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RESEARCH ARTICLE

Numerical analysis of economic and environmental benefits of marine fuel conversion from diesel oil to natural gas for container ships

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Abstract
Shipping is a significant contributor to global greenhouse gas (GHG) and air pollutant emissions. These emissions mainly come from using diesel fuel for power generation. In this paper, the natural gas is proposed as an alternative marine fuel to be used instead of conventional marine diesel oil. Numerical analysis of environmental and economic benefits of the natural gas-diesel dual-fuel engine is carried out. As a case study, a container ship of class A7 owned by Hapag-Lloyd has been investigated. The results show that the proposed dual-fuel engine achieves environmental benefits for reducing carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), and carbon monoxide (CO) emissions by 20.1%, 85.5%, 98%, 99%, and 55.7% with cost effectiveness of 109, 840, 9864, 27761, and 4307 US$/ton, respectively. The results show that the conversion process to the dual-fuel engine will comply with the current and future IMO regulations regarding air pollutant emissions. On the other hand, using the proposed dual-fuel engine on the container ship will improve the ship energy efficiency index by 29.6 % with annual fuel cost saving of 4.77 million US dollars.

Keywords Natural gas · Energy Efficiency Design Index · Ship emissions reduction · Cost-effectiveness · Container ship · IMO regulations

Introduction

Marine fuels play a major role in the growth of global seaborne trade despite the environmental problems it causes due to the emissions resulting from its combustion (Kim et al. 2015). Recent statistics from the International Maritime Organization (IMO) indicates that ships emit a huge amount of sulfur oxides (SOx), carbon dioxide (CO_2), particulate matter (PM), carbon monoxide (CO), and nitrogen oxides (NOx) (Elkafas et al. 2019). Moreover, Ammar and Seddiek (2020a) showed that ships are responsible for 4%, 2.6%, and 6.6% of the global SOx, CO_2, and NOx emissions, receptively. As a result of the continuous increase of pollutants emitted from ships, the IMO issued several rules to limit this increase, under Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) convention. This was represented in the issuance of regulation 13 to reduce pollutants of SOx and regulation 14 to eliminate NOx emissions (Yang et al. 2012; Seddiek 2016b). However, with reference to CO_2 emissions, the IMO presented two measures to evaluate the compatibility of the ship with the international regulation. These measures are Energy Efficiency Design Index (EDDI) and Energy Efficiency Operation Index (EEOI) (Rehmatulla et al. 2017). The current research concerns CO_2 emissions more than others due to the recent regulations that control it, taken into consideration that there are many ships still far from being applied. Statistics indicate that the most three ship type that contribute by a valuable percent of CO_2 emissions are container, bulk carrier, and oil tanker ships as shown in Fig. 1. As shown, those ships are sharing 55% of the total CO_2 emissions quantity (Olmer et al. 2017).

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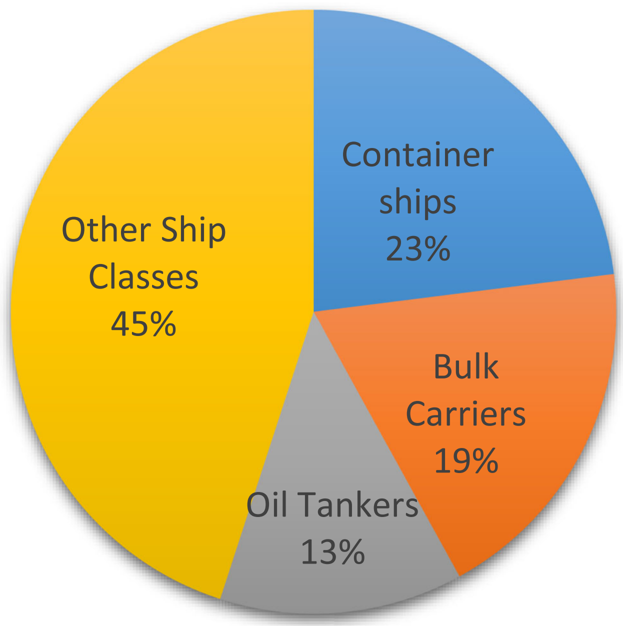


Fig. 1 Share of CO_2 emissions by ship class

Among the previous ship types, container ships seem the most type; this is due to the continuous development that the container trade market is showing. It means that the shipping industry lay between two factors: the development and the adverse effect of this development which acts in the form of emissions. The solution appears in the form of applying the measures of ship's energy efficiency. Based on reviews of mitigating measures (Psaraftis 2016; Bouman et al. 2017), emission reduction measures are commonly divided into two main categories: technical and operational. Technical measures focus, for example, on alternative fuels, improved propulsion and power system, and energy savings through improved energy efficient design. Operational measures aim at reducing emissions during operations onboard ships such as speed reduction, weather routing, and hull friction reduction by air lubrication system.

There is no doubt that the selection of the optimum energy efficient concept for a specific ship type is a comprehensive task. Therefore, it is important that all parameters which have an influence on the energy efficiency index such as economy, operation characteristics, and environmental effects are analyzed and evaluated before the final decision is made (Ammar and Seddiek 2020a). By studying the abovementioned measures, to achieve rapidly CO_2 emission reductions, the implementation of energy efficiency measures needs to be supplemented by the utilization of liquefied natural gas (LNG) as an alternative fuel with lower CO_2 emissions than conventional fuels (Hansson et al. 2019).

The aim of the present paper is to evaluate the environmental benefits for using natural gas as a marine fuel with emphasis on improving ship energy efficiency index. In addition, the economic use of natural gas-diesel dual-fuel engine onboard ships is investigated. Finally, the cost-effectiveness for each emission reduction percentages after using natural gas fuel is assessed. As a case study, a container ship of class A7 owned by Hapag-Lloyd is investigated.

Literature review for marine alternative fuels

The main alternative marine fuel types may be found in two forms—liquid and gaseous fuels. Liquid marine alternative fuels include biodiesel, methanol, and ethanol (Seddiek and Elgohary 2014). Biodiesel is a renewable fuel which could be used to reduce dependence on fossil fuel onboard ships (Kesieme et al. 2019), but it has bad starting at cold weather, storage instability, and cause increase in NOx emissions (+ 2: + 5%). Recent studies (Ammar 2019a; Paulauskiene et al. 2019) showed the possibility of using methanol as 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 main alternative gasses fuels include hydrogen, propane, and natural gas. Hydrogen has high heat content more than the conventional fossil fuels. El Gohary et al. (2015) and van Biert et al. (2016) showed the possibility of use hydrogen as a fuel for marine applications especially in fuel cell systems. Many researchers showed the possibility of using natural gas for marine application either for ships powering system (Korakianitis et al. 2011; El-Gohary 2012; Seddiek 2015) or for electric generation, using fuel cells (El-Gohary and Saddiek 2013; Welaya et al. 2013). There are some criteria that control choosing the suitable alternative fuel, such as adaptability, availability, safety, cost, renewability, performance, and environmental impact (Elgohary et al. 2015; Seddiek 2016a).

Among the previous alternative fuels, hydrogen and natural gas showed many attempts to applied onboard ships. Unfortunately, the safety issue presents an obstacle to spread the hydrogen applications onboard ships (Seddiek et al. 2015). This means that there is a priority to use the natural gas as an alternative marine fuel. Natural gas is used in the forms of compressed natural gas (CNG) and liquid natural gas (LNG) in the transportation sector (Cheenkachorn et al. 2013). LNG is more proficient in terms of storage, safety, and transportation compared to CNG, particularly in ships (Li et al. 2015). Many studies have demonstrated that LNG is favored for use over a long period of time, is more economical in significant distance transportation systems (Li et al. 2015; Spoof-Tuomi and Niemi 2020), is more environmental friendly (Arteconi et al. 2010), and has a more powerful performance (Cheenkachorn et al. 2013).

Environmental and economic assessment methodology

This section introduces the methodology applied to assess the environmental impacts of the ship with a focus on the most influential pollutants on the environment such as CO_2, NOx, SOx, CO, and PM with emphasis on the calculation of the EEDI. Finally, the methodology applied to assess the economic benefits of the conversion process from diesel to dual-fuel engine is introduced.

Environmental assessment methodology

Firstly, CO_2 emission can be assessed by using one of the IMO energy efficiency rules which called Energy Efficiency Design Index. EEDI sets a base energy efficiency level for CO_2 emissions per ton-mile for various vessel types and sizes (Ančić and Šestan 2015; Bøckmann and Steen 2016). The restrictive limit for EEDI is called required EEDI ($EEDI_{required}$). Required EEDI is established for each ship type to which regulation 21 of MARPOL Annex VI is applicable (IMO 2013). It depends on the ship type and its capacity as shown in Eq. (1) (Ammar 2018; Ammar and Seddiek 2020a).

$$EEDI_{required} = \left(\frac{a}{c^d}\right)\left(1 - \frac{X}{100}\right) \quad (1)$$

where a and d are parameters which differ with the ship type and determined from the regression curve fitting of a defined group of ships with different capacities. Table 1 lists the values of these parameters for different ship types. The parameter C is defined to be the deadweight tonnage (DWT) of ship (Germanischer-Lloyd 2013).

The required EEDI will be reduced by X% every 5 years based on the initial value (Phase 0) starting by phase 1 (Jan 2015–Dec 2019) and so on. The reduction is in general 10% for each reduction phase (Ammar and Seddiek 2020b). The required EEDI values at different phases for container ship type are shown in Fig. 2.

On the other hand, the actual index is called attained EEDI ($EEDI_{attained}$) and its value should be lower than required EEDI (IMO 2018). The attained EEDI formula includes three basic terms to estimate the CO_2 emissions per unit transport work (g CO_2/ton-NM). The first term is the determination of main engine(s) CO_2 emissions (ME_e)as expressed in Eq. (2) (IMO 2018).

Table 1 Required EEDI parameters for different ship types (Germanischer-Lloyd 2013)

Ship type	a	d
Bulk carriers	961.79	0.477
Tankers	1218.8	0.488
Container ships	174.22	0.201
Ro-Ro passenger ships	752.16	0.381

$$ME_e = \sum_{x=1}^{nME} P_{ME(x)} \times SFC_{ME(x)} \times C_{FME(x)} \quad (2)$$

where P_{ME} and SFC_{ME} are the power and specific fuel consumption of each main engine (x) and taken at 75% of maximum continuous rating (MCR) in terms of (kW and g/kWh), respectively. $C_{FME(x)}$ is a non-dimensional conversion factor between fuel consumption and CO_2 emission, and its value depends on the fuel type and carbon content as given in Table 2 (Tran 2017; IMO 2018).

The second term is the determination of auxiliary engine(s) CO_2 emissions (AE_e) as expressed in Eq. (3) which calculated as a share of the installed main engine power in case of main engine MCR is more than 10000 kW (IMO 2018).

$$AE_e = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME} + \frac{\sum_{i=1}^{nPTI} P_{PTI(x)}}{0.75}\right) + 250\right] \times SFC_{AE(x)} \times C_{FAE(x)} \quad (3)$$

where MCR_{ME} is the maximum continuous rating of installed main engine(s) and P_{PTI} is the power take in for the shaft motor and AE is subscript refers to auxiliary engine.

The third term is the determination of CO_2 emission reduction by adopting new energy-saving technologies, for example, additional sail or kite propulsion systems, or Flettner rotor systems.

For the dual-fuel (DF) engine, Eq. (4) is used to evaluate the CO_2 emission factor depending on the value of SFC of gas fuel and pilot fuel at the related load point.

$$C_{F(DF)} \times SFC_{DF} = C_{F,pilotfuel} \times SFC_{pilotfuel} + C_{F,Gas} \times SFC_{Gas} \quad (4)$$

The denominator of attained EEDI formula (transport work) is calculated as shown in Eq. (5).

$$Transport\ work = f_i \cdot f_1 \cdot f_w \cdot f_c \cdot Capacity \cdot V_{ref} \quad (5)$$

where V_{ref} is the reference speed of the ship at EEDI conditions in knots; f_i, f_1, f_w, and f_c are parameters which depend on the ship characteristics. The values for these parameters equal 1.0 if they are applicable onboard the ship. Capacity depends on the ship type; 70 % of the DWT at summer load draft should be used for container ships (Ammar and Seddiek 2020b).

Generally, the ship emissions rates (EM) in terms of (tons/hour) can be calculated by using the power of engine and the emission energy-based factor as shown in Eq. (6) (ICF International 2009; Ammar and Seddiek 2017).

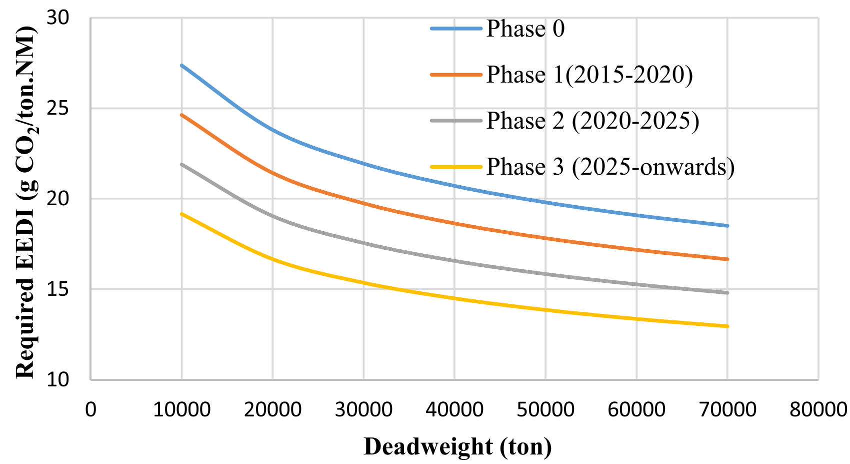


Fig. 2 Required EEDI values at different phases for container ship type

$$EM_i = \sum_j \frac{P_j \times EF_{i,j}}{10^6} \tag{6}$$

where P is the engine power at the actual load condition in kW, EF is the emission factor in terms of g/kWh, the subscript j is the type of engine (main engine or auxiliary engine), and the subscript i is the type of pollutant emissions.

The calculation of emission factor differs from one to another. CO_2 emission factor can be calculated by multiplying the SFC and the conversion factor between CO_2 and fuel. The emission of SOx is proportional to the fuel consumption and the sulfur content (S%) in the fuel. This is because virtually all the sulfur in the fuel will be oxidized into SOx in the engine. The SOx emission factor (EF_{SOx}) in g/kWh can be calculated using Eq. (7) (ICF International 2009) by assuming that 97.753% of the fuel sulfur was converted to SO_2 and taking into account the molecular weight difference between SO_2 and sulfur (molecular weight 2 times sulfur) (United States, Energy and Environmental Analysis, Inc 2000; ICF International 2009).

$$EF_{SOx} = 2 \times 0.97753 \times (SFC \times S\%) \tag{7}$$

It was found that the emission of particulates (EF_{PM}) was especially related by the Sulphur content (S) and the specific fuel consumption (SFC) as a result from different studies (Cooper and Gustafsson 2004; ICF International 2009). The following equation, Eq. (8) for the PM emission factor, has been derived based on these studies for the engines operated by MDO or MGO (Kasper et al. 2007; Agrawal et al. 2008).

$$EF_{PM} = 0.23 + \mathrm{SFC} \times 7 \times 0.02247 \times (\mathrm{S\%}{-}0.0024) \tag{8}$$

The above equation is based upon the fact that the sulfate component in PM_{10} has a molecular weight 7 times that of sulfur and that 2.247% of the fuel sulfur is converted to PM_{10} sulfate (ICF International 2009).

As per the recommendations of the air pollutant emission inventory (Trozzi and De Lauretis 2019), for slow-speed diesel engines operated by MDO or MGO, the average NOx emission factors expressed in g/kWh with respect to the year of installation are as follows: 17, 16.4, and 15.8 g/kWh for engines marked in 2000, 2005, 2010, and beyond (Ammar and Seddiek 2020b).

The NOx emission factor should be compared with the required IMO emission rate. The NOx emission limit is equal to 3.4 for the slow-speed Tier III engine as recommended from IMO (Ammar 2019b).

For the case of using dual fuel (gas and pilot oil) engine, the emission factor for the dual-fuel engine (EF_{DF}) can be expressed using Eq. (9).

$$EF_{DF} = x_{gas} \times EF_{gas} + x_{P.O} \times EF_{P.O} \tag{9}$$

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.

Table 2 Carbon contents and conversion factors of different fuel types (IMO 2018)

Type of fuel	Carbon content	C_F [t-CO_2/t-fuel]
Diesel/gas oil	0.875	3.206
Light fuel oil (LFO)	0.86	3.151
Heavy fuel oil (HFO)	0.85	3.114
Propane	0.819	3
Butane	0.827	3.03
Liquefied Natural Gas (LNG)	0.75	2.75

Economic assessment methodology

The economy study presents an important role during the applicability of using natural gas onboard ships. It includes estimating the benefits from the conversion process followed by determining the annual saving cost and ended by estimated the cost effectiveness of reducing ship emissions. The first step will include estimation of fuel cost saving as a result of shifting from diesel fueled ship to natural gas fueled ship. This value depends mainly on some main factors, which could be demonstrated in Eq. (10) (Ammar and Seddiek 2017).

$$F_{SC} = P * t_s * \left[\left(SFC_{D.O} * fc_{D.O} \right) - \left(SFC_{gas} * fc_{gas} \right) - \left(SFC_{P.O} * fc_{P.O} \right) \right] \quad (10)$$

where P is the main engine power in kW, t_s is sailing time in hours, ($SFC_{D.\ O}$) diesel engine specific fuel consumption in g/kWh, (SFC_{gas}) is the natural gas specific fuel consumption in g/kWh. $fc_{D.\ O}$, fc_{gas},and $fc_{P.\ O}$ are the fuels costs of marine diesel oil, natural gas, and pilot oil in USD $, respectively. With reference to the annual cost saving as a result of changing to the proposed alternative fuel, this value presents the benefits as a whole taken into consideration the positive and draw backs elements affect this study. The value of annual saving cost (A_{SC}) could be estimated as shown in Eq. (11) (Ammar and Seddiek 2017).

$$A_{SC} = F_{SC} + \Delta SC_{M\&O} - \left[C_A * \left(\frac{i\,(1+i)^N}{(1+i)^N - 1} \right) \right] \quad (11)$$

where C_A is the capital cost due to conversion of the main engine to be dual-fuel engine, N is the expected working years after conversion process, i is the annual interest rate, F_{SC} is the difference between fuel cost of diesel and natural gas, and $\Delta SC_{M\,\&\,O}$ is the difference between maintenance and operating cost of diesel and natural gas engines.

Finally, 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. (12) (Ammar and Seddiek 2020a).

$$E_{CE} = \frac{AAC}{\Delta E} \quad (12)$$

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.

Case study: container ship

A container ship is used as a case study to assess factors influencing the enhancement of the energy efficiency mainly EEDI assessment, environmental impacts, and economic results. The selected ship is owned 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-Lloyd 2019). The container ship (Al-Hilal) is classified as A7 ship which has a capacity of 6921 TEU. Al Hilal was built in 2008 (12 years ago) by Hyundai Heavy Industries Co., currently sailing under the flag of Liberia. The principal particulars of the case study are shown in Table 3 (Hapag-Lloyd 2019; FleetMon 2020).

The case study container ship is powered by a low-speed marine diesel engine (Wartsila 11RT-flex96C) with a maximum continuous rating of 54612 kW and operated by MDO (1% sulfur) (Wartsila 2008). The relation between the specific fuel consumption and different engine loads can be shown in Fig. 3 by using the project guide of Wartsila engine (Wartsila 2008; Morsy El Gohary and Abdou 2011).

Currently, the emission factors for the slow-speed diesel engine operated by MDO (1%S) 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 16.4 g/kWh. The selected condition is EEDI condition which uses 75% MCR so SFC is equal to 168.1 from Fig. 3. The emission factors are 539 g/kWh, 16.4 g/kWh, 3.29 g/kWh, 0.43 g/kWh, and 1.24 g/kWh for CO_2, NOx, SOx, PM, and CO, respectively.

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%.

The ship transports containers between different ports in the USA, Northern European, Mediterranean Sea, and East Asia zones. The route between Hamburg–Germany and Busan–South Korea is taken as a reference through the environmental and economic calculations. Therefore, the distance

Table 3 Main particulars of the case study container ship

Specifications	A7
Ship name	Al-Hilal
IMO NO.	9349552
Flag	Liberia
Built year	2008 (12 years old)
L.O.A, m	306
L.B.P, m	290.6
Molded breadth, m	40
Dead weight, ton	85384
Container capacity, TEU	6921
Service speed, knots	24 at MCR
Main engine type	Wartsila (11 RT-flex 96C)
MCR power, kW	54612
Auxiliary engine, kW	4 × 2650

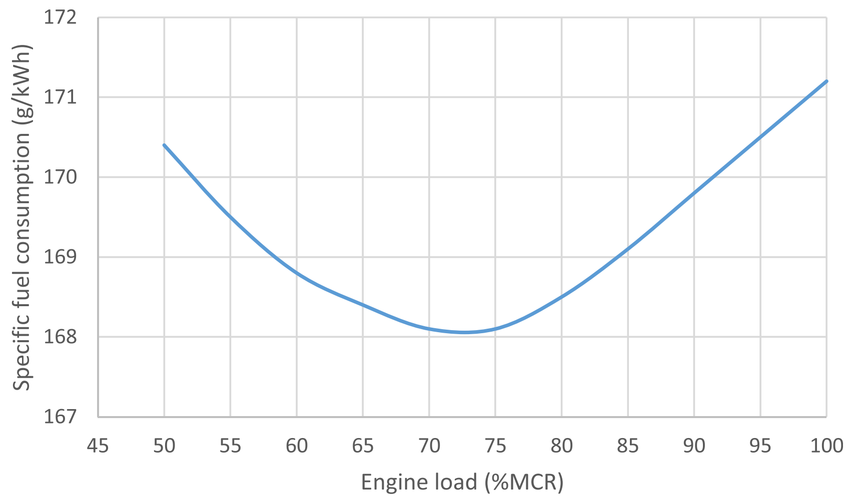


Fig. 3 Relationship between the engine load and fuel consumption for the container ship

covered by the ship is 13,000 nautical miles (NM). The travel time depends on the characteristics of the vessel, particularly the service speed. According to the service speed of 24 knots, the average time for each trip is 46 days in cruising mode. Therefore, it is assumed that the average number of trips per year is 6 trips (Ammar and Seddiek 2020a).

The conversion process depends on the engine conversion from diesel engine operated by MDO (1%S) to a dual-fuel engine operated by natural gas (NG) and MDO (1%S). The emission factors for natural gas engine are 2.16 g/kWh, 0 g/kWh, 0 g/kWh, 429.2 g/ kWh, and 0.54 g/kWh for NOx, SOx, PM, CO_2, and CO, respectively (Banawan et al. 2010; Seddiek and Elgohary 2014; Speirs et al. 2020).

Results and discussion

The study at hand is mainly focused on tracing and examining the impacts triggered as a result of utilizing natural gas as an alternative fuel in a dual-fuel engine on the container ship case study. The research is initially concerned with studying the environmental impacts as well as the rate of emissions incurred as a consequence of using natural gas as a main fuel. In addition, the ship energy efficiency can be assessed based on the value of attained EEDI and its value compared by the required IMO at different phases. In addition, the economic benefits of the dual-fuel engine are analyzed through calculating the fuel and the initial payment costs for the dual-fuel engine conversion. Finally, the cost-effectiveness for the emission reduction using natural gas fuel is analyzed.

Environmental benefits of the conversion process

The initial phase in assessing the environmental advantages of natural gas dual-fuel engine is to figure the emissions factors. The emission factors for the dual-fuel engine can be determined at different natural gas and pilot fuels percentages by utilizing Eq. (9). Table 4 presents the emission factors for the dual-fuel engine at different fuels substitution percentages. Figure 4 shows the different emission rates of the dual-fuel engine at (tons/hour), when the natural gas fuel percent increases, CO_2, NOx, SOx, PM, and CO emissions are decreased.

NOx and SOx emission rates should be compared with the IMO 2016 and 2020 emission-limit rates for NOx and SOx which are predicted based on engine speed (rpm) and fuel sulfur content (0.5%), respectively. It can be noticed that SOx emissions rates for the dual-fuel engine are compliant with the IMO 2020 limits because the dual-fuel engine operated by natural gas as shown in Fig. 5.

In addition, the NOx emission rates for dual-fuel engine operated by natural gas (above 91% NG) will be compliant with the required IMO rates as shown in Fig. 6. Therefore, dual-fuel engine (98.5% NG and 1.5% MDO) emission rates will have the least emission rates and comply with the current and the future NOx and SOx emission regulations.

The environmental benefits of dual-fuel engine are clear when compared with the diesel engine as shown in Fig. 7. For the current case study, the emission rates for slow-speed diesel engine operated by MDO (1% S) are 22.17 tons/hour, 0.675 tons/hour, 0.135 tons/hour, 0.018 tons/hour, and 0.051 tons/hour for CO_2, NOx, SOx, PM, and CO emissions, respectively. These rates are reduced after applying dual-fuel engine

Table 4 Calculated dual fuel engine emission factors

Emission factor (g/kWh)	CO_2	NO_X	SO_X	CO	PM
95% (NG) + 5% (MDO)	434.7	2.87	0.164	0.58	0.022
97% (NG) + 3% (MDO)	432.5	2.59	0.099	0.56	0.013
98.5% (NG) + 1.5% (MDO)	430.85	2.37	0.04	0.55	0.006

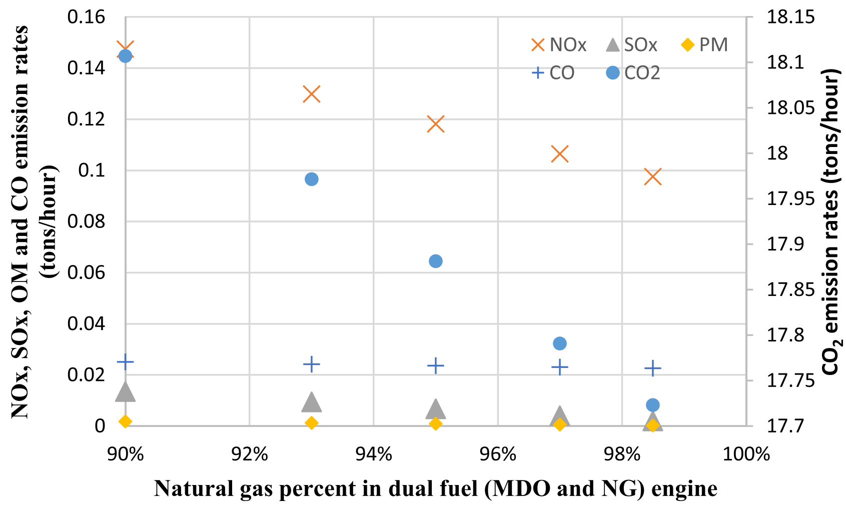


Fig. 4 Different emission rates at various methanol percentages

(98.5% natural gas and 1.5% MDO) to 17.72 tons/hour, 0.098 tons/hour, 0.002 tons/hour, 0.0003 tons/hour, and 0.023 tons/hour with reduction percentages of 20.1%, 85.53%, 98.5%, 98.5%, and 55.74%, respectively.

It is necessary to evaluate the fuel consumption of Al-Hilal container ship operated by diesel and compare it with the proposed dual-fuel engines as this is fundamental for deciding the necessary natural gas storage tanks which are needed to operate the vessel in dual-fuel mode. The trip is assumed to take 46 days with 6 trips per year. The ship is powered by slow-speed diesel engine (MDO 1%) and consumed 7634 tons of marine diesel oil per trip and 45805 tons per year. While the ship with the proposed dual-fuel engine (98.5% NG + 1.5% MDO) will consume 13513 m^3 and 152 tons of liquefied natural gas and marine diesel oil per trip with 81079 m^3 and 913 tons per year, respectively.

Environmental benefits of the engine conversion process are clear when the emission rates per trip or annually are assessed and compare these rates with those of the diesel engine as shown in Table 5 which shows the reduction rate of the different pollutant types by the conversion process from diesel engine to the proposed dual-fuel engine annually.

Energy efficiency improvement by the conversion process

The energy efficiency can be assessed based on the value of EEDI which applied by the IMO regulation. The required EEDI should be calculated at the baseline and the IMO three phases. The initial value for EEDI recommended by IMO for Al-Hilal container ship is 17.78 gCO_2/ton-NM at the maximum DWT (85384 tons). This value would be reduced to 16, 14.22, and 12.44 gCO_2/ton-NM at phases 1, 2, and 3, respectively, as shown in Fig. 2.

It is necessary to calculate the attained EEDI of the case study when operated by slow-speed diesel engine and compare it with the required EEDI values at all phases. Based on IMO guidelines in the determination of attained value, the

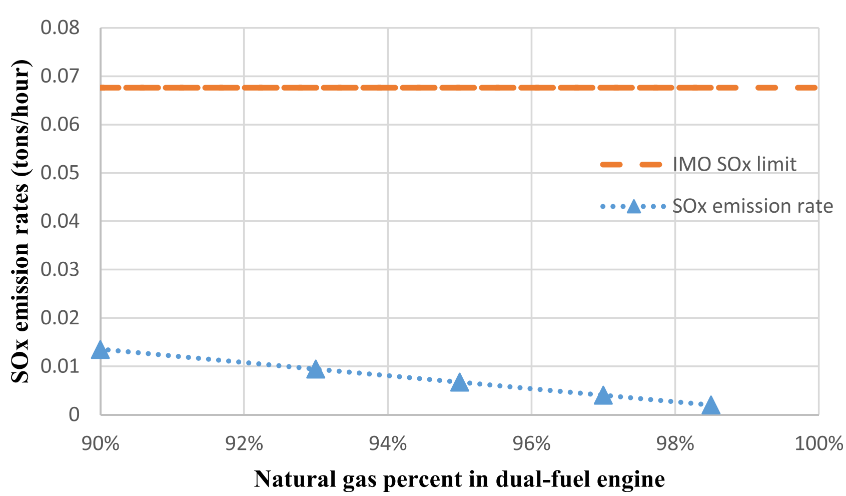


Fig. 5 Comparison between SOx emission rates at different NG percent and IMO 2020 limit

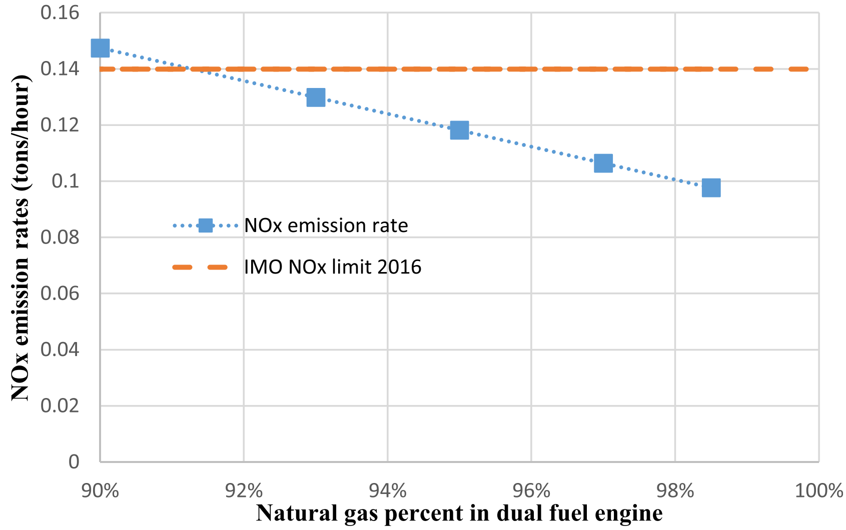


Fig. 6 Comparison between NOx emission rates at different NG percent and IMO 2016 limit

design service speed (24 knots) is assumed to be used as a reference speed (V_{ref}) in Eq. (5) and utilizing EEDI capacity which equal 70% DWT (Perera and Mo 2016). The calculated attained EEDI is 16.14 gCO_2/ton-NM. By comparing this value with the required EEDI values, it shows that attained value is lower than the baseline EEDI value by about 9.2%. The attained EEDI should be decreased by 0.89%, 11.9 %, and 22.91% to comply with the first, second, and third IMO phases, respectively, as shown in Fig. 8.

The potential benefits from energy efficiency perspective will be clear when applying the proposed dual-fuel engine (98.5% NG and 1.5% MDO). The attained EEDI value for dual-fuel engine is calculated based on Eq. (4), EEDI capacity which equals 70% DWT and by assuming that service speed is used as a reference speed (V_{ref}) in Eq. (5) (Perera and Mo 2016). The attained EEDI value is 11.37 gCO_2/ton-NM. When comparing this value with the attained EEDI value at the diesel engine, it shows that the improvement percent is equal 29.57% and proof the improvement in energy efficiency resulting from the conversion process to the dual-fuel engine.

The conversion process will improve the value of attained EEDI and achieve the IMO EEDI limits in all phases as shown in Fig. 9. By using dual-fuel engine, the attained EEDI will be lower than the required IMO EEDI at phases 1, 2, and 3 by 28.94%, 20.05%, and 8.63%, respectively, while the value of attained EEDI in case of using a diesel engine was higher than the required values by IMO at all phases. It shows that the conversion process to the dual-fuel engine will comply with the current and future IMO regulations.

Economic analysis results of the conversion process

In this section, the economic results for using dual-fuel engine based on natural gas onboard A7 container ship are discussed.

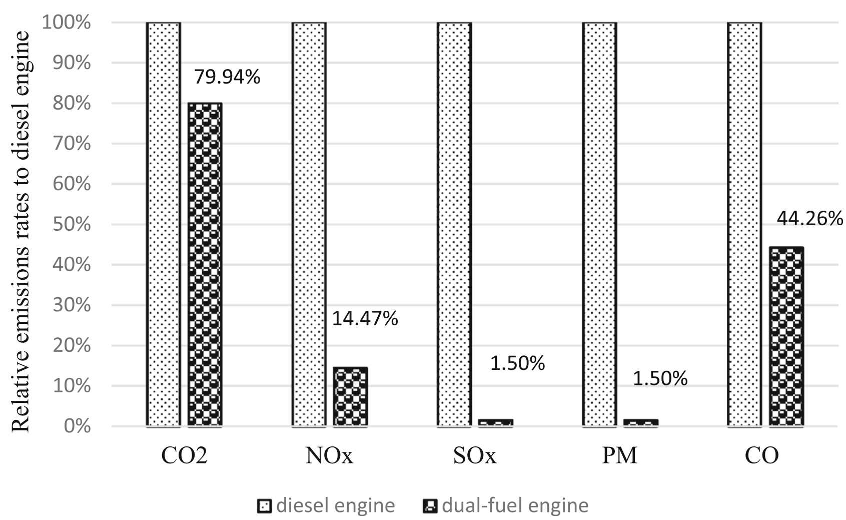


Fig. 7 Relative emissions rates of dual-fuel engine with diesel engine

Table 5 Environmental assessment of Al Hilal container ship

Pollutant type	Engine type	Rate per trip (tons)	Rate per year (tons)	Reduction (tons/year)
CO_2	Diesel engine	24474.98	146849.9	29450.89
	Dual-fuel engine	19566.5	117399	
NOx	Diesel engine	744.792	4468.752	3821.982
	Dual-fuel engine	107.795	646.7701	
SOx	Diesel engine	56.49247	338.9548	325.5222
	Dual-fuel engine	2.238774	13.43264	
PM	Diesel engine	19.57111	117.4266	115.6652
	Dual-fuel engine	0.293567	1.7614	
CO	Diesel engine	149.2516	895.5095	745.4905
	Dual-fuel engine	25.00317	150.019	

With the aim of assessing the economic benefits for the conversion process, the yearly fuel cost ought to be determined for the case study by using Eq. (10). The total annual fuel cost for diesel and dual-fuel engines are 16.03 US$ million, and 11.27 million US$, respectively, depending on the current fuel prices. Figure 10 presents the annual fuel saving costs due to the conversion process from diesel engine to dual-fuel engine. As shown in the figure, there is a possibility of achieving fuel saving costs of 4.77 US$ million per year, in case of shifting to natural gas mode.

The time needed for cash recovery is significant in the economic analysis for the conversion process from diesel engine to dual-fuel engine. Figure 11 shows the yearly expense for capital cost recovery with payback periods. These periods ought to be contrasted with the expected working years for the ship after the conversion process, by assuming that the ship life cycle is 28 years from the start date of building (Banawan et al. 2010). For the case study, the yearly capital cost recovery is $ 2,792,129 per year at an interest rate of 10% and the expected remaining ship age of 16 years.

As well as the financial advantage of investment funds in the fuel cost by utilizing natural gas rather than diesel oil, the maintenance and operating expenses are likewise viewed as a significant thing that influences the economic matters. From the past examinations on utilizing natural gas as fuel for engines, it is inferred that the expenses are expected to be decreased for the case when natural gas is utilized to around 50% of original costs (Banawan et al. 2010). For the case study, the annual saving maintenance and operating costs is US$ 480,841 per year. By using Eq. (11), the annual saving money after the conversion process at different fuel price increments over the remaining ship life cycle can be presented as shown in Fig. 12.

At the end of the ship life cycle, the total annual saving for using dual-fuel engines will be 22.42 US$ million, assuming 2% fuel price increment.

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. (12). Table 6 shows the annual cost-effectiveness for the proposed dual-fuel engine to decrease ship emissions for A7 class container ship. The annual cost-effectiveness for a dual-fuel engine installed onboard Al-Hilal

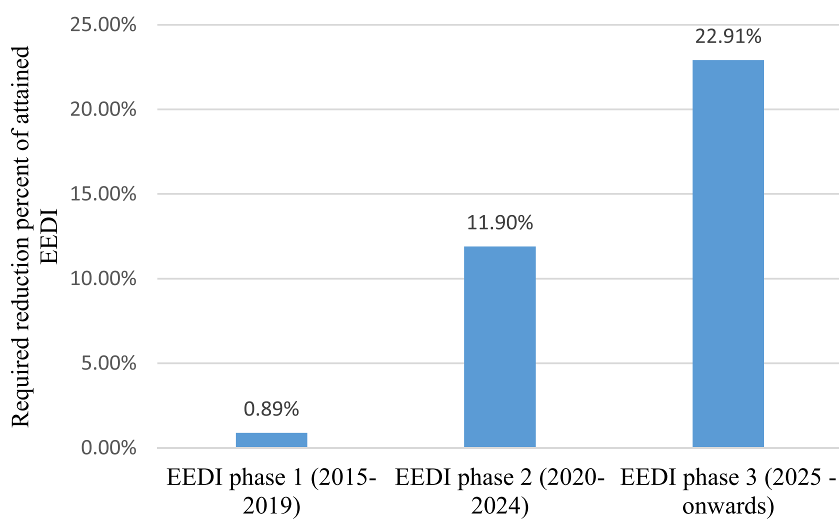


Fig. 8 Required EEDI reduction percent at second and third IMO phases

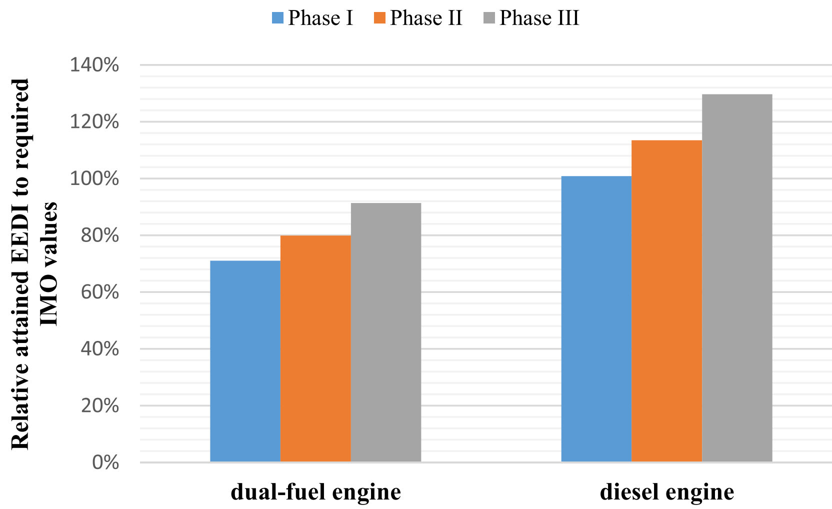


Fig. 9 Comparison of attained EEDI for different engine type with required IMO values

container ship for reducing NOx and SOx emissions are $ 840 per ton and $ 9864 per ton, respectively.

The previous results give us an approximate savings cost benefit per ship power unit of 59.68 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

Environmental concerns and new emission regulations for developing the maritime sector in an environmentally friendly manner have been the subject of the regulatory framework for years. These are the main drivers behind the introduction of alternative marine fuels. Fuel has a significant impact on emissions, so switching to alternative fuels is one of the strategies to reduce ship emissions and increase ship energy efficiency. Natural gas has become an increasingly attractive alternative to conventional marine fuels. This paper has given a detailed analysis for using the natural gas as a main fuel in dual-fuel engine from environmental and energy efficiency prospective. The study also addressed economic aspects and prospects for the conversion process from marine diesel oil to natural gas. For the larger ocean-going vessels that contribute to the majority of global GHG emissions from shipping, the results of the analysis indicated the following:

- In terms of environmental impacts, using the proposed dual-fuel engine with 98.5% natural gas and 1.5% marine diesel oil will comply with the required IMO 2016 and 2020 emission-limit rates for NOx and SOx. The environmental benefits of dual-fuel engine are clear when

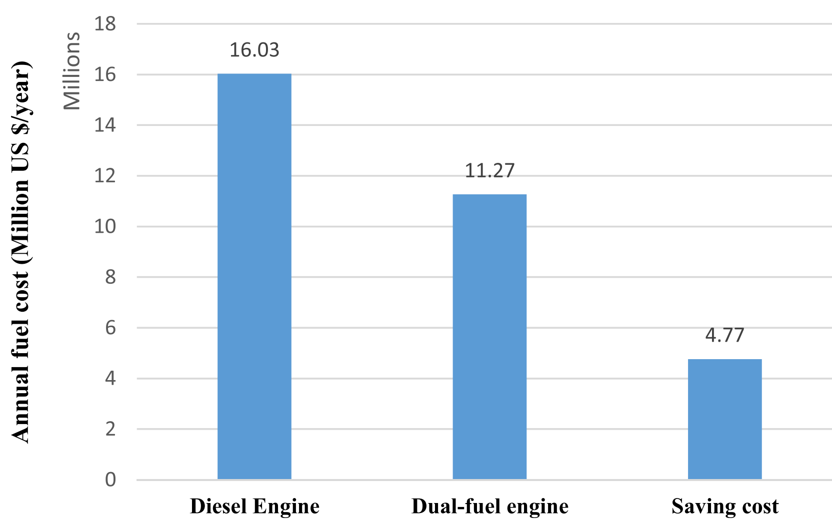
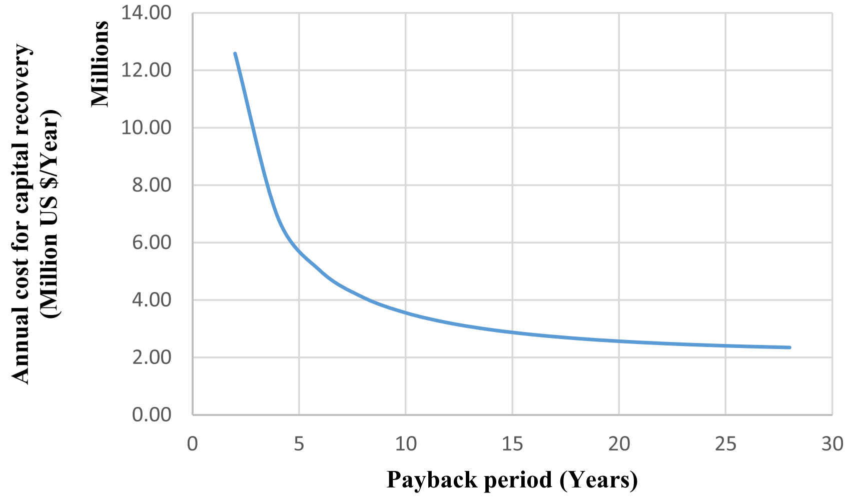


Fig. 10 Annual fuel cost for diesel and dual-fuel engines

Fig. 11 Annual cost recovery and payback periods for dual-fuel engine



compared with the diesel engine as the emission rates of CO_2, NOx, SOx, PM, and CO are reduced by 20.1%, 85.5%, 98%, 99%, and 55.7% after applying the proposed dual-fuel engine, respectively.

- In terms of energy efficiency perspective, the attained EEDI value for dual-fuel engine is 11.37 gCO_2/ton-NM with enhancement by 29.57% when compared by its value at the diesel engine. The conversion process will achieve the IMO EEDI limits in all phases as the attained EEDI will be lower than the required IMO EEDI at phases 1, 2, and 3 by 28.94%, 20.05%, and 8.63%, respectively.
- In terms of economical point of view, the total annual fuel cost for diesel and dual-fuel engines are US$ 16.03 million, and 11.27 million US$, respectively; therefore, the conversion process will achieve fuel cost savings of 4.77 million US$ per year. By assuming that the remaining ship age of 16 years, the yearly capital cost recovery is 2,792,129 $ per year at an interest rate of 10%. At the end of the ship life cycle, the total annual saving for using dual-fuel engines will be 22.42 million US$, assuming 2% fuel price increment.
- In terms of cost-effectiveness point of view, the conversion process to the proposed dual-fuel engine will reduce CO_2, NOx, SOx, PM, and CO emissions with annual cost effectiveness of 109 $/ton, 840 $/ton, 9864 $/ton, 27761 $/ton, and 4307 $/ton, respectively. In addition, using dual-fuel engine will achieve an approximate savings cost benefit per ship power unit of 59.68 $/kW.

Fig. 12 Total annual saving costs result from the conversion process at different fuel price increments

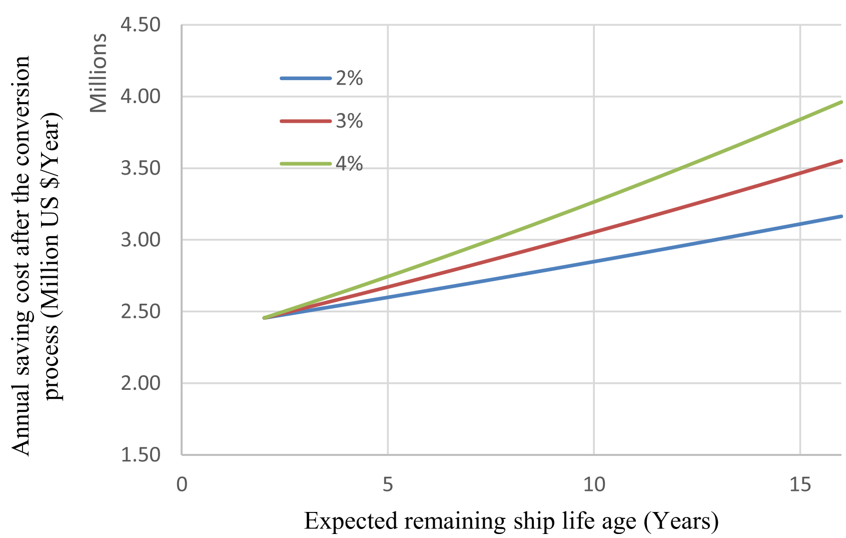


Table 6 Annual cost effectiveness for using natural gas in dual-fuel engine

Type of pollutant	CO_2	NOx	SOx	PM	CO
Cost effectiveness ($/ton)	109	840	9864	27761	4307

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

Compliance with ethical standards

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

Ethics approval Not applicable.

Consent for publication Not applicable.

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