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Research article

Environmental assessment model for scrubbers versus alternative mitigation systems for feeder vessels in liner shipping

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ABSTRACT

Implementation of the Global Sulphur Cap (GSC), in January 2020, boosted scrubber installation in vessels to fulfill the new air emission limitations. This increase in scrubbers' use has intensified concern about its environmental performance. Even though achievement of GSC requirements through this mitigation system has been widely proven, the impact of wash water discharge on the marine environment remains under discussion. In this paper, an assessment environmental model is introduced to quantify in monetary terms the performance of feeder vessels that operate with several mitigation systems. This model attempts to improve traditional air emission evaluations by including the impact of scrubbers' discharges on the marine environmental. In this way, the analysis not only allows different mitigations systems to be ranked by considering their capacity to reduce air emissions, but also provides further information about the marine eutrophication and ecotoxicity impact from scrubbers' discharge. Through the model's application to a regular shipping line between the Canary Islands and the Iberian Peninsula, it was found that, the scrubber, regardless of its operation mode (open- or closed loop), is the most efficient mitigation option after the Liquefied Natural Gas (LNG) fuel shift. The impact of scrubbers' discharge was not as significant as expected on the feeder vessel's total pollution since this provides similar relative weight to the methane emissions from a dual-engine option by operating with LNG. The results also show the need to more closely research the marine eutrophication impact of closed-loop scrubbers.

Finally, this paper warns about a significant dispersion on the monetary values of marine ecotoxicity and eutrophication, due to a high dependence of the results on the frameworks' localization. Consequently, further research is needed on the homogenization of pollution monetization in the marine environment.

1. Introduction

Since 1997, MARPOL Annex VI has constrained shipping polluting emissions by considering different areas: Emission Control Areas (ECA), Sulphur Emission Control Areas (SECA) and the rest ones. The former involves higher requirements for NO_x and SO_x emissions, whereas the latter is only more demanding for SO_x emissions. However, MARPOL Annex VI has undergone several reviews over time, with the latest commonly known as the Global Sulphur Cap (GSC). The GSC entered into force in January 2020 with a significant reduction in the maximum permitted sulphur content for marine fuels. So, outside special consideration areas (emission control area, or ECA; and sulphur emission control area, or SECA), the permitted sulphur content was reduced from 3.5% to 0.5%, by maintaining 0.1% (this value was established in 2015 when it was decreased from the initial 1%) as the maximum permitted content in fuels for shipping in ECA and SECA zones. Projections estimate that GSC implementation will lead to a reduction of 35% in morbidity and 54% in premature deaths due to shipping activity (Contini and Merico, 2021). In terms of air quality, even though limited effects are expected in NO_x emissions; metals; and polycyclic aromatic hydrocarbons (PAH) contained in particulate matter (PM); GSC implementation will mean a significant reduction in SO_2 ship emissions and primary PM and secondary sulphate contained in PM (Contini and Merico, 2021).

As a consequence of this more demanding regulation, vessel owners must take a decision about the manner in which they accomplish these

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limitations: via using low sulphur fuels or investing in abatement systems that enable them to reach equivalent emission levels to those emitted by burning fuels with the required sulphur content.

The pros and cons of the possible mitigation solutions have predominantly been analyzed through operative research, by considering the expected price difference among fuels (OPEX) and the payback period for the abatement system investment (CAPEX). However, beyond the findings reached in this regard, the truth is that there has been a notable increase in the use of scrubbers as an abatement technology in the global fleet: 4584 vessels in 2021 versus 740 in 2018 (DNV-GL statistics, 2021). Indeed, the scrubber, or exhaust gas cleaning system (EGCS), has become the most frequent option for existing vessels (through retrofitting). Among other reasons, the shipping sector acknowledges scrubbers to be a mature mitigation technology (from 2014 scrubber retrofitting was broadened - DNV-GL statistics, 2021-) that has been able to meet normative requirements and avoid the implications of a fuel shift.

EGCS technology removes SO_x and PM_x from engines' exhaust gases by spraying seawater or freshwater on them. When the former is applied, alkaline seawater cleans the gases; this scrubber is called open-loop system and it is characterized by a single-use of the wash water before its discharge into the sea. In the latter the freshwater, with added sodium hydroxide, is a multiple use effluent that recirculates in the closed-loop scrubbers. A third EGCS alternative, hybrid scrubbers, is able to shift between the two systems according to navigation requirements.

In spite of the fact that the overboard volume for closed-loop scrubbers is uniquely limited to the bleed-off, and this involves an initial environmental advantage against open-loop scrubbers ($0.3m^3$/MWh and $45m^3$/MWh, respectively according to Ytreberg et al., 2021), the reality is that 81.29% of EGCS are open-loop and 16.72% are hybrid scrubbers (DNV-GL statistics, 2021). In other words, less than 2% of the currently installed scrubbers are closed-loop and this is in itself a cause for concern, since not only the total number of EGCS have increased in the global fleet but also the relative weight of the volume of overboard effluent on the marine environment. Such is the concern that the regulations over scrubbers (IMO Guidelines for Exhaust Gas Cleaning Systems 2015 - MEPC Resolution 259 (68)) were reviewed by the IMO and adopted by the Sub-Committee on Pollution Prevention and Control (PPR 7) in February 2020, through a draft IMO Guidelines for Exhaust Gas Cleaning Systems 2020 (EGCS Guidelines 2020).

The 2020 EGCS Guidelines - as in the case of the previous ones - only establish compulsory limits for the following wash water criteria: PH, PAH_{phe}, turbidity and nitrates. However, Appendix 3 of 2020 EGCS Guidelines recommend future assessments of the EGCS technology through the analysis of discharge water samples. To address this, it has been suggested that contaminants recognized as particularly significant for marine ecotoxicity - 16 Polycyclic Aromatic Hydrocarbons (PAH) and nine metals (Ytreberg et al., 2021; Hermansson et al., 2021; Faber et al., 2021) -- are closely monitored.

Since 2020 EGCS Guidelines merely recommend, rather than enforce, an extensive 'deregulation perception' still exists. An increasing number of countries (Germany, Belgium, and Singapore, among others) have forbidden open-loop scrubber use in their waters over time, to cope with this international deregulation perception. Additionally, this lack of specific IMO criteria for relevant contaminants in the international context has addressed the research to the impact of scrubbers' wash water, based on compliance with Environmental Quality Standards (EQS) established by other regulations to ensure healthy aquatic ecosystems. Therefore, Directive 2013/39/EU that limits concentrations of contaminants in EU Member States' surface waters, or national standards (Canadian Interim Sediment Quality Guidelines, Dutch Guidelines, Danish EQS, among others), are commonly used as quality references.

While there is widespread awareness about the possible damage of scrubbers' discharge on the marine environment, very few studies have tackled the trade-off between pollutant emission reduction and the impact of wash water discharge. In order to broaden knowledge about scrubbers' performance as a mitigation system versus other alternatives, this paper introduces an environmental assessment model that is able to quantify the overall environmental impact of scrubbers in monetary terms. To achieve this, the model jointly evaluates the emissions' reduction provided by the EGCS and the impact of wash water in terms of ecotoxicity and eutrophication. Thus, the method goes beyond traditional assessments of regulation fulfillment by allowing comparison of the overall environmental performance of EGCS against other mitigation systems. Even though the model introduced is suitable for application of liner shipping regardless of its localization, the paper provides quantitative information through its application to a particular case of a feeder service between the Iberian Peninsula and the Canary Islands.

2. Literature review

Increasing concern about scrubbers' impact has intensified in recent years as more studies have analyzed scrubbers' suitability. Three groups can be differentiated among these approaches.

One group of researchers has analyzed scrubbers' performance from a techno-economical perspective (OPEX and CAPEX for shipping) by assuming the existence of other compliance options for the GSC era. Most of these studies have highlighted the fact that, while scrubbers are an efficient abatement technology (reductions of up to 98% of SO_X emissions and up to 60% of particulate matters), their economic feasibility is strongly conditioned by the price difference between heavy fuel oil (HFO) and low-sulphur fuels (OPEX), and by the initial investment costs (CAPEX). Whereas a CAPEX decrease is expected for scrubbers due to high demand, the OPEX trend is not so favorable for scrubbers. Zis and Cullinane (2020) argue that low-sulphur fuels will dominate the market in the medium term. This forecast is based on the risk of open-loop scrubbers no longer being accepted, and on a potential reduction in the gap between low sulphur fuels and HFO prices due to a fall in demand; consequently, production would increase HFO prices by reducing scrubbers' advantages (OPEX). Beyond the fuel prices, an OPEX increase (7–12% annual increases) is also expected due to the additional electric power (Ben-Hakoun et al., 2021) that is required to operate with scrubbers (an increase in energy load of 2% for open-loop and 3% for closed-loop systems-between a 1.4 and 3.4% increase in fuel consumption according to Hansen, 2012) and, consequently, higher maintenance costs. This increase in energy consumption along with greater use of low sulphur fuels will likely lead to higher CO_2 emissions after GSC implementation (Zis et al., 2021).

A second group of studies have tackled the environmental performance of the scrubbers with special attention to the effects of wash water discharges. Hansen (2012) analyzed the hybrid scrubber's performance under the two possible operation modes (open- and closed-loop options) for a two-stroke marine engine (21,060 kW MAN B&W engine, 9L60MC-C8-TI). The research confirmed that both operational modes not only broadly met the emission targets (2.2%S content for HFO), but also the wash water analytics showed broad fulfilment of EGCS Guidelines in both operational modes. Nevertheless, the study also highlighted a significant increase in energy consumption mainly due to scrubbers' pumps (resulting in a 1.4–3.4% increase in fuel consumption). Kjølholt et al. (2012) enlarged this study to other scenarios (including all ships in the region that use scrubbers and the scrubbers used in port, among others), and obtained favorable results as well. Specifically the study analyzed the effect on the marine environment of widespread scrubber use in the Kattegat Sea and the Aarhus Bight by assuming 3.5% S for fuel content and wash water cable of trapping 100% of particles (in a worst-case scenario). Despite the authors identifying inexplicable copper and zinc concentrations in the wash waters, the analysis of discharges, carried out under the European EQS for marine waters (by using the current regulation in force) and the Danish normative for territorial waters, was favorable. The worst findings were obtained when the scrubbers were operating for the auxiliary engines' exhaust in port ('scrubbers in port' scenario). In 2019 a Delft study (Faber et al., 2019) deepened the analysis in this regard by applying a MAMPEC-BW modelling tool to predict the long-term impact on Baltic and North Sea port waters and sediment of open-loop EGCS discharges. After comparing the concentrations of 11 metals and 16 PAHs from empirical data (300 wash water samples that feed the MAMPEC model) with European EQS and national regulations, the study concludes that the impact of open-loop scrubber discharge is small when assessed by 2021 water quality standards.

Finally, a third group of researchers have attempted to quantify the global environmental load of scrubbers' operation: air pollutant emissions and scrubbers' effluents, mainly in the Baltic and North Sea. According to this group, the scrubbers transfer the environmental load derived from shipping activity, from the atmosphere to the marine environment (Hermansson et al., 2021). Moreover, it has been proved that they introduce new contaminants like Cr and alter the atmospheric dispersion of air pollutants (Hermansson et al., 2021). These studies jointly analyze the emissions to air with the emissions to wash water (Hermansson et al., 2021; Ytreberg et al., 2021), with special attention to ecotoxicity (PHAs and metals concentrations- Hermansson et al., 2021). Additional effects like marine eutrophication (mainly due to phosphorus and nitrogen-N- concentrations) are also evaluated (Ytreberg et al., 2021) in the trade-off between air quality and climate change reductions. Among the research findings in this line, one is noteworthy: there are environmental disadvantages for scrubbers in economic terms (Ytreberg et al., 2021), and consequently the phasing out of HFO use is recommended in all cases, regardless of scrubbers' installation (Hermansson et al., 2021).

It is worthwhile noting that, even though the findings from the first group (techno-economic approach) suggested the need for prudence regarding the employment of scrubbers as a compliance solution, the second group concluded that their environmental performance was good, and the third group's insights were clearly unfavorable for scrubbers' use.

In order to obtain more knowledge about the convenience of scrubbers' setting, this paper introduces an assessment model that is able to quantify, in monetary terms, the total environmental load of the scrubbers versus other mitigation systems. The assessment model quantifies the environmental advantage offered by air pollutant emission reduction (air quality) and the disadvantage of increases in ecotoxicity and eutrophication in the marine context. The model's utility will be tested [through a practical case-study for a regular feeder service between the Canary Islands and the Iberian Peninsula. This application case enables insights from a different context from the Baltic and North Sea, as these, as was shown, have been the most frequently analyzed frameworks.

3. THE methodology

The environmental impact assessment model attempts to quantify the pollutant impact (*PI*) of various mitigation alternatives to meet the GSC regulation. Thus, the model evaluates the environmental performance of the vessel for every technology in terms of: climate change, air quality, ecotoxicity of the marine environment and marine eutrophication (uniquely due to nitrogen concentrations). Climate change and air quality are jointly assessed (*CEM*), through the following pollutants ($U = \{1, \ldots, u\}$): SO_X (acidifying substances), NO_x (ozone precursors), $PM_{2.5}$, PM_{10} (particulate mass), CO_2,CH_4 (greenhouse gases) and NH_3 (ammonia slip). Additionally, the ecotoxicity (*EME*) of scrubber wash water is assessed by considering the contaminants ($P = \{1, \ldots, p\}$) listed in Appendix 3 of the EGCS 2020 guidelines, namely PAHs and metals. Lastly, the evaluation of marine eutrophication by nitrogen concentrations (*EUT*) from the scrubber discharge is also assessed.

Equation (1) shows the overall pollutant impact per trip (PI €/trip, where *CEM, EME* and *EUT* are summed) by considering three possible navigation stages ($S = \{1, \ldots, s\}$): navigation in open sea, maneuvering (port pilotage, towing service and mooring time) and berthing (loading/unloading operations). Consequently, PI (see equation (1)) provides a decision-making tool for the compliance options with GSC based on environmental criteria.

$$PI = \sum_{s=1}^{3} CEM_s + \sum_{s=1}^{3} EME_s + \sum_{s=1}^{3} EUT_s;\ \forall s \in S \tag{1}$$

In order to evaluate air pollutant emissions, the model published by Martínez-López et al. (2018) was taken as a reference point, but including PM_{10} and NH_3 emissions. Indeed, PM_{10} inclusion is appropriate by taking into account its impact on human health (Contini and Merico, 2021; Gregoris et al., 2016). NH_3 emissions' evaluation attempts to include the *ammonia slip* effect, due to the operation of the selective catalytic reduction system (SCR) in marine engines.

$$CEM_1 = \sum_{u=1}^{7} (EG_{1u} \times CF_{1u} \times TVB_1) + MS \times LF_1 \times PB \times CF_{1,6} \times TVB_1; \forall \mathrm{u} \in \mathrm{U} \tag{2}$$

$$CEM_2 = 1/2 \times \sum_{f=1}^{2} CEM_{2f}; \forall \mathrm{f} \in \mathrm{F} \tag{3}$$

$$CEM_{2f} = \sum_{u=1}^{7} \left(EG_{2u} \times CF_{2ufv} \times TVB_2\right) + MS \times LF_2 \times PB \times CF_{2,6} \times TVB_2; \quad \forall \mathrm{f} \in F \wedge \forall \mathrm{V} \in \tag{4}$$

$$CEM_3 = 1/2 \times \sum_{f=1}^{2} CEM_{3f}; \forall \mathrm{f} \in \mathrm{F} \tag{5}$$

$$CEM_{3\mathrm{f}} = \sum_{u=1}^{7} \left(EG_{3u} \times CF_{3ufv} \times TVB_3\right);\ \forall \mathrm{f} \in \mathrm{F} \wedge \forall \mathrm{V} \in \mathrm{V} \tag{6}$$

Equations (2)–(6) include the vessels' whole emissions from auxiliary and main engines through: PB being the main engine power (kW); EG_{su} ($\forall s \in S \wedge \forall u \in U$ in kg/h) the emission factors for every pollutant; navigation stage and CF_{sufv} ($\forall s \in S \wedge \forall u \in U \wedge \forall f \in F \wedge \forall v \in V$) their unitary costs (€/kg pollutant). These later costs are based on the marginal social cost pricing principle for air pollution (health effects, crop loss, biodiversity loss and material damage). The European Commission regularly publishes these unitary costs in the Handbook on the External Costs of Transport (last updated in 2019; Van Essen et al., 2019) by considering the geographical localization of the sources ($F = \{1.., f\}$ countries and seas) and their pollution density ($V = \{1,..,v\}$). Likewise, for CO_2 unitary cost, the medium values for climate change avoidance costs are assumed.

The emission factors for the different mitigation alternatives in the vessels are calculated through the DTU (Technical University of Denmark[1]) tool (Kristensen and Psaraftis, 2016; Kristensen and Bingham, 2020) but considering, in addition, the relationship between $PM_{2,5}$ and PM_{10} emissions when several fuels are burned ('EMEP/EEA, air pollutant emission inventory guidebook, 2019′) to improve its accuracy (particulate matters are calculated as a whole in the DTU tool). The time invested at every navigation stage (TVB_s; $\forall s \in S$) was also included in the air pollution calculation by considering emission factor units (kg/h, see equations (2), (4) and (6)).

The emission factors related to CH_4 and NH_3 deserve special consideration since they are not included in the DTU tool. CH_4 emission factor (EG_{s6}; $\forall s \in S$) considers the emissions associated with burning the fuels in a particular engine (*hull-to-wake* emissions, Pavlenko et al.,

[1] available at: https://gitlab.gbar.dtu.dk/oceanwave3d/Ship-Desmo.

2019). To determine this factor, aside from the kind of fuel used (g CH_4/MJ), the engine technology is taken into account through its fuel consumption (MJ/kW.h; Pavlenko et al., 2019). Methane slip (unburned methane from incomplete combustion) is considered as an additional source for CH_4 emissions (*MS* in kg/h, see equations (2) and (4)) and a powerful greenhouse gas (34 times Global Warming Potential over CO_2) that is only associated with dual-fuel engines by operating with LNG. The central value of methane slip (*MS*) relating to engine technology is adapted to the load factor of the engine (LF_s $\forall s \in S$, see equations (2) and (4)), according to the navigation stage.

In turn, the NH_3 emission factor (EG_{s7}; $\forall s \in S$) was estimated by assuming an average 10 ppm in the exhaust gas when SCR is operative along with the ammonia slip catalyst (Fridell and Steen, 2008). Even though the research in this regard has led to significant improvements (ammonia slips below 3 ppm -Lee, 2017; Kim and Lee, 2019), this analysis has taken a conservative approach by limiting the average NH_3 slip to 10 ppm (maximum value for exhaust gas flow concentration, ABS, 2020).

3.1. Assessment of the scrubbers' wash waters

The method developed by Ytreberg et al. (2021) is used for the evaluation of the ecotoxicity impact on the marine environment (*EME* in €/trip) from the scrubber discharges. However, this initial approach was adapted to the navigation stages of the vessels (*EMEs*, $\forall s \in S$). Thus, equation (7) shows a calculation of the ecotoxicity in monetary terms, where besides discharge volume of scrubbers (V_s; ($S = \{1,..,s\}$ in l/trip)) and the consequent increase in the concentrations for every contaminant ($\Delta\rho_p$; $P = \{1,..,p\}$ in kg pollutant/l) regarding their base concentrations in pristine sea water, the calculation equation considers the ecotoxicological midpoint characterization factor to ocean water for every contaminant ($(ETP_{marine})_p$; $P = \{1,..,p\}$ in kg 1,4 DCB-eq/kg pollutant), along with the monetary value for marine ecotoxicity (EPE in €/kg1,4 DCB-eq).

$$EME_s = (ETP_{marine})_p \times V_s \times \Delta\rho_p;\ \forall s \in S \wedge \forall p \in P \tag{7}$$

This approach is based on the use of ReCiPe (2016) characterization factors (Huijbregts et al., 2017a) to quantify accumulative toxicity from different contaminants to several receiving compartments. The harmonized factors (ETP_{marine}), expressed as 1,4-dicholorobenzene equivalents (1,4 DCB-eq) for substances discharged to the marine environment, can be taken from Huijbregts et al. (2017b). Table 1 collects those contaminants included in Appendix 3 of the 2020 EGCS guidelines ($P = \{1, ..,p\}$; 16 PAHs and nine metals) along with their characterization factors (hierarchist perspective).

Table 1 shows the characterization factors (hierarchist perspective by assuming ReCiPe (2016) characterization factors; Huijbregts et al., 2017a) to quantify accumulated toxicity for the contaminants included in Appendix 3 of the 2020 EGCS guidelines ($P = \{1,..,p\}$): these are 16 PAHs and nine metals. ETP_{marine} corresponds to the harmonized factors, that is 1,4-dicholorobenzene equivalents (1,4 DCB-eq) for discharged contaminants that can be taken from Huijbregts et al. (2017b). However, not all contaminants included in Appendix 3 have available harmonized factors (six of the 16 PAHs are unavailable, see Table 1).

Equation (8) collects the marine eutrophication calculation (EUT_s $\forall s \in S$ in €/trip) by considering, aside from scrubbers' discharge volumes for each navigation stage ($V_s, \forall s \in S$ in l/trip), the increase in nitrogen concentration ($\Delta\rho_N$ in kg/l) regarding pristine seawater and the monetary value for marine eutrophication (EPF in €/Kg N).

$$EUT_s = V_s \times \Delta\rho_N \times EPF;\ \forall s \in S \tag{8}$$

Several methods, based on societies' Willingness to Pay (WTP) for damage costs, exist for monetizing the eutrophication and ecotoxicity impact on the marine environment. For the eutrophication (EPF), the following are notable (see Table 2): Ecovalue (Ahlroth, and Finnveden, 2011), Environmental Prices (based on ReCiPe methodology, De Bruyn et al., 2018), EPS (Systematic Approach to Environmental Priority Strategies in Product Development, Steen, 2016) and Stepwise (Weidema, 2009).

Table 1
Characterization factors for contaminants of scrubbers' wash water.

CAS Registry Number	Polycyclic Aromatic Hydrocarbons (PAH):16 EPA PAHs	ETP_{marine} (kg1,4DCB-eq/kg poll.) hierarchist perspective
83329	Acenaphthene	1.17E+01
602879	Acenaphthylene	#N/D
120127	Anthracene	3.06E+02
56553	Benzo-a-anthracene	1.70E+03
50328	Benzo-a-pyrene	2.92E+02
205992	Benzo-b-fluoranthene	#N/D
191242	Benzo-g,h,i-perylene	#N/D
207089	Benzo-k-fluoranthene	#N/D
218019	Chrysene	#N/D
53703	Dibenzo-a,h-anthracene	1.55E+01
206440	Fluoranthene	3.85E+02
86737	Fluorene	3.12E+00
193395	Indeno-1,2,3-pyrene	#N/D
91203	Naphthalene	2.13E+00
85018	Phenanthrene	4.73E+01
129000	Pyrene	1.30E+03
Metals		
7440439	Cd	1.96E+02
7440508	Cu	1.57E+03
7440020	Ni	3.21E+02
7439921	Pb	9.53E+00
7440666	Zn	3.42E+02
7440382	As	2.12E+02
7440473	Cr	3.22E+02
7440622	V	4.55E+02
7782492	Se	1.06E+02
7439976	Hg*	7.09E+02

*Due to the high toxicity of mercury, this substance was included despite it not being collected in the EGCS guidelines 2020.

In this regard, it is necessary to bear in mind that, whereas the EPS and Stepwise methods (see Table 2) incorporate monetary values for a general eutrophication impact (beyond the marine environment, such as in the agricultural context), Ecovalue and Environmental Price methods only take into account marine eutrophication (Arendt et al., 2020).

In turn, the following methods for ecotoxicity are also notable (see Table 3): Ecotax (Finnveden et al., 2006), Ecovalue (Ahlroth and Finnveden, 2011) and Environmental Prices (De Bruyn et al., 2018). It is noteworthy that both the Ecovalue and Ecotax methods only assessed impacts in Sweden.

4. Application case

This section shows the application process to a particular case of the environmental assessment method introduced in previous sections. Thus, a feeder vessel with the technical features shown in Table 4 was assumed as a study case. The feeder operates in linear traffic between the Canary Islands (Las Palmas de Gran Canaria port) and the south of the Iberian Peninsula (Cádiz port). Even though this is a particular case, this

Table 2
Monetary values associated with eutrophication (EPF).

Method	Cost Perspective	Cost $€_{2019}$/kg N_{tot}
Ecovalue	Swedish people's WTP	7.729
Environmental Prices	Effects on biodiversity based on ReCiPe	3.259
EPS	Average impact based on global NO_3 flows	0.013
Stepwise	Damages to ecosystems	0.572

Table 3
Monetary values associated with marine ecotoxicity (EPE).

Method	Cost perspective	Cost €$_{2019}$/kg 1,4-DCB
Ecotax(min/max)	Swedish people's WTP based on toxic substances in pesticides	$1.32.10^{-06}$ $5.99.10^{-02}$
Ecovalue	Swedish people's WTP	1.030
Environmental prices	Effects on biodiversity based on ReCiPe	$7.74.10^{-03}$

Table 4
Main features for a container vessel in the application case.

Features	
Lt (m)	148.00
Lpp (m)	137.82
B(m)	20.50
D (m)	11.17
T (m)	8.20
Service speed (kn)	18.50
Cp	0.6513
Cm	0.991
Cb	0.6454
Cf	0.7602
Main engine (BHP kW)	8600
TEUs	869
TEUs (reefer)	234
Auxiliary engines (kWe)	3X590
PTO (kw)	1800
Bow thruster (kW)	880
Lightweight (t)	4666.21

maritime route distance ($DM = 687$ n. m.) in linear traffic represents a habitual operative pattern between continental Europe and their archipelagos (free sailing time of 37.13 h (TVB_1); maneuvering time of 0.5 h/port for (TVB_2) and berthing time of 6 h (TVB_3) per trip).

Table 5 collects the required electrical power by the vessel for the different navigation stages and the electric load balance by considering the capacity of the PTO (power take off) driven by the main engine MAN B&W G50ME-C9.6-LPSCR, (MAN B&W two-stroke propulsion marine engine) and the generating sets' size (MAN 5L23/30DF): 590 kWe (see Table 4) at 750 rpm.

Considering these technical and operative characteristics for the vessel, four alternative abatement solutions to cope with GSC requirements will be evaluated: HFO operating with an open-loop scrubber; MGO and HFO operating with a closed-loop scrubber; and LNG in a dual marine engine.

Different scrubbers' arrangements are possible in the vessels (one scrubber per engine, one scrubber for several engines, etc). However, when focusing on electricity generating capacity planning (see Table 5), the generating sets mostly operate in ports where EU normative (Directive, 2005/33/EC, amending Directive, 1999/32/EC) forces to use 0.1%S fuel in EU ports. Although mitigation systems are also permitted in ports when equivalent emissions are met, the generating sets' technical characteristics (medium speed engines, Tier-II, four-stroke marine engines) lead to use 0.1% MGO or LNG fuels to maintain auxiliary engines' performance. Consequently, just one scrubber that operates with the main engine's exhaust will be conveniently arranged in this vessel.

Table 5
Electricity generating capacity planning.

Navigation stage	%BHP main engine (kW)	Required electrical power (kW)	Capacity planning*
Free sailing	78.00%	1570	PTO 87.22%
Maneuvering	24.31%	2400	PTO81% +2XMMAA80%
Berthing	0.00%	1470	3xMMAA 83%

*MMAA = Auxiliary engines (generating sets).

Table 6 shows the abatement solutions considered for the environmental assessment. Only the closed-loop scrubber will operate with HFO (the same fuel as that for free navigation) in port due to the widespread prohibition of open-loop scrubbers in EU countries (Spain among them). This fact, along with EU ports' requirements (Directive, 2005/33/EC), involves that, the rest of abatement solutions use 0.1%S MGO in port, for both auxiliary engines and the main engine is operating in the maneuvering stage.

Contrary to the port situation, different alternative fuels can be used by the same abatement system in the free sailing stage. Thus, whereas for dual engine and low-sulphur fuel solutions (see Table 6) only one fuel scenario is assumed (LNG in the former and 0.5% S for MGO in the latter); for each scrubber's alternative (both open-loop and closed-loop) three fuel scenarios are considered: 1%, 2% and 3.5%S for HFO (see Table 6).

To carry out an accurate evaluation, the main implications for vessel performance of the abatement system setting must be considered. The scrubbers' operation involves an increase in the required propulsion power (lightweight increases), and additional electrical power is demanded by the EGCS (see Table 7). To evaluate both aspects, scrubbers' performance and their technical features were assumed from the information provided by MAN (2020) and Alfa Laval (2021). According to these manufacturers, a minimum reduction of 55% for particulate matter ($PM_{2,5}$ and PM_{10}) and 98% of SO_x emissions in the engines' exhaust is reached through scrubbers. This is considered both for the calculation of the emission factors (EG_{su}; $\forall s \in S \wedge \forall u \in U$ see equations (2)–(6)) and for the operative requirements of the scrubbers' setting (see Table 7).

The LNG alternative necessarily forces us to evaluate CH_4 emissions for all abatement possibilities. Thus, the same engine as the base case, but in dual mode, was considered when LNG propulsion was evaluated: MAN B&W G50ME-C9.6-GI-LPSCR. Consequently, according to Pavlenko et al. (2019) for estimation of the CH_4 emission factor, two stroke diesel engines were assumed as an engine's technology when HFO with scrubber and MGO were analyzed ($EG_{s6=}0.0054$g CH_4/kW.h). In turn, when LNG is assessed as a fuel, low pressure injection of dual-fuel

Table 6
Assumptions for the abatement solutions.

Abatement solutions	Scenarios	Navigation stages	Fuel for main and auxiliary engines
Scrubber (open-loop)	Scenario 1: 3.5%S HFO	Free sailing	3.5%S HFO
		Maneuvering	0.1%S MGO
		Berthing	0.1%S MGO
	Scenario 2: 2%S HFO	Free sailing	2%S HFO
		Maneuvering	0.1%S MGO
		Berthing	0.1%S MGO
	Scenario 3: 1%S HFO	Free sailing	1%S HFO
		Maneuvering	0.1%S MGO
		Berthing	0.1%S MGO
MGO	0.5% S	Free sailing	0.5%S MGO
		Maneuvering	0.1%S MGO
		Berthing	0.1%S MGO
Scrubber (closed-loop)	Scenario 1: 3.5%S HFO	Free sailing	3.5%S HFO
		Maneuvering	3.5%HFO+ 0.1%S MGO
		Berthing	0.1%S MGO
	Scenario 2: 2%S HFO	Free sailing	2%S HFO
		Maneuvering	2%HFO+ 0.1%S MGO
		Berthing	0.1%S MGO
	Scenario 3: 1%S HFO	Free sailing	1%S HFO
		Maneuvering	1%HFO+ 0.1%S MGO
		Berthing	0.1%S MGO
DUAL	LNG*	Free sailing	LNG
		Maneuvering	LNG+0.1%S MGO
		Berthing	0.1%S MGO

*0.5%S MGO is taken as a pilot fuel.

Table 7
Scrubbers' setting implications for practical case.

Increase	Open-loop	Closed-loop
Lightweight (t)	18	21
Additional back pressure in main engine (ΔSFOC g/kWh)	+1	+1
Pumps' EGCS (kW)	49	49
Water treatment System (kW)		40
Δ Required power (main engine) kW	+0.6%	+0.6%
Δ Required electrical power (kW)	49	89

(Sources: MAN, 2020; Alfa Laval, 2021).

engines that are two stroke is taken for the CH_4 emission factor ($EG_{s6=}$0.128g CH_4/kW.h). Finally for the emission factor's estimation of the generating sets, its technology: dual-fuel engines (four stroke), was considered along with its operation with MGO ($EG_{s6=}$0.0054g CH_4/kW.h). The central value for the methane slip published by Pavlenko et al. (2019) for two stroke dual-fuel engines was considered for the calculations (MS = 2.5 gCH_4/kWh) along with its variation with the load factor of the engine (LF_1 = 0.87; LF_2 = 1.06; see equations (2) and (4); Pavlenko et al., 2019) when LNG is evaluated for the main engine as a mitigation alternative (MS = 0, for the other options).

Finally, SCR technology is included in all Tier-III engines, therefore the ammonia slip must be evaluated in all main engines. For the estimation of the emission factor of NH_3 (EG_{s7} = 157,93 mg/kWh; $\forall s \in S$) by SCR use, aside from NH_3 concentration in the exhaust gas flow -an average of 10 ppm-, the exhaust gas flow volume (m^3/h) and its temperature were taken from the engine's project guide[2] (exhaust gas mass flow 7.13 kg/kW h at 290 °C and 3.1 bar for main engine).

4.1. Unitary costs for air pollutants and contaminants in the effluents

The unitary costs for the pollutants are highly dependent on the geographical localization of the transport. The European Environmental Agency in the Handbook on the External Costs of Transport (Van Essen et al., 2019) publishes the unitary costs for air emissions (CF_{sufv}; $\forall s \in S \wedge \forall u \in U \wedge \forall f \in F \wedge \forall v \in V$; see equations (2)–(6)), for EU member states and for the European seas. In this application case, whereas the Atlantic Ocean values were taken for the free navigation stage, for the maneuvering and berthing stage the average of damage costs for transport emissions in Spain (see Table 8) were considered for all pollutants excepting for greenhouse gases. In the latter, the Global Warming Potential (GWP) was taken as a reference for CO_2 and CH_4 emission costs (GWP is standardized to 1 for CO_2, GWP is 34 for CH_4; Van Essen et al., 2019).

Table 8
Unitary costs for air pollutants CF_{sufv}.

Pollutant (*u*)	CF_{1u} (€/kg)[a]	CF_{2u11}(€/kg)[b] CF_{3u11}(€/kg)
SO_X	3.72	7.22
NO_x	9.03	4.03
$PM_{2.5}$	7.64	369.58
PM_{10}	4.35	12.64
CO_2	0.11	0.11
CH_4	2.65	2.65
NH_3	0.00	6.80

[a] CF_{1u} involves Atlantic Ocean values.
[b] $CF_{2ufv} = CF_{3ufv} = CF_{2u11} = CF_{3u11}$, the unitary costs for maneuvering and berthing stages are related to Spain and metropolitan hinterlands.

Moreover, metropolitan air pollutant costs were taken for the port operations since the density population (V = {*1,..,v*}) of the hinterlands involved (Cádiz and Las Palmas de Gran Canaria ports) surpass 0.5 million inhabitants, meaning that NO_x and $PM_{2.5}$ emissions are more harmful (higher unitary costs). Finally, since the values published in the Handbook on the External Costs of Transport (Van Essen et al., 2019) are related to 2016, an update to 2021 (see Table 8) was applied by considering CPI (6.2%; National Statistics Institute of Spain, 2021).

Among the possible methods shown in Tables 3 and 4 for monetizing eutrophication and ecotoxicity on the marine environment from the scrubbers' discharges, the Environmental Price Method (De Bruyn et al., 2018) was selected. Accordingly, Life Cycle Assessment using the ReCiPe methodology (under the hierarchist perspective) is used for marine ecotoxicity price (*EPE*=0.007959 €/kg1,4 DCB-eq, see equation (7)), thus the Ecotoxicity price for average EU28 (De Bruyn et al., 2018) was updated from 2015 to 2021 through CPI (7.7% Eurostat, 2021). Likewise, the environmental price for marine eutrophication was updated from the same reference (De Bruyn et al., 2018); however, since it is directly discharged into the sea, a 43% increase was applied (*EPF* = 4.79 €/kg N, see equation (8)).

The Environmental Price Method offers several advantages for the quantification of the scrubbers' discharge impact versus other methods (see Tables 2 and 3). Firstly, its application is not limited to particular regions but is suitable for several geographical zones; the eutrophication evaluation is specific to the marine environment, and finally; it is available to quantify both eutrophication and ecotoxicity in that environment.

4.2. Characterization of scrubbers' discharge

To quantify the ecotoxicity impact on the marine environment (*EMEs* $\forall s \in S$), it is necessary to know the contaminants' concentrations ($\rho_{p;}$ $\forall p \in P$) on the scrubbers washwaters (see equation (7)). From a database analysis of samples of scrubbers' discharge for 41 vessels, Hermansson et al. (2021) published average concentrations (μg/l for every pollutant) for open and closed-loop scrubbers discharges (see Table 9). Even though the dispersion of the sample features was wide (navigation through various seas with different fuels -from 0.7 to 3.2%S content-at broad %MCR ranges), these average values were assumed in the application case, because they are close to those published by Ytreberg et al. (2021) from the database of Jalkanen et al. (2020). Likewise, Hermansson et al.'s (2021) database in terms of N_{tot} concentrations for scrubbers' discharges were also reliable for both open- and closed mode, once compared with results provided by the samples of Kjølholt et al. (2012). Consequently, these were assumed for the eutrophication assessment due to the discharged wash waters ρ_N: 0.20–0.60 mg/l for open-loop scrubbers and ρ_N: 24–120 mg/l for closed mode for several %S fuels.

Paying attention to equations (7) and (8), the pristine seawater pattern must be characterized to determine the effective increase of the contaminants ($\Delta\rho_p = \rho_{p;}$ $\forall p \in P$). For this application case, this pattern was obtained by considering chemical analysis research in the North-East Central Atlantic Ocean. As can be seen from Table 9, the scale size of contaminants' concentration in pristine seawater allows us to assume equivalence between the overall discharged contaminants and the relative increase with regard to pristine seawater ($\Delta\rho_p = \rho_{p;}$ $\forall p \in P$).

Finally, with the intention of improving the assessment's accuracy, the database published by Hermansson et al. (2021) was considered to obtain a more realistic relationship between volume discharge flow rates (m^3/MW.h) for each and every navigation stage (V_s;$\forall s \in S$) and the power developed by the engine (%MCR) at %S fuel than those provided by the scrubbers' manufacturers (45 m^3/MW.h for open-loop systems and for closed mode systems 0.1–0.3 m^3/MW.h).

[2] https://man-es.com/applications/projectguides/2stroke/content/printed/G50ME-C9_6.pdf.

Table 9
Average concentrations for scrubbers' discharge pollutants ρ_p.

Polycyclic Aromatic Hydrocarbons (PAH)	Open-loop scrubber discharge (μg/l)	Closed-loop scrubber discharge (μg/l)	Pristine * seawater (μg/l) (max)
Acenaphthene	0.19	0.47	0.0001 [a]
Acenaphthylene	0.12	0.09	0.0002 [b]
Anthracene	0.08	1.55	<0.0001 [a]
Benzo-a-anthracene	0.12	0.3	0.0001 [b]
Benzo-a-pyrene	0.05	0.06	<0.0001 [a]
Benzo-b-fluoranthene	0.04	0.14	<0.0001 [a]
Benzo-g,h,i-perylene	0.02	0.07	<0.0001 [a]
Benzo-k-fluoranthene	0.01	0.02	<0.0001 [a]
Chrysene	0.19	0.5	0.0004 [b]
Dibenzo-a,h-anthracene	0.03	0.03	0.001 [i]
Fluoranthene	0.16	0.63	<0.0001 [a]
Fluorene	0.46	1.32	0.0005 [b]
Indeno-1,2,3-pyrene	0.07	0.04	0.001 [i]
Naphthalene	2.81	2.08	<0.0001 [b]
Phenanthrene	1.51	5	0.0006 [a]
Pyrene	0.31	0.76	0.0002 [a]
Metals			
Cd	0.8	0.55	0.07 [j]
Cu	36	480	0.10 [d]
Ni	48	2700	0.26 [c] [d]
Pb	8.8	7.7	0.004 [c]
Zn	110	370	0.80 [d]
As	6.8	22	1.18 [e] [f]
Cr	15	1300	0.16 [g]
V	170	9100	4.9 [d]
Se	#N/D	#N/D	0.05 [f]
Hg	0.09	0.07	0.0004 [c] [h]

[a] Nizzetto et al. (2008).
[b] Vecchiato et al. (2018).
[c] Pohl et al., 2011.
[d] Prego et al. (2013).
[e] Wurl et al. (2015).
[f] Cutter and Cutter, 1995.
[g] Sirinawin et al. (2000).
[h] Mason et al. (2012).
[i] Law et al. (1997).
[j] Bruland (1980).

5. Results for application case

The results, in terms of air emissions, can be seen in Fig. 1. The aggregated costs for air emissions (CEMs ∀s ∈ S) are shown by considering the navigation stages for all alternatives analyzed. Obviously, berthing stage shows no difference among mitigation systems (see Fig. 1) since in all cases MGO 0.1%S is compulsory for the auxiliary engines at port (Directive, 2005/33/EC, amending Directive, 1999/32/EC). This normative enforcement along with the prohibition of open-loop scrubbers also lead to practically coincident costs in the maneuvering stage for open-loop scrubbers (in all scenarios, that is, for all %S content in fuels) and MGO 0.5%S solution (see Fig. 1). Nevertheless, we found notable differences in this navigation stage (CEM_2 see Fig. 1) when closed-loop scrubbers and dual engines options are analyzed. This is because both options are allowed to maintain main engine operation, with the bunker employed, in free sailing (HFO and LNG respectively). Thus, main engines are not just used to propel the vessel but also to generate electrical power (through power take off-PTO-, see Table 5) along with the auxiliary engines (this navigation stage is the most demanding in terms of electric requirements, see Table 5).

Regarding the free sailing stage (CEM_1, see Fig. 1), performance differences among the abatement alternatives are significant. Dual engine offers the most suitable option in terms of air emissions, whereas the open-loop and closed-loop mode differences for scrubbers are negligible for the same fuel scenarios (same %S content in HFO). Finally, MGO was found to be an unattractive option in contrast to other solutions.

The impact of the scrubbers' discharge (*EME* and *EUT* together) on total pollution (PI €/trip), has been less significant than expected (see Fig. 2), as it is several orders of magnitude lower than the air emissions' component (see Fig. 2). Specifically, scrubbers' discharge contributes between 0.13 and 0.3% of the PI total (see Table 10).

Fig. 2 offers further information about the relevance of scrubbers' discharge by considering several air pollutants involved in the analysis. NH_3, CH_4, *EME* and *EUT* have proved to be the least significant pollutants in the analysis - in that order - excepting for the dual engine option. In this last case, the impact of CH_4 emissions surpass the greater impact of scrubbers' discharge, that is when the open-loop scrubber is operating with 3.5%S fuel (119.4€/trip for CH_4 emissions in a dual engine versus 76.64€/trip jointly reached for *EME* and *EUT*). Analyzing the total environmental performance of the abatement systems analyzed (PI €/trip), the dual engine alternative provides the most sustainable solution, followed by whatever option for scenario 3 (HFO 1%S). Paying attention to Table 10, regardless of the scrubbers' operation mode

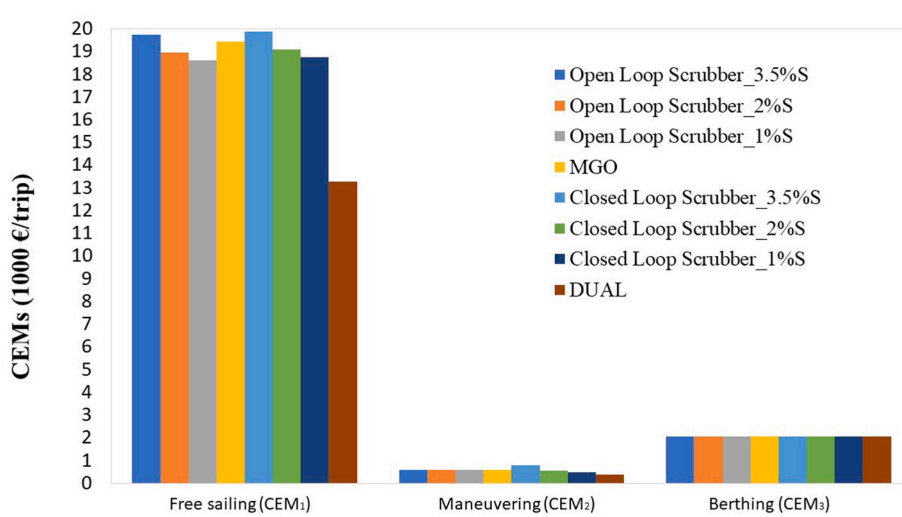

Fig. 1. CEMs values for all mitigation alternatives in every navigation stage.

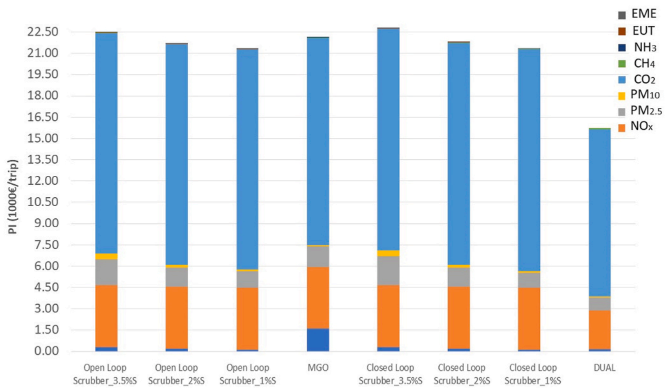

Fig. 2. Pollutant Impact (PI) components for mitigation alternatives.

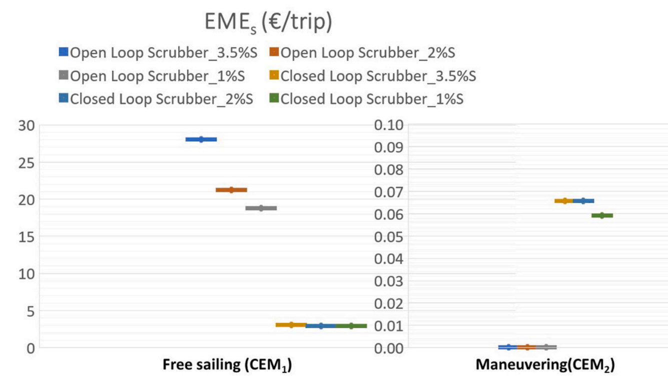

Fig. 3. Ecotoxicity values (EMEs) for open and closed loop scrubbers in every navigation stage.

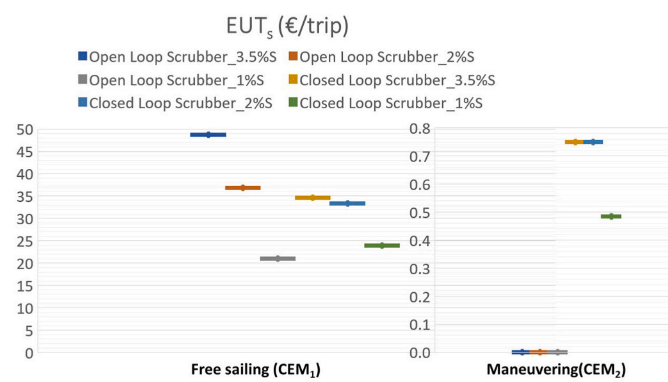

Fig. 4. Eutrophication values (EUTs) for open and closed loop scrubbers in every navigation stage.

(open- or closed-loop), this fuel scenario offers good environmental performance (see Table 10).

Table 10 shows significant differences between the volume of the overboard effluent for open- and closed loop mode, as expected (V_s; $\forall s \in S$, see Table 10). This low discharge rate for the closed-loop scrubber means that, despite the fact that the ecotoxicity impact of the closed-loop scrubbers' discharge is higher than those for open-loop mode (6.31 kg 1,4 DCB-eq/m^3 versus 0.194 kg 1,4 DCB-eq/m^3 assuming discharge patterns of Table 9), their absolute impact in terms of ecotoxicity (*EME*, see Fig. 3) is lower for closed-loop scrubbers. Unlike the case of the ecotoxicity, the small volume of the closed-loop scrubbers was not enough to offer a clear advantage in absolute terms of the eutrophication impact regarding the open-loop scrubbers. Thus, the eutrophication results proved to be very close to each other for both technologies (*EUT* see Fig. 4) due to the high nitrogen concentrations (N_{tot}) for closed-loop mode in contrast to open-loop scrubbers (ρ_N: 24–120 mg/l and ρ_N: 0.20–0.60 mg/l, respectively).

Focusing on the overall impact of the scrubbers' wash waters (*EME* and *EUT* together, see Table 10), an environmental advantage exists for closed-loop scrubbers, but this is not as significant as expected by considering that its discharge volumes are limited to the bleed-offs (0.3m^3/MWh versus 45m^3/MWh for open-loop scrubbers). Aside from the relevance of the nitrogen concentrations found for closed-loop scrubbers, its operation during maneuvering in port versus open-loop scrubbers (which are mostly not permitted) increases its environmental impact on the marine environment by reducing its sustainability versus open-loop scrubbers.

Table 10
The pollutant impact per trip and their components for the different scenarios.

Abatement solutions	Scenarios	Navigation stages	CEMs (€/trip)	CEM (€/trip)	Vs(m3)	EMEs (€/trip)	EUTs (€/trip)	EME (€/trip)	EUT (€/trip)	PI (€/trip)
Scrubber (open-loop)	Scenario 1: 3.5%S for HFO	Free sailing	19,767.46	22,434.82	18,115.7	28.02	48.62	28.02	48.62	22,511.47
		Maneuvering	600.15		0.00	0.00	0.00			
		Berthing	2067.21		0.00	0.00	0.00			
	Scenario 2: 2%S for HFO	Free sailing	18,976.84	21,644.20	13,702.5	21.19	36.78	21.19	36.78	21,702.17
		Maneuvering	600.15		0.00	0.00	0.00			
		Berthing	2067.21		0.00	0.00	0.00			
	Scenario 3: 1%S for HFO	Free sailing	18,632.03	21,299.39	12,133.4	18.77	20.93	18.77	20.93	21,339.09
		Maneuvering	600.15		0.00	0.00	0.00			
		Berthing	2067.21		0.00	0.00	0.00			
MGO		Free sailing	19,438.13	22,107.15	0.00	0.00	0.00	0.00	0.00	22,105.70
0.5% S		Maneuvering	600.69		0.00	0.00	0.00			
		Berthing	2068.32		0.00	0.00	0.00			
Scrubber (closed-loop)	Scenario 1: 3.5%S for HFO	Free sailing	19,886.05	22,754.13	60.09	3.02	34.56	3.08	35.31	22,793.03
		Maneuvering	800,31		1.30	0.07	0.75			
		Berthing	2068.32		0.00	0.00	0.00			
	Scenario 2: 2%S for HFO	Free sailing	19,091.71	21,739.38	57.98	2.91	33.35	2.98	34.10	21,776.86
		Maneuvering	579.75		1.30	0.07	0.75			
		Berthing	2068.32		0.00	0.00	0.00			
	Scenario 3: 1%S for HFO	Free sailing	18,744.81	21,303.82	57.98	2.91	23.90	2.97	24.38	21,331.62
		Maneuvering	490.69		1.17	0.06	0.48			
		Berthing	2068.32		0.00	0.00	0.00			
DUAL		Free sailing	13,273.86	15,750.73	0.00	0.00	0.00	0.00	0.00	15,750.73
LNG (*0.5%S MGO as a pilot fuel*)		Maneuvering	408.55		0.00	0.00	0.00			
		Berthing	2068.32		0.00	0.00	0.00			

6. Discussion

The research published to date has offered interesting insights into scrubbers' suitability as a mitigation system in vessels. However, there is a great heterogeneity in recommendations regarding scrubbers, depending on the research perspective. This paper offers quantitative findings in this regard through the application of an assessment model of the vessel's environmental impact by considering air emissions along with effluent discharge by scrubbers.

Based on the application case of a linear container vessel between the Canary Islands and the Iberian Peninsula, the scrubbers operating with 1%S content of fuel offer the most efficient mitigation option after LNG use in dual engines. Under the assumptions of this application case, the environmental impact of the scrubbers' discharge (*EUT* and *EME*) represents between 0.1 and 0.3% of the total of the pollutant impact (PI, see Table 10), and these discharges even show a lower impact than the CH_4 emissions for the dual engine alternative (*EUT* and *EME* is 76.64€/trip for open-loop, 3.5%S versus CH_4 emissions = 119,4€/trip for dual engine).

In this regard, it is worth highlighting the scarce difference in the environmental impact of the open- and closed mode for scrubbers. This is due to a combination of factors: the closed-loop mode demands higher energy requirements that involves light increases in air emissions (*CEM*, see Table 10); additionally its port operation along with auxiliary engines (in the maneuvering stage) has not proved to be more sustainable (air emissions) than the open-loop scrubber, which must operate with 0.1%S fuel, since the open-loop option is forbidden in port (see CEM_2 in Table 10). This additional operation of the closed-loop scrubber in port also involves more working hours and therefore, there is an extra impact of its wash water discharge. This fact has a special significance in terms of eutrophication (*EUT*), where closed-loop scrubbers have proved to be particularly harmful. This last result is in line with findings reached in previous research (Winnes et al., 2018; Yaramenka et al., 2018).

Nevertheless, it should be noted that the results achieved have several limitations. Firstly, evaluation of the ecotoxicity is based on the ReCiPe method (Huijbregts et al., 2017a). Even though this method is widely accepted, six of the 16 PAHs that are recommended for monitoring in Appendix 3 of the 2020 EGCS guidelines, do not have characterization factor available in the last update (see Table 1). This is so, even though the ecotoxicity of these PAHs is recognized in the Environmental Quality Standards (EQS) of the Water Framework Directive (WFD- Directive, 2000/60/EC) for marine waters (Faber et al., 2021). To assess the inaccuracy's effect on the ecotoxicity evaluation, a pessimistic scenario was assumed (the characterization factor for these PAHs is as high as the maximum found in the analysis: $ETP_{marine} = 1.70.10^3$ kg1, 4DCB-eq/kg, see Table 1). In such a case *EME* initial value is increased by 0.39% for the open-loop scrubber and 0.04% for the closed-loop option, and consequently the imprecision in this regard does not misrepresent the findings.

The assessment model introduced in this paper provides information in monetary terms, and therefore the unitary costs assumed for the analysis has a relevant influence on the findings. Even though broad consensus exists about the unitary cost of air emissions in transport (reports of unitary costs based on homogenous criteria have been successively updated), these were not found for the monetary values associated to eutrophication and ecotoxicity in the marine environment. In fact, a notable dispersion exists among the values offered by different methods (see Tables 2 and 3). The method assumed for evaluating these impacts on the application case was the average EU28 emissions on Environmental Prices, but these values are very far from Ecovalues (see Tables 2 and 3). Thus, even though these Ecovalues are constrained to Sweden, the difference with Environmental Prices involves several orders of magnitude (EPF = 7.229 €/kg N_{tot} versus EPF = 3.259 €/kg N_{tot} for eutrophication and EME = 1.03 versus EME = 0.0079€/kg 1,4 DCB-eq for ecotoxicity, see Tables 2 and 3). This difference is even higher when focusing on previous research that used Sweden as a case study (2010 prices 0.64–1.13€/kg 1,4 DCB-eq and a range of 52–60 €/kg N_{tot}; Ytreberg et al., 2021).

In fact, if Ecovalues were assumed instead of Environmental Prices the results obtained would be significantly different. The impact of wash water scrubbers would reach 14% of PI (total pollutant impact) in the open-loop mode versus the initial 0.3% of PI, whereas closed-loop would contribute 2% of PI instead of the initial 0.1%. Additionally, marine ecotoxicity would represent a similar impact for NOx emissions in open-loop mode and a similar impact for SOx emissions in the closed-loop mode (measured in €/trip). Finally, assuming this Ecovalue method for the monetization of scrubbers' discharge, the closed-loop mode would offer a lower environmental impact than open-loop mode (in the 5–11% range).

In light of the consistency of the results achieved (14% of PI from scrubbers' discharge in the most pessimistic scenario), despite the dispersion of the unitary costs found for different localizations (societies' Willingness to Pay (WTP) for damage) we can affirm that the previous findings about the limited environmental impact of scrubbers' wash waters on the marine environment are applicable to similar size feeder vessels operating in other similar distance routes. Moreover, considering the high preponderance of pollution during free sailing versus port activity, quantitative results about the overall pollutant impact of the possible abatement systems are especially useful for feeder vessels by operating in linear shipping in the Atlantic Ocean (EU region). Finally, the insights regarding the different environmental performance between the open- and closed-loop scrubbers are applicable regardless of the shipping localization and vessel type, because they are based on a pattern of wash waters for scrubbers (average values) obtained from shipping in several seas and with vessels operating in very different conditions (%MCR and %S content in fuels).

7. Conclusions

The Global Sulphur Cap boosted the retrofitting of scrubbers on vessels. This reality, along with the perception of insufficient regulation for scrubbers' discharge, has undermined trust in their environmental performance. In order to provide further insights in this regard, this paper introduces a model able to jointly evaluate marine impact and air emissions as a whole, to determine the environmental performance of a liner container vessel operating with several mitigations' solutions. The model offers environmental assessments in monetary terms for the navigation stages by considering the air emissions for different alternatives: CO_2, CH_4, NO_x, SO_x, $PM_{2.5}$, PM_{10} and NH_3. The analysis of the marine environment considers the eutrophication impact through N_{tot} concentrations on scrubbers' discharge and the ecotoxicity of substances collected in the 2020 EGCS Guidelines: 16 PAHs and nine metals.

The model's utility was tested through its application to a particular case: a feeder vessel operating between the Canary Islands and the Iberian Peninsula in regular shipping. This case study allowed quantitative results in a different context from the Baltic and North Sea to be obtained, as these scenarios have been most frequently evaluated in previous research. Thus, dual engines, scrubbers operating in open- and closed-loop mode (with different %S content of fuels), and Tier-III MGO engines, were evaluated to identify the most suitable solution in environmental terms. From the application case it was found that scrubbers' wash water impact was several orders of magnitude lower than that of air emission. The scrubbers' discharge contribution to total pollutant impact of the vessel per trip (0.1%–0.3% closed- and open-loop respectively) was even lower than the methane emissions impact from the LNG fuel alternative (dual-engine).

The results also show that the main engines' additional energy required for scrubbers' use is not as significant as expected: the additional main engine's power is close to 1% for scrubbers in open-loop mode; whereas for closed-loop mode it barely reaches 1.3%. These values consider the back pressure in the exhaust gas system, the additional weight of scrubbers for the lightweight and the additional electric energy for pumps and treatment system. In parallel, no significant differences were found between open- and closed-loop mode in terms of scrubbers' environmental performance. Despite the lower discharge rate of closed-loop scrubbers, these have proved to have a significant eutrophication impact compared to open-loop scrubbers. This fact, along with their higher working hours in port with lower environmental efficiency (higher cost emissions in port), and their requirements for additional energy to operate, lead to the environmental advantage for closed-loop mode regarding the open-loop scrubbers is reduced.

Even though several findings of this paper are drawn from a particular case (only one EGCS for a main engine that operates with a PTO in a particular electric supply plan), and therefore should not be generalized, the results' consistency and the inputs used for the calculations permits us to extrapolate the conclusions of this paper to other frameworks - especially those related to the performance of the abatement systems versus scrubbers – and are useful for similar linear feeders operating in the Atlantic Ocean (EU zone). Furthermore, the findings about the relative performance between open- and closed-loop scrubbers can be used regardless of the vessel type and route localization. This reality led to significant differences were found with regard to some previous publications.

The values of the inputs related to the wash water's characterization considered for the application case in this paper are in line with those assumed by previous studies. However, we have detected significant differences among the unitary costs used to evaluate the impact of scrubbers' effluents in monetary terms. Since the method assumes these monetary values are based on societies' Willingness to Pay (WTP) for damage, the framework's localization has resulted to be a key parameter on the port results. These differences in the monetization method largely justify the deviations found regarding previous studies, and indicate the need for further research and harmonization of the monetization of marine pollution. This research is essential to improve the findings' accuracy and offer more broadly applicable insights. Likewise, the results achieved also suggest the need to go further in the research on the on the knowledge of the closed-loop scrubbers impact on marine eutrophication.

Credit author statement

Martínez-López A.: Conceptualization, Methodology, Writing – original draft preparation **Marrero A.**: Validation, Investigation. **Martín-Cruz Y.**: Data curation, Visualization. **Míguez-González M.**: Supervision; Writing- Reviewing and Editing,

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The database is public and the references to the database are cited in the manuscript.

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