A Cost-Benefit Analysis of Fuel-Switching vs. Hybrid Scrubber Installation: A container route through the Chinese SECA case

Abstract

The shipping industry has been subjected to significant pressure with the increasingly stringent environmental regulations. All vessels must comply with the IMO 2020 Sulfur cap—using fuel with less than 0.5% of sulfur content in international navigation, and 0.1% within Sulphur Emission Control Areas (SECAs). Ship operators must select the most cost-effective compliance option for their vessels, especially in the current sluggish market. This research uses a cost–benefit framework to analyze ship operators' compliance options of fuel-switching versus hybrid scrubbers, and applies these to a specific liner route through the Chinese SECA. The study considers the impacts of the proportion of the entire round trip that is a designated SECA; price differences between low- and high-sulfur fuels; loading factors; freight rates and discount rates on compliance options; and possible impacts of investment cost or government subsidies on scrubber installation. Based on the current conditions, fuel-switching is found to be the best compliance option on the specific route. However, the SECA proportion, a high price difference between low- and high-sulfur fuel, or a low scrubber cost can make scrubbers a better option. In addition, from the perspective of reducing sulfur oxide and carbon dioxide emissions, the scrubber option is always preferable. This highlights the importance of providing government subsidies for scrubbers in order to reduce environmental impacts.

Keywords: Cost–Benefit Analysis; Sulphur Emission Control Area; Fuel-Switching; Hybrid Scrubber

1. INTRODUCTION

Shipping, which represents more than 80% of global trade by volume, provides livelihoods for a wide range of businesses in nearly all countries around the world (UNCTAD, 2018). However, emissions from maritime sectors account for 10–15% of sulfur oxide (SO_x) emissions and about 3% of carbon dioxide (CO_2) emissions (IMO, 2014); this has attracted much attention from scholars and environmentalists, especially in coastal cities (Lindstad and Eskeland, 2016;Tichavska et al., 2019). In the 1980s the International Maritime Organization (IMO) began to address air pollution from ships, and in 1997 the International Convention for the Prevention of Pollution from Ships implemented the Air Pollution Annex (VI), which mainly regulates emissions from ships (IMO, 1997). In addition, several Sulfur Emission Control Areas (SECAs) have been set up to reduce emissions, first in North America and Northern Europe in 2015, with the cap set at 0.1%. Outside of SECAs, the sulfur limit is also becoming stricter, rising from 3.5% to 0.5% from January 1, 2020 (IMO, 2018). China has also published several regulations that designate some of its coastal areas as SECAs effective January 1, 2019 (MSA, 2018). However, China's sulfur limit is set at 0.5%, which is higher than that of other SECAs, and its coverage is limited. With the implementation of the IMO sulfur cap, it has been considered that the sulfur limit in the Chinese SECA should also be upgraded to 0.1% to make this SECA meaningful (Fan and Huang, 2019). If the Chinese SECA is also upgraded, the question arises as to which compliance option carriers should choose when their service routes pass through this area.

To stay competitive, operators have to select the most cost-effective option to meet the requirements (Zavitsas et al., 2018). There are typically three feasible options (Nikopoulou, 2017). The first option is to switch to marine gas oil (MGO) with a sulfur content of less than 0.1% when sailing inside SECAs, and using ultra-low-sulphur fuel oil (ULSFO) with a sulfur content of less than 0.5% outside SECAs. The second option is to install a scrubber system to filter the sulfur from exhaust emissions, which enables operators to use cheaper heavy fuel oil (HFO) with a maximum sulfur content of 3.5% (Merien-Paul et al., 2019). However, this entails higher investment, installation, and operational costs, requires additional space, increases energy usage, and requires additional downtime. Hence, operators must consider the trade-off between initial capital investment and future operating costs. The third option is to adopt liquefied natural gas (LNG) as fuel. Although LNG propulsion can help to avoid nearly all pollution types, the massive capital investment, huge space requirements onboard, and limited LNG supply at ports inhibit its application. A survey carried out by Lloyd's List on compliance options revealed that most ship operators preferred distillate fuel as their compliance approach until 2020, then began using LNG for new builds and scrubbers for existing vessels. (Zis et al., 2016). Currently, the first of the two options outlined above are most frequently considered by operators and scholars (Jiang et al., 2014;Schinas and Stefanakos, 2014;Balland et al., 2015;Zis et al., 2016). Considering this, and its lack of feasibility for most existing vessels, LNG is not included in the current study.

There are three types of scrubbers: open loop, closed loop, and hybrid loop. Each has different mechanisms for sulfur recapture, different initial investment costs, and varying sulfur abatement efficiencies. Open-loop scrubbers are banned in some countries and ports, such as Singapore and China, because the sulfur-recapture waters are discharged into the sea and can cause pollution. Closed-loop scrubbers entail no additional pollution (Lindstad et al., 2017), but the cost is high. Hybrid scrubbers combine open and closed loops together: they can run in open mode while at sea and in closed mode in ports and other sensitive areas. In addition, they are less expensive compared with the closed-loop type. Therefore, in this paper we only focus on hybrid scrubbers.

Although similar studies have been conducted in this field (Schinas and Stefanakos, 2014;Panasiuk and Turkina, 2015;Zis et al., 2016;Gu and Wallace, 2017), few have considered operators' compliance choices under different scenarios. In addition, previous studies have mainly focused on the European and North American SECAs, with few discussing the Chinese SECA, which, while less stringent than other SECAs, has the potential to keep up with other SECAs around the world. In addition, Zis et al. (2016) found that government funding for technologies may change operators' compliance options, and the Chinese government provides subsidies to shipping companies for scrubber costs (Qin et al., 2017). Such initiatives may change the up-front cost, and the long-term benefit throughout the ship's lifetime, which may affect the adoption of a particular compliance choice. Therefore, we use a common approach to project analysis, net present value (NPV), to conduct a cost–benefit analysis of the two options of fuel-switching and hybrid scrubber installation.

The contributions of this study are as follows. First, by considering the proportion of the entire round trip that is a designated SECA (hereinafter referred to as "SECA distance"), we find that for coastal shipping activities with a large SECA distance, scrubbers are the best option. For those sailing on transcontinental shipping routes, it is preferable to select the fuel-switching option. This can help shipping companies serving different routes to select the most appropriate compliance options. Second, if the gap between ULSFO and HFO is large, it is preferable to use scrubbers. As the current supply of ULSFO is limited and its future demand is unclear, its price may increase following enforcement of the IMO sulfur cap. Therefore, those who select fuel-switching should consider this uncertainty in their decision. Third, if the scrubber cost is only half of the current cost, using scrubbers is a superior option not only considering the NPV, but also because scrubbers produce less SOx and CO_2 emissions. This highlights the necessity for governments to subsidize scrubber costs to reduce the environmental impact.

The remainder of the study is structured as follows. Section 2 reviews related studies. Section 3 describes the methodology used in this study. Section 4 presents a case study to compare the NPV and emission efficiency of compliance options under different scenarios. Finally, Section 5 concludes the paper.

2. LITERATURE REVIEW

The increasingly stringent environmental regulations in the shipping industry, and the uncertainties associated with different alternatives, complicate the decision-making process for ship operators seeking appropriate compliance measures. This indicates the need for an investment assessment tool that can take into account the flexibility and diversity of compliance options available to operators. Due to the ever-decreasing limit in sulfur emissions, existing studies have focused on policy recommendations for emission control and compliance options, especially following the implementation of SECAs. Many studies have demonstrated the impacts of SECAs on maritime transport and the environment, as well as on other shipping sectors (Chang et al., 2018;Cullinane and Bergqvist, 2014;Bergqvist et al., 2015;Ammar and Seddiek, 2017).

Recently, researchers have been active in analyzing sulfur compliance options, particularly since the IMO issued stricter SECA regulations. From the operators' perspective, Schinas and Stefanakos (2014) considered sulfur compliance options based on a multi-criteria decision-making (MCDM) method, which originated from the analytical network process (ANP). They compared technology selection between an exhaust gas cleaning system (EGCS) and a dual-fuel system, finding that the EGCS option pays off earlier than the dual-fuel system. Acciaro (2014) discussed environmental compliance choices using a real options model, and identified a trade-off between fuel price and capital expenses in vessel retrofit investment. Lindstad et al. (2015) assessed the cost of abatement options, and revealed that the optimal alternative option in meeting the sulfur limit is a function of engine size, annual fuel used within SECAs, and future fuel price difference between HFO and MGO. Brynolf et al. (2014) compared three strategies that can be used to comply with ECA regulations using life-cycle assessment: (1) HFO combined with selective catalytic reduction (SCR) and an open-loop scrubber; (2) MGO combined with SCR; and (3) LNG. They argued that none of these strategies reduces the life-cycle impact on climate change relative to HFO. Based on a broad sample from the Swedish Commercial Fleet database, Nikopoulou (2017) compared the incremental emission abatement cost of five alternatives—SCR, humid air motor, scrubber, MGO, and LNG—and found that MGO is the most expensive alternative but is easy to operate. Because the cost of compliance options depends on specific vessels and routes (Ammar and Seddiek, 2017), most extant research has used case studies (Koesler et al., 2015;Lähteenmäkiuutela et al., 2017;Panagakos et al., 2014). It has been recognized that case studies of compliance options can provide some general conclusions, which can aid operators in making decisions according to their respective situation (Nikopoulou, 2017).

In addition to case studies, many other methods have been applied to assess the various compliance options, such as linear programming (Balland et al., 2012;Schinas and Stefanakos, 2012), analytical hierarchy process ((Yang et al., 2012), life-cycle assessment (Brynolf et al., 2014), technique for order preference by similarity to ideal solution (Yang et al., 2012), and NPV (Jiang et al., 2014). Among these methods, NPV is commonly used to compare the costs and benefits of compliance options. Because investment effectiveness can only be assessed after the investment has been in place for some time, most previous studies have used the NPV method to compare different options during vessels' lifetime. For example, Schinas and Stefanakos (2014) analyzed the selection for sulfur compliance with MCDM, utilizing an NPV model in the process of financial evaluation between EGCS and dual-fuel system investment. Jiang et al. (2014) compared the benefits and costs of scrubber systems and MGO by integrating the private abatement costs of shipowners, and social benefits. They concluded that the price difference between MGO and HFO is a critical factor, and that it is better to install scrubbers on new ships compared with existing ones. Panasiuk and Turkina (2015) compared scrubbers with MGO using several financial methods, including NPV, discounted payback period, and return on investment, and concluded that the time factor has a critical impact on the evaluation of different options. Zis et al. (2016) used the payback period for emission abatement alternatives through cost–benefit analysis with NPV, and found that a lower price for low-sulfur fuel can increase its investment payback period. In addition, Gu and Wallace (2017) used NPV with mathematical programming models in cost comparisons between scrubbers and fuel-switching; their findings highlighted the importance of port call density in SECAs. Similarly, Abadie et al. (2017) argued that the scrubber option is favored by vessels with a high port call density in SECAs. Olcer and Ballini (2015) proposed a multiple attribute decision-making method, where they discussed the NPV as part of their proposed framework. Olcer and Ballini (2015) framework can be applied as a possible decision-making model for similar compliance issues encountered within other modes of transportation, such as rail, road, and maritime.

Other methods to reduce emissions in the shipping sector include cold ironing and slow steaming. Slow steaming is a method used to reduce fuel and costs, rather than to satisfy sulfur regulations (Woo and Moon, 2014;Zis et al., 2015). Woo and Moon (2014) analyzed the relationship between voyage speed and the amount of CO_2 emissions, and estimated the emission reduction via slow steaming in liner shipping. In addition, they demonstrated the relationship between voyage speed and operating cost. Zis et al. (2015) established a linear programming model to minimize fuel consumption through speed differentiation on a shipping route. They argued that ship specifications, port characteristics, oil prices, and voyage details heavily influence compliance effectiveness. Zis (2019) found, using case studies, that ship operators are motivated to use cold ironing under medium and high fuel price scenarios; however, such an approach is useful only in ports, not *en route*. In addition, Zis's (2019) study mainly compared the fuel-switching and hybrid scrubber installation options for the container liner market.

Alongside the discussion of sulfur emission abatement options, other regulations on maritime emissions have also been considered. For instance, Åström et al. (2018) examined the potential for emission and compliance cost reductions, and related benefits, following the introduction of a Nitrogen Emission Control Area (NECA). In their study, the benefits were mainly found to originate from the positive impact of emission abatement on the maritime sector, humans, crop growth, and climate. Similarly, the emission of particulate matter (PM) was measured in a potential NECA in the Port of Incheon (Chang et al., 2014). The authors also considered the nitrogen emissions at every stage of movement, from the moment of port entry to departure. However, from the perspective of operators, the economic benefits are the main focus. Therefore, to simulate operators' compliance options, the inclusion of relevant cost is critical. Thus, the current study develops a cost–benefit model that includes SECA distance, oil price difference between low and high sulfur, loading factor, and freight rate of a container route through the Chinese SECA.

In considering the cost of adopting different compliance options, most previous studies have incorporated initial investment, bunker cost, and fixed cost (Schinas and Stefanakos, 2014;Balland et al., 2015;Gu and Wallace, 2017;Antturi et al., 2016) in the shipping network. However, few have considered the effects of initial investment and government subsidies on scrubbers, and fewer still have analyzed additional fuel consumption in the operation of the scrubber system. In addition, while a vessel is installing a scrubber in the dock, it inevitably induces revenue losses. This has also been ignored in previous studies. Therefore, in this study, we also consider the revenue loss during dock time, which is an important consideration in compliance option decision-making. Meanwhile, changes in SECA distance and the price spread between low- and high-sulfur oil are examined to simulate operators' compliance decision-making.

Compared with other approaches, the NPV method is popular in relation to sulfur compliance choices because of its higher usability and applicability. Furthermore, the sulfur cap, investment year, and changing cost can be easily inserted in a cost–benefit analysis. Therefore, this study adopts the NPV method to model emission abatement options; this is explained in detail in Section 3. To the best of our knowledge, little attention has been paid to the increasingly strict regulations and various influencing factors of compliance choices. In addition, few studies have considered the effect of investment cost and government subsidies on compliance options. To sum up, this study aims to contribute to the literature in the following three ways. First, it conducts a comparative analysis between fuel-switching and hybrid scrubber installation under different scenarios based on a specific container route through the Chinese SECA. Second, it analyzes the potential compliance methods for particular vessels' retrofits based on cost–benefit analysis using the NPV method, where comparison analysis is conducted considering SECA distance, fuel price, loading factor, freight rate, and discount rate. Third, additional fuel consumption for HFO is also considered for the hybrid scrubber installation option, which has seldom been considered previously. Fourth, this study innovatively explores the effects of investment cost and government subsidies for scrubber systems on compliance option choices.

3. MODEL FORMULATION

This section explains the NPV analysis of two sulfur emission compliance options: fuel-switching and hybrid scrubber installation. The former is flexible and straightforward—a vessel can switch to low-sulfur fuel, such as MGO (0.1% sulfur content) within SECAs and use ULSFO (0.5% sulfur content) outside of SECAs. For the latter, operators can continue to use HFO anywhere after January 1, 2020. The basic assumptions of the analysis are as follows:

1) The round-trip distance for the liner service is D, with SECA distance D^{SECA}, both in nautical miles. Assume the liner service is weekly and the number of vessels in the service is N, then the required shipping speed can be written as $V_s = \frac{D}{168N-P}$, where 168 is the total number of hours in a week, and P is the port time (in hours).

2) Under the IMO 2020 global sulfur regulation, if the fuel-switching option is adopted, vessels use ULSFO outside of SECAs and MGO within SECAs for their main engine, and MGO for auxiliary engines on the whole voyage if they choose the fuel-switching option (Fan and Huang, 2019).

3) Following previous studies, fuel consumption is a cubic power of the vessel speed (Psaraftis, 2019;Psaraftis and Kontovas, 2013) and is independent of fuel type used.

4) All ships in the same service adopt the same compliance option. Although this assumption may be inconsistent with reality, it will not influence the relative comparison between compliance options on a specific route.

5) For sulfur abatement efficiency, hybrid scrubbers can reduce 97% of the sulfur in exhaust emissions, according to Zis et al. (2016) and Brynolf et al. (2014).

3.1 NPV of the compliance option

For an operator choosing compliance option $i \in [1, 2]$, where 1 is fuel-switching and 2 is scrubber, its revenue (B_i) is denoted as $B_i = 2nNVL \times FR$, where N is the number of vessels in the service and n is the number of round trips a vessel can make in a year. V is the vessel's capacity in twenty-feet equivalent unit (TEU), L the loading factor, and FR the one-way freight rate of the route ($/TEU).

The total cost in a year CT_i is the sum of the daily sailing cost in a year, cost incurred while calling at ports, and annual maintenance cost of option i. The total annual cost can be written as Eq. (1):

$$CT_i = \left(CT_{d,i} * \frac{D}{24V_S} + P(CB_{d,i}^A + CV_d)\right)n + C_i^{main} * N \tag{1}$$

where $CT_{d,i}$ is the average daily total cost of vessels for compliance option i, including the daily fuel cost of the main engine ($CB_{d,i}^M$) and auxiliary engine ($CB_{d,i}^A$), as well as the fixed cost (CV_d). C_i^{main} is the annual maintenance cost of the compliance option. If the option is fuel-switching, this cost is equal to zero.

The fuel costs of the main and auxiliary engines are calculated following Doudnikoff and Lacoste (2014), and are determined by the vessel's specifications and combustion temperature of fuel types. For the fuel-switching option, the calculation is conducted as shown in Eq. (2):

$$CB_{d,1}^M = F_0^M \frac{D^{SECA} V_S^2 C^{MGO} + (D - D^{SECA}) V_S^2 C^{\mathrm{ULSFO}}}{168 V_0^3} \tag{2}$$

where F_o^M is fuel consumption per day, and $F_0^M = (SFOC^M EL^M PS^M)\frac{24}{10^6}$, $SFOC$ is the specific fuel oil consumption of the engine (g/KWh), PS is the power of the engine, and EL is the engine load during sailing (%). The superscript expresses the main or auxiliary engine, where M indicates main engine and A implies auxiliary engine. In this study, we adopt the parameter value from Doudnikoff and Lacoste (2014) and Corbett et al. (2009), where $SFOC^M$= 206g/kWh, EL^M=0.8. C^{MGO} and C^{ULSFO}represent the price of MGO and ULSFO, respectively. V_0 is the design speed.

The fuel cost for the auxiliary engine with the fuel-switching option ($CB_{d,1}^A$) is defined as $CB_{d,1}^A = F^A \mathrm{N} C^{MGO}$, where $F^A = (SFOC^A EL^A PS^A)\frac{24}{10^6}$. We utilize $SFOC^A$=221g/kWh, EL^A=0.5 in the study.

The total daily fixed cost for all ships operating on the route is the product of the fixed daily cost of a vessel (C_v) and the number of vessels sailing in the service; namely, CV_d=C_vN. The fixed daily cost includes crew, repair and maintenance, insurance, store and lubes, administration, and capital cost.

Therefore, we have the total daily cost of the fuel-switching option ($CT_{d,1}$) as shown in Eq. (3):

$$CT_{d,1} = F_0^M \frac{D^{SECA} V_S^2 C^{MGO} + (D - D^{SECA}) V_S^2 C^{ULSFO}}{168 V_0^3} + F^A N C^{MGO} + C_v N \tag{3}$$

With regard to the daily cost of the scrubber option, the daily fuel cost of the main engine ($CB_{d,2}^M$) and the auxiliary engine ($CB_{d,2}^A$) are denoted as $CB_{d,2}^M = (1+m)F_0^M \frac{DV_S^2 C^{HFO}}{168V_0^3}$ and $CB_{d,2}^A = (1 + m)(F^A \mathrm{N} C^{HFO})$, respectively. C^{HFO} is the price of HFO and m is the additional energy consumption due to the operation of the scrubber.

Then we have the total daily cost of the scrubber option as in Eq. (4):

$$CT_{d,2} = (1+m)\left(F_0^M \frac{DV_S^2 C^{HFO}}{168 V_0^3} + F^A N C^{HFO}\right) + C_v N \tag{4}$$

Having defined the revenue and cost, the net annual benefit (π_i) is the difference between the total revenues (B_i) and the total cost during the voyage each year; namely, $\pi_i = B_i - CT_i$. Then, the NPV can be written as Eq. (5):

$$NPV^i = \sum_{t=0}^{Y-1} \frac{\pi_i}{(1+r)^t} - (CAPEX^i + C^{off-hire,i}) \quad (5)$$

where Y is the lifetime of the ship and $CAPEX^i$ and $C^{off-hire,i}$ are the initial investment cost and off-hire cost for the scrubber option. It takes 45 days on average (Jiang et al., 2014) to install the scrubbers; this time period begins immediately after making the decision to install the scrubbers. The initial investment cost and off-hire days are not considered for the fuel-switching option. If the *NPV* of fuel-switching is higher than that of the scrubber option, it is preferable to choose fuel-switching; otherwise, the scrubber system is the superior option.

3.2 Emissions of different sulfur compliance options

The average amount of CO_2 and SO_x can be calculated by multiplying their fuel consumption and emission factors. Table 1 shows the emission factors of CO_2 and SO_x, which are calculated from the third IMO greenhouse gas (GHG) study (IMO, 2014).

Table 1: Emission factors used in this study.

Fuel type	Emission factors (g/g of fuel)	
	CO_2	*SO_x*
HFO (2.7%)	3.114	0.05278662
ULSFO (<0.5%)	3.206	0.0097753
MGO (<0.1%)	3.206	0.00195506

Note: The emission factors are calculated according to the third IMO GHG study's specification (IMO, 2014).

Following Doudnikoff and Lacoste (2014), we transform daily emissions into annual emissions, which include the emissions during sailing and port calls.

The annual emissions of the fuel-switching option (E_j^1), *j=CO_2* or *SO_x*, are as in Eq. (6):

$$E_j^1 = n\left(\left(\zeta_j^{0.1\%} F_0^M \frac{D^{SECA} V_S^2}{168 V_0^3} + \zeta_j^{0.5\%} F_0^M \frac{(D - D^{SECA}) V_S^2}{168 V_0^3} + \zeta_j^{0.1\%} F^A N\right) * \frac{D}{24 V_S} + P \zeta_j^{0.1\%} F^A N\right) \quad (6)$$

where $\zeta_j^{0.1\%}$ and $\zeta_j^{0.5\%}$ are the emission factor for MGO and ULSFO, respectively.

The annual emissions of the scrubber are shown using Eqs. (7) and (8):

$$E_{co_2}^2 = n(1+m)\zeta_{co_2}^{2.7\%}\left(\frac{D}{24V_S}\left(F_0^M \frac{DV_S^2}{168V_0^3} + F^A N\right) + PF^A N\right) \quad (7)$$

$$E_{so_x}^2 = (1-0.97)\zeta_{so_x}^{2.7\%} n(1+m)\left(\left(F_0^M \frac{DV_S^2}{168V_0^3} + F^A N\right)\frac{D}{24V_S} + PF^A N\right) \quad (8)$$

where $\zeta_j^{2.7\%}$ is the emission factor for HFO and 0.97 is the sulfur reduction efficiency of the hybrid scrubber.

4. CASE STUDY

We selected a container service between Shanghai (China) and Nhava Sheva (India), which is a major route from China to the Middle East. The data for the container service were obtained from the company website and our interview, and the vessel information was taken from Clarksons Research (Clarksons, 2019). Table 2 presents detailed information on the route and ships involved in the case study.

Table 2: Characteristics of the route and container ships.

The service information	
Vessel capacity (TEU)[a]	8500
Main engine power (kW)[a]	68530
Auxiliary engine power (kW)[a]	3000
Design speed (knots) [a]	24.5
Round-trip Distance (nm)	10530
Distance in SECA of the voyage (nm)[b]	696
Ratio of SECA in the round-trip (%)[b]	6.61%
Number of trips for a vessel [d]	8
Freight rate ($/TEU)[c]	206
Average port call time at a port (h) [d]	30
Number of calls in the round trip (day) [d]	12
Number of vessels for the service [d]	6
Crew ($/day) [e]	3000
Repair and Maintenance ($/day)[e]	4035
Insurance ($/day)[e]	1390
Store and lube ($/day)[e]	3255
Administration ($/day)[e]	635
Capital cost ($/day)[e]	21068
Total: Fixed daily costs ($/day)	33383

[a] From World fleet register (Clarksons, 2019)
[b] The distance of the SECA is attained through the NETPAS software (Netpas, 2019)
[c] From UNCTAD 2018 (UNCTAD, 2018).
[d] From our interview with the shipping company.
[e] The daily cost refers to (Doudnikoff and Lacoste, 2014)

Since we focus on the operator's compliance options, the detailed port information is ignored as it will not impact the sailing distance ratio of the SECA to the round trip. The freight rate of the specific container service was obtained from the UNCTAD database.

With regard to the fuel-switching option, there is no initial investment cost and the main compliance cost results from the fuel consumption. Therefore, the price difference between high- and low-sulfur fuel is a critical element. This is quite different for the scrubber installation option, where the initial investment cost is an essential factor. However, vessels can continue to use the cheapest fuel—that is, HFO—if the scrubber is installed onboard. Referring to Lindstad et al. (2017), the initial investment cost for a hybrid scrubber is US$2.25 million, as well as US$70,000 per additional 1000 kW of engine power of the vessel. In addition, the running of the hybrid scrubber will increase the energy consumption by 1% compared with using low-sulfur fuels. Following Gu and Wallace (2017), the annual maintenance cost of a hybrid scrubber is considered to be 1% of its initial investment. Referring to Jiang et al. (2014), the hybrid scrubber lifespan of a vessel retrofit is 12.5 years, so we use 13 years in the calculation for simplification.

In this study, we compare the operator's compliance option between fuel-switching and hybrid scrubber on a specific container route using NPV analysis under the following scenarios:

1) Benchmark under the current situation;
2) Different SECA distances (D^{SECA});
3) Different prices between HFO and ULSFO (C^{ULSFO}-C^{HFO});
4) Different loading factors of the container ships (L);
5) Different freight rates of the container service (P);
6) Different discount rates of capital cost (r).

We also compare the impacts of various initial investment costs on compliance options in each scenario. We define Scrubber(Now) as the current initial investment cost; Scrubber(High) as a higher investment cost, which is 150% of the current investment cost; and Scrubber(Low) as a lower investment cost, which is 50% of the current investment cost. To reduce sulfur emissions, the Chinese government may also adopt a similar standard in its SECA to other countries (Chen et al., 2018), so the sulfur limit of 0.1% within the Chinese SECA is adopted in this study. Finally, following Clarksons Shipping Intelligence Network (SIN), the bunker prices of HFO, ULSFO, and MGO are \$420/ton, \$470/ton, and \$643/ton, respectively, as of July 2019. Except in Scenario 6, where the impacts of different discount rates are analyzed, the discount rate used in all other scenarios is 5%; this figure is commonly used in the maritime sector (Lindstad and Eskeland, 2016;Olcer and Ballini, 2015).

4.1 Benchmark

According to the information provided by the major shipping company in China, there are currently six container ships deployed on the route in question. To maintain a weekly frequency, the sailing speed V_S should be 16.25 knots. Fig. 1 illustrates the shipping route for a one-way trip, where the green section is the Chinese local SECA. The current route is designed so that the SECA distance (696nm) is relatively small compared to the whole round trip (10530nm).

Fig. 2 illustrates the NPVs of fuel-switching and hybrid scrubber options during the lifespan. It is obvious that the NPV of the hybrid scrubber option is always lower. The longer the lifespan, the smaller the NPV between the two options, due to the large discount factor for long-term benefits. In addition, we calculate their emissions using Eqs. (6)-(8): the annual CO_2 and SO_x of fuel-switching are 685,065 tons and 633 tons, respectively, while the emission volumes of the hybrid scrubber option are 672,060 and 341 tons. The former has a higher CO_2 emission because the low-sulfur fuel has a higher carbon content compared to the high-sulfur oil (see Table 1). It also has higher SO_x emissions because it only uses MGO in an SECA. Outside of an SECA, it uses ULSFO. Compared with fuel-switching, the scrubber will be used on the whole round trip, which can reduce sulfur emissions further. Therefore, although fuel-switching has a higher NPV, it also has higher CO_2 and SO_x emissions.

Fig. 1 Shipping route studied in this study.

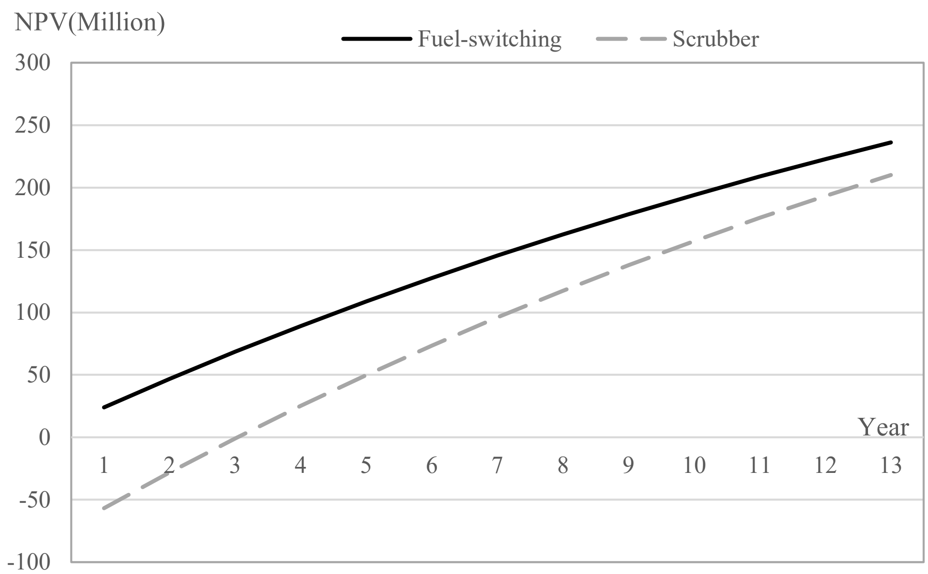

Fig. 2 NPVs under the benchmark scenario.

4.2 Scenarios for different distances in the SECA

Currently, the Chinese SECA is just 12 nm from the baseline of its territorial sea, which is narrower compared with the other SECAs, such as 200 nm in Europe and North America. Therefore, the effectiveness of the Chinese SECA in reducing sulfur emissions is a critical concern in academia and practice (Fan and Huang, 2019). Naturally, a wider SECA will make it difficult to design a route outside of the SECA. Therefore, such an initiative will be more effective in emissions reduction, but will also increase compliance costs. Thus, it is necessary to analyze the sensitivity of the compliance option under different SECA distances on the round trip. The current SECA distance is 696 nm (6.61% of the round trip) on the selected container service route. If the Chinese SECA expands, the SECA distance on the route may also increase.

Fig. 3 presents the NPVs of the two options under different ratios of SECA distance on the round trip, for three scrubber installation costs—low, now, and high—as indicated in the parentheses. The NPV of the hybrid scrubber does not change with the ratio because the SECA distance will not influence the operational cost. Therefore, these lines are horizontal. The top horizontal line is the NPV when the investment cost of the scrubber is only half the current level, which is indicated by Scrubber(Low); the middle line is based on the current scrubber cost, and the bottom line indicates the higher scrubber cost, which is 50% higher than the current level. The NPV of the fuel-switching option decreases with the SECA ratio, as it has to use more MGO.

The intersection of the lines for Scrubber(Now) and fuel-switching suggests that, based on the current scrubber cost, the scrubber system is a better option when the ratio is larger than 30%. Otherwise, the fuel-switching option is preferable. This indicates that the fuel-switching option is a superior choice for routes with a lower ratio of SECA distance. On the other hand, the fuel-switching option is more appropriate on long ocean shipping services, as most of their legs are not in SECAs.

In Fig. 3, the top horizontal line is always higher than the fuel-switching option, indicating that it is the preferred compliance option if the scrubber cost can be reduced to half of the current level. The bottom horizontal line intersects with the fuel-switching line at 70%, suggesting that it is preferable to select the fuel-switching option if the SECA ratio is less than 70%. In the extreme case, where the SECA ratio reaches 100%, which indicates that the entire global ocean has implemented a stringent emissions abatement policy similar to SECA, the scrubber system is the dominant option.

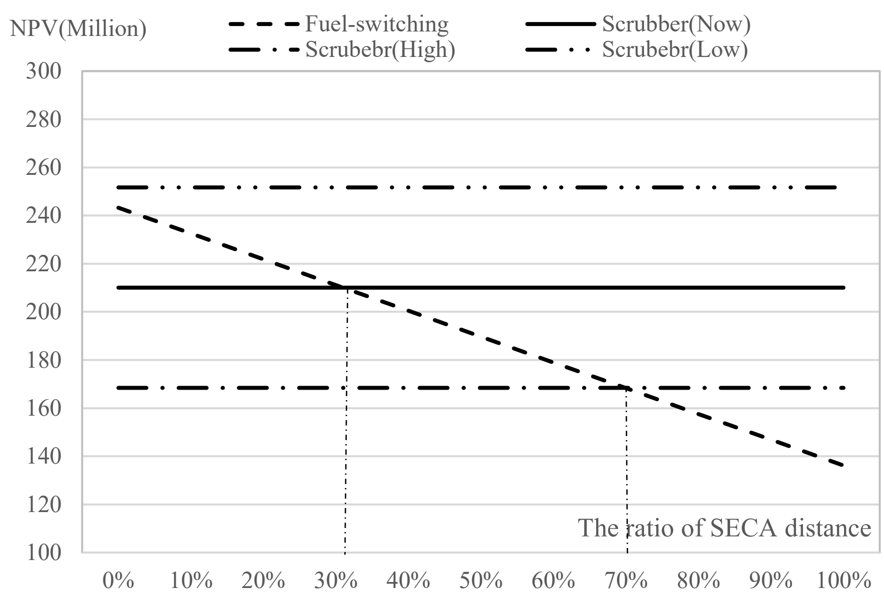

Fig. 3 Change of NPVs at different ratios of SECA distance.

The annual emissions of the two options can be calculated using Eqs. (6)–(8). For fuel-switching, the total SO_x emissions decrease from 967 tons to 452 tons when the SECA ratio changes from 0% to 100%. However, they remain at 341 tons for scrubbers. It is clear that the scrubbers have a higher sulfur abatement efficiency compared with the fuel-switching option.

4.3 Scenarios for fuel price differences

The price difference between high- and low-sulfur fuel is a critical factor, as fuel cost usually accounts for 50–60% of the total operating cost (Merien-Paul et al., 2019). Since few operators have chosen to install scrubbers, many will have to use fuel-switching when the stringent sulfur reduction policy is implemented, so the current price difference between ULSFO and HFO may increase. However, there is also an argument that with the high demand and high price of ULSFO suppliers may expand their production capacity, which may decrease its price due to economies of scale (Lindstad et al., 2015). Therefore, it is considered interesting to analyze the sensitivity of NPVs for different options with the possible change in price gaps.

Currently, the price of ULSFO is about $470/ton, while that for HFO is about $420/ton. Therefore, ULSFO costs roughly 11% more than HFO. Considering the possibilities of both narrowing and widening the price gaps, we analyze the sensitivity of NPV to a price gap ranging from 0% (no difference between ULSFO and HFO) to 50% (ULSFO is twice as expensive as HFO). The result is shown in Fig. 4, together with three horizontal lines representing the NPVs for different scrubber costs—low at the top, current cost in the middle, and high at the bottom.

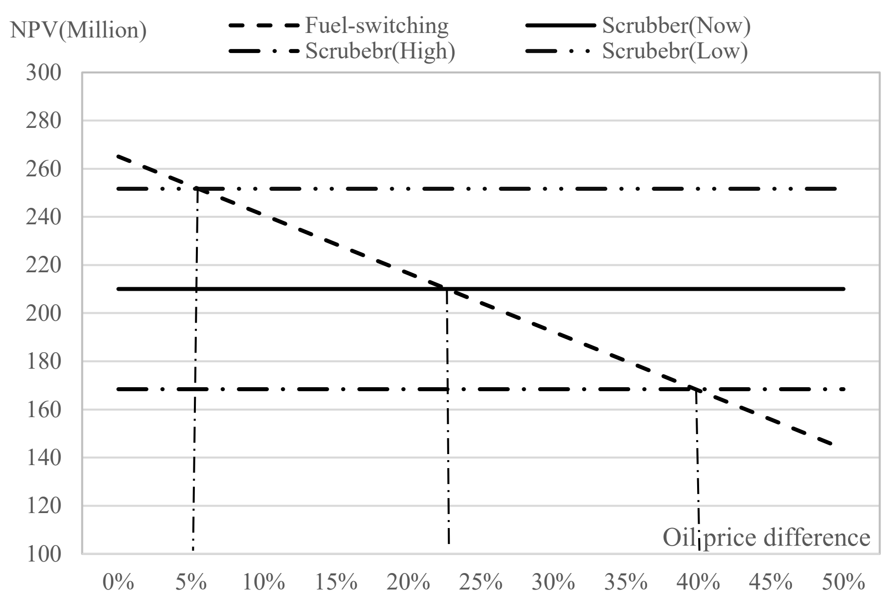

Fig. 4 NPVs for different price differences between ULSFO and HFO.

Similar to the result in Subsection 4.3, the NPV of fuel-switching continues to decrease with an increase in price gaps. Based on the current scrubber cost—Scrubber(Now)—if the oil price difference is less than 24% the NPV of the fuel-switching option is higher than that of the scrubber option. With the increase in oil price difference, the NPV of fuel-switching gradually decreases. When the price difference is larger than 24%, it is better to use scrubbers than fuel-switching.

Similarly, the choice of compliance option is sensitive to the scrubber cost. If the scrubber cost is only half of the current price (top horizontal line), when the fuel price difference is larger than 5% the scrubber option is better. However, if the scrubber cost is 50% more than the current level, fuel-switching will be a better choice as long as the fuel price difference is less than 40%. This indicates that it is better to install scrubbers if the fuel price difference is high, or when scrubber cost is low. As Merien-Paul et al. (2019) discussed, government funds for technologies deeply influence operators' abatement options. For example, funds from the European Union (Zis et al., 2016) and the Chinese government (Qin et al., 2017) for scrubber system installation have made the scrubber option more attractive.

4.4 Scenarios for different loading factors

To analyze the possible change in compliance options alongside uncertainties in shipping demand, we analyze the sensitivities of the NPVs of different options to loading factors (Lindstad et al., 2017). Fig. 5 demonstrates the NPVs of two compliance options under different loading factors, with different cost levels of scrubbers. The figure indicates that the loading factor should be higher than 65% for the shipping route to have a positive NPV.

The lines indicating the NPVs of the two options (with three lines for scrubbers) are parallel, indicating that the change in loading factors will not alter the preference order of different options. In addition, scrubbers are a better option than fuel-switching if the scrubber cost is 50% of the current level. Otherwise, fuel-switching should always be preferable. This again highlights the importance of the initial investment cost for scrubbers in the selection of compliance options. A lower initial investment cost or higher government subsidies for scrubber systems will increase operators' willingness to choose scrubber installation.

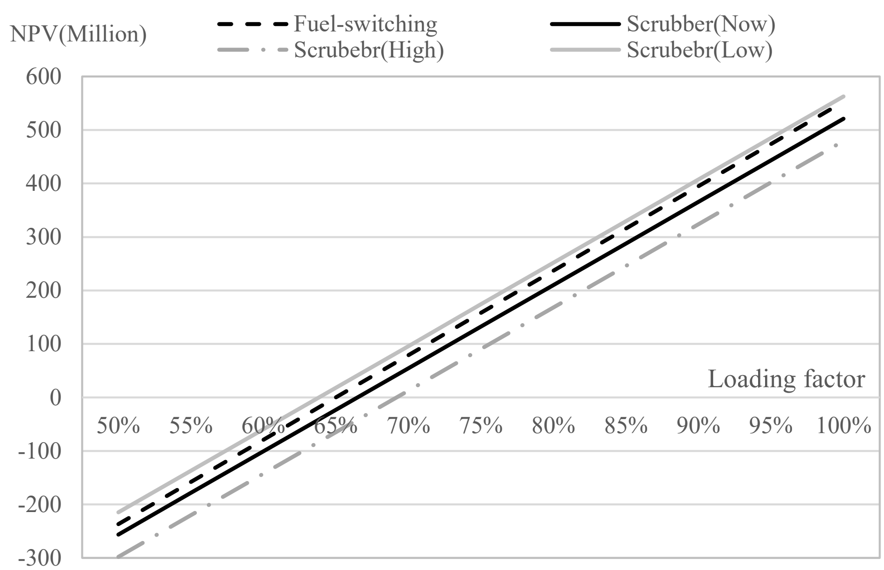

Fig. 5 NPVs for different loading factors.

4.5 Scenarios for different freight rates

The compliance choice is sensitive to the loading factor, and will also be affected by the freight rate. The current freight rates on most shipping routes are low and the future freight rate is hard to predict. To study how the freight rate can affect the selection of compliance options, we use the average freight rate on our case route to represent the market status, which is between \$140/TEU and \$240/TEU (UNCTAD, 2018).

Fig. 6 illustrates the NPVs of the two options with different freight rates. We can see that scrubbers are a better option than fuel-switching if the scrubber cost is 50% of the current level. This highlights the importance of government subsidies for the adoption of scrubbers. In addition, the figure indicates the required freight rate to make the NPVs of different compliance options positive. At the current scrubber cost the required freight is about \$170/TEU, while it is around \$163/TEU and \$179/TEU for the low and high scrubber investment costs, respectively.

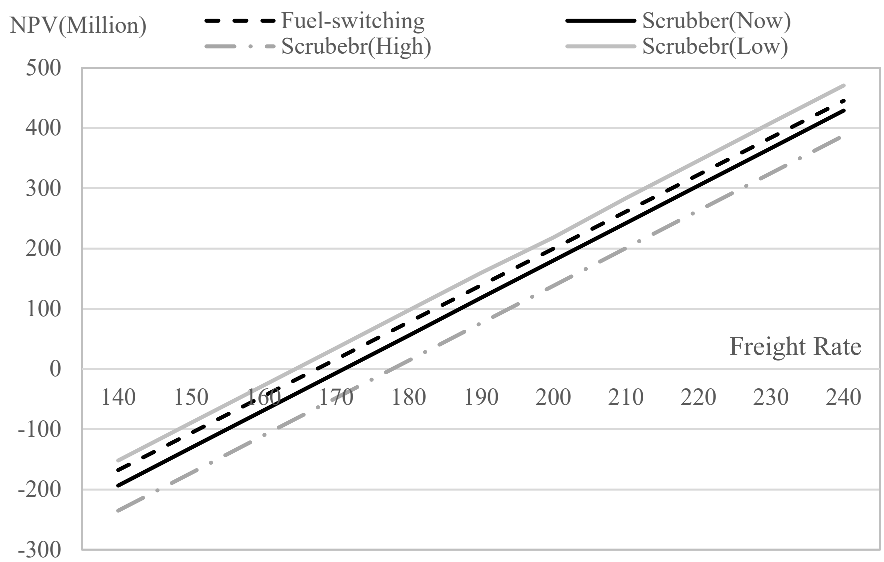

Fig. 6 NPVs for different freight rate.

4.6 Scenarios for different discount rates

The discount rate represents the decision-maker's valuation of future revenue. If one does not value future income, a high discount will be used in calculating its present value. To analyze the sensitivity of the compliance options to the discount, we use 3% as a low discount rate and 10% as a high rate (Yang et al., 2012). As mentioned in Section 3, the discount rate applied in previous scenarios is set at 5%. Hence, we compare the NPVs of the two compliance options in the benchmark scenario with the discount rates of 3%, 5%, and 10%, respectively, as reported in Fig. 7.

Since the discount rate is only used in converting future benefits to present values, it will not change the relative position of the two compliance options. Therefore, for the same discount rate the fuel-switching option is always preferable to scrubbers. Of course, if the discount rate is higher, the NPV will be lower, especially for a long evaluation period. Therefore, the NPV with a 3% discount rate is always higher than that of the other discount rates.

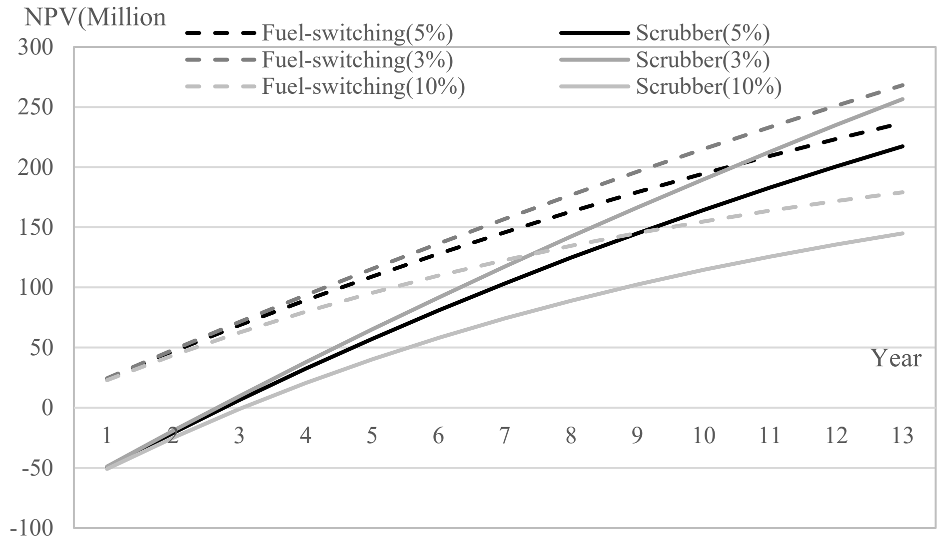

Fig.7 NPVs for different discount rate.

To sum up, the above case studies reveal the following conclusions: (1) The scrubber installation option is a better choice for shipping routes that have a large proportion of SECA areas, such as coastal shipping activities, while fuel-switching is a better option for shipping routes with shorter SECA distances, such as deep-sea shipping transportation. (2) Scrubbers are a better choice if the gap between the ULSFO and HFO price is large: based on the current investment cost, if the price gap is more than 24%, the scrubber option is preferable; otherwise, fuel-switching should be used. (3) Market conditions, such as the loading factor and freight rate, have no significant impact on compliance choices. (4) Government subsidies on the scrubber option can significantly increase the attractiveness of installing scrubbers. (5) Use of scrubbers offer superior SO_x and CO_2 emissions reduction compared with the fuel-switching option when the shipping route has a small SECA distance. (6) The discount rate will not change the relative preference for scrubber versus fuel-switching options.

5. CONCLUSIONS

Currently, the IMO is striving to reduce emissions from shipping. Therefore, emissions regulations are becoming increasingly stricter. The shipping industry, including shipowners and operators, has been under growing pressure to satisfy the more stringent environmental regulations. It is critical for these actors to choose a suitable compliance option with the least cost, so that they can remain operational in the highly competitive market. This study evaluates the NPV of compliance options for a liner shipping service that passes through the Chinese SECA. The NPVs of the fuel-switching and hybrid scrubber options are compared under different scenarios for different vessel lifespans.

Based on the current conditions for scrubber cost and the price gap between ULSFO and HFO, fuel-switching is preferred for this specific container route. However, if the route has a long SECA distance, which is very likely with tougher environmental policies in shipping, the scrubber option will be the preferred choice. This includes short-distance routes or coastal shipping, where a large proportion of the sea leg is within SECAs. For ocean shipping, where the SECA distance is only a fraction of the round trip, fuel-switching is a better choice.

The price gap between ULSFO and HFO is also a critical factor in the compliance choice. When the gap is large, the scrubber is a better choice, as it can provide savings in using HFO. Government subsidies can make scrubbers an even more attractive option. In addition, we find that scrubbers are more effective at reducing SO_x and CO_2 emissions. Finally, although our model is oriented to the liner shipping industry, a similar method can be applied to analyze compliance options in other shipping sectors, such as tankers and dry bulk shipping. This can help shipowners and ship operators in their respective decision on which option to choose in order to comply with sulfur emissions requirements.

This study has several limitations. First, for simplification, we assume the same ship speed within and outside of the SECA, however the speed differentiation could be realized using optimal shipping speed control with fuel-switching in different regions in the future. Second, the cost–benefit comparison of the compliance options assumes that the operational efficiency stays constant over the lifespan of the ship, which neglects the possible degeneration in the ship's operating parameters. Incorporating such a factor would require knowledge of the operational performance over the lifetime of the ship; future studies could include this where such information is available. Third, this paper only focuses on compliance options for the sulfur cap. Regulations on other emission types (e.g., PM, NO_x) can be discussed in future studies.

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