Ship pollution promotion – the strong economic incentives of scrubbers

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Abstract

In response to stricter regulations on ship air emissions, many shipowners have installed exhaust gas cleaning systems, known as scrubbers, allowing for use of cheap residual heavy fuel oil. Scrubbers produce large volumes of acidic and polluted water that is discharged to the sea. Due to environmental concerns, the ban of scrubbers has been discussed within the International Maritime Organization. Real-world simulations of global scrubber-vessel activity, applying actual fuel costs and expenses related to scrubber operations show that 51% of the global scrubber-fitted fleet reached economic break-even by the end of 2022, with a surplus of 4.7 billion €. Within five years after installation, more than 95% of the ships with most common scrubber systems reach break-even. However, the marine ecotoxicity damage cost, from scrubber water discharge in the Baltic Sea Area 2014–2022, amounts to > 680 million €, showing that private economic interests come at the expense of marine environmental damage.

1. Introduction

Since the mid 1900's, the marine bunker fuel market has been dominated by residual fuels, i.e., heavy fuel oils (HFO), due to their low price and high energy content [1]. HFO is a residual, sulphur containing, product and during combustion the sulphur content of the fuel content will be proportional to the emissions of sulphur oxides (SO\textsubscript{X}) and particulate matter (PM) to the atmosphere. Therefore, as of January 2020, the International Maritime Organization (IMO) implemented stricter global regulations regarding the sulphur content of marine fuels, from a maximum 3.5–0.5%, with the goal to reduce the negative impacts of ship-derived SO\textsubscript{X} and PM on air quality (MARPOL Annex VI [2]). Even stricter regulations apply for ships operating in designated sulphur emission control areas (SECA), where a maximum sulphur content of 0.1% is allowed. To meet sulphur regulations, most ships have switched to the more expensive low sulphur fuels such as distillate fuels, e.g. Marine Gas Oil (MGO), or hybrid fuels, e.g. Very Low Sulphur Fuel Oils (VLSFO). Another option is to install exhaust gas treatment systems (EGCS), also known as scrubbers, and continue to use the less expensive HFO with high sulphur content while still being compliant with the IMO regulations. Globally, scrubbers have been installed on more than 5000 ships [3] and HFO still amounts to approximately 25% of the total marine bunker fuel demand and is forecasted to continue to do so in the next coming years [4].

In the most common scrubber setup, the open loop, the exhaust gas is led through a fine spray of sea water inside the scrubber. The SO\textsubscript{X} in the exhaust gas readily dissolves and reacts with the alkaline water forming sulphuric acid. The process implies an hourly production and discharge of hundreds of cubic metres of acidic (pH ≈ 3–4) and polluted (containing e.g. metals, polycyclic aromatic hydrocarbons (PAHs)) scrubber water, which can also have elevated nitrate concentrations due to scavenging of combustion products, i.e. nitrogen oxides (NO\textsubscript{X}) [5–7]. The process is similar for closed loop system (< 2% of market share) but the water is recirculated and SO\textsubscript{X} uptake is ensured by the addition of a strong base (e.g. NaOH), resulting in smaller volumes being discharged (on average 0.45 m\textsuperscript{3}/MWh) [8, 9]. Hybrid systems are scrubbers that can operate in both open and closed loop mode. An average scrubber water discharge flow rate of approximately 90 m\textsuperscript{3}/MWh has been reported for open loop systems, although the highest reported volumes are 140 m\textsuperscript{3}/MWh [9, 10]. On a global scale, based on pre-pandemic ship traffic patterns and scrubber installations at the end of 2020, the estimated total discharge volume from open loop scrubbers is approximately 10 billion m\textsuperscript{3} per year [11].

Several studies have shown scrubber water to have adverse effects on marine organisms, including reduced growth and increased mortality of zooplankton and potential eutrophication effects on phytoplankton [12–16]. The emissions of metals and PAHs from ships running on HFO, with or without a scrubber, are substantially higher than compared to ships using MGO as fuel [17]. In addition, a recent study showed ships equipped with scrubbers to account for up to 8.5% of the total input of certain PAHs to the Baltic Sea [18] and that the discharge of scrubber water substantially increases the environmental risk associated with the release of metals and PAHs in port environments [19].

The necessity of guidelines for environmental risk and impact assessment of discharge water from scrubbers was acknowledged already in 1998 at the 41st meeting of the Marine Environment Protection Committee (MEPC), a senior...
technical body of marine pollution issues within the IMO. Since then, many Member States have commissioned research and literature reviews of the potential impact of scrubbers on the marine environment. During the 78th MEPC meeting (June 2022), new guidelines on how to assess risk and impact from scrubber water discharge were approved [20]. The guidelines provide recommendations for risk and impact assessments that Member States can use as support when considering local or regional regulations to protect the sensitive waters/environment from the discharge of scrubber water. Although the proposed risk assessment approach appears not to provide sufficient protection for port environments [19], the impact assessment described in section 7.4 of the guidelines stipulates that the adoption of restrictions or a ban on discharge water from scrubbers should be considered in areas where any of four indicative criteria are fulfilled. The first criterion is

7.4.1 environmental objectives in the areas are not met, e.g. good chemical status, good ecological status or good environmental status are not achieved under applicable legislation;

The three additional criteria are defined with respect to general deterioration of the environment and increased environmental risk, conflicts with conventions and regulations for marine environmental protection and the cost of management of dredged materials in ports [20].

In Europe, marine environmental objectives, mentioned in indicative criteria 7.4.1, are defined by the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) which aims to achieve Good Environmental Status (GES) in all of the European marine waters. The first overall marine environmental status was reported by EU Member States in 2018 (Fig. 1) (data compiled from the platform WISE-Marine [21]). When all MSFD descriptors (11 in total) are aggregated, all but six sea basins fail to reach GES (a summary of the status assessment per descriptor and criteria is shown in Supplementary Information A). As global maritime traffic is forecast to increase somewhere between 240–1200% by 2050 as compared to 2014 levels [22], the pressure on the marine environment is likely to increase. At the same time, most of the marine ecosystems are facing increased cumulative impacts where shipping is identified as one of the main stressors [23].

Restrictions or bans on open loop scrubber water discharge are already adopted in individual ports, inland waters or in territorial waters (e.g., Port of Antwerp, Germany Inland water, Singapore [24]) and during the 79th MEPC meeting (November 2022), the use of scrubbers as an appropriate means of compliance (i.e., Equivalents) was questioned [25, 26]. While support for restricting the use of scrubbers exists, there are concerns regarding the (economic) “uncertainty for the industry, which has in good faith invested in EGCS technology in accordance with the provisions of MARPOL Annex VI”[26]. The wide-scale use of scrubbers will also imply costs related to the degradation of the marine environment, and the cost of not restricting scrubbers has been raised as an important aspect that should be factored in the decision-making process [27].

The overall aim of this study was therefore to investigate several aspects connected to the potential restriction of scrubber water discharge, and more specifically to i) estimate to what extent the global scrubber fleet has reached economic break-even on their scrubber installations, and the potential monetary gain of using HFO as compared to the more expensive MGO or VLSFO, and ii) to assess external costs of not restricting scrubber water discharge by determining societal damage costs connected to marine ecotoxicity, i.e. deterioration of the marine environment, resulting from discharge of scrubber water.

The analyses are based on nine years of real-world simulations of global vessel activity (2014–2022) from the Ship Traffic Emissions Assessment Model (STEAM), version 4.3.0 [28 and references therein]. STEAM combines ship location data from automatic identification systems (AIS), fleet technical description, and ship specific modelling of energy consumption, and compute emissions to the atmosphere and direct discharges to the marine environment. The output from STEAM is combined with high resolution fuel price differences from Ship&Bunker (https://shipandbunker.com/) to calculate the annual balance from the time the scrubbers were installed until the end of 2022. A selection of the scrubber fleet, operating within the Baltic Sea Area, is further assessed with respect to societal damage cost as an example of the cost of not restricting scrubber water discharge. The societal damage cost associated to marine ecotoxicity from scrubber water discharge is estimated by combining results from previous willingness-to-pay (WTP) studies [29, 30] with calculated toxicity potentials (from ReCiPe characterization factors [31]) of open and closed loop scrubber water.
2. Results

A total of 3818 unique ships were included in the study, of which 3283 ships (86%) are equipped with open loop, 502 ships (13%) with hybrid and 28 ships (1%) with closed loop scrubber systems. Most of the scrubber installations (onboard over 2000 ships) are registered between December 2019 and December 2020. The scrubber fleet included in this study is dominated by the ship categories bulk carriers (36%), container vessels (22%), crude oil and product tankers (26%) and cruise ships (4%) and > 90% of the studied scrubber fleet belong to the Medium (6000–15000 kW installed engine power) and Large (>15000 kW installed engine power) size category.

2.1. Economic break-even assessment of the global scrubber fleet

In total, the global scrubber fleet has a surplus of 4.7 billion €\textsubscript{2019} by installing scrubbers and using HFO instead of MGO (in SECA) or VLSFO (outside SECA since 2020) (Median balance scenario in Table 1). For the median balance scenario, 51% of the scrubber fleet (1981 ships) has reached break-even with a summarised positive balance of 7.6 billion €\textsubscript{2019} by the end of 2022. The ships that have not reached break-even (in total 1869 ships, corresponding to 49%) have a summarised negative balance of 2.9 billion €\textsubscript{2019}. The total monetary savings from using HFO instead of more expensive fuel amounts to 18 billion €\textsubscript{2019}. The Min Balance scenario (high costs and low fuel price difference) and the Max Balance scenario (low costs and high fuel price difference) represent the extremes of realistic favourable (Max) and unfavourable (Min) conditions from the shipowner perspective.

Table 1

<table>
<thead>
<tr>
<th>Balance Scenario</th>
<th>Reached break-even</th>
<th>Not reached break-even</th>
<th>Sum all ships</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Median</strong></td>
<td>Number of ships (%)</td>
<td>1918 (51%)</td>
<td>1869 (49%)</td>
</tr>
<tr>
<td></td>
<td>Sum balance (billion €\textsubscript{2019})</td>
<td>7.6</td>
<td>-2.9</td>
</tr>
<tr>
<td></td>
<td>Savings on fuel (billion €\textsubscript{2019})</td>
<td>14</td>
<td>4.1</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>Number of ships (%)</td>
<td>395 (10%)</td>
<td>3392 (90%)</td>
</tr>
<tr>
<td></td>
<td>Sum balance (billion €\textsubscript{2019})</td>
<td>2.5</td>
<td>-14</td>
</tr>
<tr>
<td></td>
<td>Savings on fuel (billion €\textsubscript{2019})</td>
<td>4.5</td>
<td>7.9</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>Number of ships (%)</td>
<td>3467 (92%)</td>
<td>320 (8%)</td>
</tr>
<tr>
<td></td>
<td>Sum balance (billion €\textsubscript{2019})</td>
<td>22</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>Savings on fuel (billion €\textsubscript{2019})</td>
<td>28</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Within five years from the installation, more than 95% of the open loop systems have reached break-even, after which the monetary gain from fuel savings will contribute to the surplus (Fig. 2). The distribution between vessels that have and have not reached break-even within a certain number of years after the scrubber installation shows that the payback time differs between the three scrubber systems. Although it takes longer for the hybrid fleet to reach point of break-even, there is a larger fraction compared to the open loop scrubber fleet that have reached break-even already after one and two years. This can partly be explained by the year of installation as well as fuel consumption, where higher fuel consumption and fuel price difference will result in faster payback times. On the contrary, the longer payback times of hybrid and closed loop scrubbers can be explained by higher investment and operational costs and, for some vessels, lower annual fuel consumption due to smaller engines. In addition, the number of ships included in the analysis vary depending on scrubber type (Fig. 2) and over
the years from investment as not every ship has had their scrubbers installed for 9 years or more (Supplementary Information B Table S.5).

Grouping all vessels that had their open loop scrubbers installed between December 2019-December 2020 (n = 1835), it can be expected that 50% of these vessels reached the point of break-even 2.5 years after the investment (Fig. 3). The initial balance, i.e. the cost of investment, varies between 2.1 to 5.1 million €2019, with the average being 3.1 million €2019, showing good agreement between the 2020-group and the entire open loop scrubber fleet (Supplementary Information B Fig. S.2 and Table S.3). The small balance change between the start of 2020 and the start of 2021 can be attributed the relatively small price difference between HFO and low sulphur fuels during this period (Fig. 4B). At the end of 2022, the variability within the selection of the fleet has increased and the large spread in balance (from −1.8 to 6.4 million €2019) can be explained by the large fuel price difference during 2022, where ships with high fuel consumption would increase their balance substantially. By the end of 2022, in the Median Balance scenario, 953 (52%) of the 1835 open loop scrubber fleet group that installed their scrubbers in 2020 had passed their break-even point and the surplus is almost 1.5 billion €2019. The positive balance of the fleet that have reached break-even (2.2 billion €2019) is almost three times higher than the corresponding negative balance of the 900 ships that have not reached payback (-0.8 billion €2019). The two other scenarios in Fig. 3 show that in the Max Balance scenario, all but 47 ships have reached break-even (nearly 50% did so within the first year) and the average surplus amounts to 9 billion €2019. For the Min Balance scenario, the installation costs are higher (4.1–9.2 million €2019) and the low fuel price difference result in a slow increase of the balance and only 89 ships have reached break-even by the end of 2022.

2.2. The cost of not restricting scrubbers – A Baltic Sea case study

Between 2014–2022, the number of ships equipped with scrubbers in the Baltic Sea Area has increased with a peak of 957 ships in 2020 (Fig. 5A). In 2022, there were 804 unique vessels that operated with scrubbers in the area. The growing scrubber fleet within the Baltic Sea has paradoxically resulted in an increased HFO consumption in this designated SECA. Since the designation in 2015, 9.6 million tonnes of HFO have been used and 3.2 billion m³ of open loop scrubber water plus 0.4 million m³ of closed loop scrubber have been discharged within the area. Most of the contribution (80%) has happened since 2019.

By combining WTP studies with toxicity potentials of scrubber water, the average societal damage cost, limited to marine ecotoxicity from open loop scrubber water discharge, amounts to 0.21 ± 0.07 €2019/m³. The cumulative societal damage cost, by not restricting scrubbers in the Baltic Sea Area since the implementation of SECA in 2015, amounts to 680 million €2019 (Fig. 5B). From the private perspective, the shipowners have saved more than 1.7 billion €2019, by not switching to the more expensive but less polluting MGO when operating in the Baltic Sea Area.

3. Discussion

Our assessment, comprising over 3000 individual ships equipped with scrubbers between 2014–2022, shows the strong economic incentives of installing scrubbers. Although the number of ships that have not reached their break-even point constitute almost 50% of the scrubber fleet, the balance calculations show that the positive balance is more than twice as high as the corresponding negative balance, resulting in a surplus of 4.7 billion €2019 by the end of 2022. The same trend is valid for the selection of the fleet that installed their scrubbers in 2020 (Fig. 3) as it appears that 50% of the fleet had reached break-even after 2.5 years, coinciding well with Fig. 2. During 2023, the fuel price difference has fluctuated but remained high as compared to the annual statistics from 2014–2022 (Fig. 4). For MGO/HFO, the fuel price difference between January and August 2023 range between 280–600 USD/tonne fuel, while the VLSFO/HFO fuel price difference is lower and ranges between 70–240 USD/tonne fuel (https://shipandbunker.com/). This suggest that many more ships will have reached their break-even point by the end of 2023 and the surplus to be even higher. Assuming that the fuel consumption for 2023 is equal to the 2022 fuel consumption, and that the fuel price difference is 100 (for VLSFO/HFO) or 400 (for MGO/HFO) €2019/tonne fuel, an additional 500–1400 ships would have reached break-even by the end of 2023, resulting in a total of 63–86% of the entire scrubber fleet to have reached break-even. Although the results from the balance calculations might not be absolute for each vessel, this study presents realistic conservative estimates of the scrubber fleet on a global level. For example, the three
scenarios represent different economic conditions and can capture some of the market variability where the Max and Min Balance scenarios are representing best- and worst-case scenarios from the shipowner perspective. Given the economic incentives of installing scrubbers and the competitiveness of the maritime sector, it is reasonable to assume that the Max Balance scenario is more likely than the Min Balance scenario for most ships. If so, the time to reach break-even would be even shorter than assumed in the Median balance scenario and the 2022 surplus of the scrubber fleet higher than 4.7 billion €. Our results show that the majority of the fleet (>51%) already had reached break-even by the end of 2022 and are now having an economic advantage due to the lower fuel costs as compared to running their ships on the more expensive low sulphur fuels.

Due to the lack of integrated global marine status assessments that incorporate economic and social aspects [32], the cost of not restricting scrubber water discharge was limited to the Baltic Sea Area and includes only the aspect of marine ecotoxicity damage cost based on WTP studies [9, 29, 30]. On a Baltic Sea level, the monetary gain of the scrubber fleet, by not switching to more expensive fuels, could be put in relation to the societal damage cost that their choice of installing scrubbers have on the marine environment. The use of scrubbers, i.e., a continued use of HFO, will allow ships to run on fuels with higher metal and PAH content [17] than was allowed prior to the global sulphur cap, resulting in a higher net load of metals and PAHs entering the marine environment [18]. The discharge of scrubber water has been shown to result in adverse effects in marine organisms [12–16] and is in direct conflict with the sustainable development goal 14 and especially target 14.1 stating that we shall “...prevent and significantly reduce marine pollution of all kinds...” [33]. Although the external costs in this Baltic Sea case study only include marine ecotoxicity limited to a few selected contaminants, the cumulative damage cost from 2015 to 2022 is substantial (≈ 700 million €).

The estimated societal damage cost of this study is meant to show an added cost due to scrubber water discharge and should not be interpreted as a full damage cost analysis. In a previous Baltic Sea case study focusing on external costs in 2018 [9], when there were less than 200 vessels equipped with a scrubber operating in the Baltic Sea Area, the damage cost of marine ecotoxicity due to scrubber water discharge constituted approximately 1% of the total damage cost of the impact categories marine ecotoxicity, marine eutrophication, reduced air quality and climate change. When compared to the highest annual damage cost due to marine ecotoxicity listed in Fig. 5 (= 210 million € in 2020), leaving all other damage costs from Ytreberg et al. (2021) unchanged, the scrubber water discharge contribution increases and instead constitute 6% of the summarised damage cost (2.9 billion €=3.3 billion €).

The Baltic Sea case study shows that the cost of not restricting scrubber water discharge can be substantial. The installation of scrubbers has resulted in increased HFO consumption in this fragile sea area, classified as particularly sensitive by IMO [34], where it has been determined that contaminant loads must be reduced [35]. With the implementation of a Mediterranean SECA in 2025, there is a risk that a larger fraction of the scrubber fleet will be operating within the Mediterranean Sea as the price difference between HFO and MGO remains high. Learning from the Baltic Sea case study, this could imply higher HFO consumption in the area and an overall increased pressure on the marine environment with added societal damage cost with respect to the marine environment.

Further, scrubbers enable a continued use of fossil fuels, hampering the transition to a sustainable transport system. In addition, the water needed for the scrubbing process requires more energy for pumps etc., resulting in higher fuel consumption, i.e., higher CO₂ emissions, per travelled distance. A previous study also suggested that shipowners are economically encouraged to increase the operating speed on a ship with scrubber as compared to one without [36]. The increased speed will raise the CO₂ emissions, because of the cubic dependence of speed and engine power (fuel consumption). Higher CO₂ emissions is both in conflict with sustainable development goal 13 [33], and directly opposes the ambitions set by the IMO, for greenhouse gases from international shipping to reach (close to) net zero by 2050 [37]. Another aspect of scrubber water discharge includes strong acid addition to the sea, which can have significant effects in areas of high shipping intensity, reducing the seawater buffer capacity, i.e. reducing the uptake of CO₂, and affecting marine life [38].
To conclude, our results show a strong economic incentive to install scrubbers, which in combination with an increasing number of scientific studies showing adverse effects on marine organisms [12–16], contradicts the claims of shipowners acting in good faith stated during the 79th MEPC meeting Agenda item 15 [26].

4. Methodology

To assess the use of scrubbers, two different perspectives were analysed with respect to costs and environmental damage:

1. The investor, i.e. the shipowner, perspective: Calculating the break-even time of ship-specific scrubber installations of the global scrubber fleet based on installation cost, annual operational costs and monetary gain by using HFO instead of MGO (inside SECA) or VLSFO (outside of SECA).
2. The socio-economical perspective: as a Baltic Sea Area case study, assess the cost of not restricting scrubber water discharge by estimating the damage costs due to marine ecotoxicity of metals and PAHs from scrubber water discharge.

All costs (€) have been indexed to 2019 (€2019) according to OECD complete database of Consumer Price Indices (CPIs) for comparison (https://stats.oecd.org/).

4.1. Calculating payback time after scrubber installation

The Ship Traffic Emissions Assessment Model STEAM [28 and references therein], version 4.3.0, was used to estimate ship specific annual energy and main engine load, fuel consumption, amount of scrubber discharge water, amount of energy consumed for scrubber usage and kilometres travelled in different sea areas. The data was provided for each individual ship using Automatic Identification System (AIS), mandatory for ships > 300GT [39], between 2014–2022. These data were provided by Orbcomm Ltd and included position reports from both terrestrial and satellite AIS networks. Technical description of the global fleet, which enables STEAM modelling at vessel level, were obtained from SP Global. From all data, those ships that had registered a certificate of approval of scrubber installation within the timeframe (2014–2022) were selected for further analysis (maximum of 3922 ships in 2022). STEAM identifies ships based on IMO numbers, registry numbers that remain with the vessel from construction to scrapping, and MMSI codes, which is the Maritime Mobile Service Identity number of the ship’s radio system, but the output data was anonymized by creating an artificial but unique Id-number for each ship.

Annual balance was calculated for each unique ship by accounting for investment cost, as starting conditions, and annual operational costs and monetary savings on fuels from using HFO instead of MGO or VLSFO (Fig. 6). Each ship was modelled from the date of installation until the end of 2022 (see example of ship with open loop scrubber in Fig. 6). The date of installation was given as year and months in STEAM based on the ship specific class certificate letter stating the date of approval to operate the scrubber.

The investment cost per kilowatt (€2019/kW, Fig. 4A) for scrubber systems was collected from literature (e.g. [40–46] and see detailed description in Supplementary Information B Table S.1) where the median (50th ), 5th and 95th percentiles were used in the different scenarios (Table 1 and Supplementary Information B Table S.1). Due to limited data availability, the hybrid systems were assigned the same investment cost as closed loop systems. Due to the variability in price connected to installed engine power, the ships and the cost were divided into three size categories based on total installed main engine power (Fig. 6). The total installed main engine power of the specific ships in the scrubber fleet were determined from SP Global ship database where power-regression equations based on a selection of 110000 ships (65000 excl. fishing vessels, tugs and service vessels) in different ship categories were used to calculate the engine power from the ship category and gross tonnage (derivations found in Supplementary Information C). Due to poor data fit, statistical data binning was used instead of power-regression for container ships and RoRo vessels. The total investment cost per ship is summarised in Supplementary Information B Fig. S.2 and Table S.3.

The operational costs were estimated from literature (e.g. [46–50] and see detailed description in Supplementary Information B Table S.1) and calculated for each ship based on annual main engine power output associated to scrubber-use from
To assess the variability of market fluctuations, the balance was estimated from three different calculation scenarios:

1. Median balance scenario: Using the median for all costs, i.e. fuel price difference, investment cost and operational cost;
2. Min balance scenario: using the 5th percentile in fuel price difference and the 95th percentile of investment and operational cost;
3. Max balance scenario: using the 95th percentile in fuel price difference and the 5th percentile of investment and operational cost.

The net surplus of the global fleet was calculated by summarising the balance for every vessel at the end of 2022 (Eq. (6)).

$$net\text{surplus}_{global\text{fle}t} = \sum_{ship} balance_{2022, ship} \tag{6}$$

4.2. Cost of not restricting as damage cost on marine environment

To assess the societal cost of not restricting scrubber water discharge, the dataset was limited to a Baltic Sea case study. The selection of ships were based on their operating area, i.e. distance sailed in the Baltic Sea, the Gulf of Bothnia, Gulf of Finland, Gulf of Riga, Kattegat and Skagerrak (Supplementary Information Table S.2), since installing a scrubber. The HFO consumption and the volumes of scrubber water discharged within the Baltic Sea area is estimated from the total annual HFO consumption and the fraction sailed within Baltic Sea, calculated from the distance sailed in the Baltic Sea area divided by the total distance sailed for any given year.

The damage cost calculations were limited to marine ecotoxicity from the discharge of scrubber water, i.e. metals and PAHs in the scrubber water. The calculations were based on previous studies [29, 30] that valued ecotoxicological impacts from the organotin compound tributyltin (TBT) in Sweden. The damage cost of marine ecotoxicity (in €\text{2019} /kg 1,4-DCB eq, i.e. the toxicity potential expressed as 1,4-dichlorobenzene equivalents [31]) based on Willingness to pay estimates of Swedish households’ amounted to 1.07 €\text{2019} /kg 1,4-DCB Eq. (0.73–1.29 €\text{2019} /kg 1,4-DCB eq). The cumulative toxicity potential (i.e. kg 1,4-DCB eq/m\text{3}) of open and closed loop scrubber water was calculated from the concentrations (average and 95 confidence interval) of 9 metals and 10 PAHs and their respective characterization factors from ReCiPe (Supplementary Information B Table S.4). ReCiPe offers a harmonised indicator approach where characterisation factors for organic substances and metals for different environmental compartments, including marine waters, have been produced [31].

The annual damage cost for marine ecotoxicity resulting from scrubber discharge water in the Baltic Sea Area (including Skagerrak) was calculated by multiplying the total volume scrubber water discharged in the area with the damage cost of marine ecotoxicity (1.07 €\text{2019} /kg 1,4-DCB Eq. [29]) and the marine toxicity potential (kg 1,4 DCB eq. /m\text{3}) of open and closed loop scrubber water (Supplementary Information B Table S.6 and S.7).

Declarations

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**Figures**

![Marine Strategy Framework Directive (MSFD)](image-url)
Figure 1

Aggregated environmental status, considering all descriptors and indicators, of European sea basins. The result is based on Member States’ 2018 reporting under the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) on the extent to which they have achieved Good Environmental Status (GES) (blue) or not (red). Data was collected from WISE-Marine [21].

Figure 2

Distribution of vessels that have (orange)/have not (red) reached break-even within 1-9 years after the installation of scrubber system. The three panels show the distribution of the open loop (upper panel), hybrid (middle panel) and closed loop (lower panel) fleets. n=the number of ships that are included in the calculation for each year.
Figure 3

Annual balance of the part of the fleet that installed open loop scrubbers in 2020 plus Dec 2019 ($n_{\text{tot}}=1835$ ships out of which 319 were installed in December 2019). The three different scenarios represent Max balance (square, dotted/dashed line, red interval), Min balance (triangle, dotted line, yellow interval) and Median balance (circle, dashed line, grey interval) scenario (Methodology and Table 1). Line and scatter plot show the average balance of the ships included and the confidence interval shows the 5th and 95th percentiles.

Figure 4

A: Investment cost per kW of open and closed (hybrid) loop scrubbers divided into size categories (Small<6000 kW; 6000 kW<Medium<15000kW; Large>15000kW. B: Fuel price difference of MGO and HFO (black) and VLSFO and HFO (red) from
2014 (MGO)/2020 (VLSFO) until 2022. The boxplots are based on fuel price difference with daily resolution of the 20 largest bunkering ports provided by Ship & Bunker (Supplementary Information B Fig. S.1). The mid-line is the median, the box represents the 25th-75th percentiles, the whiskers mark the 5th and 95th percentiles and outliers are marked as plus signs.

**Figure 5**

Baltic Sea Case study results of A: number of vessels operating within the Baltic Sea Area during the selected period (data collection from STEAM) and B: Societal damage cost due to environmental deterioration of the marine environment as calculated for marine ecotoxicity based on willingness-to-pay (WTP) studies in the Baltic Sea Area and toxicity potential of open and closed loop scrubber water. The error bars are derived from the damage cost calculations if the lower and higher 95 confidence interval of metal and PAH concentrations in scrubber water are used (Supplementary Information Table S.6).
Figure 6

Example of balance calculation of a ship with an open loop system installed since September 2015. The upper level of the balance range corresponds to calculation with the Max Balance scenario and the lower range correspond to the Min Balance scenario. The full line represents the outcome of the Median Balance scenario. At the Date of Installation, the balance equals the investment cost ($\text{cost}_{\text{inv}}$) and the balance at the end of each year is calculated according to equations (4) and (5). The payback time is defined as the time between date of installation and the point of break-even, i.e. the time when Balance=0.

**Supplementary Files**

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- [SupplementaryInformationAll.pdf](#)