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Open-loop Scrubbers and Restricted Waterways: A Case Study Investigation of Travemünde Port and Increased Sulphur Emissions Immediately After the Scrubbers are Turned Off

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ABSTRACT: Open-loop sulphur scrubbers must be switched off, and the fuel must be changed to low-sulphur fuel before entering German inland waters. Immediately after the scrubbers are turned off, warm exhaust gases cause the residue left in the scrubber to vaporise, leading to the increased sulphur content of the exhaust gas. The momentary increase in sulphur emissions immediately after the open-loop scrubbers are turned off has received little attention in research. This paper presents the onboard measurement results of exhaust gases and examines the effects of sulphur compounds released into the air. In this case, the observed sulphur emission peak is problematic due to the geographical location. The ship sails to the river port, passing the coastal town of Travemünde, where the exhaust gases are released. Due to this, the emissions are more harmful when compared to emissions generated in the open seas.

1 INTRODUCTION

The Baltic Sea has been a sulphur emission control area (SECA) defined by the IMO (International Maritime Organization) for several years. Since 2015, the maximum sulphur content of fuel has been set at 0.1 %, which is still stricter than international non-SECA standards (0.5 % from 2020) [1]. In practice, shipowners have two options when operating in a sulphur emission control area: use a low-sulphur fuel (such as low sulphur marine gas or diesel oils, LNG, etc.) or install sulphur scrubbers on the ship [2,3]. In 2020, more than 400 scrubber ships were operating in the Baltic Sea and more than 3000 worldwide [4]. Many shipping companies chose to use low-sulphur fuel, but some invested in scrubbers to use cheaper, high-sulphur heavy fuel oil in their fleet. The popularity of scrubber investments strongly depends on the type of vessels and the shipowner's business model. In 2017, almost 50 % of RORO (roll-on, roll-off) vessels operating in the Baltic Sea region had scrubbers installed. This is mainly related to investment decisions, which are based on the fact that RORO/ROPAX vessels typically have permanent routes and fixed timetables. During normal operations, they do not leave the SECA area of the Baltic Sea like some other ship types, such as bulk carriers, tankers, or container ships [5].

Chemically, the operating principle of sulphur scrubbers is quite simple [6]. The sulphur compounds in the flue gases react easily with water; the sulphur binds as various compounds in the wash water and does not migrate into the atmosphere, causing acid rain and environmental damage [2,7]. The technical structures of sulphur scrubbers can be divided into two main categories [8,9]: In open-loop systems, the seawater used in the wash cycle is discharged untreated back to the sea afterwards. Closed-loop systems have a separate wash cycle, where the sulphur compounds react with sodium hydroxide. These systems do not depend on the properties of seawater (salinity, alkalinity, temperature) and thus work in low-salinity brackish or freshwater areas. The amount of wash water discharged into the sea from the closed-loop scrubbers is minimal, and the water is purified. In addition, there are hybrid scrubber models in which it is possible to change the operating mode from open loop to closed loop and vice versa. Globally, the most common scrubber type is an open-loop scrubber, but in the Baltic Sea region, closed-loop or hybrid scrubbers are common [4].

Open-loop scrubbers have sparked a debate about the possible adverse effects of discharging wash water into the sea [10-12]. The sulphur compounds in the wash water are not an actual problem, but heavy metal concentrations and PAH compounds are of particular concern [4,13]. The limit values set for wash water are presented in tables 1 and 2 [14]. There is significant discussion, especially in environmentally sensitive areas, concerning the adequacy of these values in the boundary conditions [15,16].

Table 1. Wash water limit values for acidity and turbidity

Condition	Limit
Difference in turbidity	Below 25 FNU (15 min average)
Difference in pH	Below 2 pH (difference)
Seawater pH	pH at least 6.5 measured at 4 meters from the discharge outlet

Table 2. Wash water limit values for PAH concentration

Wash water flow (t/MWh)	PAH concentration (μg/l)
<1	2250
1-2.5.0	900
2.5-5.0	450
5.0-11.25	200
11.25-22.50	100
22.50-45.00	50
45.00-95.00	25

Despite these boundary conditions (tables 1 & 2), the discharge of wash water is prohibited on German internal waterways, because there is insufficient information on the environmental effects of wash water [17]. For this reason, many other countries, such as Finland, Sweden, the United Kingdom, France, the United States and China, have also banned the use of open-loop scrubbers in certain port areas [17,18]. On ships equipped with open-loop scrubbers, this means that before entering internal waterways, the fuel must be changed to a low-sulphur variant, and the scrubbers must be switched off [18,19]. The fuel change process is carried out in advance so that it is certain that there is no more sulphurous fuel in the fuel lines before arriving at the restricted area. The actual switch-off threshold depends on the technical structure of the scrubber. If there is no flue gas bypass, the scrubber is often kept running as long as it is allowed to reduce the thermal stress inside the scrubber. Thus, the total environmental impact of scrubbers is seen as essential to reducing the environmental impact of ships.

The objective of this paper is to explore the impact of switching off open-loop scrubbers in a localised area. Taking the port of Travemünde as a case example, we examine the sulphur dioxide emissions when a ship arrives at port. The actual operational situation is the object of interest because it can reveal phenomena that do not appear in standard measurements or methods based on emission factors. In addition, studying the research problem with simulation would require quite advanced models. The studied vessel is a ROPAX-type (roll on/roll off passenger) ship equipped with open-loop scrubbers. Ships of the same type arrive at the port of Travemünde every day. The fuel is changed to low-sulphur marine gas oil before arrival, and the scrubbers are switched off when the restricted area is reached. After this, the hot exhaust gases vaporise the sulphur-containing material left in the scrubber column, causing a momentary increase in sulphur emission levels. Our measurement results show that sulphur emissions increase when the ship passes through the channel in Travemünde. Although the sulphur emissions are not large in principle, the settlement's proximity makes them more harmful than the emissions generated in the open sea. Considering the concern about the discharge of wash waters, this peak in sulphur emissions has received surprisingly little attention in the research field.

2 METHODS

The studied vessel is a ROPAX ship with four main engines (9L46D Wärtsilä, power 10,395 kW/engine). Four open-loop scrubbers (ECO-DeSOx, Ecospray technologies) are installed in the stacks of each main engine. The scrubbers were retroactively installed on the ship at the end of 2014 before the stricter SECA restrictions came into force. The scrubbers are in constant and daily use, except in the restricted areas of Germany. The scrubbers operate for approximately 60 engine hours before entering the restricted area.

The ship operates on a regular route between Finland and Germany. Measurements were conducted in both cases when the ship was in the open sea and approaching port. This paper reports only the measurements done when approaching the port. During the open sea cruise, the scrubbers worked efficiently without problems, and the emissions were within the permitted limits. Upon arrival at the port, the ship operated fully in accordance with the requirements set by legislation and regulations. Two different fuel types are used: ultra-low sulphur marine gas oil (ULS MGO) is used when the ship arrives at the port of Travemünde, but heavy fuel oil (RMG 380) is used for cruises in the open sea.

The destination port of the vessel during the measurement trip was Travemünde, located in the estuary of the Trave River (figures 1 and 2). It is one of the largest ferry ports in the Baltic Sea region; there are usually around 20-40 port calls per day (arrivals/departures). RORO/ROPAX vessels (passenger or cargo) cover 35 % of the vessels regularly calling at the port. [20]

The fuel is changed to ultra-low sulphur marine gas oil about 90 minutes before arriving at the restricted area. Changing the fuel takes approximately 40 minutes and thus ensures that the fuel has been changed before the restricted area. The scrubbers are switched off when reaching the restricted area starting in front of the breakwater of the Molenfeuer beacon. Since the scrubbers do not have exhaust gas bypass channels, the scrubbers are kept running as long as possible, even though the fuel has already been changed. This is done to reduce the thermal load on the scrubbers.

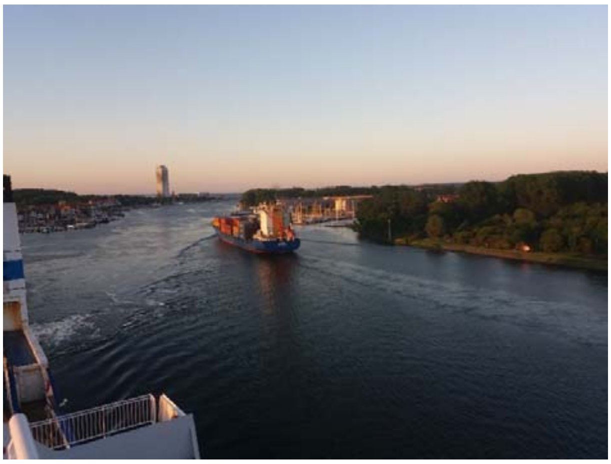

Figure 1. The port entrance channel (© Elias Altarriba)

Figure 2. Travemünde port (Source: OpenStreetMap Deutschland)

This study is based on the emission measurements conducted on the ship during normal operations when the ship arrives at port. This approach has been chosen because there are relatively few studies based on shipboard emission measurements, and actual emissions may differ from the measurements made during the ship classification process. Operational situations, such as this case, cannot be adequately modelled with emission factors or coefficients.

The portable analyser Horiba PG350 was used as the measurement device. The device was located after the scrubber in the stack. The measured emission components, measurement methods and related standards are listed in table 3 [21-25]. The temperature, humidity, and pressure of the combustion air of the engines have been estimated considering the prevailing conditions.

Table 3. Emission components, measurement methods and standards

Component	Method	Standard
NO_x	Chemiluminescence	[21] SFS-EN 14792/2017
SO_2	IR-absorption	[22] CEN/TS 17021/2017
CO	IR-absorption	[23] SFS-EN 15058/2017
CO_2	IR-absorption	[24] ISO 12039/2019
O_2	Paramagnetic	[25] SFS-EN 14789/2017

The ship's voyage data has been recorded on the L3 Valmarine APIS terminal so that the results of emission measurements can be compared with engine load and fuel consumption. In addition, the data recorded by the control system of the scrubbers has been applied to verify the moment when the system was turned off. Moreover, the analysis utilises the exhaust gas temperature data provided by the system. The data obtained from both sources, as well as from emission measurements, have been recorded at one-minute intervals. The sources of voyage data are shown in table 4.

Table 4. Variables and data sources

Variable	Source
Fuel consumption	L3 Valmarine APIS
Engine power	L3 Valmarine APIS
Fuel rack position	Ecospray control system
Temperature (inlet deSOx)	Ecospray control system
Temperature (stack)	Ecospray control system
Water flow	Ecospray control system
Scrubber on/off	Ecospray control system

3 RESULTS

This chapter presents the measurement results when the ship approaches the port of Travemünde on 13 September 2022. The measurement results are presented for a period of 70 minutes. Ultra-low sulphur marine gas oil is used as fuel throughout the entire period. At the time stamp 00:23, the scrubbers are turned off. About a few minutes after this procedure, the ship passes the Molenfeuer breakwater and travels along the channel through the town. The ship starts manoeuvring to the Skandinavienkai pier (approximately 00:50). Upon arrival at the port and channel area (after 00:20), all four main engines (ME1-4) are running. Still, in practice, ME2 and ME3 are almost idle, while ME1 and ME4 produce most of the required thrust. The power curves of the engines are illustrated in figure 3.

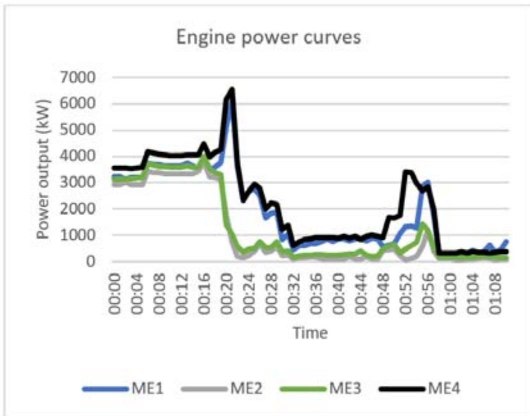

Figure 3. Main engine power curves.

The sulphur dioxide concentrations measured in the flue gas of ME4 are shown in figure 4. The curve shows a relatively rapid rise in the concentration level after the scrubbers are switched off. When using ultra-low sulphur fuel, the flue gases should not contain many sulphur compounds because the sulphur content of the fuel is about 6 mg/kg, according to the bunker delivery note. The concentration of about 2 ppm produced by the measuring device in the period of 00:00-00:27; could contain a measurement error (figure 4). The Horiba PG350 applies the IR-absorption method to measure carbon monoxide, carbon dioxide, and sulphur dioxide emissions, and especially the increase in CO concentration (in this case about 50-60 ppm) when the engine operates under partial load, often produces a slight measurement error in SO_2 concentrations [22-24]. This same problem has been observed when measuring LNG ships, where there should be no sulphur emissions at all (but CO concentrations can be 100-300 ppm, in which case the SO_2 concentration given by the measuring device can be 5-10 ppm).

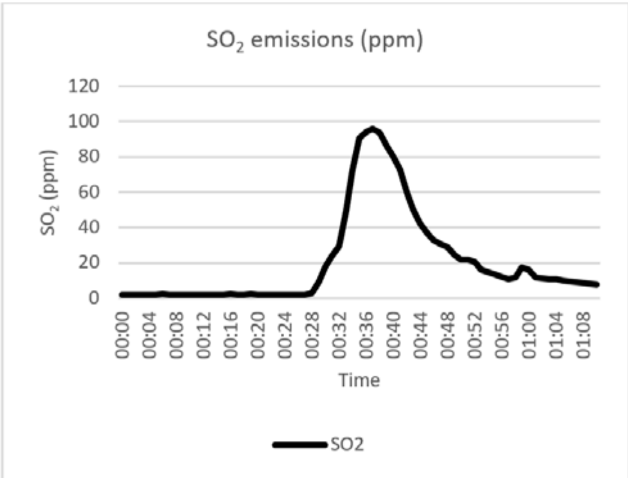

Figure 4. SO_2 emission level (ME4)

The sulphur scrubbers are switched off at 00:23, but the concentrations increase a few minutes later. There is no information available about how quickly the scrubbers turn off. The water flows are 900-1000 m^3/h, which leads to a certain delay in the system. The temperature data recorded by the scrubber system gives an indication of this. Unfortunately, the temperature sensors of the ME4 scrubber gave incorrect values. However, a similarly loaded ME1 scrubber can be used as a reference for how quickly the temperature levels rise after turning off the water circulation. A steadily rising curve indicates that the scrubber binds part of the thermal energy contained in the flue gases when the engine runs at partial load. This period is surprisingly long, about 20 minutes. No exact information is available on the condition of the temperature sensors. It is well known that the cooled, moist exhaust gas coming from the scrubber effectively smears all surfaces. If the stack temperature sensor is dirty, the values given by this sensor may be too low. In any case, when comparing the increase of the concentration curve (figure 4) with the temperature level curve (figure 5), a strong rise in concentrations is timed to the initial stage, which lasts about 10-15 minutes.

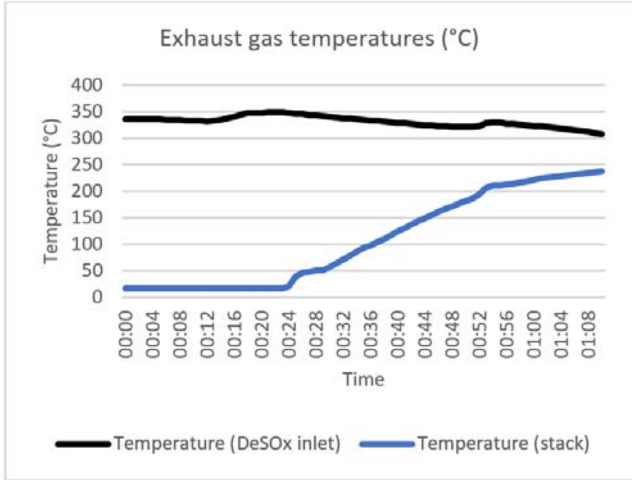

Figure 5. Exhaust gas temperature levels (ME1)

The measured sulphur dioxide emissions in relation to the fuel consumed by the engine are shown in figure 6. Relative to fuel consumption, a more reliable understanding of the development of emission levels is obtained. The concentration alone can vary considerably depending on operating and load conditions. The maximum increase was found between 00:32 and 00:48. After this, both concentrations (figure 4) and the values in relation to the consumed fuel (figure 6) settled down and approached a concentration level of 10 ppm (figure 4). As a rule of thumb, when the SO_2 concentration drops by around 10 ppm and the CO concentrations are high (125-168 ppm during the last 10 minutes), the SO_2 values should be approached with caution. However, sulphur compound emissions may still be at a higher level, even though most of the sulphur-containing material left in the scrubbers has already been vapourised.

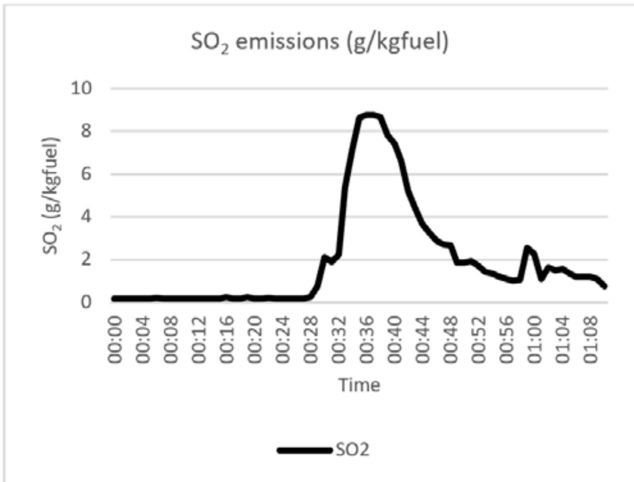

Figure 6. SO_2 emission level (ME4)

The emission measurement results presented in this paper concern only one main engine (ME4). As shown in figure 3, the load conditions of the engines vary upon arrival at the port. Each is equipped with a separate scrubber, and the amount of exhaust gases affects the heating time and the vaporisation of sulphur-containing material. This issue still requires further measurements, but another measurement session performed on 3 May 2022 in the same ship and port will provide us with more data.

Unfortunately, due to technical problems, no engine data is available from that period, but figure 7 shows the SO_2 concentrations (ppm) of main engines ME1 and ME2. The manoeuvring method has been quite similar, whereby ME1 is more heavily loaded while ME2 is idling. Figure 7 shows how SO_2 concentrations rise quickly when the scrubber is switched off. The shape of the curve is very similar compared to the curves in figures 4 and 6. Otherwise, when the ME2 is idling, less exhaust thermal energy is available to heat the scrubber, so concentration levels increase more slowly. On the other hand, vaporisation continues longer. The temperature of the exhaust gas, the chemical composition of the deposit, and the rate of heat increase could influence the phenomenon.

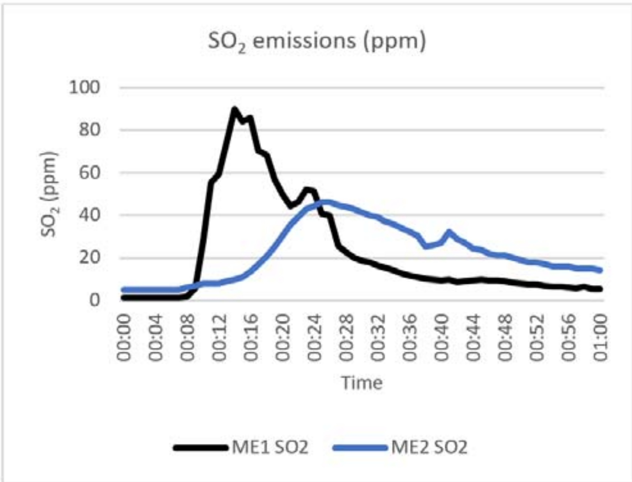

Figure 7. SO_2 emission level (ME1 and ME2)

The measurements presented in this study are insufficient to accurately calculate the total amount of sulphur dioxide released into the air. At that time, all four engines should be measured simultaneously, for which our measuring device is insufficient. However, the amount can be estimated as follows. When the cumulative sulphur dioxide emission of the ME4 (after the time stamp 00:23) until the end of the measurement period is calculated in relation to the fuel consumption, the total amount of released sulphur dioxide is 862 g. The ME1 has been run with a similar load profile, so the amount of sulphur dioxide emissions can be estimated at the same level. It is more difficult to estimate the emission levels of the idling ME2 and ME3 without complete measurements. As shown in figure 7, the idling engine heats up the scrubber slowly, so the emission peak is not as sharp but lasts longer. In addition, this peak is not directly caused by the engine running but by the vaporisation of the sulphur compounds left in the scrubber. Since all main engines and scrubbers are operational when the ship is at sea, the scrubbers of idling engines can also be estimated to be equally dirty compared to the scrubbers of ME1 and ME4. Suppose it is estimated that scrubbers of ME2 and ME3 engines release approximately 50 % of the sulphur emissions compared to the level caused by ME1 and ME4. In that case, a total of 2500 g of sulphur dioxide emissions were produced by a ship arriving at the port. If more sulphur dioxide is released from the scrubbers of idling engines, the total amount will naturally increase. The assessment of the harmful effects of this is significantly influenced by the immediate proximity of the settlement, as in the open sea, these numbers would not be a matter of concern.

4 DISCUSSION AND CONCLUSIONS

The Baltic Sea is a SECA area where the maximum sulphur content of the fuel is set very low (0.1 %). When the restrictions came into force in 2015, there was much discussion about the most economical and environmentally friendly option to implement the new restrictions; low-sulphur fuel or different scrubbers [26,27]. Later, concern also arose about the effects of discharge water from the open-loop scrubber on the marine environment [11,12]. However, this was hardly discussed when scrubber investments were topical, nor has much thought been given to the sulphur emission peaks presented in this article.

In this study, with the help of experiments carried out onboard, it has been possible to monitor the vessel's air emissions, particularly sulphur dioxide, when reaching the open-loop scrubber ban area. This paper presents the momentary increase in the sulphur content of exhaust gases when the sulphur scrubbers are switched off. Our measurements showed that the SO_2 emission levels were very low apart from the observed peaks. The momentary increase is likely due to the vaporisation of sulphur-containing material left in the scrubber under the influence of hot exhaust gases. The same phenomenon could be detected in two different measurement sessions, and there are also previous observations of the problem [15]. This evaporation is a short-term phenomenon. When on the open sea, it is hardly significant, considering the total emission levels of the ship. For example, according to Jalkanen et al. [16], in 2020, the total amount of SOx emissions from ships operating in the Baltic Sea was 8.3 thousand tons.

However, in this case, the ship does not voyage in the open sea but in the immediate vicinity of a settlement. This makes assessing the harmfulness of emissions more challenging. It is generally known that SO_2 emissions cause adverse environmental effects, such as acidification. SO_2 can also affect particle matter (PM) emission; PM emission can be created by secondary formation from precursor emissions, such as SO_2. The health risks of air pollution are largely caused by particles, such as immunological and toxic effects in the lungs, increased cardiovascular system diseases and mortality. For example, Ytreberg et al. [28] have evaluated that the damage costs for SO_2 are 4,000–19, 000 €2010/$t_{emission}$ in the Baltic Sea region. According to Matthey and Bünger [29], the average health damage cost of SO_2 due to emissions from an unknown source is 13,600 in €2016/$t_{emission}$ in Germany. The corresponding values for PM2.5 emissions are 6,000 – 30,000 €2010/$t_{emission}$ [28] and 58,400 €2016/$t_{emission}$ [29]. However, our measurements did not include PM, so we do not know if the phenomenon affected, for example, the chemical composition of the particles. Nor is there much information in the literature about the phenomenon's effects on PM measurements. Teinilä et al. [15] found that the increase in temperature in the port operation of the scrubber increased the organic matter of PM. In this case, this research problem is further complicated by the chosen scale. Will the issue be considered at a general level or from the point of view of the health of residents of the town? Or should this research problem be generalised to all port cities in a similar position?

When assessing adverse effects, the amount of ship traffic, which produces sulphur emission peaks when arriving at the port, must be considered. In this study, a broader review has not been carried out, but similar ships are known to arrive at the port every day. On the other hand, it is known that pure open-loop scrubbers are in the minority in the Baltic Sea region: According to Ytreberg et al. [4], 83 % of the Baltic Sea scrubber fleet can switch to a closed-loop mode. The closed-loop scrubbers can be used in a restricted area, eliminating the sulphur peak problem. The issue would also be resolved if the open-loop scrubber had an exhaust gas bypass channel.

A ban on open-loop scrubbers has been proposed, but in the Baltic Sea region, this has only applied to internal waterways in Germany. In Sweden, a discussion has started about banning open-loop scrubbers in internal waterways after the Swedish Transport Agency and the Swedish Agency for Marine and Water Management proposed it [18,30]. Thus, it is good to consider whether the internal waterway ban is sufficient or whether it should be implemented more widely. Often in environmental protection, a ban can lead to new problems, and the effects must be evaluated extensively. For example, this peak of sulphur dioxide emissions immediately upon arrival at port is due to the restriction of open-loop scrubbers. If a similar regulation is introduced more widely, but only for internal waterways, will such unnecessary sulphur dioxide peaks also increase in other ports? On the other hand, if open-loop scrubbers are completely banned, the problem is solved.

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