Journal of
Marine Science and Engineering

MDPI

Article

Feasibility Analysis of the Effects of Scrubber Installation on Ships

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Abstract: A feasibility analysis was conducted on a crude oil tanker. Differences in power generation and fuel consumption of the diesel generators based on the noon report of the specified marine vessel were analyzed for similar periods before and after the scrubber application. Accordingly, the changes in releasing amounts of emissions were calculated. Then, a financial evaluation was realized with three economic indicators. As a result of the analysis performed, it is found that the power generation and fuel consumption realized by each diesel generator are increased after scrubber application. Nevertheless, its implementation on board may be considered acceptable in light of the economic findings. However, it has been determined that scrubber implementation causes an increase in all pollutants' amounts except SO_X. Therefore, it contradicts the zero-emission ship target and decarbonization strategy stated by IMO.

Keywords: maritime transportation; ship; scrubber; emission; feasibility analysis

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Citation: Karatuğ, Ç.; Arslanoğlu, Y.; Guedes Soares, C. Feasibility Analysis of the Effects of Scrubber Installation on Ships. *J. Mar. Sci. Eng.* **2022**, *10*, 1838. https://doi.org/10.3390/jmse10121838

Academic Editor: Tie Li

Received: 20 October 2022
Accepted: 27 November 2022
Published: 30 November 2022

1. Introduction

The maritime industry has significant importance in worldwide cargo transportation since it ensures 80% of global transportation [1,2]. Additionally, it has been determined that the world fleet has been growing an average of 4.6% from 2008 to 2018 each year [3]. However, shipping contributes to the increase in pollutants caused by the combustion of huge amounts of fuel [4,5] that cause global warming, bad air quality, and visibility. From 2012 to 2018, greenhouse gas (GHG) emissions released by ships into the atmosphere increased by 9.6%, and the percentage of global emissions related to the maritime industry was 2.89% in 2018 [6]. In the case where no precautions are taken, it was predicted that the emission ratio from shipping could increase to 19% [7], and it will become the main environmental concern if effective policies are introduced [8,9].

Accordingly, priority cautions in reducing the environmental pollution caused by maritime transportation were introduced by the International Maritime Organization (IMO), which is the rule-maker and a significant authority for the shipping industry. Strict rules based on Annex-VI of the International Convention for the Prevention of Marine Pollution from Ships (MARPOL) have been enforced within the scope of air pollution. In this regard, to control and reduce ship-based SOx and NOx emissions, Emission Control Areas (ECAs) have been designated.

The measures considered include the development of new procedures for operating diesel engines to reduce fuel consumption [10,11] and emissions [12,13].

Other measures are associated with the way the ship is handled, as operation in rough weather leads to higher fuel consumption and emissions [9,14]; therefore, using weather routing contributes also to the decrease in emissions [15,16].

As a result of the limitation indicating the decrease in the sulfur content in the fuel used in global seas since 2020, shipowners and researchers have started to investigate various methods to meet this limit [17]. Scrubber retrofitting on ships is one of the preferred methods by the maritime industry to achieve compliance with the SOx limitation in existing ships.

1.1. Problems Statement

The scrubber system that is particularly considered offers an effective solution to prevent SOx emission on marine vessels [18]. However, it causes extra power generation in diesel generators (DG) and, accordingly, extra fuel consumption. Since heavy fuel oil (HFO) is used on ships equipped with the scrubber to reduce operational expenses, it is possible to increase other emission types, unlike SOx, as a result of the extra fuel consumption. Although there are studies on scrubbers in the literature, there is a gap since there is no study that reveals the effects of scrubber installation on diesel generators on issues such as power generation and fuel consumption, taking into account the noon report of a ship.

1.2. Contributions of the Study

In this study, the feasibility analysis of scrubber installation is realized. Initially, to perform the feasibility analysis, two months periods before and after the scrubber adaptation are collected from the noon reports of the ship. For this process, attention is paid to ensuring that the ship's cruising conditions (shipload conditions, weather conditions) are almost equal. Then, a comparison has been made on power generation, fuel consumption, and the amount of emission released by diesel generators. Lastly, to examine the system economically, the net present values (NPVs), and the payback periods of the installation have been calculated with various interest rates. Some contributions of the paper are as follows:

- The scrubber installation is analyzed with real-time ship cruising data.
- The application is examined from points of view of both environmental and economic.
- It is revealed that scrubber application can decrease SOx emission, but it has a negative impact on the other emissions based on the increase in fuel oil consumption.

The rest of the paper is organized as follows. The literature review is realized under Section 2. General information about the scrubber systems is presented in Section 3. In Section 4, the case study is conducted. The findings are discussed in Section 5. Finally, the conclusions of the paper are given in Section 6.

2. Literature Review

In the maritime literature, three feasible options have drawn attention to meet SOx restrictions introduced by IMO: fuel switching, adoption of liquified natural gas (LNG) as fuel, and implementation of an exhaust gas cleaning system (scrubber) [19]. In the first option, it is possible to operate the ship in compliance with the sulfur limits by using marine gas oil with 0.1% of sulfur content in the SOx-ECAs and using very low sulfur fuel oil (VLSFO) in the other seas. The second option is an adaptation of the LNG system of ships. Although this approach provides a notable reduction in almost all pollutants, it has the disadvantages of a large initial investment cost, system installation requirements on the ship (tank space, line design), and immaturity of the bunkering supply chain. The third one is the application of a scrubber system on board.

Scrubber installation allows maritime companies to operate their ships more economically with HFO, which has a sulfur content of 3.5%. In this method, the exhaust gas emitted into the atmosphere is purified from almost all of the sulfur by washing it [20]. Among these three options, LNG is planned for new-built ships, while the others have been preferred primarily during compliance with the IMO 2020 sulfur cap [21].

In the literature, these three approaches have been frequently analyzed in a comparative way [22–24]. Despite the huge amount of investment cost for LNG installation, it was concluded that it could be a good option for new-built ships [25]. Lindstad et al. [26] examined various emission abatement methods and showed that the effects could change according to some parameters, such as engine size and fuel price. A useful decision-making tool that was developed based on the analytical network process method has been presented to operators to make financial comparisons during periods of compliance with

IMO sulfur limitations [27]. According to Zis et al. [21], while the use of distilled fuel was preferred before 2020, the scrubber application for existing ships has come to the forefront after the beginning of the restriction. Lindstad et al. [28] stated that while high-speed cruising was preferred by ships equipped with scrubbers, marine vessels using more costly distilled fuels such as MGO were realized by lower-speed cruising due to the aim of reducing fuel expenses.

Kim and Seo [29] conducted a survey that was conducted with the Korean shipping industry, and they concluded that a scrubber could be a good option based on differences in fuel prices and the reduction rate of sulfur. Wilailak et al. [30] determined the parameters that affected the De-SOx process and proposed a new design of an open-loop scrubber to minimize the power requirement of the system pumps. Yang et al. [31] conducted an experimental analysis to determine scrubber effectiveness and showed that SOx and $PM_{2.5}$ contents in the exhaust gases have decreased by more than 95% and approximately 10%, respectively. Caiazzo et al. [32] carried out an experiment on a ship in which a two-stroke diesel engine was equipped with an open-loop scrubber, and they calculated the SO_2 reduction as 93%. Similar experimental studies have been carried out with different types of diesel engines on various loads, and the rate of SOx reduction has been observed up to 99% [33–35].

Wu and Lin [36] evaluated the scrubber installation for a container ship. They proposed that although scrubber implementation allows good opportunities for short-term plans, using VLSFO as a marine fuel to comply with SOx restrictions is more advantageous in a long-term application. Başhan et al. [37] examined three scrubber types in health, safety, and environmental failure framework based on the multi-criteria decision-making approaches. Tan et al. [38] conducted a case study for inland Yangtze River ships by comparing scrubber installation to the vessel and green fuel usage onboard and found that scrubber implementation is a more effective approach to decreasing SOx emission. Giroth and Ang [39] developed a design for the marine scrubbers and tested their model on ANSYS software to determine the superiority of their design compared to conventional ones. Lee et al. [40] performed simulations with open- and closed-loop scrubber systems to determine the differences in the performances and validated their results with sea-trial data to increase the reliability of the simulation results. The papers regarding the scrubber installation in the literature are summarized in Table 1.

Table 1. The summary of the papers regarding scrubber installation to ships.

Paper	Scrubber Type	Objectives
Kim and Seo [29]	General scrubber application	Determination of the best SOx reduction strategy for the Korean shipping industry
Wilailak et al. [30]	Hybrid wet scrubber	Improving system design for reducing power consumption
Yang et al. [31]	Open-loop scrubber	Comparing the parameters pre- and post-scrubber installation on a container ship
Caiazzo et al. [32]	General scrubber application	Performing experimental study to determine desulfurization performance
Zhou et al. [33]	Closed-loop scrubber	Determination of SOx removal performance and its economic evaluation compared to low-sulfur fuel usage
Winnes et al. [34]	Closed-loop scrubber	Evaluation of desulfurization performance of scrubber installation and low-sulfur fuel usage
Karjalainen [35]	Open-loop scrubber	Comparing the amount of exhaust gas emission as a result of operating with the scrubber and marine gas oil
Wu and Lin [36]	General scrubber application	Determination of SOx removal performance and its economic evaluation compared to low-sulfur fuel usage for a container ship
Başhan et al. [37]	Types of wet-type scrubber	Evaluation of different types of scrubber systems with multi-criteria decision-making methods
Tan et al. [38]	General scrubber application	Examination of the impact on sulfur emission as a result of scrubber installation and fuel switching for an inland container ship over the Yangtze River
Giroth and Ang [39]	General scrubber application	Improving the effectiveness of scrubber systems by developing new design
Lee et al. [40]	Open- and closed-loop scrubber	Comparing the performance of open- and closed-loop scrubber implementation

Apart from the papers in the literature, this paper comprehensively handles the scrubber implementation on ships. The differences in the fuel consumption and power demand of the ship are determined and analyzed based on real voyage data. In addition, this paper contributes to the literature by presenting operational differences as a result of the scrubber application.

3. Scrubber System

The scrubber is a system that ensures the removal of SOx and the decrease in PM particles in exhaust gases. Although its usage in land applications is very advanced, the maritime industry's interest in the adaptation of scrubbers to ships has increased during the period of compliance with the IMO 2020 sulfur restriction. According to regulation, the introduced limitations by IMO corresponding with SOx are presented in Table 2.

Table 2. Introduced limitations by IMO [41].

IMO SOx Limitations			
Global Seas		SECA/ECA	
Date	Sulfur (%)	Date	Sulfur (%)
Initial limit	4.5	Initial limit	1.5
1 January 2012	3.5	1 July 2010	1.0
1 January 2020	0.5	1 January 2015	0.1

The rise in the total number of ships with a scrubber (in operation and on order) is shown in Figure 1.

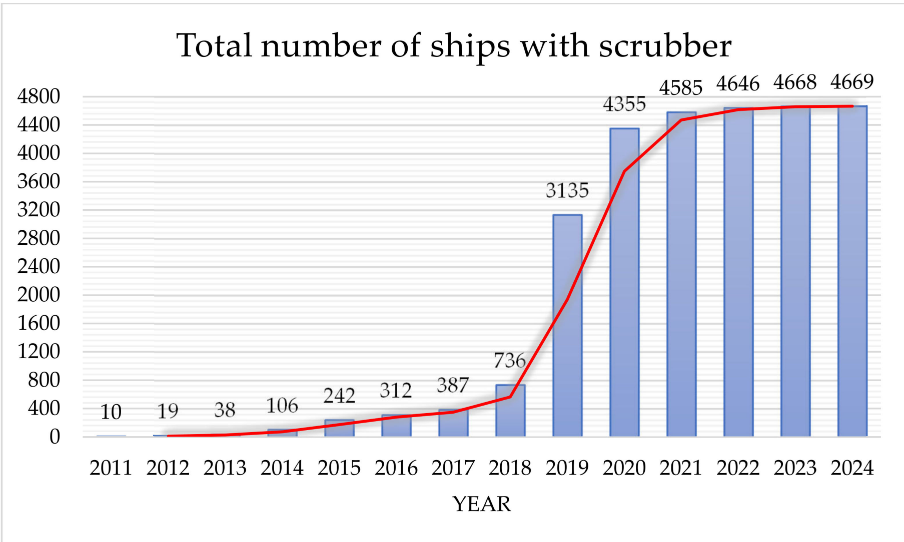

Figure 1. The rise in the total number of ships with scrubbers (in operation and on order) [42].

During the transition phase, the scrubber installation occurred as a retrofit and new built by approximately 70% and 30%, respectively. The adaptation of scrubbers has been realized mostly in dry bulks, containers, crude oil/chemical tankers, and Ro-Ro ships [42].

There are two different scrubber concepts, the dry and wet ones. The dry type of scrubber is not preferred because of the heavy equipment, instability, and requirement of the large areas [43]. The wet type of scrubber, which is more suitable for applications to marine vessels, is of three types: open-loop, closed-loop, and hybrid [44]. In the open-loop system, the elimination of the SOx is carried out based on the natural alkalinity of the seawater, while in the closed-loop system, it is made with alkaline chemicals such as sodium hydroxide (NaOH) or rarely by magnesium oxide (MgO). The open-loop system has some advantages, such as lower CAPEX and OPEX, less requirement of space for system and components, and no risk of storing any chemical. However, its efficiency can change according to the alkalinity level of seawater, and the discharge of effluent of open-loop scrubber is banned or restricted at some certain coastal or port areas such as the Kiel canal in Germany, territorial waters or ports of Latvia, the Panama Canal and the ports of China.

On the other hand, the operation of the closed-loop system is independent of the operation location of the ship and the alkalinity of seawater. Since its effluent is stored onboard, the operation of the system limits according to the waste tank capacity. The closed-loop type is also needed more space for adaptation, and its CAPEX and OPEX are relatively higher. It reveals additional risks for seafarers due to hazardous materials that are required in operation. The hybrid approach neutralizes the disadvantages of both open-loop and closed-loop design and provides significant flexibility in the operation of ships, but it has the highest OPEX and CAPEX [45]. The design and structure of open-loop and closed-loop scrubber systems are given in Figure 2.

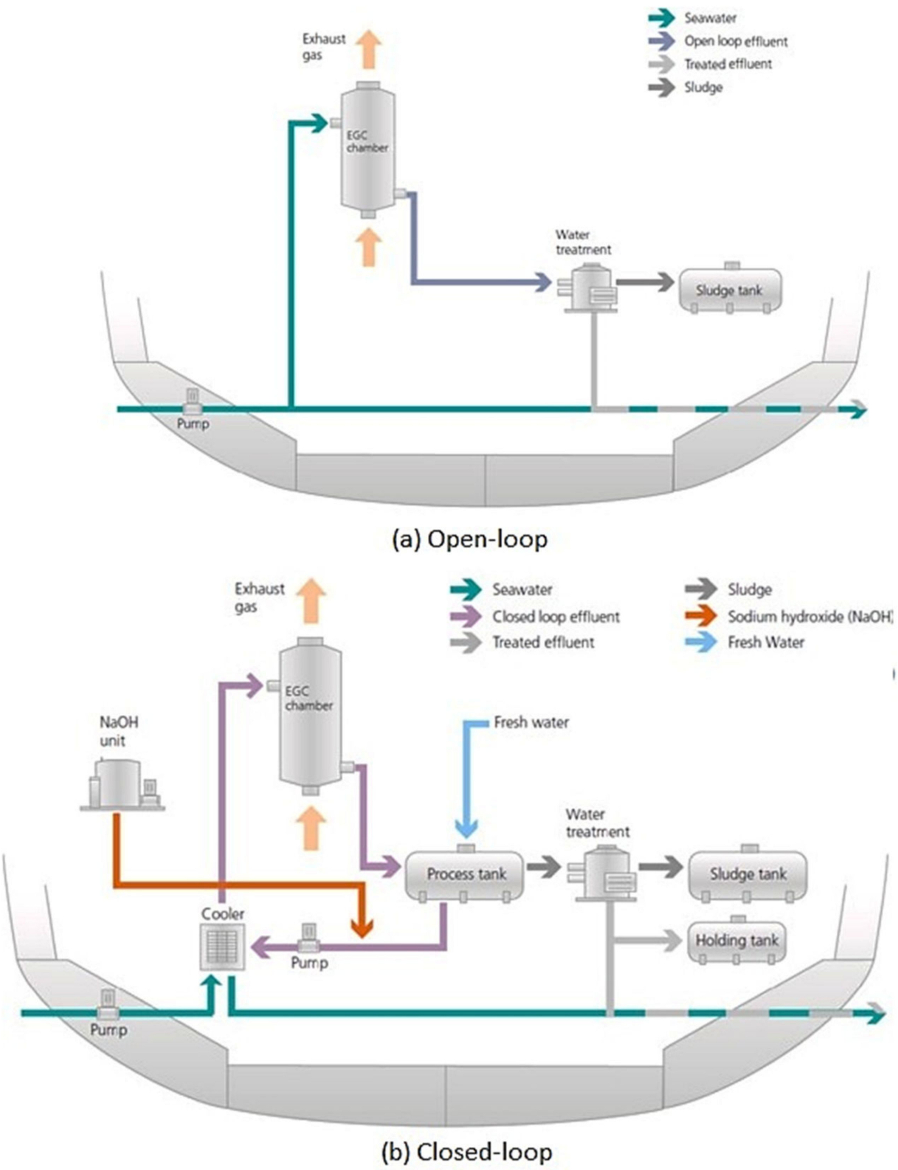

Figure 2. Structure of open-loop and closed-loop scrubbers [46].

4. Case Study

In the process of complying with the IMO 2020 sulfur limitation, the application of scrubbers on marine vessels has been frequently preferred by shipowners, and the number of ships with scrubbers is increasing every year. However, it is thought that the adaptation of this system causes some differences in the operation of the ship, as well as reducing SOx emissions; therefore, in this study, the scrubber system has been analyzed with a methodological approach that is shown in Figure 3.

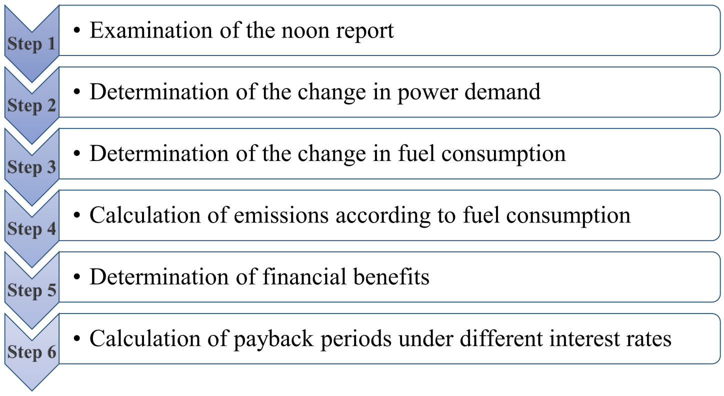

Figure 3. The methodology of the study.

The feasibility analysis of the case study is limited to the open-loop design since the ship where data have been obtained from this type of scrubber. However, the following calculations could be easily applied to the data set obtained from another marine vessel with a different type of scrubber. In addition, the analysis and findings of this study provide significant foresight for the scrubber systems.

The analysis was carried out using noon reports of a large commercial marine vessel cruising on the open seas. The operation chart of the ship is illustrated in Figure 4. Further, the specifications of the ship are presented in Table 3.

To compare the differences that occur in power generation and fuel consumption in diesel generators, similar pieces of data that covered before and after the scrubber installation (sample day periods, ship's load condition, ship's cruise condition) have been determined from the noon report of the ship. Most sea voyages have been performed in the Baltic sea and the Red sea. While the ship was at the loaded situation in 59% of the analyzed dataset duration, it was at the ballasted condition on the rest times. During the voyage periods, its average speed was about 9 knots.

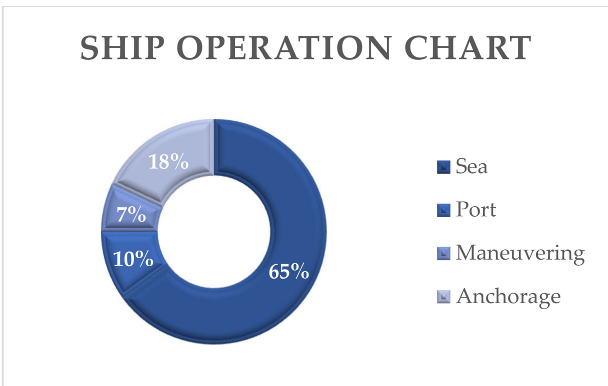

Figure 4. The operation chart of the ship.

Table 3. Specifications of the ship.

Ship Specifications	
Type of ship	Suezmax crude oil tanker
Deadweight (DWT)	159,500
Gross tonnage (GRT)	83,377
Length	273.7 m
Width	48 m
Main engine	MAN 6S70ME-C
Main engine power	19,620 kW
Generator	MAN 7L23/30 × 3 sets
Generator power	1050 kW × 3 sets
Boiler	Alfa Laval Aalborg OL Boiler × 2 sets
Type of scrubber	U-type open-loop wet scrubber

Emissions emitted to the atmosphere have been calculated, based on the amount of fuel consumption and emission factor [47] as:

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

where E_{trip} is the amount of emission over a complete trip (tons), FC is the fuel consumption (tons), EF is the emission factors (kg/tons), i is a type of emission (NOx, SOx, CO_2, $PM_{2.5}$, PM_{10}), 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, maneuvering). The used emission factors are presented in Table 4.

Table 4. The used emission factors [6].

Fuel Type	NO_X (kg/ton)	SO_X (kg/ton)	PM_{10} (kg/ton)	$PM_{2.5}$ (kg/ton)	CO_2 (kg/ton)
HFO	75.90	50.83	7.55	6.94	3.114
MGO	56.71	1.37	0.90	0.83	3.206

The VLSFO is a blended fuel that is a mixture of MGO by 80% and HFO by 20% [48]. The emission factor has been determined according to mixing ratios and used in the calculations. The emission reduction efficiency of the scrubber has been considered 97% for SOx [45] and 10% for $PM_{2.5}$ [31].

The economic evaluation has been realized with net present value (NPV), simple payback period calculation (SPP), and discounted payback period calculation (DPP) [49].

$$NPV\ (currency) = T\left\{\sum_{t=0}^{L} \begin{matrix}\left[C_{(t,\,r)} + B_{(t,\,r)}\right] \\ d = 8\% \\ d = 5\%\end{matrix}\right\} \tag{2}$$

$$SPP\ (years) = T\left\{\begin{matrix}\sum_{t=0}^{L}\left[C_{(t,\,r)} + B_{(t,\,r)}\right] = 0, \\ d = 0\end{matrix}\right\} \tag{3}$$

$$DPP\ (years) = T\left\{\begin{matrix}\sum_{t=0}^{L}\left[C_{(t,\,r)} + B_{(t,\,r)}\right] = 0, \\ d = 8\% \\ d = 5\%\end{matrix}\right\} \tag{4}$$

where $C_{(t,\,r)}$ represents costs and $B_{(t,\,r)}$ represents benefits, and these parameters could be calculated as follows [49]:

$$C_{(t,\,r)} = C_I + \sum_{t=1}^{L} \frac{O\&M_t}{(1+d)^t} \tag{5}$$

$$B_{(t,\,r)} = \sum_{t=1}^{L} \frac{[(F_{HFO} \times P_{HFO}) - (F_{VLSFO} \times P_{VLSFO})] + B_{ind}}{(1+d)^t} \quad (6)$$

where C_I is the CAPEX of the scrubber, $O\&M_t$ represents maintenance cost, d is the discount rate, P_{HFO} and P_{VLSFO} are prices of fuels and F_{HFO}. and F_{VLSFO} the present amount of consumption. B_{ind} indicates the indirect benefits, such as the prior entry to the port, and carbon credits [49]. The CAPEX of the scrubber was determined as 55 USD/kW [50] and $O\&M_t$ is considered % 1 of CAPEX [51].

5. Results and Discussion

5.1. Findings

To carry out the feasibility analysis, average power demands and total amounts of fuel consumption from DGs are determined by covering the periods of 2 months before and after scrubber installation based on the noon reports. The findings are presented in Table 5.

Table 5. Results of power and fuel analysis.

Power Demand (kW)			
	Before Scrubber Installation	**After Scrubber Installation**	**Increase Rate**
Average power of DG 1	416.43	463.41	11.28%
Average power of DG 2	403.16	473.42	17.43%
Average power of DG 3	409.77	476.18	16.21%
Fuel consumption (Tons)			
	60 days before scrubber installation	**60 days after scrubber installation**	**Increase amount**
Used fuel	VLSFO	HFO	
Consumption	2953	3388	435

In similar navigation conditions of the ship, it is understood that the total power demand increases as a result of the scrubber application. It is observed that there is an increase in power generation of DGs at approximately 11%, 17%, and 16%, respectively. Accordingly, an extra 435 tons of fuel is consumed in the 2 months after the scrubber application.

Since two types of fuels that have different emission factors for pollutants have been used in the compared periods, the emissions emitted into the atmosphere have varied. The findings related to releasing emissions are presented in Table 6.

Table 6. Comparison of releasing emissions before/after scrubber installation.

Releasing Emissions (tons)					
	CO_2	**NOx**	**SOx**	**PM_{10}**	**$PM_{2.5}$**
2 months before scrubber installation	9413	178,798	30,091	4719	4335
2 months after scrubber installation	10,550	257,149	5166	25,579	21,161

It is found that as a result of the scrubber installation, SOx emissions are effectively reduced, while other types of emissions increase due to the use of HFO and higher fuel consumption. In addition, although the reducing effect on $PM_{2.5}$ is considered as 10%, the amount of this pollutant is higher compared to the specified ship without a scrubber. Besides, the increase in the amount of emitted CO_2 is against the decarbonization strategy introduced by IMO.

The CAPEX of the scrubber that is determined based on the variable investment cost factor is calculated at USD 1,079,100 and the $O\&M_t$ is found to be USD 10,791. Prices of VLSFO and HFO have been taken at USD 773 and USD 497, respectively [52]. In line with this information, an economic evaluation of the application of the scrubber system is realized with NPV, SPP, and DPP using financial equations specified in Section 3. The NPV and DPP are calculated for 1 year using 2 different discount rates that are 5% and 8%. Accordingly, $NPV_{d=5\%}$ and $NPV_{d=8\%}$ are calculated as USD 2,407,946.27 and USD 2,352,598.17, respectively. The differences in the cash flow of the investment based on the discount rates, and corresponding payback periods are shown in Figure 5.

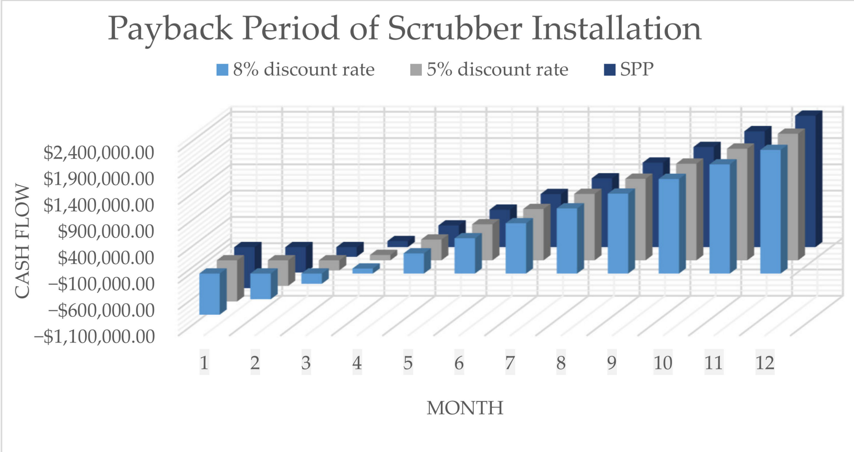

Figure 5. Cash flow and payback period of scrubber installation based on different discount rates.

While the SPP is found at 0.30 years, the DPP is calculated at 0.34 and 0.37 years for 5% and 8% discount rates, respectively. Considering the ship life span, these economic results make it understandable that shipping companies conduct intensive scrubber adaptation in the process of complying with the sulfur restriction.

5.2. Discussion

In line with the conducted feasibility analysis via noon reports received from the ship, it has been determined that the generated power and the fuel consumption in the DGs increased as a result of the scrubber application. As a result of the higher fuel consumption, it is found that all emissions except SOx are released into the atmosphere more. This situation shows that a scrubber implementation is an effective option for complying with the sulfur restriction, but it contradicts the decarbonization strategy specified by IMO.

On the other hand, despite the increase in fuel consumption, operational expenses are saved as the HFO is cheaper than the VLSFO. The scrubber investment is financially evaluated within the three different economic indicators: NPV, SPP, and DPP. According to the values calculated, the installation is found to be acceptable in a financial way. The period of redemption has been determined between 0.3–0.4 years, which is changed according to the discounted rate.

6. Conclusions

In this study, the scrubber system, which is frequently preferred by maritime companies in the process of complying with the 2020 sulfur regulation enforced by IMO in shipping, has been examined in detail. Some of the adverse impacts of its application for ships are determined.

In this sense, a feasibility analysis is carried out on an oceangoing vessel. To conduct the analysis, the noon reports of a crude oil tanker have been obtained, and similar cruising conditions of the ship on the same periods before and after scrubber installation are compared. Since the ship has an open-loop system, the analysis is limited to this one, but at this point, it should be underlined that approximately 81% of the ships with scrubbers in the world fleet have an open-loop design [42]. As a result of the comparison, it is determined that there is an increase in the power generation and fuel consumption of the DGs. HFO was used as a fuel since the SOx in the exhaust gas can be removed in a huge percentage.

It has been determined that this situation causes a decrease in operational fuel expenses despite higher fuel consumption but an increase in emission gases except for SOx. Finally, the investment is evaluated within the scope of three different economic parameters, and it is found acceptable.

The main contributions of the paper are as follows:

i. As a result of the case study carried out on the specified crude oil vessel, some adverse effects of scrubber adaptation on issues such as emissions and fuel consumption have been identified.
ii. Differing from the literature, the power and fuel consumption increase in DGs as a result of the scrubber installation is presented based on the ship's real noon report data.
iii. Emission analysis is carried out not only specifically for SOx but also for all pollutants, and the amounts of increases have been presented.
iv. The financial results have been obtained parallel to the scrubber-related studies.
v. The scrubber utilization is against the zero-emission ship target and decarbonization strategy stated by IMO.

The findings of the study provide significant results and foresight to maritime companies, authorities, and stakeholders about the scrubber application on marine vessels. In line with the calculated results, although scrubber application is acceptable to comply with the sulfur regulation in the short term, other options, such as alternative fuels and more beneficial De-SOx technologies, should be considered because of both environmental concerns and to meet environmental policies and strategies introduced by IMO.

Author Contributions: Ç.K.: Formal analysis, Visualization, and Writing—Original Draft; Y.A.: Writing—Review and Editing; C.G.S.: Writing—Conceptualization, Review and Editing, and Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by The Scientific and Technological Research Council of Turkey BIDEB 2214-A International Doctoral Research Fellowship Programme (Grant no.: 1059B142100431) and the Research Fund of the Istanbul Technical University (Project No.: 43048).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work contributes to the Strategic Research Plan of the Centre for Marine Technology and Ocean Engineering (CENTEC), which is financed by the Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia—FCT) under contract UIDB/UIDP/00134/2020.

Conflicts of Interest: The authors declare no conflict of interest.

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