the transport work. On the other hand, it represents the actual transport efficiency of a ship in operation. The unit of EEOI depends on the measurement of cargo carried or the transport work done, e.g., ton CO₂/ (tons/nautical miles), tons CO₂/ (TEU/nautical miles),

or tons CO₂/(person/nautical miles). The EEOI is calculated by the following formula, in which a smaller EEOI value means a more energy-efficient ship (Ammar 2019):

$$EEOI = \frac{\sum_i FC * C_F}{\sum_i m_{cargo} * D} \quad (6)$$

where i is the navigation voyage number, FC is the mass of consumed fuel at voyage, C_F is the conversion factor between fuel and CO₂ which can be calculated according to Fig. 1, m_{cargo} is the weight of cargo carried on ship, and D is the distance of voyage in nautical miles corresponding to the cargo carried or work done.

Ship emission assessment methodology

The emissions from ships included many kinds of pollutants such as CO₂, SO_x, NO_x, and PM emissions. The individual emission energy-based rate in g/kWh differs from one type to another. When looking based on g CO₂ per kilowatt-hour, it is found that it is proportional to the specific fuel consumption and also the conversion factor between fuel and CO₂ as discussed in Fig. 1 which concluded that the quantity of CO₂ emission depends on the fuel type (Elkafas et al. 2021). On the other hand, SO_x 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_{SO_x}) in g/kWh can be calculated by Eq. (7) (EPA 2000; ICF 2009).

$$E_{SO_x} = SFC \times 2.1 \times (S\%) \quad (7)$$

where S is the percentage mass sulfur content in the fuel and SFC is in g/kWh. It is seen that lower sulfur content in fuel led to the reduction of the specific emission rate of SO_x, 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) and Pedersen et al. (2010). Based on these outcomes, Eq. (8) 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).

$$E_{PM} = 0.26 + 0.081 \times S + 0.103 \times S^2 \tag{8}$$

The emission rate of nitrogen oxide (NOx) depends on the type of engine and its year of installation as recommended from the air pollutant emission inventory (Trozzi and De Lauretis 2019), and illustrated in Fig. 2. As shown, the highest allowable specific NOx emission rate (IMO Tier I level for engines manufactured before 2011) is 17 g NOx/kWh for low-speed engines, while the rate for medium-speed engines (750 RPM) is approximately 12 g NOx/kWh. For high-speed engines, at about 1100 RPM, the allowable NOx 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% NOx reduction, respectively, compared with the Tier I level (Ammar and Seddiek 2020a).

The conversion factor of each emission type between fuel and pollutant type can be determined in g (pollutant)/g (fuel) through dividing 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. (9).

$$F_i = FC \cdot C_{F(i)} \tag{9}$$

where F is the emission rate factor for each pollutant type (i) on t/h, FC is the fuel consumption in t/h, and 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 natural gas 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 analyzed by evaluating the emission factor rate and then convert 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 as expressed in Eq. (10).

$$EF_{DF} = x_{gas} \times EF_{gas} + x_{P.O} \times EF_{P.O} \tag{10}$$

where x_{gas} and $x_{P.O}$ are the percentages of gas and pilot fuels in the case of using dual-fuel engine (DF) and EF_{gas} and $EF_{P.O}$ are the emission factors for gas and pilot fuels, respectively.

Cost-effectiveness calculation methodology

The annual cost-effectiveness of reducing ship emissions (E_{CE}) is mainly determined by the entire cost of applying natural gas as a main fuel onboard ship including the capital cost due to conversion process. The value of (E_{CE}) can be calculated as shown in Eq. (11) (Ammar and Seddiek 2020b).

$$E_{CE} = \frac{AAC}{\Delta E} \tag{11}$$

where E_{CE} is the annual cost-effectiveness of reducing emissions in \$/ton pollutant, AAC is the added annual costs of applying natural gas as a main fuel including the maintenance and operating costs, and (ΔE) is the expected annual emission reduction in tons/year due to conversion of the main engine to be a dual-fuel engine.

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 has a total of 235 container ships and its fleet total twenty-foot equivalent unit (TEU) capacity amounts to 1.7 million TEU (Hapag 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).

The container ship is propelled by a low-speed marine diesel engine (MAN B&W 8K90MC-C) with a MCR of 42504 kW which is operated by HFO (MAN Diesel and Turbo 2012). Currently, the emission factors for the low-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

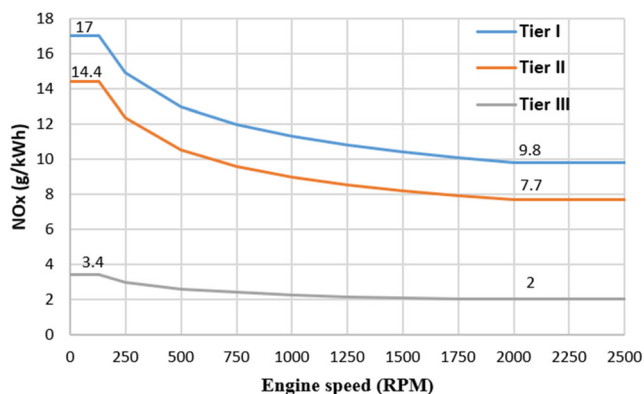


Fig. 2 NOx limits in MARPOL Annex VI

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

installation year of engine, which is before 2010; therefore, NO_x 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 CO₂, NO_x, SO_x, PM, and CO, respectively (Elkafas et al. 2021).

It can be noticed that NO_x and SO_x emission rates for the current engine are not compliant with the IMO 2016 and 2020 emission limits as IMO NO_x 2016 limit for low-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 specifications of the main engine are shown in Table 2 (MAN Diesel and Turbo 2012).

Using the Computerized Engine Application System (CEAS) online calculation tool, the specific consumption of

Table 2 Main specifications of the selected main engine (MAN Diesel and 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
Number of cylinders	8

gas and pilot fuel can be determined in different power loads by specifying a mixture of 97% natural and 3% diesel fuel as shown in Fig. 3 (MAN 2020).

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.

Results and discussions

The energy and environmental impacts of using natural gas as an alternative fuel in a dual-fuel engine on the container ship case study are discussed. Firstly, the environmental effects of using natural gas and the rate of exhaust emissions are discussed including the effect of pilot fuel percentage on different ship emissions. Secondly, results of the EEDI assessment for the diesel engine and the proposed dual-fuel engine have been discussed regarding the three IMO phases; then, the energy efficiency has been assessed by studying the effect of the conversion process on EEOI of the case study. Moreover, the cost-effectiveness of the conversion process has been studied for the conversion process.

Environmental impact of using natural gas

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 corresponding 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 corresponding to the CSR (%MCR).

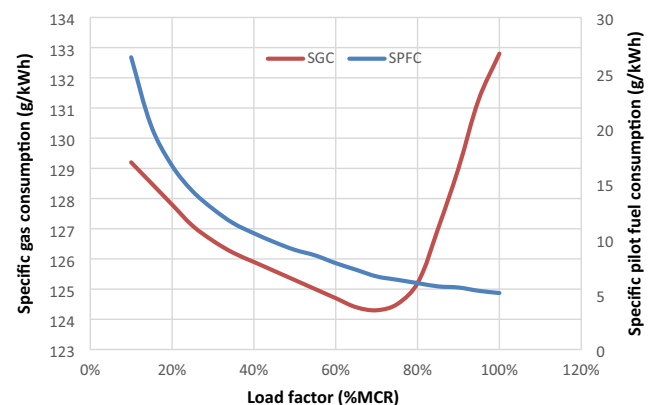
**Fig. 3** Specific gas and pilot fuel consumption for different power factors

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/h)	4.1
Pilot fuel consumption (t/h)	0.19

Finally, the data corresponding to the actual condition can be shown in Table 3.

The values of emissions factors of CO₂, NO_x, SO_x, PM, and CO for two-stroke diesel engine operated by marine diesel oil (MDO) are 545 g/kWh, 13.6 g/kWh, 3.53 g/kWh, 0.43 g/kWh, and 1.24 g/kWh, respectively (Elkafas et al. 2021), while emission factors of CO₂, NO_x, SO_x, 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; Elkafas et al. 2021). 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. 2021).

The exhaust gas emissions rates in (g/dwt.nm) can be calculated when multiplying the fuel consumption to the corresponding specific emission factor as discussed in the “Ship emission assessment methodology” section and the results are presented in Table 5.

The emission factors for the dual-fuel engine can be determined at different natural gas and pilot fuel percentages by using Eq. (10). The effect of pilot fuel percentage on the ship emissions is presented in Fig. 4 which have different pilot fuel percentage ranges from 1.5 to 10% and the emissions rates of dual-fuel engine are presented at tons/h.

When the pilot fuel (MDO) percent increases, CO₂, NO_x, SO_x, PM, and CO emissions increase significantly. Therefore, the studied pilot fuel percentage is taken to be 3% to produce a little amount of ship emissions.

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	0.106	0.328	0.042

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

NO_x and SO_x emission rates have been compared with the IMO 2016 and 2020 emission limit rates, respectively. Figure 5 shows a comparative diagram between IMO SO_x 2020 limit and the SO_x emission rates at different pilot fuel percentages; it can be noticed that SO_x emission rates for the dual-fuel engine comply with the IMO 2020 limits.

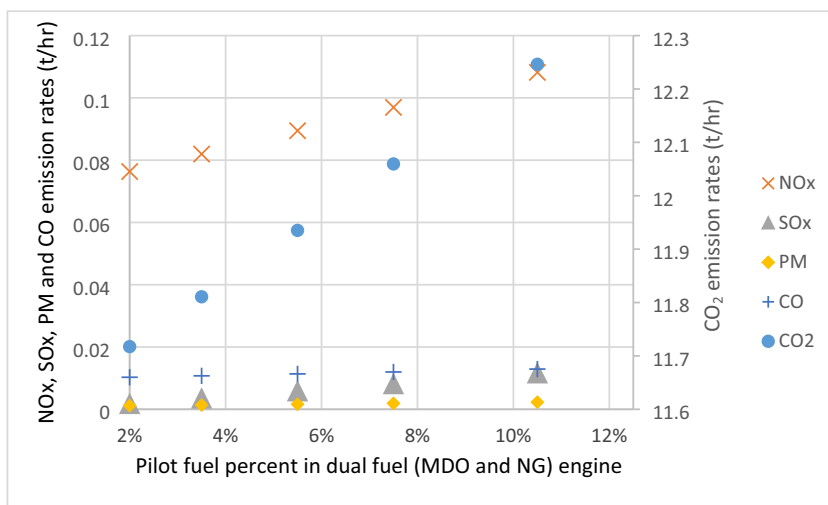
Furthermore, NO_x emission rates at different pilot fuel percentages are compared with the required IMO 2016 rate as shown in Fig. 6 which shows that dual-fuel engines operated by pilot fuel at any percentage until 10% will be compliant with the required IMO rates.

Exhaust emission rates in (t/h) 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, CO₂ emission rates are 11.8 t/h and 16.96 t/h for dual-fuel engine and HFO diesel engine, respectively, so that the percent of CO₂ emission saving corresponding to using the dual-fuel engine is 30.4%.

NO_x emission rates are 81.96 kg/h and 556.65 kg/h for dual-fuel engine and HFO diesel engine, respectively, so that NO_x saving percent corresponding to using the dual-fuel engine is 85.3%. On the other hand, SO_x emission rates are 3.47 kg/h and 114.28 kg/h for dual-fuel engine and HFO diesel engine, respectively, so that SO_x saving percent corresponding to using the dual-fuel engine is 97%. 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. 7 which shows that the dual-fuel engine has lowered the emissions rates of CO₂, NO_x, SO_x, CO, and PM by 30.4 %, 85.3 %, 97 %, 67.2 %, and 90.4 %, respectively.

Fig. 4 Different emission rates at various pilot fuel percentages



Natural gas effect on marine energy efficiency

IMO has introduced an index to measure the marine energy efficiency (EEDI). The required EEDI is the greatest suitable limit for the index which 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 ship building year; it is about 10%, 20%, and 30% in 2015, 2020, and 2025 at phase 1, 2, and 3, respectively, for the case study.

Figure 8 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 gCO₂/ton-NM to 17.7, 15.73, and 13.76 gCO₂/ton-NM at the three phases, respectively.

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 the “Energy Efficiency Design Index calculation methodology” section 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 the “Energy Efficiency Design Index calculation methodology” section and presented in Table 6.

The result of applying Eq. (3) for the attained EEDI is set to be 13.66 gCO₂/ton-NM at the design service speed. Figure 9 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

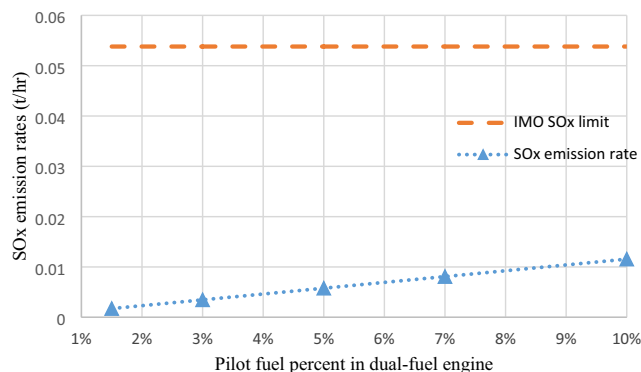


Fig. 5 SOx emission rates of dual-fuel engine compared with IMO 2020 limit

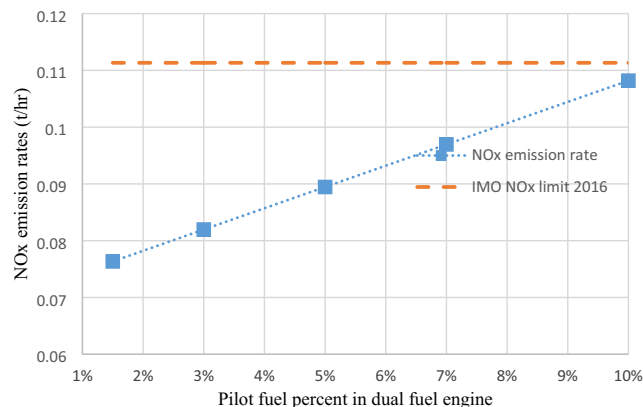
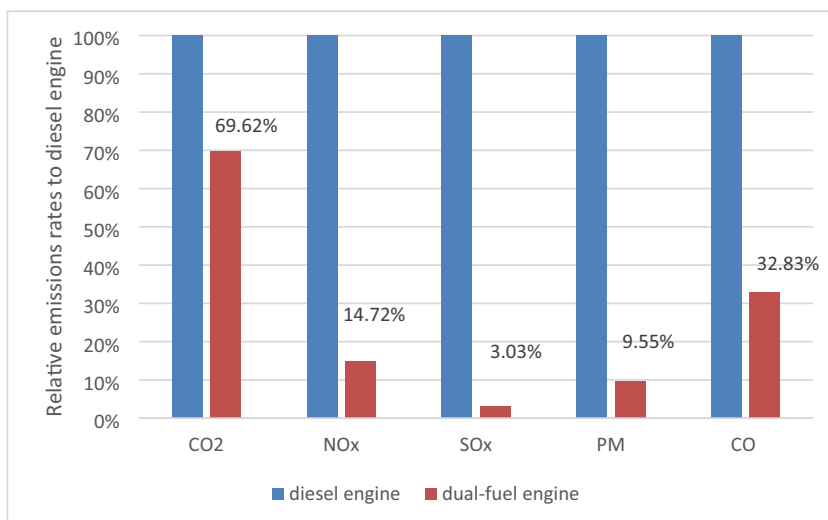


Fig. 6 NOx emission rates of dual-fuel engine compared with IMO 2016 limit

Fig. 7 Relative emissions of dual-fuel engine and diesel engine for the case study



3% MDO will comply with not only the current IMO EEDI requirement but also with the future ones Fig. 9

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.

On the other hand, EEOI can be used to evaluate the improvement in ship energy efficiency after the conversion process to natural gas fuel. The average EEOI is calculated using Eq. (6) assuming the average transported cargo is 4250 TEUs each voyage over 11044 NM which is the distance between Hamburg, Germany, and Busan, South Korea, via Suez Canal. The average EEOI values are 0.000176 and 0.000123 ton CO₂/TEU-NM by using diesel engine and dual-fuel engine, respectively. As shown from the calculated value of EEOI, the conversion process to natural gas in a dual-fuel engine improves the EEOI by 30%. Figure 10 predicts the average

EEOI values at different natural gas percentages and introduces the average EEOI by using diesel engine by a continuous line.

As shown in Fig. 10, using a dual-fuel engine operated by natural gas in a percentage of 93%, 95%, 97%, and 98.5% will reduce EEOI by 23.9%, 25.8%, 30%, and 31.8% when compared with the diesel engine operated by HFO, respectively.

Cost-effectiveness of the conversion process

Moreover, the annual cost-effectiveness should be calculated for the conversion process to dual-fuel engine. The cost-effectiveness should be calculated for each pollutant depending on the added annual cost of the conversion process as discussed in Eq. (11). Table 7 shows the annual cost-effectiveness for the proposed dual-fuel engine to decrease ship emissions for the container ship. The annual cost-effectiveness for a dual-fuel engine installed onboard RIO GRANDE EXPRESS Container Ship for reducing NO_x and SO_x emissions are 903 \$/ton and 3870 \$/ton, respectively.

Fig. 8 The restrictive limit of EEDI based on IMO regulations for container ship type

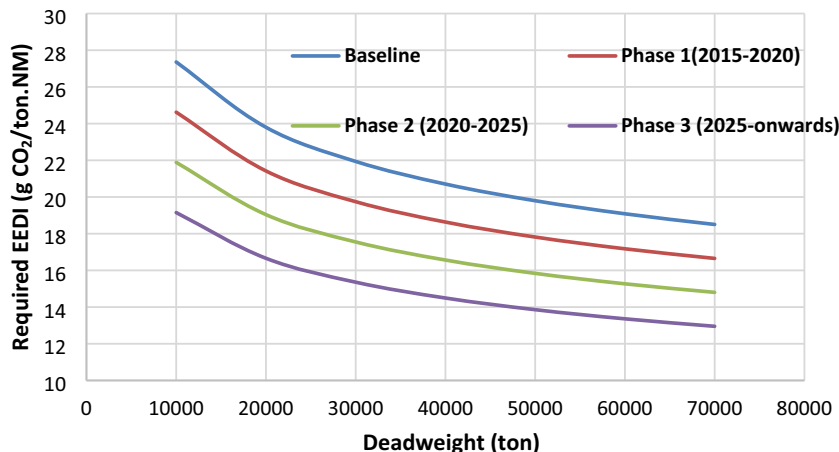


Table 6 Attained EEDI parameters for dual-fuel engine

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 previous results give us an approximate savings cost-benefit per ship power unit of 60.4 US \$ /kW. This will surely confirm the idea of changing from diesel engine to dual natural gas-diesel engine and make it more applicable.

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. Natural gas (NG) in a dual-fuel engine 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 CO₂, NO_x, SO_x, and PM emissions saving percent corresponding to using a dual-fuel engine

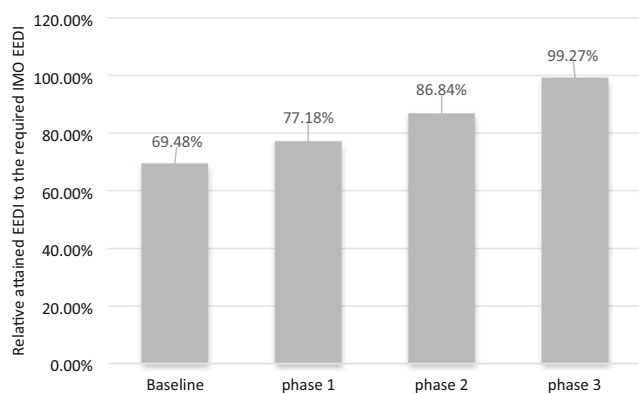


Fig. 9 Comparison of attained and required EEDI values for dual-fuel engine

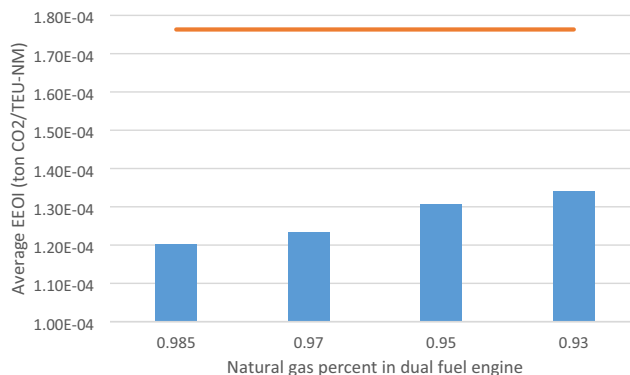


Fig. 10 Average EEOI values for a dual-fuel engine operating at different percentages of natural gas

operated by natural gas instead of diesel engine operated by HFO is about 30.4%, 85.3%, 97%, and 90.4%, respectively. So, converting diesel engines to dual-fuel engines operated by natural gas will reduce the emission rates and comply with not only the current IMO emission rates but also with the future ones. The proposed dual-fuel engine will comply with the required IMO 2016 and 2020 emission limit rates for NO_x and SO_x.

- From an energy efficiency point of view, the attained EEDI value at the case of using natural gas in a dual-fuel engine is set to be 13.66 gCO₂/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% NG and 3% MDO will comply with not only the current IMO EEDI requirement but also with the future ones. On the other hand, the improvement in energy efficiency is assessed by calculating the EEOI; the average EEOI values are 0.000176 and 0.000123-ton CO₂/TEU-NM by using diesel engine and dual-fuel engine, respectively.
- From cost-effectiveness point of view, the conversion process to the proposed dual-fuel (97% NG + 3% MDO) engine will reduce CO₂, NO_x, SO_x, PM, and CO emissions with annual cost-effectiveness of 83 \$/ton, 903 \$/ton, 3870 \$/ton, 32907\$/ton, and 19497 \$/ton, respectively. In addition, using dual-fuel engine will achieve an approximate savings cost-benefit per ship power unit of 60.4 US \$ /kW.

Table 7 Annual cost-effectiveness for using natural gas in dual-fuel engine

Pollutant type	CO ₂	NO _x	SO _x	PM	CO
Cost-effectiveness (\$/ton)	83	903	3870	32907	19497

Abbreviations *AE*, Auxiliary engine; *CSR*, Continuous service rating; *CO₂*, Carbon dioxide; *DF*, Dual fuel; *DWT*, Deadweight; *EEDI*, Energy Efficiency Design Index; *EEOI*, Energy Efficiency Operational Indicator; *CEAS*, Computerized Engine Application System; *GHG*, Greenhouse gas; *HFO*, Heavy fuel oil; *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; *ME*, Main engine; *MEPC*, Marine Environment Protection Committee; *ME-GI*, Main engine gas injection; *NG*, Natural gas; *NO_x*, Nitrogen oxides; *PM*, Particulate matter; *SFC*, Specific fuel consumption; *SG*, Shaft generator; *SO_x*, Sulfur oxides; *TEU*, Twenty-foot equivalent unit

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 commented and reviewed the previous versions of the manuscript. Supervision of the research: Mohamed Khalil and Mohamed M. Elgohary. All authors read and approved the final manuscript.

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

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare that they have no conflict of interest.

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