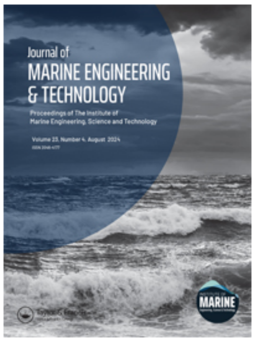


Taylor & Francis
Taylor & Francis Group

Journal of Marine Engineering & Technology

ISSN: 2046-4177 (Print) 2056-8487 (Online) Journal homepage: www.tandfonline.com/journals/tmar20

Cost-benefit analysis of emission reduction techniques: a case for container vessel

Emir Ejder, Çağlar Karatuğ & Yasin Arslanoğlu

To cite this article: Emir Ejder, Çağlar Karatuğ & Yasin Arslanoğlu (2024) Cost-benefit analysis of emission reduction techniques: a case for container vessel, Journal of Marine Engineering & Technology, 23:4, 259-269, DOI: 10.1080/20464177.2024.2317511

To link to this article: https://doi.org/10.1080/20464177.2024.2317511

Published online: 16 Feb 2024.

JOURNAL OF MARINE ENGINEERING & TECHNOLOGY
2024, VOL. 23, NO. 4, 259–269
https://doi.org/10.1080/20464177.2024.2317511

Cost-benefit analysis of emission reduction techniques: a case for container vessel

Emir Ejder, Çağlar Karatuğ and Yasin Arslanoğlu

Maritime Faculty, Istanbul Technical University, Istanbul, Turkey

ABSTRACT

One of the most important issues in the maritime industry is controlling and reducing the amount of emissions caused by marine vessels. In this respect, the International Maritime Organization sets some air pollution-related regulations and encourages maritime companies to utilise current and innovative emission abatement methods on their ships. The application of these approaches to ships not only provides environmental benefits but also creates additional financial costs for the company. In this study, operational data of a container ship has been acquired and examined. Methods such as ammonia, LNG, scrubber, low sulphur fuel use, and selective catalytic reduction have been considered to determine the most appropriate emission reduction approach. Nine different scenarios have been created with the use of stated methods and each scenario is analysed both environmentally and economically and compared to each other. Finally, the most suitable scenario has been determined by calculating the payback period of each investment. Since there is a relatively longer period of redemption, using a dual-fuel engine could be more suitable for long-lasting and newly built ships. For the currently cruising ships, the use of scrubber systems with selective catalytic reduction is an effective solution to reduce the number of emissions.

ARTICLE HISTORY
Received 8 June 2022
Accepted 7 February 2024

KEYWORDS
Ammonia; LNG; emission reduction; scrubber; SCR; cost-benefit analysis

1. Introduction

Shipping realises 80% of the cargo transportation in the world (UNCTAD 2017) due to its advantages such as high carrying capacity and safety and relatively advantageous operating cost. In maritime transportation, the cargo capacity of 8 billion tons in 2007 rose to 10.7 billion tons in 2017 (Lee et al. 2020), which correspondingly caused an increase in the amount of fuel consumption. The International Maritime Organization (IMO) stated that Heavy Fuel Oil (HFO) which has crucial pollution potential due to combustion is still the dominant marine fuel with a ratio of 79% in 2018. In addition, a notifiable increase in methanol use as an alternative marine fuel has been observed (IMO 2020).

The major pollutants emitted to the atmosphere sourced from fuel consumption on marine vessels are CO_2, NO_x, SO_x, and particulate matter (PM). The rising fuel consumption in the maritime industry led to increases in the global emission values, which directly affect air quality negatively, in the atmosphere. In addition, increasing the amount of emissions triggers respiratory disorders such as heart disease, lung cancer, and asthma, and cause premature deaths (Silva et al. 2016).

For the control of air pollution caused by ships and to minimise its negative effect, the IMO adopted Annex VI of the International Convention for the Prevention of Pollution from Ships in 1997 that implemented the regulations related to emissions (IMO 1997). Accordingly, Emission Control Areas (ECAs) have been established around the world seas, and in certain areas such as North America and Northern Europe, extra restrictions on sulphur emission have been enforced. The sulphur content of the fuel that could be used by ships cruising in ECA was determined as 0.1% since 2015 while restriction has been further solidified and decreased from 3.5% to 0.5% for the ships navigating global seas since 2020 (IMO 2018a). Besides, to limit the NO_x release, a series of regulations about the marine diesel engine was established, and via Tier III, which was presented on January 1, 2016, the limit of NO_x emission was aimed to reduce by 75%.

To fulfil the obligations/restrictions and continue shipping activities without interruption, maritime companies should determine the appropriate method to meet their requirements and adapt them to their ships. In line with this subject, there are mainly three approaches. The first option is to use marine gas oil (MGO) and very low sulphur fuel oil (VLSFO) with low sulphur content as fuel. MGO could be used as fuel in whole seas while the use of VLSFO, which meets the 0.5% limitation for cruises outside of the ECA, reduces the operating cost. The second option is to eliminate pollutants such as SO_x, NO_x, etc. by some exhaust gas after-treatment technologies such as selective catalytic reduction (SCR) and exhaust gas cleaning system (EGCS). EGCS is commonly referred to as a scrubber in the marine industry and has three types of applications; (1) open-loop, (2) closed-loop, and (3) hybrid loop. This ensures the use of HFO which is the cheapest marine fuel by cleaning the sulphur in the exhaust, by the IMO 2020 limitations. However, the adaptation of the scrubber in marine vessels requires a high investment cost, and implementation area, and reveals more energy consumption, increasing operational cost. Thus, during an application to ship, the maritime company should determine the period of redemption and the type of scrubber to be adapted. On the other hand, SCR which is one of the after-treatment technology allows the reduction of the amount of NO_x in the exhaust gas. It is able to reduce NOx emission by 3561 tons/year which equals a reduction of 90% (Ammar 2019). SCR requires high investment costs as much as the scrubber and increases operational expenses. The third option is the use of liquefied natural gas (LNG) and ammonia as fuel and the modification of the engine system accordingly. Although the use of LNG-type fuel is a completely environmentally friendly application, some issues

CONTACT Yasin Arslanoğlu arslanoglu@itu.edu.tr Maritime Faculty, Istanbul Technical University, Tuzla, Istanbul 34940, Turkey

such as excessive investment cost and space requirements appear as disadvantages during the ship application. It was determined that during the compliance of the IMO 2020 restrictions, while distilled fuels were used before 2020, after 2020, the use of LNG for the new build and adaptation of the scrubber on existing ships were preferred (Zis et al. 2016). In addition to LNG, ammonia has recently become an important alternative in the maritime industry. Ammonia is considered an advantageous fuel for greenhouse gas emissions due to its carbon-free structure and the fact that it does not produce CO_2 emissions during combustion. The use of these alternative fuels has the potential to comply with the IMO tightening regulations on emissions. However, the development and commercial deployment of ammonia-fuelled engine technologies brings significant challenges, such as high costs and technical barriers (Ejder and Arslanoğlu 2022). These challenges could prevent the technology from becoming widespread and widely accepted in the maritime industry. In this context, (Van Rheenen et al. 2023) investigate hydrogen carriers using PEM fuel cells for zero-emission ship propulsion systems and emphasize the importance of factors such as gravimetric and volumetric energy density, technology readiness levels, safety considerations and recycling potential in determining the suitability of hydrogen storage technologies for marine applications. The transition towards exploring various energy solutions, such as hydrogen carriers, underscores the evolving nature of sustainable practices in the maritime sector.

This study, it is aimed to determine the environmental and economic results of different emission abatement methods for the container ship. According to the methodology, the cost-benefit analysis of each scenario created has been carried out. Accordingly, significant results were presented to maritime experts, stakeholders, and companies in the process of compliance with IMO 2020 regulation, and a sample methodology was served on the pathway of the research of reduction solutions.

The main contributions of the study are as follows;

(i) The 9 different scenarios that cover Ammonia, LNG, SCR, scrubber, and conventional fossil fuels have been created and, analysed based on the ship's noon report and cruising situation.
(ii) The subject of compliance with the CO_2, SO_X and NO_X limitations has been evaluated under various scenarios as both individuals and with combinations of different types of emission reduction strategies.
(iii) A reference study has been realised for shipping companies that especially have a container fleet and consider the adaptation of emission reduction methods, and researchers that plan to investigate.
(iv) The study provides crucial results on the most appropriate approach that could be applied to newly built and currently cruising ships.
(v) The study analyses the cost and environmental impacts of innovative technologies, in particular ammonia engines, and demonstrates their potential economic viability in the transition to sustainable maritime practices.

The remainder of the paper is realised as follows. A comprehensive literature review on related emission reduction methods within the cost-benefit framework is presented in Section 2. Emission reduction methods are introduced in Section 3. The methodology of the paper is presented in Section 4 in detail. The case study is realised in Section 5. In Section 6, both environmental and economic results are presented and discussed. Finally, the conclusions are given in Section 7.

2. Literature review

The IMO aims to gradually decrease the amount of emissions emitted to the atmosphere caused by the ships and released the Initial IMO Strategy for the reduction of both carbons by 70% and greenhouse gas (GHG) emissions by 50% by 2050 compared to 2008 (IMO 2018b). Thus, maritime companies to ensure compliance with regulations frequently investigate applications of different emission reduction methods on ships. Besides, feasibility studies of single and hybrid implementations of stated methods have been studied intensively by researchers recently.

Yang et al. (2012) developed an evaluation tool that enables the prioritisation of emission abatement techniques to determine applicable SOx and NOx control methods using the quantitative technique for order preference by similarity to the ideal solution (TOPSIS) method. Jiang et al. (2014) conducted a study that offered a comparative perspective between the use of MGO as fuel and the installation of scrubbers, beneficial to maritime companies. In the process of compliance with MARPOL Annex VI restrictions, Schinas and Stefanakos (2014) presented a decision-making tool based on the analytical network process (ANP) method, which ensures financial comparisons that operators can use to determine which emission reduction method to adopt. Brynolf et al. (2014) discussed emission abatement approaches within three alternatives in Swedish waters and indicated the requirement of the regulation about ammonia slip from the use of SCR and the methane slip from LNG engines.

Seddiek and Elgohary (2014) evaluated different kinds of emission abatement approaches within a case study on a Ro-Ro ship that operates in the Red Sea. They stated that the use of the SCR and scrubber is an effective solution for SO_x and NO_x emission reduction. (Woo et al. 2023) investigated the application of a solid-SCR system using ammonium salt in a 1.1 MW marine engine and reported that this system effectively reduced NOx emissions, offered lower ammonia leakage than the UWS-SCR system and achieved over 90% NOx reduction efficiency during endurance testing. Lindstad et al. (2015) evaluated different emission reduction methods and proposed that the advantages of the approaches could vary depending on factors such as engine size, foreseen fuel price etc. Zis et al. (2016) presented a cost-benefit analysis of the emission reduction methods such as scrubber, cold ironing, etc., and indicated that a decrease in fuel price affects the payback period of the abatement approaches. Lindstad et al. (2017) carried out a study to evaluate sulphur reduction strategies and presented that ships modified with scrubber prefer high-speed cruise with the use of the HFO while ships that use MGO as the main fuel reduce voyage speed to decrease operational expenses (OPEX). Abadie et al. (2017) examined the switching to low-sulphured fuel and scrubber installation in line with the cost-beneficial perspective in terms of emission reduction, considering various factors such as operation time, cruise area, and age of a marine vessel, and fuel price. Ammar and Seddiek (2017) realised a case study on a Ro-Ro type of vessel that navigates at the Red Sea region, and evaluated emission reduction strategies such as SCR, scrubber, LNG, and MGO on both economic and environmental.

Abadie and Goicoechea (2019) discussed the type of main engine to be placed on a newly built ship and the option to use or not use a scrubber. They stated that using a dual-fuel engine is the best option that minimises investment and operational expenses. Kim and Seo (2019) conducted a questionnaire that was carried out with the Korean shipping industry to handle SO_x regulation from maritime companies' perspective. The obtained responses were analysed with a fuzzy analytical hierarchy process (AHP) to determine important factors. In their study conducted in line with the emission regulation published by China, Fan et al. (2020) presented that the use of scrubbers would be advantageous on ships cruising on the coast, but that switching fuel in ships navigating transcontinental could be applied considering the uncertainties of fuel pricing. (Eriksson and Llamas 2020) analysed the robustness of dual-actuator EGR controllers in marine two-stroke diesel engines, highlighting their contribution to emission reduction and performance optimisation, noting the impact of pressure sensor bias on controller robustness, and demonstrating the potential for improvement through sensor calibration or alternative sensor types. Ni et al. (2020) reviewed emission regulations, current status, and impact of different emission reduction technologies such as LNG, methanol, water addition, exhaust gas recirculation, high-pressure common rail injection systems, etc., and presented a comprehensive guide to ship owners, researchers, and engineers. Li et al. (2020) conducted a study to assist marine stakeholders' decisions in the process of compliance with the 2020 emission regulation based on the analysis of the Clarkson World Fleet Register database through the multinomial logistic regression. Some influential parameters on the decision, the suitable methods according to the type of ship, and preferred abatement strategies were presented based on LNG, LSFO, and scrubber.

Wu and Lin (2020) evaluated the effectiveness of scrubber installation and VLSFO usage as the main fuel on a container ship. They presented that the use of VLSFO is more effective in complying with emission limitations in the long-term perspective. Zhu et al. (2020) carried out a study where a cost-benefit analysis is made on a container vessel that cruises between the Far East and Europe to lead the way for shipowners during compliance with sulphur 2020 limitations. Deng et al. (2021) examined and reviewed the emission abatement approaches under three headings; fuel optimisation, pre-combustion operation, and exhaust after-treatment, and proposed that the use of LNG is the best option because of the economic and environmental advantages. Fan et al. (2021) discussed three solutions to reduce SO_x emissions for a very large crude oil carrier (VLCC); the use of LNG as a fuel, the adaptation of the scrubber, and the use of LSFO. It is determined that after the amortisation of conversion, LNG is the most effective strategy to comply with IMO and GHG regulations.

In addition to these assessments on LNG, recent research on the use of ammonia in the maritime sector also forms a critical part of innovation and sustainability efforts in this field. Seddiek and Ammar (2023) state that the use of ammonia reduces NOx and GHG emissions on RO/RO vessels and provides lifetime cost savings for blue ammonia-powered vessels. Harahap et al. (2023) highlighted the profound carbon reduction of renewable fuels and policy implications in the maritime sector. Zanobetti et al. (2023) compared the sustainability performance of hydrogen, ammonia, and natural gas as alternative power systems. Wu et al. (2023) conducted an emission reduction and cost-benefit analysis of ammonia and green hydrogen fuels in Guangzhou Port and found that these fuels provide significant advantages in emission reduction but are not yet cost-competitive. Nadimi et al. (2023) investigated the potential of ammonia as a carbon-free fuel to replace conventional fossil fuels in internal combustion engines, while Estevez et al. (2023) provided an overview of the use of green ammonia as a sustainable energy carrier and highlighted the technical barriers and the need for improvements in NOx emission control. Liu et al. (2022) examined the feasibility of using ammonia in low-speed two-stroke marine engines and found that ammonia is a suitable candidate fuel but with higher NOx emissions.

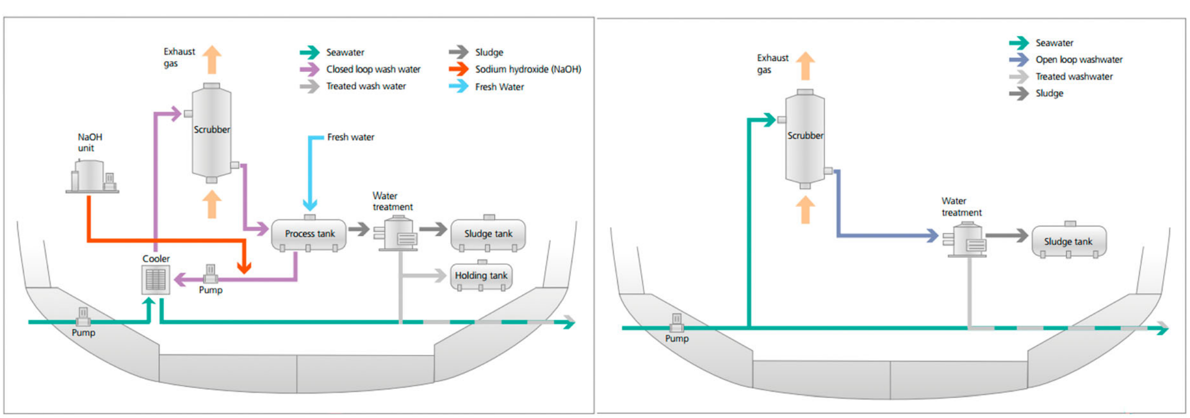
3. Emission reduction methods

3.1. Use of low sulphur fuel

In maritime, between 2012 and 2018, 247.94 million to 276.30 million tons of fuel were consumed annually and fuel consumption negatively affects greenhouse gas (GHG) emissions from international shipping. GHG emissions increased by 9.6% compared to 2012 data and reached 1.076 million tons in 2018 (IMO 2020). With the implementation of a new step of the SO_x regulation in 2020, maritime companies have tended to the use of low sulphur distilled fuel on marine vessels. In this respect, VLSFO with 0.5 wt% and MGO with 0.1 wt% are produced and preferred mostly as a marine fuel. In line with the policy of the company, while MGO could be used both in ECA and outside of the ECA, on the other hand, the use of VLSFO could be preferred outside of the ECA. Thus, the fuel-switching policy based on the cruising region could ensure a decrease of operational costs.

3.2. Scrubber

Scrubbers which are an exhaust after-treatment method, are one of the most preferred methods for application on ships during the adaptation of sulphur limitation. There are two types of scrubbers: dry type and wet type. Dry scrubbers are not used in marine vessels because of heavy equipment, instability, and the requirement of large areas (Brynolf et al. 2014). Wet scrubbers that are commonly used for the application in maritime are applied in three different ways: open-loop system, closed-loop system, and hybrid system (Exhaust Gas Cleaning Systems Association 2012). The open and closed-loop system arrangements are presented in Figure 1 (Lloyd's Register 2021).



(a) closed loop (b) open loop

Figure 1. Closed and open-loop scrubber diagrams.

While SO_x is neutralised with the natural alkalinity in seawater in the open-loop system, in closed-loop systems this process is realised by the additive that includes water and sodium hydroxide. The open-loop system has advantages such as lower operational costs, and simplicity but its de-SO_x efficiency is low, and it causes seawater pollution. It has been stated that a 93% rate of SO_2 is removed from the exhaust gas produced by combusting of HFO in the marine diesel engine using the open-loop scrubber (Caiazzo et al. 2012). The efficiency and operational costs of the closed-loop system are higher than the open-loop system and seawater is not polluted in the case of its application. It has been determined that the SO_x elimination process is carried out by the closed-loop scrubber system generated by Wärtsilä with 98% (Ni et al. 2020). In hybrid applications, while eliminating the disadvantages of the two approaches with good optimisation, system efficiency could be increased by using their advantages.

3.3. Selective catalytic reduction

SCR technology is applied in different areas such as power plants, cars, marine diesel engines, etc. In the maritime industry, it is one of the most used approaches to controlling NO_x emissions. Urea-water solution is added to the exhaust gas. Thus, urea thermolysis reaction realises N_2 and H_2O reveal from NO_x and O_2.

There are two types of SCR applications: Low-pressure SCR and high-pressure SCR. HP-SCR could be used for systems where all fuels are consumed regardless of the sulphur level, while LP-SCR is suitable for systems where fuels with a sulphur content of at most 0.1 wt% are used (Ni et al. 2020).

Lee (2017) stated that diesel engines modified with SCR technology are suitable for IMO Tier III limitation. Magnusson et al. (2012) proposed that the amount of NOx in the exhaust gas could be decreased by SCR above the ratio of 90% at a minimum of 300 °C. In addition, Jayaram et al. (2011) realised a case study on the container vessel and presented that as a result of the SCR application, the NOx ratio decreased by 90–91% for HFO and 82–84% for distilled fuel.

3.4. Liquefied natural gas

Recently, the use of LNG as a fuel on ships by maritime companies has been frequently studied concerning meeting IMO emission regulations. It provides a great advantage in reducing ship-related emissions since it contains almost no sulphur and causes lower NOx emissions compared to marine diesel engines (Doug 2010). According to the necessity of the regulations, it is stored in vacuum insulated tanks at −163 C and 1.7 bars (Brynolf et al. 2014). The liquefaction process is one of the advantages of LNG storage on ships where there is limited space. On the other hand, the disadvantage of LNG-operated engines is producing CH_4 emission that is called methane slip more than diesel engines. However, according to (Wärtsilä 2014), it is possible to reduce emission release with new dual-fuel engines that have 40–50% thermal efficiency and, compared to total world GHG emissions, these rates could be neglected (Corbett et al. 2014). It is indicated that LNG systems are more sustainable than diesel-fuelled engines, have a total environmental impact of 41%, and also, its safety index is better than diesel at a rate of 61%. While some environmental indicators such as global warming potential, rain acidification potential, human toxicity potential, and eutrophication potential were taken into account during the determination of the environmental index, security and diversity of supply, public acceptability, health and safety, and intergenerational issues were considered for the safety index (Iannaccone et al. 2020).

3.5. Ammonia

Ammonia is being studied alongside alternative fuels, such as LNG, to comply with IMO emission regulations in the maritime industry. With the chemical formula NH_3, ammonia can liquefy at −33°C and has an energy density of about 18.6 MJ/kg (ABS 2020). These properties enable ammonia to offer high energy storage capacity in limited ship storage spaces. However, the combustion characteristics of ammonia present challenges due to its low cetane number and high auto-ignition temperature, often requiring additional pilot fuels (Zhu et al. 2023). Due to its toxic nature and reactivity with alloys, ammonia requires particular safety and material selection precautions (Niels de Vries 2019; The Royal Society 2020). From an environmental perspective, ammonia offers low carbon emissions, making it an option for reducing the carbon footprint in the marine sector. However, aside from these advantages, further research is required to understand ammonia's environmental and operational impacts fully. This could significantly affect ship design, safety protocols and operational practices (Green Shipping Programme 2021).

4. Methodology

In this study, different emission reduction approaches that ensure to decrease in emissions emitted to the atmosphere released by the container ship were evaluated both environmentally and economically. The examination and comparison of the methods have been carried out based on the steps where is shown in Figure 2.

In the base case where the operational data received from the ship, HFO and MGO have been used as fuel. To determine the best reduction option, various scenarios are created and analysed. Accordingly, from scenarios 1–8, respectively, the use of MGO, use of VLSFO with MGO, an adaptation of open-loop scrubber, utilisation of hybrid scrubber, application of SCR, hybrid use of open-loop scrubber with SCR, combination hybrid scrubber with SCR and, implementation of dual-fuel engine for Ammonia and LNG approaches is realised.

Firstly, estimation of the emission of each scenario and the environmental benefits are determined. Then capital expenses (CAPEX) and OPEX are calculated, and cost-benefit analysis is realised via the net present value (NPV) method. Finally, the payback period of each scenario is presented. During the calculations, the fuel consumption and price of fuels were considered unchanged.

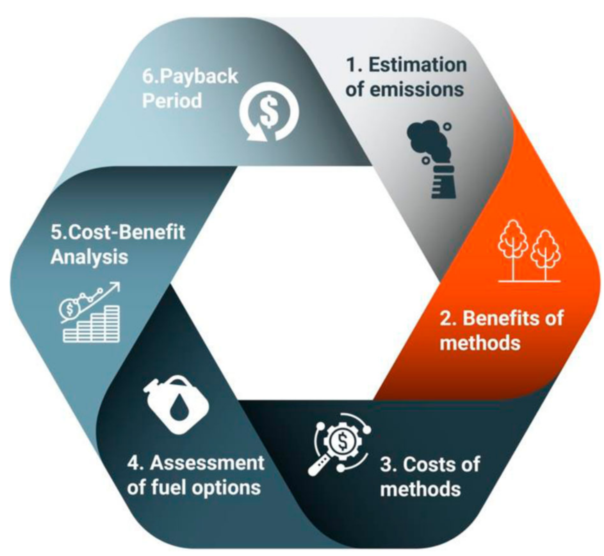


Figure 2. The followed methodology of the study.

4.1. Estimation of ship emissions

There are two types of emission factors for the ships: fuel-based (kg/tonnes) and energy-based (g/kWh). In this study, the top-down method that ensures the creation of ship emission inventory by the total fuel consumption and emission factors has been used to estimate the amount of exhaust emissions based on fuel-based emission factors. The emission inventory of the marine vessel is created for each ship, taking into account factors such as fuel type, time travelled during a manoeuvre, anchorage, and port time. According to the top-down approach, the amount of the emission of the ship is calculated with Equation (1) (Trozzi 2010).

$$E_{trip} = \sum_{p} (FC_{j,m,p} \times EF_{i,j,m,p}) \quad (1)$$

where E_{trip} is the amount of emission over a complete trip (tonnes), FC is the fuel consumption (tonnes), EF is the emission factors (kg/tonnes), i is a type of emission (NO_x, SO_x, CO_2, PM), j is the engine type (slow speed, medium speed, high speed), m is the fuel type (VLSFO, HFO, MGO/MDO) and p is the different situation of the trip (cruise, berth, manoeuvring).

Emission factors are determined according to fuel types with the database created by the IMO with the data collected in the Fourth IMO GHG Study in 2020. These emission factors are presented in Table 1 (IMO 2020).

The VLSFO is a blended fuel that is a mixture of MGO by 80% and HFO by 20% (Pavlenko et al. 2020). The emission factor has been determined according to mixing ratios and used in the calculations.

4.2. Calculation of environmental benefits

The amount of emission that affects marginal external costs causes loss of welfare. Ships release a certain number of pollutants into the atmosphere. However, with the adoption of emission reduction methods, it is possible to control emissions and reduce marginal external costs. In vessels, the annual environmental benefit based on the use of these approaches could be calculated with Equations (2) and (3) (Jiang et al. 2014).

$$B_{ij}^{s} = \mathrm{N} \times \sum_{k} (\Delta E_{i,j}^{s,k} \times MEC_k) \quad (2)$$

$$B_{ij}^{Fuel} = \mathrm{N} \times \sum_{k} (\Delta E_{i,j}^{Fuel,k} \times MEC_k) \quad (3)$$

where B_{ij}^{s} is the environmental benefit of using an emission reduction method, B_{ij}^{Fuel} is the environmental benefit of using HFO, MGO, VLSFO, etc., N is the number of trips in a year, MEC_k is the marginal external costs ($/tonne), k is an emission type, i is the loading or discharging port, j is the loading or discharging port, $\Delta E_{i,j}^{Fuel,k}$ is decreased emission amount between ports i and j after using HFO, MGO, VLSFO, etc. and $\Delta_{i,j}^{s,k}$ is decreased emission amount after using the emission reduction method between ports i and j.

The marginal environmental costs of substances per kilogram based on emission type are given in Table 2 (CE Delft 2023).

Table 1. The emission factors presented by IMO.

Fuel type	NO_X (kg/tonne)	SO_X (kg/tonne)	PM_{10} (kg/tonne)	$PM_{2.5}$ (kg/tonne)	CO_2 (kg/tonne)
HFO	75.90	50.83	7.55	6.94	3.114
MGO	56.71	1.37	0.90	0.83	3.206
LNG	13.44	0.03	0.11	0.10	2.750

Table 2. Environmental costs of pollutants per kilogram.

Emission type	(€/kg)	($/kg)
CO_2	0.13	0.13
$PM_{2,5}$	121	121
PM_{10}	69.3	69.3
NO_x	29.9	29.9
SO_x	57.5	57.5

∗The parity between the EURO and Dollar has been considered 1.00.

According to the appropriate analysis made via the stated environmental prices, it is possible to determine the loss of economic welfare caused by the one additional kilogram pollutant released into the atmosphere.

4.3. Capital and operational cost estimation of methods

In determining the emission reduction strategy to be used for compliance with the IMO regulations, factors such as the ship's age, the sector it serves, and the regions in which it operates are prominent. Besides, while choosing the abatement methods to be preferred, the OPEX of the system, as well as CAPEX, are factors affecting the selection criteria that companies consider. Within the scope of the study, scrubbers, SCR, dual-fuel engines, and different kinds of fuels were economically evaluated.

Scrubber systems are one of the commonly preferred reduction methods the meet limitations (IMO 2019). The system requirements vary based on the type of scrubber application and CAPEX and OPEX values take form according to the type of the application. The closed-loop and hybrid types of scrubbers were evaluated in the study. Therefore, the investment fixed cost and variable cost according to the engine power of these types are presented in Table 3 (Vanhamme 2016).

The OPEX value of the scrubber system to be installed on the ships could be determined with Equations (4) and (5) (Vanhamme 2016).

$$OPEX_{\text{Open - Loop}} = 1\% \text{ additional fuel} + 13000 \text{ USD} + 0.4 \times P_{M.E.} \quad (4)$$

$$OPEX_{\text{Hybrid}} = 0.5\% \text{ additional fuel} + 25000 \text{ USD} + 0.4 \times P_{M.E.} \quad (5)$$

where $OPEX_{\text{Open - Loop}}$ and $OPEX_{\text{Hybrid}}$ are operational cost of open-loop and hybrid scrubber system, respectively and $P_{M.E.}$ is the main engine power (kW).

SCR system is a beneficial and promising approach for the reduction of NO_x emissions in exhaust gases, and recently, the adaptation of this method on the ship is frequently carried out. In this paper, the calculations of the CAPEX and OPEX values of the SCR system have been realised via the directives and knowledge provided by the maritime company.

Another emission abatement method evaluated in the study is the use of a dual-fuel engine. There are two strategies for the application of this method; (*i*) retrofitting of the diesel engine, (*ii*) renewing of

Table 3. Financial parameters of the scrubber system.

Scrubber type	Fixed investment costs (million USD)	Variable investment costs (USD/kW)
Open-Loop (Retrofit)	2.3	55
Open-Loop (New Building)	1.9	38
Hybrid System (Retrofit)	2.8	58
Hybrid System (New Building)	2.4	44

the main engine. The CAPEX value of retrofitting for a four-stroke dual-fuel engine is 740 $/kW, while the CAPEX value of a new two-stroke engine is 700 $/kW (Trivyza et al. 2018). In this study, a similar cost analysis was also performed for ammonia. The CAPEX for a four-stroke ammonia engine is $370/kW, while the CAPEX for a two-stroke ammonia engine is $600/kW (Inal et al. 2022). The OPEX value of the LNG-fuelled ship varies according to its size, type, navigation area, ports for bunker operations, the amounts of bunkers, etc. Similarly, OPEX values for ammonia-fuelled vessels vary according to these factors. Hourly LNG, ammonia and pilot fuel consumption for main engines and diesel generators can be calculated with Equations (6) and (7) (MAN Energy Solutions 2018). In this framework, using ammonia and LNG in dual-fuel engines should be considered comparable alternatives in terms of cost and operational efficiency.

$$\mathrm{ME}_{gasconsumption}\ (\mathrm{tonnes}) = \mathrm{Load}_{(MW)} \times \mathrm{SGC}_{(g/kWh)} \times 10^{-3} \tag{6}$$

$$\mathrm{ME}_{pilotoilconsumption}\ (\mathrm{tonnes}) = \mathrm{Load}_{(MW)} \times \mathrm{SPOC}_{(g/kWh)} \times 10^{-3} \tag{7}$$

where *SGC* and *SPOC* are specific gas consumption and specific pilot oil consumption, respectively.

The fuel prices used in the calculation were USD 502 per ton for HFO, USD 849 for MGO and USD 618 for VLSFO. The analysis of gas prices was carried out from December 2022 to December 2023, and the average price for this period was calculated as USD 673 per ton (Ship & Bunker 2024). In this analysis, the price of ammonia is included, which is priced at USD 812 per tonne (S&P 2024).

4.4. Cost-benefit analysis of the methods

The net present value (NPV) approach was used for the realising cost-benefit analysis of the emission reduction methods. The emission reduction method with a high NPV indicates the best option and the NPV can be calculated with Equation (8) (Jiang et al. 2014).

$$NPV = -CAPEX + \frac{1-(1+r)^{-t}}{r} \times (B - OPEX) \tag{8}$$

where, *NPV* is the net present value, *B* is the environmental benefit of the method, *r* is the rate of interest and *t* is the usage period of the corresponding method.

Contrary to other approaches, the NPV of the fuel could be calculated with Equation (9) since it has no parameter of usage period *t* (Jiang et al. 2014).

$$NPV = \left(\frac{B_{FO} - C_{FO}}{r}\right) \tag{9}$$

where B_{FO} and C_{FO} are environmental benefit and cost of the corresponding fuel, respectively.

The net present values cannot be directly compared, as the lifetime of new productions and post-construction is different. The results can be achieved by comparing the equivalent annual net benefits (EANB) which could be calculated with Equation (10).

$$EANB = \frac{NPV}{a_i^t} = \frac{NPV}{(1-(1+r)^{-t})/r} \tag{10}$$

where *EANB* is the equivalent annual net benefits and a_i^t is a function for determining annual regular instalment amounts for interest rate payment.

4.5. The payback period of investment

The planned payback period (PBP) for investment is the value that indicates how long the investment cost can be recovered. According to Panasiuk and Turkina (2015), PBP is directly related to the difference between the fuel and the cost of installation of the system to be installed and the cost of operation. PBP can be determined by Equation (11).

$$PBP(year) = \frac{CAPEX_{E.R.M} - OPEX_{E.R.M}}{OPEX_{Fuel}} \tag{11}$$

where *PBP* is the payback period of the investment, $CAPEX_{E.R.M}$ and $OPEX_{E.R.M}$ are CAPEX and OPEX values of the emission reduction method, respectively. $OPEX_{Fuel}$ is the annual fuel consumption of the ship.

5. Case study

A container ship that cruises in the ECA has been selected for the case study. The specifications of the ship are presented in Table 4.

To realise the environmental and financial analysis, some kind of information such as FO consumption, operation situations, etc. have been obtained as data from the ship's noon report that is prepared by the operators of the ships. The data relating to the ship covers a year, from November in 2018 to October in 2019. The ship navigated approximately 75,463.60 nautical miles during this period and according to labelled data by marine engineers, the ship spent 51% of the time at sea, 34% at the port, 11% at manoeuvre, and 4% at anchor. In this respect, 6997.59 tons of HFO and 621.83 tons of MGO were consumed by the ship. The number of emissions emitted to the atmosphere in the base case has been determined according to Equation (1) and presented in Figure 3.

It is determined that 566.38 tonnes of NO_x, 356.54 tonnes of SO_x, 53.39 tonnes of PM_{10}, 49.08 tonnes of $PM_{2.5}$, and 23,784.08 tonnes of CO_2 were released by the ship, annually.

Table 4. Specifications of the ship.

Specifications	
Type of the ship	Container
Container capacity (TEU)	1208
Built year	2001
Length O. A. (m)	155.60
Breadth (m)	24.50
Deadweight (Tonnes)	17,264
Main engine type	Slow speed
Main engine power (kW)	11,060
Auxiliary engine (pcs)	3
Auxiliary engine power (kW)	782

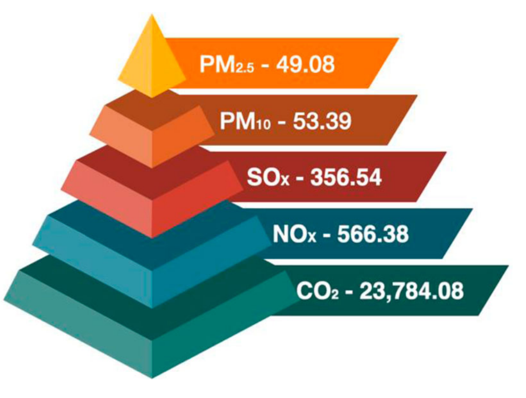


Figure 3. The amount of emissions in the base case.

In the next section, an analysis of each created scenario is conducted. The environmental and economic findings for each scenario as a result of the analysis have been presented and discussed.

6. Results and discussion

6.1. Environmental results

In order to compare each scenario from an environmental perspective, firstly, using the ship's noon report information, gas consumption and pilot oil consumption have been determined via Equations (6) and (7). Accordingly, these values are presented in Table 5 in a monthly chart depending on the navigational situation of the ship.

Table 5 presents the impact of ammonia and LNG use on total fuel consumption in dual-fuel engines. As a result of determining the amount of fuel consumption by the dual-fuel engine, it becomes possible to calculate the emission values in scenario 9, as in other scenarios. The amount of emission emitted into the atmosphere for each scenario is presented in Table 6, separately and comparatively.

Accordingly, the most effective approach to reducing the environmental impact of CO_2 is the use of a dual-fuel engine. In Scenarios 1 and 2, there is a significant reduction in SO_x and PM values due to the use of fuels such as VLSFO and MGO instead of HFO use. Today, SCR application is widely used to reduce NO_x emissions in the maritime industry. However, in the case of the examination of the results of scenario 5, it is determined that using SCR alone in emission reduction applications is not sufficient. On the other hand, it has been observed that the adaptation of SCR with scrubber systems to ships has a crucial positive effect in reducing emissions. It has been determined that the environmental effects of the use of scrubber types are close. Therefore, when planning the adaptation of these systems to ships, preference should be conducted according to the OPEX of the system and the voyage plan of the ship.

The environmental benefits and harms of each reduction method are determined by marginal external costs. The financial results of environmental losses due to exhaust emissions are given in Figure 4.

It has been observed that using only MGO has greater environmental benefits than the options of the use of low-sulphur fuel. Similar to the results in Table 6, the implementation of SRC with a scrubber system is found to greatly reduce environmental harm. The highest environmental benefit is realised in the use of the ammonia-fuelled engine.

6.2. Economical results

The investment cost of the emission abatement method and its operational cost during the following process should be known before deciding on the application. In this subject, OPEX and CAPEX are one of the most important economic parameters for the implementation of the method to be applied on a ship.

In this study, emission reduction approaches have been realised in different scenarios for a container vessel. CAPEX and OPEX values that present the additional costs of the system adaptation of each scenario have been determined and presented in Table 7.

When the investment costs of the emission reduction methods are examined, it is observed that the highest cost is required for the use of the dual-fuel engine, while the lowest cost is required in the SCR application. Since there are various necessities for the different types of scrubber system implementation, cost variations occur in open-loop and hybrid scrubber applications. The hybrid type of scrubber system needs more initial cost. The CAPEX of the combined application of SCR and scrubber systems is higher compared to individual applications.

In the use of the low-sulphured fuel, the operational fuel price increased annually by $2,428,164 in scenario 1 where only MGO is used and increased annually by $811,720 in scenario 2 where VLSFO is used instead of HFO. Among the scrubber types, the OPEX value of the hybrid application is lower. The use of the dual-fuel engine has the highest OPEX of all abatement applications.

Table 6. Effects of reduction methods on emission amounts.

Emissions	Methods	CO_2	NO_X	SO_X	PM_{10}	$PM_{2.5}$
Base Case	Use of HFO with MGO as fuel	23784.08	566.38	356.54	53.39	49.08
Scenario 1	Use of MGO as fuel	24427.86	432.10	10.44	6.86	6.32
Scenario 2	Use of VLSFO with MGO as fuel	24299.10	458.95	79.66	16.16	14.88
Scenario 3	Adaptation of open-loop scrubber	24021.92	572.04	7.20	1.08	0.99
Scenario 4	Adaptation of hybrid scrubber	23903.00	569.21	7.17	1.07	0.99
Scenario 5	Adaptation of SCR	23784.08	56.64	356.54	53.39	49.08
Scenario 6	Application of SCR with open-loop scrubber	24021.92	57.20	7.20	1.08	0.99
Scenario 7	Application of SCR with hybrid scrubber	23903.00	54.37	7.17	1.07	0.99
Scenario 8	Application of dual-fuel LNG engine	13293.11	70.32	0.32	0.63	0.58
Scenario 9	Application of dual-fuel Ammonia engine with SCR	3536.57	1.25	1.51	0.99	0.92

Table 5. Gas and pilot oil consumption values of the dual-fuel engines for LNG and Ammonia.

	Gas Consumption (tonnes)						Pilot Oil Consumption (tonnes)					
	Sailing		Manoeuvring		Port		Sailing		Manoeuvring		Port	
Months	LNG	Ammonia	LNG	Ammonia	LNG	Ammonia	LNG	Ammonia	LNG	Ammonia	LNG	Ammonia
10/18	292.79	675.79	28.51	63.69	25.70	42.64	9.88	85.58	1.18	10.20	0.41	0.82
11/18	311.91	754.80	38.98	87.43	26.99	44.78	9.29	80.13	1.53	13.27	0.43	0.86
12/18	352.12	815.66	59.00	134.40	27.88	46.26	9.05	78.52	1.91	16.52	0.44	0.89
01/19	337.33	787.50	32.60	73.33	33.60	55.75	8.40	72.81	1.23	10.61	0.53	1.07
02/19	315.45	737.67	28.02	82.24	25.49	42.29	8.19	70.73	1.31	12.74	0.41	0.81
03/19	377.75	884.76	31.23	89.43	27.80	46.12	9.46	81.78	1.44	13.90	0.44	0.88
04/19	372.22	865.13	29.86	86.94	24.88	41.28	10.07	86.67	1.39	13.53	0.40	0.79
05/19	319.67	738.34	43.45	106.28	31.03	51.48	8.95	77.23	1.67	14.99	0.49	0.99
06/19	352.36	819.99	32.59	92.05	27.49	45.61	8.99	77.80	1.44	13.81	0.44	0.87
07/19	350.69	806.35	35.37	96.62	27.91	46.31	9.77	84.40	1.43	13.59	0.44	0.89
08/19	251.10	579.99	35.27	97.34	22.76	37.76	7.15	61.70	1.41	13.53	0.36	0.72
09/19	308.97	709.28	19.14	57.54	23.86	39.59	9.18	79.46	0.95	9.28	0.38	0.76
TOTAL	3942.36	9175.25	414.02	1067.3	325.39	539.86	108.38	936.8	16.89	155.96	5.17	10.35

Figure 4. Comparison of the environmental benefits of scenarios.

Table 7. CAPEX and OPEX values of each scenario.

	CAPEX	OPEX
Base Case	–	$4,040,724
Scenario 1	–	$6,468,888
Scenario 2	–	$4,852,444
Scenario 3	$2,908,300	$57,831
Scenario 4	$3,441,480	$49,628
Scenario 5	$774,200	$127,175
Scenario 6	$3,682,500	$185,006
Scenario 7	$4,215,680	$176,802
Scenario 8	$9,546,000	$6,304,737
Scenario 9	$9,096,400	$9,819,041

Table 8. NPV and EANP values of each scenario.

	NPV	EANP
Scenario 1	$515,229,883	–
Scenario 2	$418,637,222	–
Scenario 3	$240,243,126	$28,922,604
Scenario 4	$240,634,876	$28,969,766
Scenario 5	$124,770,103	$15,020,934
Scenario 6	$366,407,650	$44,111,411
Scenario 7	$366,542,571	$44,127,654
Scenario 8	$321,871,636	$38,749,769
Scenario 9	$321,214,906	$38,670,706

To realise better economic analysis, a cost–benefit analysis has been carried out. Therefore, NPV and EANP values have been calculated for each scenario. Assuming that the average working life of a ship is approximately 30–35 years, the usage period of the systems planned to be installed is considered 10–15 years for the ship. On the other hand, the interest rate is an important parameter for the economic evaluation. Different values from 5% to 10% have been considered in the literature (Abdon et al. 2017; Qiu et al. 2019). In this study, it has been taken into account as 5% which is the lower value. The findings are presented in Table 8.

According to Table 8, it is observed that scenarios 6 and 7 where scrubber systems are used with the SCR, and scenario 9 where the ammonia-fuelled engine is used are the most cost-beneficial approaches.

The period of redemption of the methods is determined as the last step of the economic evaluation. The determined periods are presented in Figure 5.

Accordingly, SCR implementation has the shortest time while the use of dual-fuel engines has the longest. Among the scrubber applications, the hybrid type needs more time to meet the application cost of the method.

6.3. Discussion

In this study, various emission abatement methods on the container vessel have been comparatively examined under different scenarios. To realise analysis, scenarios are created such as the use of MGO, use of VLSFO with MGO, an adaptation of open-loop scrubber, utilisation of hybrid scrubber, application of SCR, hybrid use of open-loop scrubber with SCR, combination hybrid scrubber with SCR, and implementation of the dual-fuel engine, from scenario 1–9, respectively. While it is possible that the stated marine vessel could comply with the sulphur regulation within each created scenario, the NOx limitation could not be met in all scenarios. It has been observed that the highest contribution to the reduction of GHG impact is achieved by the use of a dual-fuel engine.

The amount of fuel consumption is decreased when the use of a dual-fuel engine. It is found that it is the most promising approach to reduce CO_2 emissions. In addition, this method significantly reduces the emission of other pollutants. On the other hand, it has the biggest period of redemption which is 3.2 years. While the assumption of the remaining time of the ship is 11 years, it's payback period is relatively long.

SCR application has the shortest payback period and is also very efficient for the elimination of NO_x substances in the exhaust. However, it is not suitable for the alone implementation since it does not affect or decrease the amount of other pollutants. In this case, the ship could not be able to navigate in the ECA regions since the sulphur content of exhaust gas cannot be decreased, and therefore, limitations on the company's commercial activities occur.

Within the scope of this study, the dual-fuel ammonia engine and SCR application introduced in scenario nine have been shown to have the highest environmental benefit in terms of emission reduction. The dual-fuel ammonia engine produces less harmful emissions than the other scenarios while having an acceptable payback period of 4.7 years. This approach is a crucial step towards a sustainable future for the maritime industry. The ammonia engine can facilitate compliance with current and future international standards regulating ships' emissions.

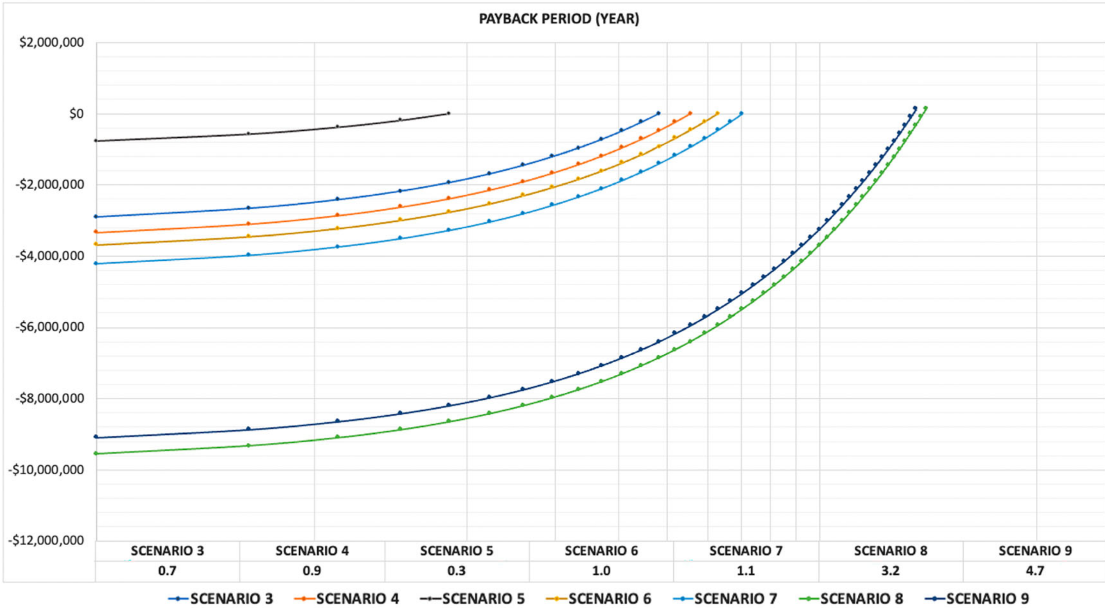


Figure 5. Payback period of the scenarios.

It is observed that similar results in both environmental and economic evaluations with the utilisation of open-loop and hybrid type of scrubber are found. Although open-loop is preferred widely (Clarkson Research Services Limited 2020), hybrid-loop is more attractive since it could be used as closed-loop in berth and as open-loop in open seas (Korean Register 2018). During the decision process of the application of the type of scrubber, some parameters such as the voyage plan of the ship, regulations of the governments, and the financial situation of the maritime company should be considered. In addition, while the scrubber installation is an effective solution to decrease SO_X emission, it is not sufficient for all types of pollutants. Therefore, after a while, the company requires new solutions for the elimination of the other emissions.

The application of the scrubbers with the SCR has revealed better environmental results compared with a single application of each of them. In terms of reducing the amount of emission, except for the CO_2 emission, results and environmental financial benefits close to the use of a dual-fuel engine have been obtained. In addition, for the specified container vessel, the payback periods of the investment in scenarios 6 and 7 are equal to approximately one-fourth of the period, compared to LNG conversion.

In the use of the low sulphur fuel approach, it has been determined that using only MGO is more effective than using VLSFO instead of HFO in terms of reducing the amount of emission. However, it creates more operating expenses depending on the fuel price. Also, since NOx emissions are not affected, the low sulphur fuel approach is insufficient for long-term usage in general.

7. Conclusion

Pollutants emitted into the atmosphere from ships are one of the most important issues in maritime. In this regard, IMO tries to control and reduce these emissions with different sanctions. Hence, to meet the obligations, different emission reduction methods are being researched by shipping companies and researchers, and these methods are adapted to ships.

In this study, noon reports which cover between November 2018 and October 2019 from a container ship that was built in 2001, were obtained and analysed. The emission inventory of the vessel has been created based on the base case where the ship consumes HFO and MGO as fuel. The nine different scenarios that cover SCR, scrubber, LNG and ammonia-fuelled engine and different types of fuel have been created for the examination and comparison of the emission reduction options for the marine vessel. According to the findings, the combination of scrubber and SCR systems is an effective approach to reduce emissions and to comply with SO_X and NO_X regulations for the marine vessel which is data analysed. With this approach, almost all pollutants emitted to the atmosphere by ships are reduced. In addition to decreasing amount of the emissions, the implementation meets the investment cost after approximately 1–1.1 years. The use of dual-fuel engines is one of the most promising ways to reduce greenhouse gas impacts in the maritime industry as it is effective in reducing all pollutants released by vessels.

As a result, using different fuel types and emission reduction technologies can significantly reduce the amount of pollutants ships emit into the atmosphere. Dual-fuel engines using ammonia are among the most effective ways to reduce ships' environmental footprint. Scenario 9 outperformed the other scenarios in reducing emissions to the atmosphere and provided a return on investment in 4.7 years. These findings provide the necessary motivation and knowledge base for the shipbuilding and ship management sectors to transition to sustainable maritime practices. Implementing innovative solutions such as the ammonia engine is critical to improving the environmental performance of the maritime sector.

Besides, the payback period of the LNG-fuelled engine approach is calculated for the container ship as 3.2 years, which is an acceptable time in the operation period of a marine vessel. It could provide economic and financial benefits to maritime companies in shipping with long lifetimes and newly built ships.

In future studies, the effect of the emission reduction methods will be determined for different types of vessels on various voyage routes. In addition, the impact of the application of these methods on coastal cities will be examined.

Nomenclature

AHP: Analytical hierarchy process
ANP: Analytical network process

CAPEX: Capital expenses
EANB: Equivalent annual net benefits
ECA: Emission control areas
EGCS: Exhaust gas cleaning system (Scrubber)
GHG: Greenhouse gas
HFO: Heavy fuel oil
HP: High pressure
IMO: International Maritime Organization
LNG: Liquefied natural gas
LP: Low pressure
MGO: Marine gas oil
NPV: Net present value
OPEX: Operational expenses
PBM: Planned payback period
PM: Particulate matter
SCR: Selective catalytic reduction
TOPSIS: Technique for order preference by similarity to an ideal solution
VLCC: Very large crude oil carrier
VLSFO: Very low sulfur fuel oil

Symbols

$\Delta E_{i,j}^{Fuel,k}$: Decreased emission amount between ports i and j after using fuel
$\Delta E_{i,j}^{s,k}$: Decreased emission amount after using the emission reduction method between ports i and j
B_{ij}^{Fuel}: Environmental benefit of using fuel
B_{ij}^{s}: Environmental benefit of using an emission reduction method
MEC_k: The marginal external costs ($/tonne)
r: Rate of interest
t: Usage period of the corresponding method
$P_{M.E.}$: Main engine power (kW)
a_i^t: A function for determining annual regular instalment amounts for interest rate payment
N: Number of trips in a year
*E*trip: The amount of emission over a complete trip (tonnes)
EF: Emission factors (kg/tonnes)
FC: fuel consumption (tonnes)
SGC: Specific gas consumption
SPOC: Specific pilot oil consumption

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Yasin Arslanoğlu http://orcid.org/0000-0002-9492-2975

References

Abadie LM, Goicoechea N. 2019. Powering newly constructed vessels to comply with ECA regulations under fuel market prices uncertainty: diesel or dual fuel engine? Transp Res Part D Transp Environ. 67:433–448. doi:10.1016/j.trd.2018.12.012.
Abadie LM, Goicoechea N, Galarraga I. 2017. Adapting the shipping sector to stricter emissions regulations: fuel switching or installing a scrubber? Transp Res Part D Transp Environ. 57:237–250. doi:10.1016/j.trd.2017.09.017.
Abdon A, Zhang X, Parra D, Patel MK, Bauer C, Worlitschek J. 2017. Techno-economic and environmental assessment of stationary electricity storage technologies for different time scales. Energy. 139:1173–1187. doi:10.1016/j.energy.2017.07.097.
ABS. 2020. Ammonia as marine fuel. NH3 Fuel Conference.
Ammar NR. 2019. An environmental and economic analysis of methanol fuel for a cellular container ship. Transp Res Part D Transp Environ. 69:66–76. doi:10.1016/j.trd.2019.02.001.
Ammar NR, Seddiek IS. 2017. Eco-environmental analysis of ship emission control methods: case study RO-RO cargo vessel. Ocean Eng. 137:166–173. doi:10.1016/j.oceaneng.2017.03.052.
Brynolf S, Magnusson M, Fridell E, Andersson K. 2014. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transp Res Part D Transp Environ. 28:6–18. doi:10.1016/j.trd.2013.12.001.
Caiazzo G, Langella G, Miccio F, Scala F. 2012. An experimental investigation on seawater SO2 scrubbing for marine application. Environ Prog Sustain Energy. 32:1179–1186. doi:10.1002/ep.11723.
CE Delft. 2023. Handboek Milieuprijzen 2023.
Clarkson Research Services Limited. 2020. World Fleet Register.
Corbett JJ, Thomson James Winebrake HJ, Manager P, Yuska D. 2014. Natural gas for waterborne freight transport: a life cycle emissions assessment with case studies.
Deng J, Wang X, Wei Z, Wang L, Wang C, Chen Z. 2021. A review of NOx and SOx emission reduction technologies for marine diesel engines and the potential evaluation of liquefied natural gas fuelled vessels. Sci Total Environ 766:144319. doi:10.1016/j.scitotenv.2020.144319.
Doug W. 2010. Dual-fuel and gas engines, pounder's marine diesel engines and gas turbines. 9th ed. Oxford: Butterworth-Heinemann.
Ejder E, Arslanoğlu Y. 2022. Evaluation of ammonia fueled engine for a bulk carrier in marine decarbonization pathways. J Clean Prod. 379:134688. doi:10.1016/j.jclepro.2022.134688.
Eriksson L, Llamas X. 2020. Robustness analysis of dual actuator EGR controllers in marine two-stroke diesel engines. J Mar Eng Technol. 19:17–30. doi:10.1080/20464177.2020.1712065.
Estevez R, López-Tenllado FJ, Aguado-Deblas L, Bautista FM, Romero AA, Luna D. 2023. Current research on green ammonia (NH_3) as a potential vector energy for power storage and engine fuels: a review. Energies 16:5451. doi:10.3390/en16145451.
Exhaust Gas Cleaning Systems Association. 2012. A practical guide to exhaust gas cleaning systems for the maritime industry. EGCSA Handbook, London UK.
Fan H, Tu H, Enshaei H, Xu X, Wei Y. 2021. Comparison of the economic performances of three sulphur oxides emissions abatement solutions for a Very Large Crude Carrier (VLCC). J Mar Sci Eng. 9:221. doi:10.3390/jmse9020221.
Fan L, Gu B, Luo M. 2020. A cost-benefit analysis of fuel-switching vs. hybrid scrubber installation: a container route through the Chinese SECA case. Transp Policy. 99:336–344. doi:10.1016/j.tranpol.2020.09.008.
Green Shipping Programme. 2021. Ammonia as a marine fuel safety handbook 2, 1–28.
Harahap F, Nurdiawati A, Conti D, Leduc S, Urban F. 2023. Renewable marine fuel production for decarbonised maritime shipping: pathways, policy measures and transition dynamics. J Clean Prod. 415:137906. doi:10.1016/j.jclepro.2023.137906.
Iannaccone T, Landucci G, Tugnoli A, Salzano E, Cozzani V. 2020. Sustainability of cruise ship fuel systems: comparison among LNG and diesel technologies. J Clean Prod. 260:121069. doi:10.1016/j.jclepro.2020.121069.
IMO. 1997. International Maritime Organization, Annex VI of Marpol 73/78: Regulations for the prevention of air pollution from ships and Nox technical Code. London, UK.
IMO. 2018a. International Maritime Organization, Implementation of Suphur 2020 limit – carriage ban adopted. Mepc, vol. 7. London, UK.
IMO. 2018b. International Maritime Organization, Initial IMO strategy on reduction of GHG emissions from ships.
IMO. 2019. International Maritime Organization, The 2020 global sulphur limit: FAQ. Int Marit Organ 1–5.
IMO. 2020. International Maritime Organization, Fourth IMO GHG study, 2020.
Inal OB, Zincir B, Deniz C. 2022. Investigation on the decarbonization of shipping: an approach to hydrogen and ammonia. Int J Hydrogen Energy. 47:19888–19900. doi:10.1016/j.ijhydene.2022.01.189.
Jayaram V, Nigam A, Welch WA, Miller JW, Cocker DR. 2011. Effectiveness of emission control technologies for auxiliary engines on ocean-going vessels. J Air Waste Manag Assoc. 61:14–21. doi:10.3155/1047-3289.61.1.14.
Jiang L, Kronbak J, Christensen LP. 2014. The costs and benefits of sulphur reduction measures: sulphur scrubbers versus marine gas oil. Transp Res Part D Transp Environ. 28:19–27. doi:10.1016/j.trd.2013.12.005.
Kim AR, Seo YJ. 2019. The reduction of SOx emissions in the shipping industry: the case of Korean companies. Mar Policy. 100:98–106. doi:10.1016/j.marpol.2018.11.024.
Korean Register. 2018. Guide to strengthened global SOx regulation. https://www.krs.co.kr/eng/.
Lee C. 2017. Performance evaluation of a urea-selective catalytic reduction system in a marine diesel engine. Proc Inst Mech Eng Part M J Eng Marit Environ. 231:801–808. doi:10.1177/1475090216667238.
Lee HJ, Yoo SH, Huh SY. 2020. Economic benefits of introducing LNG-fuelled ships for imported flour in South Korea. Transp Res Part D Transp Environ. 78:102220. doi:10.1016/j.trd.2019.102220.

Li K, Wu M, Gu X, Yuen KF, Xiao Y. 2020. Determinants of ship operators' options for compliance with IMO 2020. Transp Res Part D Transp Environ. 86:102459. doi:10.1016/j.trd.2020.102459.

Lindstad H, Sandaas I, Strømman AH. 2015. Assessment of cost as a function of abatement options in maritime emission control areas. Transp Res Part D Transp Environ. 38:41–48. doi:10.1016/j.trd.2015.04.018.

Lindstad HE, Rehn CF, Eskeland GS. 2017. Sulphur abatement globally in maritime shipping. Transp Res Part D Transp Environ. 57:303–313. doi:10.1016/j.trd.2017.09.028.

Liu L, Wu Y, Wang Y. 2022. Numerical investigation on the combustion and emission characteristics of ammonia in a low-speed two-stroke marine engine. Fuel. 314:122727. doi:10.1016/j.fuel.2021.122727.

Lloyd's Register. 2021. Exhaust gas cleaning systems: guidelines for the management of consumables and waste products. https://www.egcsa.com/wp-content/uploads/EGCSA-Handbook-2012-A5-size-.pdf.

Magnusson M, Fridell E, Ingelsten HH. 2012. The influence of sulfur dioxide and water on the performance of a marine SCR catalyst. Appl Catal B Environ. 111–112:20–26. doi:10.1016/j.apcatb.2011.09.010.

MAN Energy Solutions. 2018. 11.000 teu container vessel. An ME-GI powered vessel fitted with fuel gas supply system and boil-off gas handling. https://www.man-es.com/docs/default-source/document-sync/11-000-teu-container-vessel-eng.pdf?sfvrsn = 9d6e1e01_2.

Nadimi E, Przybyła G, Lewandowski MT, Adamczyk W. 2023. Effects of ammonia on combustion, emissions, and performance of the ammonia/diesel dual-fuel compression ignition engine. J Energy Inst 107:101158. doi:10.1016/j.joei.2022.101158.

Ni P, Wang X, Li H. 2020. A review on regulations, current status, effects and reduction strategies of emissions for marine diesel engines. Fuel 279:118477. doi:10.1016/j.fuel.2020.118477.

Niels de Vries. 2019. Safe and effective application of ammonia as a marine fuel.

Panasiuk I, Turkina L. 2015. The evaluation of investments efficiency of SOx scrubber installation. Transp Res Part D Transp Environ. 40:87–96. doi:10.1016/j.trd.2015.08.004.

Pavlenko N, Comer B, Zhou Y, Clark N, Rutherford D. 2020. The climate implications of using LNG as a marine fuel. https://theicct.org/sites/default/files/publications/Climate_implications_LNG_marinefuel_01282020.pdf.

Qiu Y, Yuan C, Tang J, Tang X. 2019. Techno-economic analysis of PV systems integrated into ship power grid: a case study. Energy Convers Manag. 198:111925. doi:10.1016/j.enconman.2019.111925.

Schinas O, Stefanakos CN. 2014. Selecting technologies towards compliance with MARPOL Annex VI: the perspective of operators. Transp Res Part D Transp Environ. 28:28–40. doi:10.1016/j.trd.2013.12.006.

Seddiek IS, Ammar NR. 2023. Technical and eco-environmental analysis of blue/green ammonia-fueled RO/RO ships. Transp Res D Transp Environ. 114:103547. doi:10.1016/j.trd.2022.103547.

Seddiek IS, Elgohary MM. 2014. Eco-friendly selection of ship emissions reduction strategies with emphasis on SOx and NOx emissions. Int J Nav Archit Ocean Eng. 6:737–748. doi:10.2478/IJNAOE-2013-0209.

Ship & Bunker. 2024. Average bunker prices. [accessed 2024 Mar 1]. https://shipandbunker.com/prices/av.

Silva RA, West JJ, Lamarque J-F, Shindell DT, Collins WJ, Dalsoren S, Faluvegi G, Folberth G, Horowitz LW, Nagashima T, et al. 2016. The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. Atmos Chem Phys. 16:9847–9862. doi:10.5194/acp-16-9847-2016.

S&P. 2024. Interactive: Ammonia price chart | S&P Global Commodity Insights. [accessed 2024 April 1]. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/051023-interactive-ammonia-price-chart-natural-gas-feedstock-europe-usgc-black-sea.

The Royal Society. 2020. Ammonia: zero-carbon fertiliser, fuel and energy store. The Royal Society London, UK.

Trivyza NL, Rentizelas A, Theotokatos G. 2018. A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability. Energy Convers Manage. 168:128–149. doi:10.1016/j.enconman.2018.04.020.

Trozzi C. 2010. Emission estimate methodology for maritime navigation. 9th International Emissions Inventory Conference, San Antonio, Texas.

UNCTAD. 2017. Review of maritime transport 2017. United Nations 1–25. doi:10.18356/e9e3b605-en.

Vanhamme E. 2016. Assessment of fuel oil availability final report. July.

Van Rheenen ES, Padding JT, Slootweg JC, Visser K. 2023. Hydrogen carriers for zero-emission ship propulsion using PEM fuel cells: an evaluation. J Mar Eng Technol 1–18. doi:10.1080/20464177.2023.2282691.

Wärtsilä. 2014. Wärtsilä gas-fired engines. https://www.wartsila.com/docs/default-source/energy-docs/technology-products/brochures/gas-and-multi-fuel-power-plants.pdf?sfvrsn = 6f4dbb45_22.

Woo SH, Raza H, Kang WM, Choe SB, Im MH, Lim KS, Nam JG, Kim H. 2023. An ammonia supplying system using ammonium salt to reduce the NOx emissions of a 1.1 MW marine engine. J Mar Eng Technol. 22:45–54. doi:10.1080/20464177.2022.2127402.

Wu P-C, Lin C-Y. 2020. Cost-benefit evaluation on promising strategies in compliance with low sulfur policy of IMO. J Mar Sci Eng. 9:3. doi:10.3390/jmse9010003.

Wu Y, Chen A, Xiao H, Jano-Ito M, Alnaeli M, Alnajideen M, Mashruk S, Valera-Medina A. 2023. Emission reduction and cost-benefit analysis of the use of ammonia and green hydrogen as fuel for marine applications. Green Energy Resour. 1:100046. doi:10.1016/j.gerr.2023.100046.

Yang ZL, Zhang D, Caglayan O, Jenkinson ID, Bonsall S, Wang J, Huang M, Yan XP. 2012. Selection of techniques for reducing shipping NOx and SOx emissions. Transp Res Part D Transp Environ. 17:478–486. doi:10.1016/j.trd.2012.05.010.

Zanobetti F, Pio G, Jafarzadeh S, Muñoz Ortiz M, Cozzani V. 2023. Decarbonization of maritime transport: sustainability assessment of alternative power systems. J Clean Prod. 417:137989. doi:10.1016/j.jclepro.2023.137989.

Zhu J, Zhou D, Yang W, Qian Y, Mao Y, Lu X. 2023. Investigation on the potential of using carbon-free ammonia in large two-stroke marine engines by dual-fuel combustion strategy. Energy. 263:125748. doi:10.1016/j.energy.2022.125748.

Zhu M, Li KX, Lin KC, Shi W, Yang J. 2020. How can shipowners comply with the 2020 global sulphur limit economically? Transp Res Part D Transp Environ. 79:102234. doi:10.1016/j.trd.2020.102234.

Zis T, Angeloudis P, Bell MGH, Psaraftis HN. 2016. Payback period for emissions abatement alternatives: role of regulation and fuel prices. Transp Res Rec J Transp Res Board. 2549:37–44. doi:10.3141/2549-05.