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RESEARCH ARTICLE

Methanol as an Eco-environmental Alternative Fuel for Ships: A Case Study

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Abstract

Global emissions of Green House Gases and air pollutants are significantly influenced by shipping. Diesel fuel use for energy production is primarily responsible for these emissions. The substitution of traditional marine diesel oil with methanol as a marine fuel is recommended in this study. Moreover, the methanol-diesel dual-fuel engine's environmental and financial benefits are investigated numerically. A cruise passenger ship named Costa Toscana has been evaluated as a case study. Based on the data, the suggested dual-fuel engine reduces emissions of CO_2, NO_x, SO_x, and PM by 25.7%, 38.46%, 45%, and 45%, respectively, with a cost-effectiveness of 286.5, 6645, 268403.4, and 358759.8 US$/ton, respectively. According to the findings, converting an engine to run on two fuels will comply with all current and upcoming IMO standards regulating emissions of air pollutants. In addition, the cruise ship's recommended dual-fuel engine will save 17.57 million USD/year in fuel costs.

Keywords: Methanol, Dual fuel engine, Emissions reduction, IMO regulations, Economic study

1. Introduction

Sea transportation has significantly facilitated trade between nations, regions, and continents for ages. It has recently been a crucial enabler of globalization, trade liberalization, and telecommunication [1]. Because of its enormous carrying capacity and low fuel consumption per ton moved, shipping is considered an energy-efficient mode of transportation compared to road and air transportation. As of January 1st, 2022, around 58,000 merchant ships were operating abroad, of which 17,800 were Ro−Ro/general cargo ships. Thus, roughly 31% of the global merchant fleet consisted of Ro−Ro and general cargo ships. Vessels handle more than 80% of all worldwide trade, making them the biggest consumers of fuel used in the transportation industry. Internal combustion engines utilized in marine applications with compression ignition are the most efficient. Low cetane values in inexpensive diesel fuels produce knocking unless utilized in an engine with a high compression ratio, cetane improvers are added, or an additional energy source is introduced [2]. According to the 4th IMO Greenhouse Gas Research Report, global greenhouse gas emissions increased from 977 million to 1.076 billion tons. Additionally, the shipping sector's overall greenhouse gas emissions climbed by 10.1%. Compared to 2008, CO_2 emissions will rise by about 90−130% by 2050 [3]. The Marine Environment Protection Committee (MEPC) was created by the International Maritime Organization (IMO) in 1973 to combat marine pollution and GHG emissions. Since then, several international protocols and regulations have been developed and established to limit shipping emissions [4].

1.1. Methods for limiting ship emissions

The stringent regulations forced the ships to seek new strategies for lowering emissions. A variety of approaches can be applied individually or

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collectively to the process of reducing ship emissions. The three main categories of emissions reduction technology are those found in internal combustion engines, fuel systems, and exhaust cleaning systems [5]. Alternatively, as indicated in Table 1, it can be categorized according to pollutant type. Due to their negative impact on the marine ecosystem, CO2, NOx, and SOx emissions are the subject of most emission reduction technologies. For NOx emissions reduction, three primary techniques are possible. Water addition was one of the outdated techniques applied to liquid fuel. Due to heat, dilution, and chemical effects, injecting water directly into the combustion process can minimize NOx emissions in exhaust gas [6]. Exhaust Gas Recirculation (EGR), a technology used in internal engines, is considered the main method for reducing NOx. Due to the low volume calorific value of the resulting exhaust gas and fresh air mixture, combustion chamber temperatures are lowered, and NOx production is reduced by at least 40% [7]. Selective Catalytic Reduction (SCR) is the most widely used and well-established exhaust gas treatment technique for reducing NOx emissions from marine engines [8]. SCR can potentially decrease NOx, CO2, and PM (particulate matter) emissions by up to 90%, 50%−90%, and 30%−50%, respectively [9]. However, some issues still affect the technology, such as reduced urea conversion efficiency, wall accumulation, ammonia slip, lower NOx reduction efficiency, and catalyst poisoning.

The Diesel Particulate Filter (DPF) is among diesel vehicles' most appropriate diesel PM (particulate matter) removal techniques. The DPF can potentially eliminate PM from exhaust gas through gravitational attraction, sedimentation, physical retention, and inertial crash. The DPF's efficiency in collecting PM is greater than 90% [6]. The exhaust gas cleaning system (EGCS) is the most common method that can potentially eliminate solid particles and SOx emissions from the exhaust before it is released into the environment [10]. Due to the bulky equipment, massive space dominated by scrubbers, and insecurity, dry scrubbing was forbidden on ships. Instead of this, wet scrubbing is used in marine engines to remove PM and SO_x emissions. The IMO regulation seeks to cut CO_2 emissions from maritime activities using high-efficiency techniques such as carbon capture and storage (CCS). The cost parameter, on the other hand, significantly impacts usage [11].

The most common and effective way to reduce the percentage of emissions from all types of pollutants is to replace fossil fuels with alternative and clean fuels. Alternative fuels have been the topic of significant scientific study since their beginnings [12]. Alternative fuels such as liquid natural gas (LNG), ammonia, hydrogen, and methanol are being investigated to determine whether they are usable and capable of replacing conventional fuels. The research has concentrated on environmental, safety, sustainability, performance, and economic effects [13].

Natural gas demand has dramatically expanded because it can satisfy environmental criteria and has features that allow for clean burning [14]. Regarding shipping, safety, and preservation, LNG outperforms CNG, particularly on ships [15]. LNG is more affordable than traditional fuels and has the

Table 1. Emission reduction methods.

Type of pollutant	Methods
NO_x	• Water addition • EGR • SCR • Alternative fuels
SO_x	• Scrubbers • Alternative fuels
PM	• DPF • Alternative fuels
CO_2	• CCS • Alternative fuels

Terms Abbreviations

CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CI	Compression Ignition
CO_2	Carbon Dioxide
CNG	Compressed Natural Gas
DF	Dual Fuel
DPF	Diesel Particulate Filter
DWT	Dead Weight
EEDI	Energy Efficiency Index
EGCS	Exhaust Gas Cleaning System
EGR	Exhaust Gas Recirculation
GHG	Green House Gases
GT	Gross Tonnage
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LNG	Liquified Natural Gas
MARPOL	Marine Pollution Convention
ME	Methanol
MT	Metric Ton
NO_x	Nitrogen Oxides
OPEX	Operational Expenditures
PEMFC	Proton-exchange membrane fuel cells
PFI	Port Fuel Injection
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SO_x	Sulfur Oxide
TDC	Top Dead Center

potential to cut emissions. LNG agrees with the IMO NO_x Tier III limit and significantly reduces NO_x emissions. However, methane slips are present in LNG. With the methane slip taken into account, LNG has a tank-to-propeller NOx reduction of 20–24% compared to MGO (Marine Gas Oil). SO_x, PM, and black carbon emissions are significantly decreased or eliminated. LNG fuel tanks demand two to three times the volume of MDO fuel tanks for the same amount of energy. These extra charges should be offset by lower OPEX, which is determined by fuel prices and maintenance costs[16].

Ammonia (NH_3) is composed of hydrogen and nitrogen. The most prevalent application for this mixture is fertilization. Ammonia as a marine fuel has gained popularity in recent years. As ammonia does not contain carbon, it does not release carbon dioxide. Because combustion can produce NO_x emissions, this does not always mean the process is entirely emission-free. These have been linked to acid rain, smog, ozone layer depletion, and potentially harmful effects on human health [17]. Due to its ease of storage and high hydrogen content, some argue that ammonia should not be considered a fuel in and of itself but rather a source of hydrogen. This technique would require an "ammonia cracking" procedure, which transforms ammonia again into hydrogen. Although this process is somewhat cost-effective, high temperatures are required. If the splitting process does not radiate any NO_x or N_2O, this could reduce NO_x and N_2O emissions from ammonia use and serve as a transitional phase until pure hydrogen storage technology advances [18].

Numerous H_2 production processes are available, which can be divided into two categories based on the raw materials used: conventional and renewable technologies [19]. A renewable energy source that is generally gaseous is hydrogen. Due to the highly purified exhaust produced when it reacts with oxygen to create water, it has caught the attention of scientists [20]. Hydrogen's other remarkable properties include its wide flammability range, higher ignition speed, high diffusibility, low minimum ignition energy, carbon neutral content, and smaller quenching gap, allowing more burning [21]. The fundamental problem with using hydrogen gas as a fuel is that it is naturally scarce, so low-cost production techniques are required. In terms of pollution, it is clear that hydrogen emits fewer emissions practically anywhere an engine operates. However, because of the higher combustion temperature in hydrogen engines, NOx rates were sometimes high, leading to the development of numerous solutions that all use tried-and-true methods currently used with conventional engines, such as exhaust gas recirculation and catalytic reduction filters [22]. Hydrogen, used in fuel cells like PEMFC (Proton-Exchange Membrane Fuel Cells), may be used as fuel by ships and submarines. It can therefore be utilized without requiring much preparation [23].

1.2. Methanol as an alternative fuel

As a feedstock for other chemicals, including formaldehyde, acetic acid, and polymers, methanol (CH_3OH) is one of the most significant substances generated by the chemical industry. Using fossil fuels like coal and natural gas, methanol is produced [24]. The traditional process of making methanol involves two phases. Gasification of natural gas feedstock first produces synthesis gas (Syn-gas), which is composed of carbon monoxide and hydrogen after being reacted with steam (steam reforming), oxygen (partial oxidation), or a mix of both (auto thermal reforming, ATR). Syn-gas is subsequently converted into methanol [25]. Methanol production has increased significantly, and it is predicted to reach 500 Mt per year by 2050 at a cost of between $100 and $250 per ton [26].

Methanol works well in diesel engines and is an excellent alternative to gasoline in mixed fuels. It requires the addition of an ignition enhancer, which could be a small amount of diesel oil, for use in diesel engines. Methanol showed good combustion characteristics, energy efficiency, and minimal combustion emissions at each test. Alcohol fuels, like methanol, have lower energy levels than conventional fuels, which is one drawback. The area needed in a tank to store methanol will be around twice that of conventional diesel fuels, assuming comparable energy density [27]. Table 2 shows the typical properties of methanol [28].

Compression ignition engines make up the majority of ICEs in ships. On the other hand, the high-octane number of methanol makes it an optimum fuel for use in engines using spark ignition (SI), whether used alone or in combination with gasoline (low tendency to knock). Contrarily, because CI engines need fuels with a high cetane number and methanol has a cetane number of only roughly 3, it

Table 2. Characteristics of methanol.

Molecular weight (g)	32
Boiling temperature (°C)	64.7
Density (kg/m^3)	790
Lower heating value (MJ/kg)	19.7
Octane number	110
Cetane number	<5
The heat of evaporation (kJ/kg)	260

is inappropriate for use in these engines (diesel has a cetane rating that ranges from 40 to 55). To attain a cetane rating similar to diesel, methanol can be supplemented with chemicals. Contrarily, these ignition enhancers are often made of hazardous and/or carcinogenic nitrogen-containing substances like octyl nitrate and tetrahydrofurfuryl nitrate. As a result, running methanol in CI engines should utilize alternative technology[29].

1.3. Techniques for allowing the use of methanol in CI engines

Dual Fuel (DF) operation is one of the technology solutions used in CI engines to burn alcohol fuel. Many DF techniques are used to achieve this using methanol [30]. Methanol is injected by port fuel injection (PFI), allowing it to mix with the intake charge before being ignited with a pilot diesel injection before the top dead center (TDC). This strategy is referred to as the "fumigation concept." A pre-mixed fuel oil and methanol mixture is injected using one direct injector close to TDC. Using a single injector with numerous fuel lines and needles, a single, dual direct injector injects diesel and methanol individually, close to TDC. There are two direct injectors, one for methanol and the other for diesel [30]. However, this study aims to evaluate the environmental benefits of methanol as a maritime fuel.

Moreover, the efficiency of methanol-diesel dual-fuel engines for ships is investigated. An estimated cost for converting a diesel engine to a dual-fuel engine is given. Diesel and methanol fuel consumption are computed using the economically selected input methanol fuel percentage. The cost-effectiveness of each emission reduction percentage is assessed after using methanol fuel. A passenger cruise ship is examined as a case study.

2. Methodology

An environmental impact study is carried out by comparing the ship's exhaust emissions when utilizing the suggested alternative fuels to conventional diesel fuel. Pollutants like CO_2, SO_x, and NO_x emissions were among the various types of pollutants released by ships.

Eq. (1) can be used to determine the amount of exhaust emissions produced during a single trip ($E_{Q\ Trip}$), based on the engine power [31]:

$$E_{Q\ Trip} = P_Y * L_Y * T * EF \tag{1}$$

where P_Y is the power output of the engine in kW, Y is either the primary engine or an auxiliary engine, L_Y is the load factor of the engine, T is the time of the vessel operation in one trip in an hour, and EF is the emission factor in ton/kW.h. When evaluating the emission factor for dual-fuel engines, it is crucial to consider the proportions of each fuel, as indicated in Eq. (2) [31]:

$$EF_{DF} = x_{AF} * EF_{AF} + x_{PF} * EF_{PF} \tag{2}$$

where, x_{AF} and x_{PF} are the proportions of alternative and pilot fuels in the dual-fuel engine, EF_{AF} and EF_{PF} are the emission factors for alternative and pilot fuels, respectively.

One of the rules provided by the IMO to prevent pollution is MARPOL Annex VI Regulation 13, which deals with NO_x emissions. This regulation applies to ships built on or after January 1st, 2000, and engines with more than 130 kW of output power. According to the engine speed (n), introduced in January 2000, 2011, and 2016, there are three categories of reduction for NO_x emissions: Tier I, Tier II, and Tier III. Tier III is used in the Emission Control Area and seeks to cut NO_x by 80% compared to Tier I [15]. Table 3 shows the NO_x limits for each tier.

The load factor is calculated as a percentage of the overall power of the vessel. For example, the load factor is 89 percent when traveling at service or cruising speed. It is calculated, as illustrated in Eq. 3, according to the different speeds of the ship [32]:

$$LF = (AS/MS)^3 \tag{3}$$

where LF is a load factor, AS = actual speed (knots), and MS = maximum speed (knots). Auxiliary engine load factors depend on the kind of ship and time in mode. It was formerly believed that all means of transportation—except for hotels—used propulsion engines to generate electricity. Several investigations have revealed that auxiliary engines are constantly running, with the highest loads coming from hoteling (except when cold ironing) [32]. In 2011, the IMO authorized a new measure with a set of performance and technical innovation standards to improve the energy efficiency of new ships during the design stage. This new index, the Energy Efficiency Design Index (EEDI), seeks to reduce CO2 emissions and environmental harm worldwide by using fewer fossil

Table 3. Permissible NOx emission limits in g/kW.h.

Tier	n < 130 rpm	130 <n < 1999	n > 2000
Tier I (January 2000)	17	$45.n^{-0.2}$	9.8
Tier II (January 2011)	14.4	$44.n^{-0.23}$	7.7
Tier III (January 2016)	3.4	$9.n^{-0.2}$	2.0

fuels and creating fewer greenhouse gases. All new ships that are 400 GT or larger must use EEDI. The new ships will be more energy-efficient thanks to this new measure, thanks to their optimized hulls, engines, propellers, etc. Starting with the design phase, EEDI mandates minimum energy use and CO_2 emissions per unit load per ton/mile in various ship types and models [33].

Restrictive EEDI limits, or required EEDI, are specified for each ship category covered by MARPOL Annex VI's Regulation 21. The capacity of the ship and its type are determined by Eq. (4) [34]:

$$EEDI\ required = \left(1 - \frac{X}{100}\right) * q * capacity^{-z} \tag{4}$$

where q and z are parameters that vary depending on the type of ship and are found by fitting a regression curve to a specified group of ships with various capacities. However, *capacity* is defined as a dead weight (DWT) or a gross tonnage (GT), depending on the ship type. X is the ratio of the required EEDI reduction. The attained EEDI calculates a specific number for one ship, expressed in grams of carbon dioxide (CO_2) per ship's capacity ton, based on the technical design specifications for a particular ship (the lower the EEDI, the more energy efficient the ship design will be). Eq. (5) illustrates the EEDI formula in a simple format [35]:

$$EEDI\ attained = \frac{\left(\sum_{i=1}^{n\,ME} P_{ME\,i} * CF_{ME\,i} * SFC_{ME\,i}\right) + (P_{AE} * CF_{AE} * SFC_{AE})}{fi * fc * capacity * V} \tag{5}$$

where ME and AE are the abbreviations of Main Engine and Auxiliary Engine, respectively, and fi and fc are correction factors according to ship characteristics. According to the type of ship, the *capacity* for EEDI loading conditions is measured in MT, where V is the ship's speed in knots.

Economic assessment is essential in evaluating the viability of using alternative marine fuels onboard ships. It begins with assessing the advantages of the conversion process, then determines the annual savings cost and estimates the cost efficiency of reducing ship emissions by shifting to alternative fuels. The first step will be calculating the fuel cost savings this change will achieve. This estimate depends on various factors, as shown in Eq. (6) [36]:

$$F_{SC} = P * T * \left[(SFC_{DO} * FC_{DO}) - \left[(SFC_j * FC_j) + (SFC_{PO} * FC_{PO})\right]\right] \tag{6}$$

where FC_{DO} , FC_j, and FC_{PO} are the fuel cost of the diesel oil, alternative fuel, and pilot oil, respectively; otherwise, P and T refer to power and trip time, respectively. To expect the average value of ship age after conversion, as shown in Eq. 7:

$$AC = CA * CRF \tag{7}$$

where CA is the capital cost of the engine conversion process. Moreover, CRF, the capital recovery factor, has been calculated as expressed in Eq. 8:

$$CRF = \frac{ir(1+ir)^n}{(1+ir)^n - 1} \tag{8}$$

where the interest rate (10%) is ir, and the number of years the ship operated after conversion is n. The second step is to calculate the value of the annual saving cost, as shown in Eq. 9 [37]:

$$ASC = F_{SC} + \Delta SC_{M,O} - AC \tag{9}$$

where F_{SC} indicates fuel cost savings. The operation and maintenance costs of diesel engines and any alternative fuel engines vary by a factor called $\Delta SC_{M,O}$. The economic assessment's third and final step is determining the annual cost-effectiveness of reducing ship emissions (CE). This computation is based primarily on the total cost of deploying methanol as an alternative fuel on ships, including the capital investment necessary for the upgrade process. The value of (CE) as measured in dollars per ton of pollutants can be calculated as shown in Eq. 10:

$$CE = \frac{AAC}{ER} \tag{10}$$

where AAC represents the annual added cost of using methanol-diesel blending, equal to the sum of the capital cost associated with changing the main engine to a dual-fuel engine and the operation cost. ER represents the anticipated annual emission reduction in tons per year associated with switching the primary engine to a dual-fuel engine [36]

3. Case study

This study examined the environmental and economic consequences of using methanol as a substitute for diesel fuel using a cruise liner (passenger) ship. The Costa Group Fleet-owned cruise passenger ship Costa Toscana, which sails under the Italian flag, was built in 2021. It can accommodate 6554 passengers. The ship's medium-speed diesel engine, converted to a dual-fuel engine powered by LNG, sailed between many ports, including Oman and

Dubai. The ship's propulsion system consists of four MaK 16M46DF engines with a total output of 61,700 kW at 500 r/min. Its power is divided into propulsion (37,000 kW) and auxiliary (24,700 kW). The cylinder liner has a bore (internal diameter) of 46 cm and a stroke of 61 cm. Table 4 summarizes the case study's key details [38]. According to Eq. 6, the load factors for each trip are 89 percent while cruising, 16 percent while maneuvering, and 5 percent in standby modes. The study aims to optimize the methanol-diesel ratio to meet the IMO criteria for ship air pollution while analyzing the financial impact of dual fuel.

4. Results and discussion

The current study focuses on tracking and analyzing the consequences of using methanol as an alternate fuel in a dual-fuel engine in the case study of a cruise ship carrying passengers. The study will initially concentrate on the environmental effects and the rate of emissions brought on by employing methanol as an alternative fuel. To assess the ship's energy effectiveness, it is crucial to consider the value of the actual EEDI and how it conforms to the various IMO requirements. Furthermore, it is possible to evaluate the financial benefits of the engine by figuring out the gasoline and upfront costs for the dual-fuel engine conversion. Finally, it is discussed if using methanol fuel to cut emissions is cost-effective. According to earlier studies [15], calculating the emissions factors is the initial step in evaluating the environmental benefits of a methanol dual-fuel engine. The emission factors for the dual-fuel engine at various methanol-diesel ratios can be calculated using Eq. 2. Table 5 shows the emission factors (g/kW.h) for the dual-fuel engine at various percentages of fuel substitution. All the factors are taken at the engine's MCR (maximum continuous rate). Fig. 1 depicts various dual-fuel engine emissions rates at g/kW.h, indicating that CO2, NOx, SOx, and PM emissions decrease as the methanol fuel percentage increases.

Table 4. Costa Toscana particulars.

Specifications	A (cruise passenger)
Ship's Name	Costa Toscana
IMO No.	9,781,891
Built	2021
Length m	337
Breadth, m	58
Gross Tonnage, a ton	186,364
Deadweight, ton	13,000
Ship speed, Average/Maximum	14.8/21.9 kn
Main engine type	4 x MaK 16M46DF
Total power (kW)	57,600 (37,000 kW for propulsion)
Trip duration	7 days (48 trips/year)

Table 5. Emission factors for NO_x, SO_x, PM, and CO_2 for various percentages of methanol blended with diesel.

Methanol%	Diesel%	EF CO_2	EF NO_x	EF SO_x	EF PM
0	100	589.904	17	0.359731	0.26913
10	90	556.2136	15.547	0.323758	0.242217
20	80	522.5232	14.094	0.287785	0.215304
30	70	488.8328	12.641	0.251812	0.188391
40	60	455.1424	11.188	0.215839	0.161478
45	55	438.2972	10.4615	0.197852	0.148022
50	50	421.452	9.735	0.179866	0.134565
60	40	387.7616	8.282	0.143892	0.107652
70	30	354.0712	6.829	0.107919	0.080739
80	20	320.3808	5.376	0.071946	0.053826
90	10	286.6904	3.923	0.035973	0.026913
100	0	253	2.47	0	0

According to IMO 2016 and 2020, the global sulfur content of fuel used or transported on board ships must not exceed 0.5% m/m [34]. A comparison to the previous IMO rule should be made between the expected NO_x and SO_x emission rates dependent on engine rpm and diesel sulfur content, respectively. The SO_x emissions rates meet the IMO 2020 requirements since the dual-fuel engine runs on methanol and diesel (0.1% S), as shown in Fig. 2.

Furthermore, as shown in Table 3, IMO regulations (Tier II) state that the operation of a marine diesel engine installed on a ship built on or after January 1st, 2011, is prohibited, except when the engine's nitrogen oxide emissions are less than 10.536 g/kW.h [34]. As demonstrated in Fig. 3, the NO_x exhaust emissions for dual-fuel engines running on methanol (above 45% ME) at 500 rpm will fulfill the necessary IMO standards.

The EEDI is the best tool for evaluating a ship's energy efficiency based on IMO standards that have been examined. The required EEDI has been computed in Eq. (4), where X is the reduction percentage and rises from 5% to 30% between 2015 and 2025. As shown in Fig. 4, at the GT 186364 ton, the required EEDI for the Costa Toscana ship, built in 2021, is 12.727 gCO_2/ton. Nm. IMO states that in phase 2, this outcome should be reduced to 20% and equal to 10.1817 gCO_2/ton. The derived EEDI, determined using Equation (5), has a different value. The required EEDI is then compared to this value. The service speed, which is 14.8 knots, can be used as a reference velocity (Vref) according to IMO regulations, and GT is considered a shipping capacity. Using 100% MDO, the actual EEDI is 12.319 gCO_2/ton Nm, lower than the required EEDI for phase 0 but inconsistent with phase 1 from 2015 to 2020. While using 45% ME, which achieves IMO

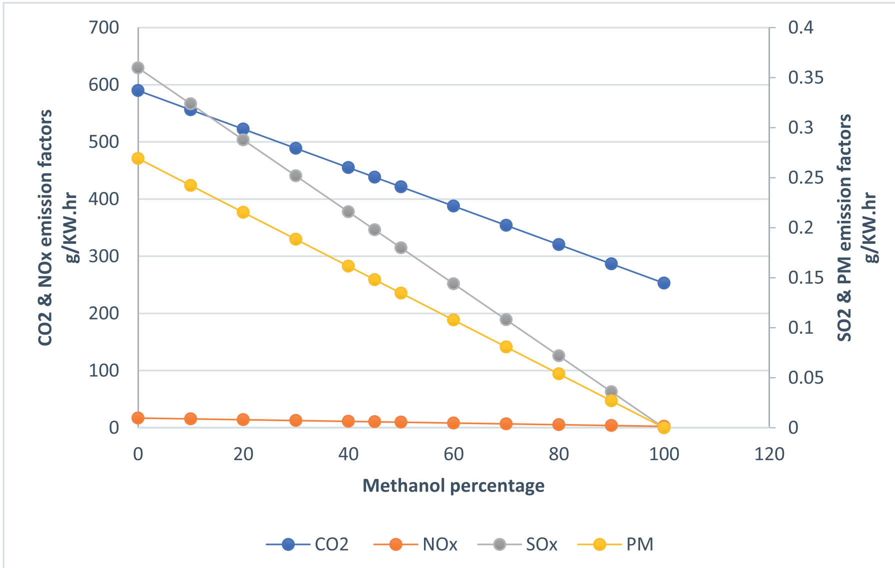

Fig. 1. The various emission factors at different methanol percentages.

NO_x limitations, the practical EEDI is 9.153 gCO_2/ton. Nm complies with Phase 2 from 2020 to 2025 but not with Phase 3 from 2025 to 2030. The load factors of 89%, 16%, and 5% were considered for operation, maneuvering, and standby mode, respectively.

Fig. 5 depicts the differences in emission factors during the previously discussed modes. It is now necessary to determine the annual emission for each emission factor as well as the overall emission per trip. As shown in Table 6, a dual-fuel engine containing 45% methanol was used to assess emission reduction.

This section explores the cost-effectiveness of using methanol to reduce ship emissions of NO_x, CO_2, SO_x, and PM and the financial implications of converting a diesel engine to a dual-fuel engine. To calculate the fuel savings cost for this case study, with an engine installed with an SFC of 184 g/kW.h, annual fuel consumption and fuel cost were calculated, as shown in Table 7. Methanol costs $575 per ton, while diesel costs $1023 per ton. Calculations include 8$/m^3 for the bunkering process [39]. According to fuel calculations, switching from a diesel engine to a dual diesel engine saves roughly 17.59 M$ annually.

The onboard alternative fuel systems' capital (CAPEX) and operating (OPEX) costs are included in the total. The investment expenses of alternative fuel systems, which include system parts, engine

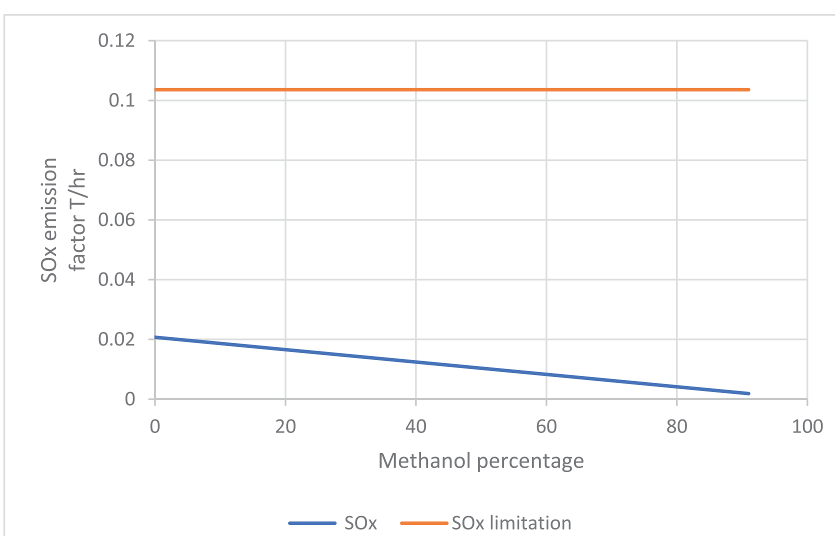

Fig. 2. The evaluation of SOx emission rates for various ME percentages concerning the IMO limit.

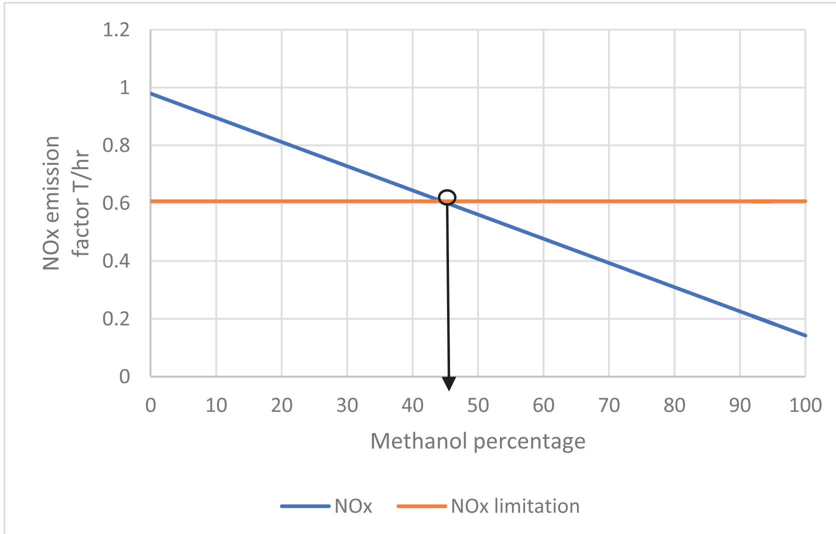

Fig. 3. The NO_x emission rates at different methanol concentrations.

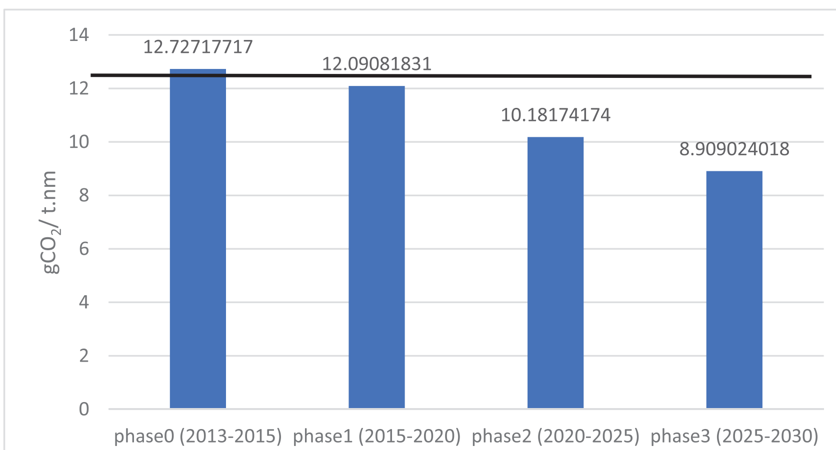

Fig. 4. The required EEDI for the Costa Toscana ship.

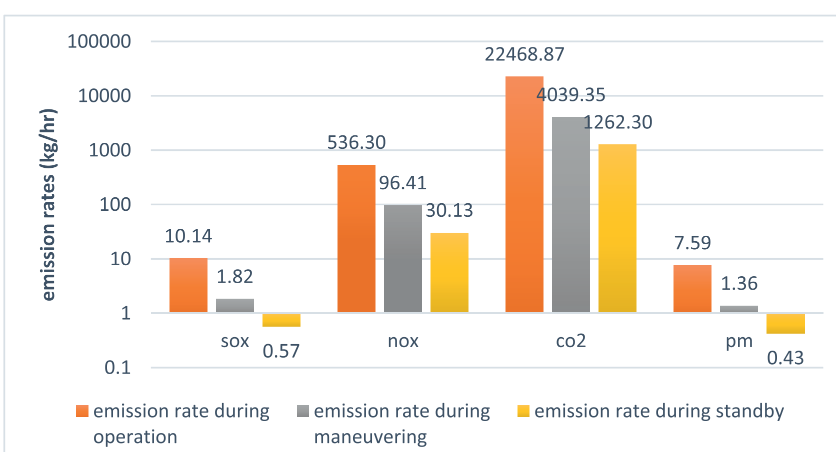

Fig. 5. The emission rates during various modes of operation.

Table 6. Emission analysis for Costa Toscana ship

	ton/trip	ton/year	Reduction ton/year	Reduction percentage
SO_x	2.106032423	101.0895563	82.70963699	45
NO_x	111.3572275	5345.146921	3340.748759	38.4617647
CO_2	4665.445779	223941.3974	77461.22642	25.7002495
PM	1.575611896	75.62937102	61.87857629	45

Table 7. Fuel calculations for Costa Toscana ship

	Diesel engine	Dual-fuel engine	
	MDO	45% ME	55% MDO
Fuel consumption (t/year)	85465.4976	38459.47392	47006.02
Fuel cost (M$/year)	88.20039352	22.1141975	48.51022
Bunkering (M$/year)	0.581165384	0.245525282	0.319641

Table 8. Annual cost-effectiveness of using methanol-diesel blending

pollutant	NO_x	SO_x	PM	CO_2
Cost-effectiveness ($/ton)	6645.081867	268403.4	358759.9	286.5891753

upgrades, and engine room improvements, are referred to as CAPEX. The engine conversion budget depends on the ship's type and size. The capital expenditures for a methanol dual-fuel system are comprised of engine conversion costs and engine room safety modifications, which are around $373 per year [21]. OPEX are operational costs that include maintenance, consumables, and fuel prices. Engine maintenance intervals and system complexity influence maintenance costs. The maintenance and operation costs for the case study are 0.7147 $M/year [40]. According to Eq. (9), the annual savings cost for using 45% methanol equals 15.1 $M/year. Calculating the annual cost-effectiveness of the dual-fuel engine upgrade process is necessary. Each pollutant's cost-effectiveness should be evaluated using the increased annual cost of the conversion procedure, as shown in Eq. (10) and Table 8.

5. Conclusion

The regulatory framework has been focused on environmental issues and new emission restrictions for years to develop the maritime industry while protecting the environment. These are the primary reasons that alternate marine fuels have been introduced. One method to reduce emissions from ships and increase their energy efficiency is to choose alternative fuels. Fuel has a substantial impact on emissions. Methanol is a more and more alluring substitute for traditional maritime fuels. The effects of using methanol as the fuel source in a dual-fuel engine on the environment and energy efficiency are thoroughly examined in this research. Besides, the study addressed the potential and economics of converting marine diesel oil to methanol. Environmental and financial studies of methanol dual-fuel engines for passenger cruise ships have been conducted. The following are the main findings of the current study.

- Using a dual-fuel engine with 45% methanol and 55% MDO will meet the necessary IMO emission limits from an environmental point of view. This will decrease 38.46%, 45%, 55%, 25.7%, and 45% of NO_x, SO_x, CO_2, and PM emissions, respectively.
- The dual-fuel engine's achieved EEDI value is 9.153 gCO_2/ton-NM, which is a 25.7% increase over the value of the diesel engine in terms of energy efficiency. Phases 1 and 2 of the conversion procedure will result in the IMO EEDI limits not being reached until 2025 because the achieved EEDI will be less than the necessary EEDI by 25,7 percent and 10,1 percent, respectively (Phase 2).
- Since the average annual fuel expenses for diesel and dual-fuel engines are 88.2 and 70.6 million dollars, the conversion process will save 17.57 million dollars in fuel costs every year.
- With an annual cost-effectiveness of 286.5, 6645, 268403.4, and 358759.8 $/ton, respectively, the proposed dual-fuel engine conversion technique will reduce CO_2, NO_x, SO_x, and PM emissions. Moreover, switching to a dual-fuel engine will save about 262.16 $/kW in costs per ship power unit.

Conflict of interest

There is no conflict of interest.

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