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Decarbonization of Short Sea Shipping in European Union: Impact of market and goal based measures

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ABSTRACT

In July 2021, the European Union (EU) published a package of measures for the decarbonization of maritime transport: Market Based Measures (MBM) and Goal Based Measures (GBM) that will gradually be phased in over 2023. The measures derive from an EU decision taken independently of the International Maritime Organization. This fragmentation of maritime transport governance leads to new working scenarios in the EU that have given rise to concern in the shipping industry. This paper analyzes the monetary consequences of EU decarbonization regulation on Short Sea Shipping (SSS) by introducing a mathematical model to meet this aim. From the application of this model to SSS container vessel operating between the Canary Islands and the Iberian Peninsula, it is found that, although MBM accurately reflect the pollutant impact of SSS vessels in the aftermath of the 2020 Global Sulphur Cap, only GBM along with non-compliance deterrents can redirect the vessels' investments towards more sustainable solutions in the medium-term.

1. Introduction

Even though Market Based Measures (MBM) were considered by the International Maritime Organization (IMO), through the Marine Environment Protection Committee (MEPC), as a control tool for greenhouse gas (GHG) emissions in 2010, the debate closed in 2013 without any decision being made. In 2018, MEPC 72 adopted the so-called *Initial IMO Strategy*; this involved, aside from the implementation of the 2020 Global Sulphur Cap (2020 GSC), a strategy for the reduction of GHG emissions where MBM were again included as possible incentives. However, the lack of celerity shown in MEPC 73 and 74 (2019) regarding implementation of the IMO strategy (Monios and Ng, 2021), finally led to the European Union (EU) departing from its traditional alignment with IMO decisions (Psaraftis and Kontovas, 2020) by publishing its intention to include shipping in the EU-ETS (European Green Deal framework- EU (2019), and therefore adopting MBM for shipping, irrespective of the IMO agreement.

Taking into account that ship traffic in the European Economic Area ports emits for some 11% of all EU CO_2 from transport and 3–4% of the EU CO_2 emissions (EU, 2021b), the European Parliament approved in September 2020[1] a proposal by Paulus to add shipping to the EU-ETS Directive from 2022. This includes the creation of an "Ocean Fund" from 2023 to 2030, financed by revenues from auctioning allowances, under the ETS, to make ships more energy efficient.

Even though no MBMs have been imposed by the IMO to date, MEPC 76 (June 2021) approved ambitious Goal Based Measures (GBM) for reducing GHG emissions based on the Annual operational carbon intensity indicator -CII- (MEPC.336(76)) and a CII rating (MEPC337(76) and MEPC338(76)). The CII is presented as a yearly index with application from January 1, 2023 for vessels over 5000 Gross Tonnage (GT). This involves, aside from regular evaluation of the vessels' accomplishment according to a reduction schedule of yearly CO_2 emissions over time (from 2019 values: 5% for 2023, 7% for 2024, 9% for 2025, etc), a vessels categorization according to their operational energy efficiency performance. This rating (from A to D) will be expectedly considered by the institutions to incentivize sustainability through significant reductions in vessels' operating costs. Proof of this is the strong intention of the International Association of Harbours and Ports (IAHP) to include CII in the Environmental Ship Index (ESI) equation for the port Eco-bonus. It is probable that CII implementation is considered the

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[1] https://www.europarl.europa.eu/legislative-train/api/stages/report/current/theme/a-european-green-deal/file/revision-of-the-eu-system-to-monitor-report-and-verify-co2-emissions-from-ships.

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IMO's 'second great milestone, after the 2020 GSC, in terms of the prevention of air pollution for ships.

Just after the MEPC 76 took place, the EU published, in July 2021, a set of Communications containing details about the implementation of the GHG reduction measures in maritime transport in EU waters. The first, EU (2021b), is a GBM that involves an additional GHG reduction schedule to the CII Regulation (IMO) but reducing CO_2 equivalent per megajoule (MJ) from the based-data of 2020 emissions (Regulation (EU) 2015/757 reports). On the other hand, EU (2021a) and EU (2021c) introduce MBM for shipping in the EU. The former includes, for vessels over 5000 GT, the gradual inclusion of CO_2 emission for shipping in the EU-ETS from 2023 (20%) to 2026 (100%), through the EU-ETS Directive review. The latter advances a review of the Energy Taxation Directive (-ETD- Council Directive 2003/96/EC) by including minimum levels of taxation for marine fuels. Thus, from 2023 to 2033 the expected levy (EUR/GJ) for fossil fuels is: HFO: 0,9 MDO:0.9 and LNG/LPG: 0.6; thereafter 0.9 for all of them. The bunker levy will drop to half of these values (0.45 EUR/GJ) for sustainable fuels (sustainable biogas, sustainable bio-fuel and low-carbon fuels) and even more for renewable fuels (0.15 EUR/GJ) after 2033.

Despite the above measures being phased in over time, their impact on post-2020 GSC working scenarios, as expected, will be significant. The joint incorporation of MBM and GBM only three years after GSC enforcement is stressing, not only the shipping recovery capacity from the de-sulphuration investments, but also distorting stated knowledge about mitigation systems' performance in monetary and environmental terms. The lack of quantitative assessments about mitigation systems' suitability in the EU post-decarbonization era, is fomenting distrust in the sector (Psaraftis and Kontovas, 2020) - in both the proportionality of MBM and the effectiveness of GBM. Further doubts have been sown in the light of notable divergencies between the IMO and EU (Monios and Ng, 2021) and the low technological maturity of the most effective compliance solutions (low- and zero-carbon fuels are still too expensive,[2] Faber et al., 2021). This situation is particularly acute in Short Sea Shipping (SSS), where the positive effects of economies of scale are smaller when assuming new investments (CAPEX) and/or taking on additional operating costs (OPEX) for GBM and MBM compliance. EU-SSS decarbonization is even more challenging, because most recommended 'bridge-solutions' provided by operative research for compliance in the short-term (like low-steaming) are unfeasible under SSS operative requirements (Zis and Psaraftis, 2021).

Given this context, the purpose of this paper is providing a quantitative analysis of the joint impact of MBM and GBM on EU working scenarios for SSS in the 2020 GSC aftermath by addressing the following key questions:

- Are MBM proportional to EU-SSS vessels' real pollutant impact?
- Are SSS vessels equipped with 2020 GSC mitigation systems able to meet GBM in the EU?
- Are decarbonization measures in the EU able to promote more sustainable mitigation options in SSS?

Thus, this paper contributes to broadening knowledge about the effects of decarbonization regulation on SSS through their quantification by covering so, the existing gaps (see Section 2).

To this aim, the paper introduces a mathematical model (Section 3) that is able to quantify the costs of decarbonization compliance (MBM) for SSS vessels when they were equipped with different mitigation systems. In turn, vessels' pollutant impact of the vessels is estimated in the model by taking into account their technical features to determine the accomplishment level with GBM. Application of the model to an SSS container vessel, operating between the Iberian Peninsula and the Canary Islands (Section 4), has allowed to draw comprehensive conclusions, beyond the application case, relating to the proportionality of MBM versus SSS vessels' pollutant impact, the performance of mitigation systems under the most recent decarbonization regulation framework and the effectiveness of GBM and MBM to promote sustainable strategies among vessel operators (Sections 5 and 6). Finally, on the basis of this analysis, the paper offers some recommendations for policymakers and vessel operators to incentivize a transition to more sustainable patterns in SSS (Section 7).

2. Literature review

The following sub-sections provide a brief literature review where the main knowledge gaps are identified by justifying the need for the paper's targets (introduced in the previous section) and how these contribute to broadening existing knowledge.

2.1. *Abatement systems' choice*

A recurring theme over the last decade has been which abatement option is best to meet emission regulations in the maritime industry. This is because enforcement of this environmental normative involves a challenge for maritime transport and consequently policy-oriented research is required. Despite several technically-mature solutions being available for its compliance, the GSC in January 2020 (a maximum of 0.1% sulphur content is demanded for fuels in Emission Control Areas -ECA- and 0.5%S for remaining zones) stimulated numerous research projects to support decision-making from the techno-economic standpoint. Thus, Martínez-López et al. (2018) concluded that dual engines with Liquefied Natural Gas (LNG) were the most cost-effective option for feeder vessels by operating in SSS conditions under ECA requirements. Patricksson and Erikstad (2017) also found dual fuel engines to be optimal in feeder vessels but warned about a potential increase of CO_2 emissions under ECA regulations. The latter was also found by other authors (Lindstad et al., 2017; Ben-Hakoun et al., 2021) for post-2020 GSC performance, mainly due to the massive use of low-sulphur fuels and a possible increase in speed for vessels with scrubbers installed. Even though, forecasts about vessels' behaviour in operative terms following the 2020 GSC cannot yet be tested due firstly to the distorting effect of COVID-19 (Psaraftis et al., 2021), and then to Russia's aggression against Ukraine, a massive retrofitting of the vessels was a reality. The notable increase in vessels with scrubbers (4584 vessels in 2021 versus 740 in 2018; DNV-GL statistics, 2021) motived the latest publications about the scrubbers' performance as 2020 GSC abatement systems (Martínez-López et al., 2022) by considering the environmental impact of their wash-waters for open and closed-loop systems (Ytreberg et al., 2021; Hermansson et al., 2021). Likewise, the weaknesses of the remaining 2020 GSC mitigation systems have attracted attention due to their widespread implementation: mainly, methane slip for LNG-fuelled engines and ammonia slip for Selective Catalytic Reduction systems (NO_x reduction in Tier-III engines).

The aforementioned studies have provided a solid knowledge-base about the suitability of 2020 GSC mitigation systems in monetary and environmental terms, however the working scenarios assumed by these quantitative analysis were constrained to ECA requirements. Therefore, the impact of decarbonization measures on existing mitigation options' performance for SSS vessels has not been assessed by rendering the previous findings obsolete.

2.2. *Operative research in post-2020GSC*

In the post-2020 GSC era, the risk of evading regional environmental measures (Faber et al., 2022) along with the suspicion that the costs of compliance with emission limitations might be higher than the penalties for non-compliance (Zis and Cullinane, 2020), have been recurring concerns. Most relevant studies have suggested ensuring the

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[2] 3300 USD/tonne for H_2 against 375 USD/tonne for VLSFO in 2030, according to the IMO (2020).

effectiveness and accomplishment of the emissions reduction normative by imposing homogenous fines when non-compliance exists. However, in this regard, researchers are also warning that a fine system can only be effective through uniform maritime governance: this necessarily involves a clearly stated structure for all geographical areas (Zis and Psaraftis, 2021; Monios and Ng, 2021). The current context - characterized by a debilitation of maritime transport governance in global terms, especially for the environmental normative (Monios and Ng, 2021; Psaraftis and Kontovas, 2020) makes its effective implementation difficult (Monios and Ng, 2021). Even though these studies have contributed comprehensive findings relating to the need for a stricter penalty strategy for non-compliance regulations, these analyses do not jointly consider MBM and GBM proposed in the last EU framework, and therefore the total non-compliance cost for the SSS fleet have not yet been quantified in the literature and therefore the risk of non-compliance is uncertain.

2.3. Decarbonization regulations in shipping

Numerous decarbonization regulation studies have evaluated the reduction in GHG (from the initial IMO Strategy: a reduction of 50% in emissions by 2050, from the baseline year 2008) through GBM and MBM and therefore their effectiveness and feasibility in general terms (Chen et al., 2023). Among other conclusions, it has been highlighted that, whereas GBM has been found to be a useful tool to promote a smooth transition to more energy-efficient linear shipping (Zis and Psaraftis, 2021), from a comprehensive comparison of several MBMs (Chen et al., 2023; Psaraftis et al., 2021), levy-based measures (price-control approaches) are preferable to Emission Trading Systems (ETS) because, aside from regulatory coherence (Chen et al., 2023), the former reduces the uncertainty of carbon pricing fluctuation, administrative burdens and additional costs imposed by ETS administrators (Psaraftis et al., 2021). Although, these assessments have provided significant insights about the advantages and disadvantages of decarbonization measures, these were independently analyzed, without considering the implementation of several measures at the same time. Therefore, the relative weight of ever measure on overall compliance cost, together with their combined impact on (required) vessel investments, have been mostly left unattended.

2.4. Decarbonization compliance options

Transition from fossil to low- and zero-carbon fuels is widely recognized to be the most effective compliance solution for decarbonization (Tadros et al., 2023). However, most ship operators rule it out in the medium-term because it is excessively expensive (emerging technology, IMO, 2020). There is also often poor availability of these fuels in attending ports, due to the lack of bunker facilities (Faber et al., 2021). Given this situation, operative research has meanwhile attempted to find ‘bridge solutions’ for GBM compliance and offer general information about the mitigation capacity of different technologies (Marginal Abatement Cost Curves-MACC).

Thus, slow steaming (IMO, 2019a; Psaraftis et al., 2021; Zis and Psaraftis, 2021; Tadros et al., 2023), even, through Engine Power Limitation mechanisms (-EPL- IMO, 2019b; Ghaforian Masodzadeh et al., 2022; Bayraktar and Yuksel, 2023), has been suggested as the easiest solution (‘bridge solution’) for GBM compliance beside being the most cost-effective alternative in the short-term (Faber et al., 2021; Schroer et al., 2022). However, slow steaming was also found to be unfeasible in SSS (Raza et al., 2019) and liner shipping with perishable cargo (Zis and Psaraftis, 2021) as, aside from expected modal shifts caused by freight rate changes (Zis and Psaraftis, 2017; Zis et al., 2019), the increase in the number of vessels required to compensate the longer transit times to meet frequency requirements (scheduling) does not result to be a comprehensive solution for a sustainable SSS (Mallouppas and Yfantis, 2021).

Finally, information about GHG mitigation solutions (emerging and mature technologies) has often been provided through the MACC (GHG emission reduction versus cost efficiency, IMO, 2020; Faber et al., 2021) by estimating their abatement potential and the costs incurred for generalized vessel models. However, since abatement performance is highly dependent on each vessel’s profile (Irena et al., 2021; Faber et al., 2021), the specific navigation context and the technical specifications and cargo rates (Ghaforian Masodzadeh et al., 2022; Schroer et al., 2022); researchers have applied improvement tools over time to address the shortcomings from the MACC: Pareto frontiers (Yuan and Ng, 2017; Irena et al., 2021); sensitivity analysis (Hu et al., 2019); and a combination of them all (Irena et al., 2021).

Even though decarbonization compliance options have been a recurrent research topic over the last five years, the research has frequently focused on their cost-effectiveness without contextualizing the analysis to particular decarbonization measures (regional schedules and additional measures beyond IMO), for a particular time period, by considering the technical-operative features of the vessels. Consequently, the initial compliance level of SSS vessels is understated and therefore conclusions about the feasibility of new investments in decarbonization options are undermined.

Considering the above, the decarbonization impact on SSS was barely tackled from a quantitative standpoint in the aftermath of 2020 GSC, among other reasons, because MBM and GBM were not concreted by the EU until mid-2021. This paper attempts to address this research gap by broadening knowledge about the compliance level of SSS vessels with the actual EU decarbonization regulation when different 2020 GSC mitigation alternatives were adopted; the influence of MBM and GBM as tools of operative leverage towards sustainability and MBM proportionality in meeting the Polluter Pays Principle (PPP).

3. The method

The following paragraphs collect the calculation models that enable assessment of MBMs’ effectiveness (see Sections 3.1 and 3.2) and the performance of the 2020 GSC abatement systems to meet the new GBM (see Sections 3.3 and 3.4). In turn, once port impact - via the Environmental Ship Index calculation - is defined (see Section 3.5), Section 3.6 shows the Pollutant Impact (PI; in €/trip) calculation for SSS vessels equipped with several 2020 GSC mitigation alternatives (see Fig. 1). The comparison of SSS vessels’ PI versus the OPEX increase via MBM allows to assess the effectiveness of the normative in PPP accomplishment. Additionally, the analysis of GBM compliance by the SSS vessels equipped with several 2020 GSC mitigation systems enables to determine their performances and additional investment needs. Finally, Section 3.7 includes the NPC (Net Present Cost) calculation. This tool will be employed to analyze the feasibility of 2020 GSC abatement system investments by considering the new decarbonization regulation (see Fig. 1).

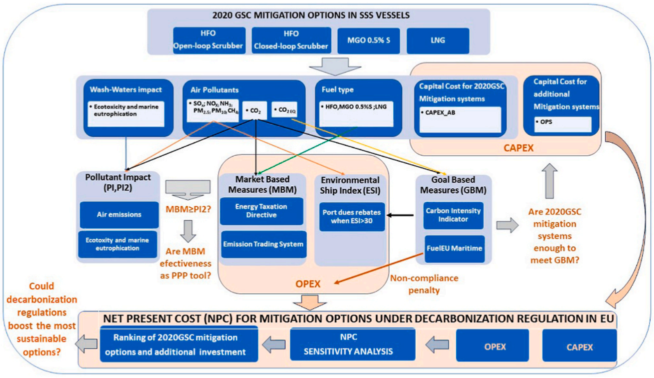

Fig. 1. Block diagram of the method.

3.1. MBM: energy taxation

Equations (1) and (2) show the Energy Taxation, yearly value and per trip respectively (N involves the annual trips, see Appendix A), from the enforcement of EU (2021c). Aside from the taxation level for kind of fuel ($J = \{1, \ldots, j\}$) used by the vessel (TL_j; $\forall j \in J$ in €/GJ), Equation (2) calculates the energy developed (in Gigajoules) at all navigation stages ($SS = \{1, \ldots, s\}$) by considering their operational times (TVB_s; $\forall s \in SS$), along with the calorific values of the fuels (CVj; $\forall j \in J$ in GJ/g), the propulsion power developed by the main engine at every navigation stage (PB_{1s}; $\forall s \in SS$ in kW), and its specific fuel consumption ($SFOC_{js1}$; $\forall j \in J \wedge \forall s \in SS$). The latter is dependent not only on the fuel type and navigation stage (%MCR of the engine) but also on the type of engine (2-stroke or 4-stroke). On-board electricity production is exempt from taxation, and likewise, the on-shore electric power supply to vessels can be exempted under the Member State's decision.

$$\mathrm{ETD} = \mathrm{N} \times \mathrm{ETU} \tag{1}$$

$$\mathrm{ETU} = \sum_{s=1}^{s} \left(\mathrm{TL_j} \times \mathrm{CV_j} \times \mathrm{SFOC_{j1l}} \times \mathrm{PB_{1s}} \times \mathrm{TVB_s}\right); \forall j \in J \wedge \forall s \in SS; \tag{2}$$

3.2. MBM: emission trading system

Equation (3) provides the annual carbon allowance cost for an SSS vessel operating under EU-ETS (see Appendix A), whereas Equation (4) offers this cost per trip by taking into account the EU carbon price (CP in €/CO_2 ton). Since the proposed EU-ETS (COM2021 (551) final) takes the CO_2 emissions from EU-MRV, Equation (4) assumes estimated CO_2 emissions by considering fuel consumption and conversion factors (CFF_{jl}; $\forall j \in J \wedge \forall l \in L$ in t CO_2/t fuel), from Annex VI to Commission Regulation (EU) No 601/2012). Fuel consumption is estimated by considering - aside from the power developed by on-board engines (PB_{ls}; $\forall l \in L \wedge s \in SS$) - their specific consumption ($SFOC_{jls}$; $\forall j \in J \wedge \forall l \in L \wedge \forall s \in SS$) and time invested at all navigation stages (TVB_s; $\forall s \in SS$). Additionally, the influence of jurisdiction of the port calls (from/to Member State $I = \{1, \ldots, i\}$, see also Appendix A) on emission quantification for EU-ETS is considered (α_i; $\forall i \in I$), along with the progressive inclusion of the whole emissions over years, collected in COM2021 (551) final (β_k; $\forall k \in K$).

$$\mathrm{ETS_k} = \mathrm{N} \times \mathrm{ETSU_k} \ \forall k \in K \tag{3}$$

$$\mathrm{ETSU_k} = \mathrm{CP} \times \alpha_i \times \beta_k \times \sum_{s=1}^{s} \left(TVBs \left(\sum\nolimits_{l=1}^{l} \left(\mathrm{SFOC_{jls}} \times \mathrm{PB_{ls}} \times \mathrm{CFF_{jl}}\right)\right)\right); \forall j \in J \wedge \forall k \in K \wedge \forall l \in L \wedge \forall s \in SS; \tag{4}$$

3.3. GBM: carbon intensity indicator accomplishment

In order to know the vessels' GBM fulfilment of IMO regulations over time, the CII (MEPC 336(76)) is evaluated by considering both attained CII (*CII_A*) and required CII (*CII_Rk*; $\forall k \in K$*) for every year*. The calculation for the former (Resolution MEPC.336(76) - 2021 Guidelines on Operational Carbon Intensity Indicators and the Calculation Methods (CII Guidelines, G1)) involves CO_2 grams per nautical mile and transported cargo tonnes (C representing cargo capacity of the vessel and D the trip distance, see Appendix A), as shown in Equation (5). Separately, *CII_Rk* - which is modified over time ($K = \{1, \ldots, k\}$) according to a yearly reduction factor (Z_k; $\forall k \in K$, MEPC338(76)-CII reduction factors guidelines,G3) relative to 2019 emissions (MEPC337 (76)-CII Reference line guidelines, G2) - is estimated in Equation (6). Moreover, Equation (6) collects factors *a* and *c* that are constant and dependent on vessel type (MEPC337(76)).

$$CII\_A = \sum_{s=1}^{s} \left(TVBs \left(\sum\nolimits_{l=1}^{l} \left(\mathrm{SFOC_{jls}} \times \mathrm{PB_{ls}} \times \mathrm{CFF_{jl}}\right)\right)\right) \Big/ (\mathrm{C} \times \mathrm{D}); \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \tag{5}$$

$$CII\_R_k = \left(1 - \frac{Zk}{100}\right) \times a \times C^{-c}; \forall k \in K \tag{6}$$

Guidelines on the operational carbon intensity rating of ships (CII Rating Guidelines- MEPC.339(76) – 2021-) collects the classification of vessels over time by warning about the obligation to introduce an energy efficiency strategy in SEEMP (-Ship Energy Management Plan, see MEPC.346(78)) to return to C or superior level, when a vessel obtains a score of D for three consecutive years, or an E rating in one year.

3.4. GBM: fuel EU maritime initiative

EU (2021b) addresses the Fuel EU Maritime initiative, which limits greenhouse gas intensity (grams of CO_2 equivalent per MJ) according to a progressive reduction over a reference value (average greenhouse gas intensity of the energy used on-board by ships in 2020 determined by data monitored and reported within the framework of Regulation (EU) 2015/757) with the following schedule: −2% from January 1, 2025; −6% from January 1, 2030; −13% from January 1, 2035; −26% from January 1, 2040; −59% from January 1, 2045; −75% from January 1, 2050. This scheduling was tightened for 2035 aftermath (−14.5 from January 1, 2035; −31% from January 1, 2040; −62% from January 1, 2045; −80% from January 1, 2050) by the Provisional agreement resulting from interinstitutional negotiations ((2021/0210(COD)) -Approval 23rd, May 2023).[3]

Non-compliance involves a penalty in euros ($Fuel\_EU_k$, $\forall k \in K$; see Equation (7)), with this value being proportional to the difference between the greenhouse gas intensity of the energy used on-board for the reported period ($GHGIE_{actual}$; in g $CO_{2\ eq}$/MJ) and the target one ($(GHGIE_{target})_k$, $\forall k \in K$; see Equations (7) and (9)) defined by the restriction's schedule established in the regulation for a particular year ($\forall k \in K$). The GHGIE estimation (in g $CO_{2\ eq}$/MJ, see Equation (9)) considers, aside from GHG emission factors ($CO_{2eq\ WtT,j}$; $\forall j \in J$; $CO_{2eq\ electricity,\ c}$; $\forall c \in C$, see Equation (10) and Appendix A), CO_2 equivalent emissions of combusted fuel ($CO_{2\ eq\ TtW,j}$; $\forall j \in J$, see Equations (11) and (12), and Appendix A).

The FuelEU penalty calculation assumes as vessel energy (in MJ, see Equation (8)) not only that produced by on-board engines ($L = \{1, \ldots, l\}$, see the first component of Equation (8)) but also the energy from the electricity delivered to the vessel at berth (in MJ, Ej; $\forall j \in J$) through an On Shore Power Supply (OPS).

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[3] https://www.europarl.europa.eu/RegData/commissions/tran/inag/2023/04-26/TRAN_AG(2023)746978_EN.pdf.

$$Fuel\_EU_k 2.4 \Big/ 41MJ \Big/ kg \times \left(\sum\nolimits_{s=1}^{s} \left(TVBs \times \sum\nolimits_{l=1}^{l} \left(SFOC_{jls} \times PB_{ls} \times CV_j \times 1 / 1000\right)\right) + \sum\nolimits_{c=1}^{1} E_c\right);$$

$$\left(\left(GHGIE_{t\ \mathrm{arg}\ et}\right)_k - GHGIE_{actual}\right) \Big/ GHGIE_{actual}; \forall c \in CC \wedge \forall j \in j \wedge \forall k \in K \wedge \forall l \in L \tag{7}$$

$$\mathrm{Vessel\_\_(Energy)} = \left(\sum_{s=1}^{s} (TVBs\left(\sum\nolimits_{l=1}^{l} \left(\mathrm{SFOC_{jls}} \times \mathrm{PB_{ls}} \times \mathrm{CV_j} \times 1 / 1000 \times \mathrm{RWD_{jl}}\right)\right) + \sum\nolimits_{c=1}^{1} \mathrm{E_c}\right); \forall \mathrm{c} \in \mathrm{CC} \wedge \forall \mathrm{j} \in \mathrm{J} \wedge \forall \mathrm{l} \in \mathrm{L} \wedge \forall \mathrm{s} \in \mathrm{SS}; \tag{8}$$

$$\mathrm{GHGIE} = \mathrm{WtT} + \mathrm{TtW} \tag{9}$$

$$\mathrm{WtT} = (1 / \mathrm{Vessel\_energy}) \times \left[\sum_{s=1}^{s} (TVBs\left(\sum\nolimits_{l=1}^{l} \left(\mathrm{SFOC_{jls}} \times \mathrm{PB_{ls}} \times \mathrm{CV_j} \times 1 / 1000\right)\right) \times \mathrm{CO_{2eqWtT,j}}\right.$$

$$\left. + \sum\nolimits_{c=1}^{c} \mathrm{E\_(c)} \times \mathrm{CO\_(2eq, electricity, c)}\right] \forall \mathrm{c} \in \mathrm{CC} \wedge \forall \mathrm{j} \in \mathrm{J} \wedge \forall \mathrm{l} \in \mathrm{L} \wedge \forall \mathrm{s} \in \mathrm{SS}; \tag{10}$$

$$TtW = (1 / Vessel\_energy) \times \left(\sum\nolimits_{s=1}^{s} \left(TVBs\left(\sum\nolimits_{l=1}^{l} \left(SFOC_{jis} \times PB_{ls} \times CV_j \times 1 / 1000\right)\right)\right)\right)$$

$$\times \left[CO_2 eq \quad TtW, j \times \left(1 - 1 / 100 \times C_{engine\_slip,j}\right) + CO_{2\ \ eq} TtW \ \ slippage, j \times 1 / 100 \times C_{engine\_slip,j}\right]; \forall j \in j \wedge \forall l \in L \wedge \forall s \in SS; \tag{11}$$

$$\mathrm{CO_{2\ eq\ TtW,j}} = \mathrm{CFF_j} \times \mathrm{GWP_{CO2}} + \mathrm{CFM_j} \times \mathrm{GWP_{CH4}} + \mathrm{CFN_j} \times \mathrm{GWP_{N2O}}; \forall \mathrm{j} \in \mathrm{J} \tag{12}$$

Moreover, according to this Communication, container and passenger vessels without zero-emission technologies, must be connected to OPS during berthing in ports from January 2030 (this enforcement might be moved to 2035 for comprehensive ports).[3]

3.5. Environmental ship index

Equation (13) collects the Environmental Ship Index[4] ($\mathrm{ESI_k}$; $\forall k \in$ K*)* value based on the formula developed by the IAPH (International Association of Ports and Harbors) to assess vessel sustainability by considering its fulfilment with IMO standards. This index is broadly used to articulate 'green charges' in port, however its application is patchy.

The Environmental Ship Index (see Equation (13)) considers the following pollutant emissions: $\mathrm{NO_x}$ ($\mathrm{ESINO_x}$), $\mathrm{SO_x}$ ($\mathrm{ESISO_x}$) and $\mathrm{CO_2}$ $(\mathrm{ESICO_2})_\mathrm{k}$; $\forall k \in$ K). $\mathrm{ESINO_x}$ calculation considers the NOx reductions on the basis of rated emission levels $(\mathrm{RVNO_x})_\mathrm{l}$; $\forall l \in$ L for the engines versus their normative thresholds ($\mathrm{LVNO_x}$); these being collected in MARPOL (ANNEX IV, Chapter 3, Regulation 13). Regarding the $\mathrm{ESISO_x}$ component (see Equation (15)), the emission reductions (%) are considered over the kind of consumed fuel (X_{ls}; $\forall l \in$ L$\wedge$ $\forall s \in$ SS for fuel-content less than 0.50% but greater than 0.10% S in MDO and Y_{ls}; $\forall l \in$ L$\wedge$ $\forall s \in$ SS for fuel equal to or less than 0.10% S; for all engines at the different navigation stages) along with the factors: *b* ($b = 50$) and *d* (this constant can achieve the values: 50, 70 or 100, according to the fuel type schedule in a trip[1]). In turn, Heavy Fuel Oil (HFO) consumption for vessels equipped with scrubbers (Bunker Delivery Notes -BDN) is transformed to the equivalent S% content fuel in terms of emissions after scrubbing.

Before the CII Regulation was approved, $\mathrm{CO_2}$ was assessed through the EEOI (Energy Efficiency Operational Indicator, MEPC.1/Circ.684) to determine $\mathrm{ESICO_2}$, however according to the IAPH[5] the next ESI version will incorporate CII, so this modification has been already considered for the $(\mathrm{ESICO_2})_\mathrm{k}$ ($\forall k \in$ K) calculation in Equation (13), where the seconds summand can only be positive or zero. Thus, to consider the CII Regulation, the $\mathrm{CO_2}$ contribution must be assessed annually (K = {*1, …,k*}) by obtaining an annual ESI value ($\mathrm{ESI_k}$; $\forall k \in$ K, see Equations (13) and (16)) *conditioned by the CII implementation schedule.* Since the relative reduction in energy efficiency, which was initially compared to the baseline, must be updated according to the difference between the required and attained CII (*CII_A* versus *CII_R$_k$*; $\forall k \in$ K when a saving exists, see Equation (16)) for every year (MEPC337(76)-CII Reference line guidelines, G2). Finally, 10 sub points are added to the vessels with OPS technology (see Equation (17)).[6]

$$(ESI)k = ESINOx \times (2/3) + ESISOx \times (1/3) + (ESICO2)k + ESIOPS \ \forall k \in \mathrm{K} \tag{13}$$

$$ESINOx = \frac{100}{\sum\limits_{l=1}^{l} PBRl} \cdot \sum_{l=1}^{l} \frac{(LVNOx - RVNOx)l \cdot PBRl}{(RVNOx)l}; \forall l \in \mathrm{L} \tag{14}$$

$$ESISO_x = \sum_{s=1}^{s} \sum_{l=1}^{l} (b \times X_{ls} + d \times Y_{ls}); \forall \mathrm{l} \in \mathrm{L} \wedge \forall \mathrm{s} \in \mathrm{SS} \tag{15}$$

$$(ESICO2)k = 5 + 10 \times (CII\_Rk - CII\_A)/CII\_Rk \ \forall k \in \mathrm{K} \tag{16}$$

$$ESIOPS = 10; (if\ fitted) \tag{17}$$

Even though the IMO encourages port authorities to provide additional incentives for A or B rated ships to stay up-to-date, there is no specific initiative in this regard.

3.6. Pollutant impact

Pollutant Impact (PI, see Appendix A) offers a tool to evaluate the sustainability (see Equation (18); Martínez-López et al., 2022) of different 2020 GSC compliance options in terms of the cost (€/trip), by considering climate change and air quality (CEM_s; $\forall s \in$ SS) along with ecotoxicity (EME_s; $\forall s \in$ SS) and marine eutrophication (ETR_s; $\forall s \in$ SS) of scrubbers' wash waters.

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[4] https://www.environmentalshipindex.org/info.

[5] https://www.iaphworldports.org/news/iaphnews/13183/.

[6] The second summand can only be positive or zero.

Table 1
Initial characteristics for Feeder vessels.

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
Main engine[a] (BHP kW)	8300
TEUs/(reefer)	869/234
Auxiliary engines (kWe)[b]	3X590
PTO (kw)	1800
Bow thruster (kW)	880
Lightweight (t)	4666.21

[a] MAN B&W G50ME-C9.6-LPSCR.
[b] MAN 5L23/30DF.

$$PI = \sum_{s=1}^{n} CEM_s + \sum_{s=1}^{n} EME_s + \sum_{s=1}^{n} ETR_s; \forall s \in SS \quad (18)$$

The CEM_s ($\forall s \in SS$) calculation considers the unitary costs and emission factors[7] from different abatement systems for SSS vessels (Martínez-López, et al., 2022) by taking into account the following pollutants: acidifying substances (SO_X), ozone precursors (NO_x), particulate mass ($PM_{2.5}$ and PM_{10}), greenhouse gases (CO_2, CH_4) and ammonia slip (NH_3). In turn, the contaminants collected in Appendix 3 of the 2021 Guidelines for Exhaust Gas Cleaning Systems –(MEPC.340 (77)), mainly Polycyclic Aromatic Hydrocarbons (PAHs) and metals, are taken into account for the ecotoxicity evaluation of scrubbers' wash waters (*EMEs*; $\forall s \in SS$). Regarding the marine eutrophication assessment (*EMEs*; $\forall s \in SS$), nitrogen concentrations from the scrubber's discharge are considered.

The environmental impact of wash waters from scrubbers in terms of ecotoxicity (*EMEs*; $\forall s \in SS$) is estimated by assuming ecotoxicological midpoint characterization factor to ocean water for every contaminant in kg 1,4 DCB-eq/kg pollutant (ReCiPe, 2016) and the monetary value for marine ecotoxicity (€/kg1,4 DCB-eq) following the approaches from Martínez-López et al. (2022) and Ytreberg et al. (2021), among others. Thus, whereas the Environmental Price Method (De Bruyn et al., 2018) can be used to monetize eutrophication and ecotoxicity on the marine environment from scrubbers' discharge, in the EU context, the European Commission's Handbook on the External Costs of Transport (last updated in 2019; Van Essen et al., 2019) collects the unitary cost for pollutant emissions (per country, by considering pollution density in geographic locations).

3.7. Net present cost

Often Net Present Value (NPV) is often used to assess investments, especially in engineering projects. However, in the current normative framework, GBM and MBM provide negative cash-flows over time (CF_m; $\forall m \in M$, see Equation (20)) due to additional capital and operative costs. Consequently, the expected NPV will be negative in the new scenarios for analysis. For this reason, the Net Present Cost (NPC) is proposed as assessment tool with the same meaning as NPV, but with a negative sign. That is, the present value of the costs of installing the 2020 GSC abatement systems (*CAPEX_AB,* see Equation (19)) through retrofitting SSS vessels and the present value of all the costs ($CAPEX_m$ and $OPEX_m$; $\forall m \in M$, see Equation (20)) that it incurs over the project lifetime.

Since the evaluated investments in 2020 GSC mitigation systems do not only involve different revenues, but also different capital and operative costs over the project lifetime, NPC (see Equation (19)) offers information about the investment's alternative that is not only able to meet the decarbonization regulation and the 2020 GSC, but also minimizes the NPC. Therefore, the 2020 GSC abatement system alternatives are classified according to their higher *NPC* values (minimum life cycle cost).

$$NPC = -CAPEX\_AB + \sum_{m=1}^{m} \left(\frac{CF_m}{(1+R)^m} \right) \forall m \in M \quad (19)$$

Equation (19) shows the *NPC* calculation by considering, aside from the discounting rate (R), the total cash flow (CF_m; $\forall m \in M$) for every year considered over the investment lifetime $M = \{1, \ldots, m\}$, by assuming 2019 to be the retrofitting year for SSS vessels. The Cash Flow calculation (CF_m, $\forall m \in M$ see Equation (20)) integrates only costs. Thus, along with the $OPEX_m$ ($\forall m \in M$, see Equation (21)), the possible investments ($CAPEX_m$; $\forall m \in M$) in additional mitigation systems (aside from the initial retrofitting for 2020 GSC mitigation alternatives-*CAPEX_AB*-) are taken into account when the SSS vessel does not fulfil the GBM (see Sections 3.3 and 3.4).

$$CF_m = CAPEX_m + OPEX_m; \forall m \in M \quad (20)$$

$$OPEX_m = MBM_m + BUNKER_m + PortDues_m + Fuel\text{-}EU_m \ \forall m \in M \quad (21)$$

$$MBM_m = ETS_m + ETD_m \ \forall m \in M \quad (22)$$

Even though, bunker and Port Due costs ($BUNKER_m$ and $PortDues_m$ $\forall m \in M$ respectively in Equation (21)) exist for all years, the MBM_m ($\forall m \in M$, see Equation (22) where ETS_m and ETD_m; $\forall m \in M$ are defined in Equations (1) and (3)) only involves costs when the evaluated year is in the aftermath of 2022 ($m \geq k$; $\forall m \in M \wedge \forall k \in K$, see Appendix A). Likewise, the $FuelEU_m$ ($\forall m \in M$) will only involve a penalty in costs from 2025. Additionally, port dues (see Equation (21)) are conditioned by the rebates due to the *ESI* values (see Section 3.5).

4. Application case

The method introduced above is applied to a particular feeder vessel (see Table 1) operating between Cadiz port (in the south of the Iberian Peninsula) and Las Palmas port (Canary Islands), which covers a maritime distance of 687 nautical miles. Assuming linear shipping conditions (SSS), the vessel invests $TVB_1 = 37.14$ h in free sailing (18.5 kn of average speed); $TVB_2 = 0.5$ h (per port) in manoeuvring (4 kn) and; $TVB_3 = 3$ h (per port) in loading/unloading operations. However, due to sleeping time (scheduling requirements), every trip involves 14 additional hours at berth ($TVB_4 = 7$ h -per port-).

To comply with 2020 GSC, four possible abatement alternatives are assessed for the vessel's retrofitting by providing different environmental performances (Martínez-López et al., 2022): HFO fuel with open-loop scrubber, HFO fuel with closed-loop scrubber, MGO and LNG fuelled engine. Although the MGO option does not involve a significant cost in the vessel's retrofitting (see Table 1), the other alternatives mean significant CAPEX. In all cases, the analysis assumes investment decisions made in 2019, in order to meet the 2020 GSC, and a study time range: from 2019 to 2031.

During free sailing, the sulphur content for the bunker is assumed to be 0.5%S for MGO whereas for HFO, three possible scenarios are assessed: 3.5%S, 2%S and 1%S. Nevertheless, these %S must be reduced to 0.1% S (or equivalent emissions) in EU port operations (Directive 2005/33/EC; amending Directive 1999/32/EC). This fact, along with the prohibition of open-loop scrubbers in Spanish ports, means that open-loop scrubbers and MGO alternatives take 0.1%S MGO as bunker for main and auxiliary engines in port (manoeuvring and berthing navigation stages). Furthermore, abatement capacity of 98% for SO_2 emissions and 55% for $PM_{2,5}$ for all scrubbers is assumed for emission calculations (Ship Design Programs for Emission Calculations, DTU).

4.1. Market based measures, pollutant impact and OPEX

The PI calculation follows the Martínez-López et al. (2022) approach

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[7] https://www.mek.dtu.dk/english/sections/fvm/software/ship_emissions.

Table 2

Capital costs for investments over the project's lifespan.

2020 GSC Mitigation systems[a]	Minimum	Average	Maximum
Scrubber(Open-loop) (€/kW)	156	209.25	296.52
Scrubber(Closed-loop) (€/kW)	363	412.75	486
MGO (€/kW)	16.01	16.63	17.25
LNG (€/kW)	603.63	723.52	783.28
Additional investments[b]			
OPS (€/GT)	38.4	48	57.6

[a] Costs for 2019.

[b] Costs for 2022.

(see Section 3.6) of using Spanish CPI (12.7% from 2016 to 2022, National Statistics Institute of Spain, 2022) to update air pollutants' unitary costs published by Van Essen et al. (2019). Additionally, the EU-27 countries' average CPI (13.3% from 2016 to 2022, Eurostat, 2022) are considered to calculate monetary values of ecotoxicity and eutrophication under the Environmental Price Method (De Bruyn et al., 2018).

MAN B&W G50ME-C9.6-LPSCR and MAN B&W G50ME-C9.6-GI-LPSCR for fuel-based engines and LNG-fuelled engines respectively, are chosen for the vessels and consequently, their technical features (engines' power PB_{ls}; $\forall l \in L \wedge \forall s \in SS$; specific fuel consumption: $SFOC_{jls}$; $\forall j \in J \wedge \forall l \in L \wedge \forall s \in SS$) for a free sailing speed of 18.5 kn and 4 knots in manoeuvring are taken for the GBM and MBM estimations. In turn, it is necessary to bear in mind that Power Take Off (PTO) produces full electrical power during free sailing (1,570 kW) in all cases, and therefore the generating sets (MAN 5L23/30DF, see Table 1) only operate in port (2400 kW for manoeuvring and 1470 kW for the berthing stage) in the base case.

The $OPEX_m$ calculation ($\forall m \in M$, see Equation (21)) requires estimation over time, so to meet this aim, the projection of the expected average CPI for EU-27 countries over the next 10 years (at an annual increase of 0.89%; Eurostat, 2022) is applied as the inflation rate. In such a way, aside from updating port dues ($PortDues_m$; $\forall m \in M$, see Equation (21)), this rate is used to update the MBM, from 2023 to the folowing years: the taxation level applicable to fuels (TL_j; $\forall j \in J$, see Annex A) and the Carbon Price (-CP- see Equation (4)) for the Carbon Allowance Cost (EU-ETS (COM2021 (551) final). Despite the relevance of the bunker costs on the OPEX, the assessment carried out in this application case does not include these costs ($BUNKER_m$; $\forall m \in M$, see Equation (21)) due to their high volatility in recent years. This behaviour distorts performance of the 2020 GSC mitigation systems versus the decarbonization normative and introduces an uncertainty level that is too high (due to inconsistent forecasts) to achieve reliable findings.

For the Carbon Allowance Cost in the EU-ETS, a base value $CP = 67€/tCO_2$ (Faber et al., 2022; Lagouvardou and Psaraftis, 2022) is considered for 2022. At this point, it is interesting to highlight the difference between the carbon pricing for the MBM calculation based on the EU-ETS ($CP = 67€/tCO_2$, for 2022) and the unitary price for CO_2 in the PI calculation (see Section 3.6 and Martínez-López et al., 2022). For the latter, the central value for the climate change avoidance cost is taken: $100€/tCO_2$ for 2016 in the short and medium term (up to 2030; Van Essen et al., 2019). This is so for the standard PI estimation in order to provide accurate estimations about the harmful effect of the shipping emissions in absolute terms. However, the same source (the Handbook on the External Costs of Transport; Van Essen et al., 2019), collects a low value for CO_2 as well: $60€/tCO_2$ for 2016. This value enables to establish a realistic comparison between the vessel's environmental impact and the MBM in monetary terms by calculating, aside from the standard PI with CO_2 central values (PI), the Pollutant Impact with $CP = 67€/tCO_2$ (PI2), since the latter is very close to the low value of CO_2 when this is updated to 2022.

Estimation of the penalty, due to FuelEU non-compliance (FuelEU, see Equation (7)), has been carried out by considering the default values indicated in the Annex of EU (2021b) ($CO_{2\ eq\ WtT,j}$; CFM_j; CFN_j; $\forall j \in J$, see Equations (10) and (12)). To meet this aim, the Global Warming Potential for the pollutants (GWP_{CO2}; GWP_{CH4}; GWP_{N2O}, see Equation (12)) was taken from information published by The Intergovernmental Panel on Climate Change (IPCC),[8,9]. Finally, the engine fuel slippages were not considered in the evaluation, except for LNG. In this case, since the engine is dual-diesel, $C_{engine\_slip,\ 3} = 0{,}2\%$ (see Equation (11) and Appendix A).

In order to simplify the ESI application in EU ports (see Equation (13)), a charging scheme that rewards vessels with an ESI score >30 is assumed for all ports in the EU (numerous EU ports impose this threshold: Rotterdam, Gothenburg, Bergen, Antwerp, etc). Despite the large variety of applicable discounts, a 10% rebate is assumed over base port ship dues when a vessel's score achieves 31 (Final Report, 2017 from CONTRACT MOVE/B3/2014-589/SI2.697889). Finally, a charge based on gross tonnage (GT) is applied for the calculation because this is the most frequent charging method in the EU. Therefore only 'ship duty' (tonnage charge) will be affected by the eco-rebate. In this application case ship duty for the vessel was calculated by considering the tariffs of the ports involved (i.e., Las Palmas de Gran Canaria[10] and Cádiz[11]).

4.2. Net present cost, CAPEX, and the sensitivity analysis

Whereas the assumed discount rate is 4% (this rate was used by the IMO (2020) in the MACC calculations) for NPC calculation, the inflation rate was applied on the Cash Flow calculations (CF_m; $\forall m \in M$, see Equation (20)) according to the CPI, as was seen in the previous section related to the OPEX update over time.

Regarding the capital costs, the LNG investment includes not only the dual engine cost but also the LNG system: tanks, bunker station, gas preparation and gas line (Danish Environmental Protection Agency, 2013; Germanischer Lloyd, 2013; SSPA SWEDEN AB, 2012, Danish Maritime Authority, 2012). Likewise, the scrubbers cost: closed-loop (Danish Environmental Protection Agency, 2013; Den Boer and Hoen, 2015) and open-loop (Germanischer Lloyd, 2013; Den Boer and Hoen, 2015) include the whole equipment. The MGO investment involves the engine retrofit for the fuel change from HFO to MDO on the base engine (MAN B&W G50ME-C9.6-LPSCR, see Table 1). Finally, OPS costs are based on information provided by the IMO[12] for investment in new shipbuilding but considering the extra cost by its installation in an existent ship (additional 50%[13]). Taking into account dispersion found for the industry prices, Table 2 shows updated values from mentioned sources (through CPI for EU-27 countries, Eurostat, 2022) for the average, minimum and maximum costs of 2020 GSC mitigation systems in 2019 (CAPEX_AB, see Equation (19)), along with the capital cost for OPS installation (CAPEX for 2022, see Equation (20)). These values are suitable to estimate the capital costs of conventional SSS vessels (6000–12,000 kW and 5000–10,000GT).

Aside from the capital cost dispersion, the high volatility of the Carbon Allowance Cost (daily values) and the current economic instability (the post-COVID-19 era along with **Russia's aggression against Ukraine, among other drivers), which** has led to unusual inflation rates in the EU (very high CPI values), suggest the need to test the consistency of the results achieved (base scenario) through a sensitivity analysis. This will be carried out by considering probability functions for the inputs: investments' capital costs (see Table 2), possible fluctuation for the average yearly value of the Carbon Allowance Cost ($CP = 67€/tCO_2$ in 2022) in the EU-ETS: 30–150 $€/tCO_2$ (Faber et al., 2022;

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[8] 2000 IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.

[9] Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.

[10] https://www.palmasport.es/en/fees/.

[11] https://www.puertocadiz.com/en/services-for-professionals/fees-and-tariffs/.

[12] https://glomeep.imo.org/technology/shore-power/.

[13] https://sustainableworldports.org/ops/costs/investments/.

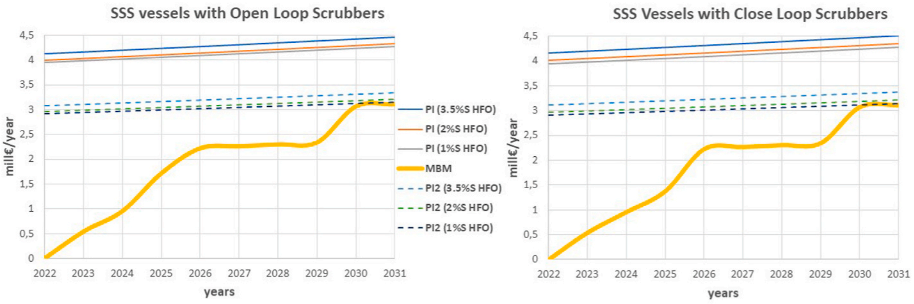

Fig. 2. MBM versus PI in an SSS containership with scrubbers by assuming central and low avoidance costs for CO_2 in climate change.

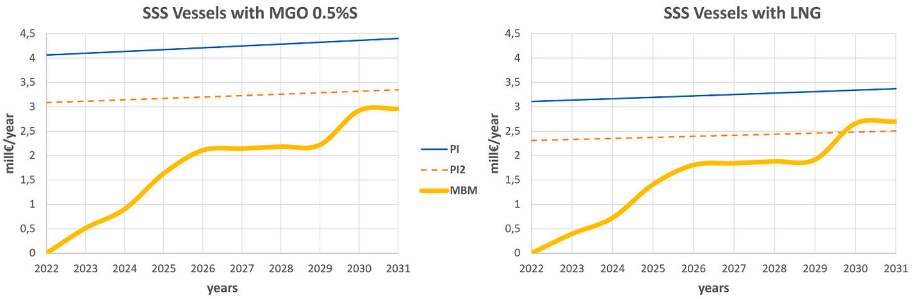

Fig. 3. MBM versus PI in an SSS containership with MGO and LNG propulsion by assuming central and low avoidance costs for CO_2 in climate change.

Lagouvardou and Psaraftis, 2022) and the expected average inflation rate for the project's lifespan in EU (CPI = 0.89–3%, 2023–2031).

5. Results

The following sections show the analysis undertaken under the assumptions in the application case.

5.1. *Effectiveness of the market based measures*

The MBM (ETD and ETS, see Equations (1) and (3)) were estimated along with the penalty for non-compliance with the FuelEU Regulation (see Equation (7)) in order to know the proportionality of these measures with regard to the ship's actual environmental impact. Thus, the aggregated MBM are compared with the vessel's pollutant cost through its pollutant impact (PI and PI2, see Equation (18)) by considering several mitigation systems that enable fulfilment of the 2020 GSC. The MBM estimation provides the expected costs from 2022 to 2031 by taking into account the fact that, despite the decarbonization regulations being effective from January 2023, their requirements and therefore its stringency levels are progressive over time. This is the case of ETS (COM2021 (551) final), in which surrender allowances are gradually phased in from 2023 to 2025; it is only from 2026 when the total CO_2 emissions recorded by EU-MRV ($\beta_k = \beta_4 = 100\%$; see Equation (4) and Annex A) will be considered for surrendered allowances. Likewise, the FuelEU Regulation imposes step reductions over 2020 records (grams of CO_2 equivalent per MJ), with the first step in 2025 and the next in 2030 (2% and 6% respectively, see Section 3.4). This progressive inclusion of the restrictions justifies the shape of the MBM curves in Figs. 2 and 3, where the significance of the years 2025, 2026 and 2030 (previously explained) motives the MBM performance steps.

Fig. 2 shows the evolution of MBM's effectiveness as PPP tools through the assessment of the vessel's pollutant impact equipped with scrubbers. Both the closed- and open-loop scrubber alternatives show the MBM level (the thickest line) to be practically coincident or lower than the vessel's pollutant impact. The latter was estimated by assuming

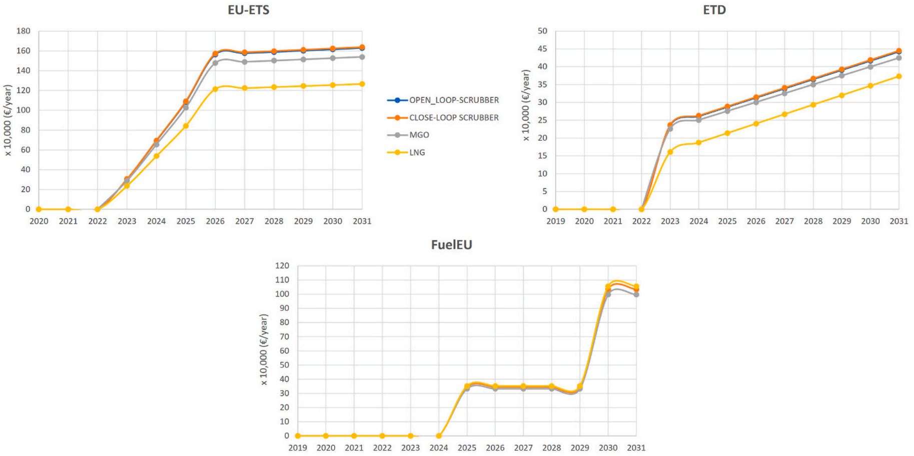

Fig. 4. Evolution of MBM costs for the 2020GSC mitigation alternatives.

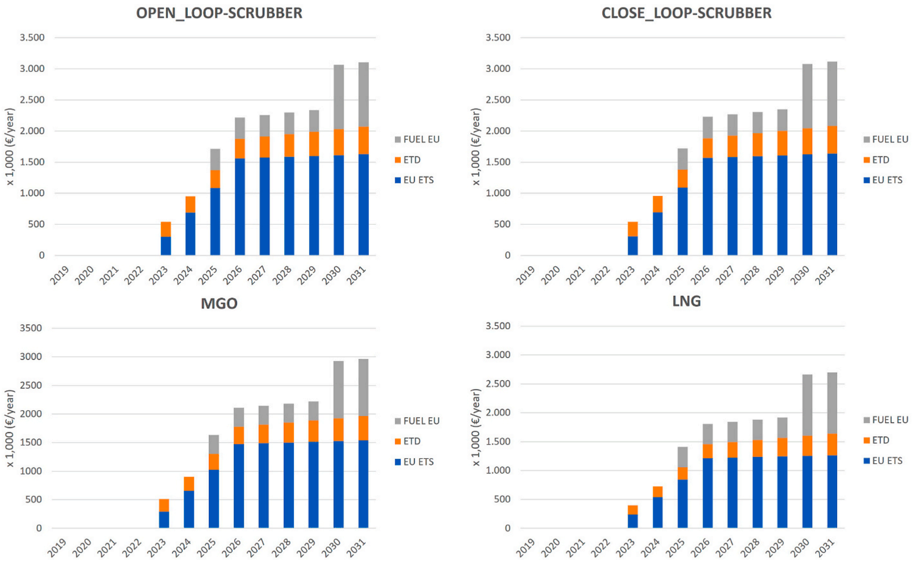

Fig. 5. Relative weigh of every measure in the total MBM for the 2020 GSC mitigation alternatives.

several possible Sulphur concentrations for HFO (3.5%S, 2%S and 1%S, see Fig. 2). The central value for the climate change avoidance cost of CO_2 was also considered for the calculation (PI, continuous lines, see Fig. 2), along with its low value (PI2, see interrupted lines in Fig. 2) to enable a balanced comparison with MBM in the analysis of the results.

In all cases a progressive approach of MBM to pollutant impact is found, such that in 2030 the deviation between MBM and PI2 is low in all scenarios: from 1.62% to 7.12% for open-loop scrubbers and from 0.97% to 7.61% for closed-loop scrubbers. In other words, at least 92.4% of the pollution produced by the shipping with scrubbers would be covered by the aggregated MBM (ETD, EU-ETS and the penalty for non-compliance with the FuelEU Regulation) in monetary terms. MBM achieves maximum effectiveness (98–100%) to cover vessels' pollutant impact when the measures are applied to SSS vessels with scrubber by using HFO under 3.5%S (1%S and 2%S, see Fig. 2) or LNG-fuelled engines in the aftermath of 2030.

However, when the measures are applied to LNG vessels (dual engines) in the aftermath of 2029, MBM achieve higher values than the vessels' pollutant impact (7.72% over PI2 in 2030, see Fig. 3). MBM effectiveness would reach the lowest fitting in its application to MGO vessels (0.5%S fuel) by covering 88.47% of the pollutant impact in monetary terms Thus, although this approach reveals a good fit of MBM (including FuelEU penalty) to the actual harmful environmental impact of the vessels, by ensuring PPP through progressive effectiveness, MBM application to LNG-fuelled engines should be adjusted to real pollutant impact of these vessels from 2029.

5.2. Market based measures' impact on the OPEX

Figs. 4 and 5 show the evolution of disaggregated MBM for every mitigation alternative. Whereas LNG dual-engine provides a clear advantage for ETD (increase in the minimum levels of taxation shall be fixed at one tenth per year, -TL_j; $\forall j \in J$-according to COM(2021)563, see Fig. 4) and EU-ETS compared with the other options, due to the minor CO_2 emissions from this alternative, the possible FuelEU Regulation penalty for non-compliance is practically equivalent in all (See Fig. 4). This is so, even though FuelEU is a little higher for LNG due to its lower GHG intensity of the energy used on-board ($GHGIE_{actual}$, see Equation (7)), mainly due to a lower $CO_{2\ eq\ TtW,j}$ ($\forall j \in J$; see Equations (9)–(12)) value. Fig. 5 collects the relative weight of every measure in the total MBM, with EU-ETS being the most significant (47–53% of the total in 2031) and the ETD, those with the least relative weight (13–15% in 2031). As expected, LNG has the lowest total MBM, and the closed-loop scrubber the highest (see Figs. 2 and 3). This is due to the increase in required power for recycling the wash-water and the additional weight of this equipment versus the open-loop scrubber (Martínez-López, et al., 2022).

5.3. Goal based measures' impact on the CAPEX

Even though the 2020GSC mitigation systems do not result to be a solution on their own for decarbonization, LNG proves to be the most promising option to meet the decarbonization normative in the medium term. However, it is also necessary to assess the impact of GBM compliance, since regardless of the MBM cost (OPEX increase), non-compliance in the time range (2022–2031) demands modifications on vessels' operative pattern and/or their mitigation technology (CAPEX). In this way, emissions can be reduced over time compared to those initially expected (see Figs. 2–5) and consequently, PI, PI2 and the costs of MBM would be also modified.

Table 3 collects the CII influence on the ESI calculation. Due to the similar environmental performance of the closed- and open-loop scrubbers, their ESI are coincident. Likewise these values are constant over the years for vessels with scrubbers because the $(ESICO_2)_k$ only introduces annual modifications when the vessel provides a better performance than that required (see Equation (16)); however, this also motivates the annual ESI modification in the LNG fuelled vessel (see also the CII class evolution in Table 3). Regardless of the ESI evolution, all alternatives of mitigation systems offer ESI scores over 30 points, therefore all will obtain port dues' return (10% rebates according to the initial assumptions for the application case).

Table 3 also shows the accomplishment with CII regulation (GBM) during the time range analyzed; thus, from 2025 vessels equipped with scrubbers, regardless of their mode (open- or closed-loop), should consider possible retrofitting or a severe modification of their operational pattern (a corrective action plan to return to the required rating of C or higher, because since the D score is achieved for three consecutive years) to fulfil this GBM (Regulation 26, MARPOL Annex VI). The same need is found for the MGO 0.5%S option, but in 2028. However, this is not the case for vessels with LNG fuelled engines as 2020 GSC mitigation systems because, in this case, they fulfil the CII regulation (with at least a C score, MEPC.339(76)) for all evaluated years.

Paying attention to other GBM, FuelEU Regulation's accomplishment, this requires two reductions in $CO_{2\ eq}$ are required in the time range considered: -2% from January 1, 2025 and -6% from January 1, 2030. Even though this Regulation only demands a non-compliance

Table 3
CII class and ESI evolution of the SSS containership using various 2020 GSG abatement systems.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
OPEN LOOP SCRUBBERS	C	D	D	D	D	D	E	E	E	E
3.5%S HFO	55.46	55.46	55.46	55.46	55.46	55.46	55.46	55.46	55.46	55.46
2%S HFO	56.53	56.53	56.53	56.53	56.53	56.53	56.53	56.53	56.53	56.53
1%S HFO	57.32	57.32	57.32	57.32	57.32	57.32	57.32	57.32	57.32	57.32
OPS INVESTMENT 2024	**C**	**D**	**D**	C	C	C	C	D	D	**D**
CLOSED LOOP SCRUBBERS	**C**	**D**	**D**	**D**	**D**	**D**	**E**	**E**	**E**	**E**
3.5%S HFO	55.46	55.46	55.46	55.46	55.46	55.46	55.46	55.46	55.46	55.46
2%S HFO	56.53	56.53	56.53	56.53	56.53	56.53	56.53	56.53	56.53	56.53
1%S HFO	57.32	57.32	57.32	57.32	57.32	57.32	57.32	57.32	57.32	57.32
OPS INVESTMENT 2024	**C**	**D**	**D**	C	C	C	C	D	D	**D**
MGO 0.5%S	**C**	**C**	**C**	**C**	**D**	**D**	**D**	**D**	**E**	**E**
	41.70	41.34	41.34	41.34	41.34	41.34	41.34	41.34	41.34	41.34
OPS INVESTMENT 2024	**C**	**C**	**C**	B	C	C	C	C	C	D
LNG	A	A	B	B	B	B	B	C	C	C
	58.97	58.56	58.38	58.20	58.00	57.80	57.59	57.37	57.13	56.89
OPS INVESTMENT 2024	A	A	**B**	A	A	A	A	A	A	B

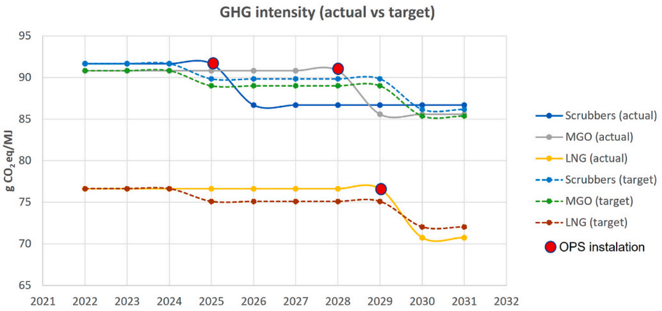

Fig. 6. Evolution of the actual GHG intensity (FuelEU) versus the target value when OPS is installed for 2020 GSC mitigation alternatives.

penalty, and therefore the vessel's retrofitting or an operative modification is not required, the Communication (EU, 2021b) does include an obligatory OPS connection at berth for container vessels from January 2030.

Therefore, an implicit obligation exists for OPS vessels' retrofitting under the conditions assumed in this application case. Given the lack of compliance with CII for MGO and scrubber alternatives before 2030, the OPS arises as the most probable solution to meet both GBM in the time range assumed. Table 3 shows a positive evolution of the CII score when the OPS is installed in 2024 in all cases.; 2024 taken as the year's investment would permit additionally, to meet the reduction schedule specified in the FuelEU Regulation (start date 2025). This investment decision would therefore avoid significant economical penalties (see Fig. 5) by keeping the actual GHG intensity below target values up to 2030 in all cases (see Fig. 6).

Post-2030, OPS installation also enables vessels to reach the required 6% reduction in LNG fuelled vessels (see Fig. 6) and significatively reduces the FuelEU penalties for the remaining alternatives. Even though the OPS does not modify the expected ETD because it does not affect the electricity generated on-board, the OPS indeed reduces the EU-ETS costs, and consequently the MBM overall. Table 4 shows the expected reduction achieved over time in MBM through OPS installation in 2024. These percentages are strongly conditioned by the Measure's phased introduction milestones (see β_k; $\forall k \in$ K in the EU-ETS and $(\mathrm{GHGIE}_{\mathrm{target}})_{\mathrm{k}}$ $\forall k \in$ K in the Fuel-EU): 2025, 2026 and 2030.

Despite the OPS being an efficient solution to achieve significant savings in the expected OPEX for vessels, when we focus attention on CII evolution (see Table 3) it is not a sufficient compliance-solution over the time studied for vessels fitted with scrubbers, since in 2031 they would return to non-compliance under the CII Regulation (following the third D) and, consequently, they would need to introduce a new corrective solution.

Given the above, the GBM force to additional CAPEX to meet their requirements: OPS investment at the latest by 2024 and additional investments in vessels with scrubbers by 2031. Consequently, the investments in abatement systems to meet the 2020 GSC (*CAPEX_AB,* see Section 3.7), regardless of the alternative chosen, will be insufficient for decarbonization compliance, in such a way the needs of new investments must be implemented on the scenarios of analysis along with additional OPEX generated by MBM effects in the 2020 aftermath.

5.4. Analysis of investments in 2020 GSC mitigation systems under the decarbonization regulations

Previous sections evinced a right fit between the PI2 and MBM (see Figs. 2 and 3) that suggests that, due to the significant environmental advantage provided by LNG fuelled vessels versus the other 2020 GSC mitigation alternatives (see Figs. 4 and 5), MBM could boost an operative leverage towards this mitigation alternative in the years to come. To this end, Table 5 collects the NPC calculated for all possibilities of a vessel's retrofitting in 2019 to meet 2020 GSC requirements until 2031. Likewise, according to previous findings, an additional investment in OPS retrofitting is also assumed in 2024 for all possibilities to meet GBM.

The NPC results reveal that the LNG alternative, even though it offers a better perspective in the 2031 aftermath in terms of new investments (see CII score in Table 3), continues to be strongly hampered by its initial investment (see Table 5). Thus, the advantage obtained from MBM in relation to the remaining alternatives (a 24–27% relative reduction in MBM costs, see Table 5) does not prove to be enough to motive a clear tend towards LNG election. Despite the fact that open-loop scrubbers

Table 4
Reduction in the MBM costs when OPS is installed in 2024.

	2025	2026	2027	2028	2029	2030	2031
OPEN-LOOP SCRUBBER	28.08%	24.35%	24.25%	24.15%	24.05%	38.65%	38.49%
CLOSED-LOOP SCRUBBER	27.95%	24.23%	24.13%	24.03%	23.93%	38.54%	38.39%
MGO	28.76%	25.04%	24.94%	24.84%	24.74%	41.33%	41.17%
LNG	35.05%	30.66%	30.54%	30.42%	30.30%	49.99%	49.81%

Table 5

Net present cost obtained for the investment projects in 2020 GSC mitigation systems under the decarbonization normative for an SSS container vessel.

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
OPEN LOOP-SCRUBBER													
CAPEX	1.736.775	0	0	0	0	483.438	0	0	0	0	0	0	0
MBM					540.024	952.750	1.247.881	1.697.055	1.734.484	1.772.009	1.809.631	1.945.262	1.983.081
ESI DISCOUNT	0	1.666	1.666	1.666	1.681	1.696	1.711	1.727	1.742	1.758	1.774	1.790	1.806
CF	−1.736.775	1.666	1.666	1.666	−538.343	−1.434.491	−1.246.169	−1.695.328	−1.732.742	−1.770.251	−1.807.858	−1.943.473	−1.981.275
NPC	**−11.875.670**												
CLOSED-LOOP SCRUBBER													
CAPEX	3.425.825	0	0	0	0	483.438	0	0	0	0	0	0	0
MBM					543.207	958.317	1.255.869	1.707.952	1.745.613	1.783.371	1.821.227	1.956.054	1.994.108
ESI DISCOUNT	0	1.666	1.666	1.666	1.681	1.696	1.711	1.727	1.742	1.758	1.774	1.790	1.806
CF	−3.425.825	1.666	1.666	1.666	−541.526	−1.440.059	−1.254.157	−1.706.225	−1.743.871	−1.781.613	−1.819.453	−1.954.265	−1.992.302
NPC	**−13.624.455**												
MGO 0.5%S													
CAPEX	138.029	0	0	0	0	483.438	0	0	0	0	0	0	0
MBM					513.760	904.101	1.176.494	1.598.259	1.633.930	1.669.690	1.705.542	1.781.083	1.817.119
ESI DISCOUNT	0	1.666	1.666	1.666	1.681	1.696	1.711	1.727	1.742	1.758	1.774	1.790	1.806
CF	−138.029	1.666	1.666	1.666	−512.079	−1.385.843	−1.174.782	−1.596.532	−1.632.187	−1.667.932	−1.703.768	−1.779.293	−1.815.313
NPC	**−9.657.004**												
LNG													
CAPEX	6.005.216	0	0	0	0	483.438	0	0	0	0	0	0	0
MBM	0	0	0	0	397.533	724.620	932.680	1.275.902	1.311.068	1.346.307	1.381.619	1.417.003	1.452.461
ESI DISCOUNT	0	1.666	1.666	1.666	1.681	1.696	1.711	1.727	1.742	1.758	1.774	1.790	1.806
CF	−6.005.216	1.666	1.666	1.666	−395.852	−1.206.362	−930.968	−1.274.175	−1.309.326	−1.344.549	−1.379.845	−1.415.213	−1.450.655
NPC	**−13.693.454**												

were the preferred option for shipowners in 2019, and offer a lower NPC than LNG fuelled engines, the clear need for new investments after 2031 (see Table 3) to meet GBM, makes them a risky choice. Finally, MGO 0.5%S is found to be a compromise solution; since it enables delaying new investments until at least 2033 and, although it involves an MBM cost increase between 24 and 29% over LNG (see Table 5), the difference between their initial investment (CAPEX_AB, see Table 5) is wide enough to provide a minimum NPC.

The variables assumed for the scenario's analysis (2019–2031, see Table 5) involve values with high dispersion levels, especially those with significant dependence on the moment in the market and the economic situation (see Section 4.2). This is the case of: the capital costs (CAPEX_AB and CAPEX), the Carbon Allowance Cost for the EU-ETS (CP is highly volatile; it changes daily) and the inflation rate (CPI). Although the assumed values for CP and CPI aim to be appropriate for the project's entire lifespan (average values), the definition of these inputs is based on historical data projections and evolution of the economic situation and therefore, these forecasts involve risk. Following the COVID-19 pandemic and the Russian invasion of Ukraine, the world economy is experiencing an adjustment that has led to unusually elevated inflation rates in the EU and a current escalation of the Carbon Allowance Costs. However, according to ECB (European Central Bank) macroeconomic projections, the EU economy will stabilize in 2024.

Given this reality, with the aim to widening the robustness the results achieved, a sensitivity analysis is carried out to determine not only the consistency of this first approach, but also the dependence of the results on the key variables assumed: capital costs (CAPEX_AB and CAPEX) and the carbon allowance cost for the EU-ETS calculation (CP) aside from the inflation rate (CPI). So, a probabilistic analysis is undertaken (Montecarlo simulations) by taking triangular distributions as probability of occurrence functions for the variables, where the most and least probable values are those included in Section 4.2 (Table 2 values, CP = 30–150 €/tCO$_2$ and CPI = 0.8–3%).

Table 6 collects the results obtained for a 100% certainty level in the simulations (100,000 trials); the NPC distributions obtained show low dependence on the capital costs versus the Carbon Allowance Cost (CP) evolution. Despite wide CP range considered and its influence on the results, the coefficients of variation achieved (below 25% in all cases, see Table 6) for the NPC distributions obtained in the simulations, indicates that these are homogenous in all cases; consequently, the NPC mean can be taken as a representative value of the expected NPC. Thus, by assessing the mitigation alternatives through the NPC means, MGO 0.5% S still occupies the preferred position whereas the LNG results to be a more interesting option than the closed-loop scrubbers, since their NPC difference has been broadened (see Table 6).

6. Discussion

The analysis of the results reveals a high adequacy level of EU-imposed MBMs to the current pollutant impact of SSS vessels. The proportionality found between the MBMs and environmental harm is relevant since, although the shipping industry is reluctant to adopt these measures (specially ETS, Psaraftis and Kontovas, 2020; Psaraftis et al., 2021), this stance is even more decisive in SSS, where the unavailability of significant operative modifications complicates the adoption of bridge solutions in the short-term. Despite this good match, MBM have been found over the pollutant impact of LNG fuelled vessel from 2029. This is mainly due to the influence of the yearly increase of taxation levels (fixed at one tenth until January 1, 2033) on ETD (article 9, EU, 2021c) for all fuels excepting "low-carbon-fuels"; for the latter, the minimum taxation level of the transitional period is maintained until January 1, 2033. The results achieved (see Fig. 3) evidence the need of reviewing LNG category in COM (2021) 563 for the shipping; if this was assumed as "low-carbon-fuel" in the ETD framework, the total MBM would not exceed the vessel's pollutant impact by covering 99.71% in 2031. In the light of this, the current debate about the role of LNG as a

Table 6
Statistics and sensitivity chart of NPC distribution under Montecarlo simulations.

	BaseCase (€)	Mean (€)	Coeff Variation	Influence of CP	Influence of CAPEX_AB	Influence of OPS investment	Influence of CPI
Scrubber(Open-loop)	−11.875.670	−13.749.967	20.52%	99.30%	0.70%	0.00%	0.00%
Scrubber(Closed-loop)	−13.624.431	−15.470.649	18.26%	99.50%	0.40%	0.10%	0.00%
MGO 0.5%S	−9.657.004	−11.249.755	23.26%	100.00%	0.00%	0.00%	0.00%
LNG	−13.693.430	−14.806.286	14.29%	98.10%	1.90%	0.00%	0.00%

(Crystal Ball software).

transitional "lower carbon" fuel in shipping (**(2021/0213(CNS))** is appropriate.

The 2020 GSC led to decisions about the most suitable mitigation solution for SSS vessels based on expected 2019 aftermath scenarios where, despite of the fact that the scrubbers were the most frequent decision from SSS operators (Ytreberg et al., 2021; Martínez-López et al., 2022) - the LNG was mostly shown to be the most adequate in the medium term (Patricksson and Erikstad, 2017) despite its high initial investment (Martínez-López et al., 2018). According to the analysis undertaken, GBMs can significantly modify future scenarios from those assumed in 2019; the scrubber (regardless of its operation mode) proves to be an insufficient tool to meet the CII requirements in the 2031 aftermath and, meanwhile, their costs in terms of MBM are the highest, leading to shorten the NPC difference regarding LNG-fuelled engines.

Consequently, SSS vessels with scrubbers will be forced to face further investment decisions that are strongly driven by the vessel's lifespan: this is likely to involve retrofitting for using zero-emission fuels or scrapping the vessel. In this regard, given previous experience with the 2020 GSC, shipowners predominantly tend to deliver as much as possible the mitigation investments' decisions, with CAPEX being, especially significant in SSS by considering its magnitude versus the vessels' size. However, the achieved results suggest moving investments in decarbonization forward to 2024, although this decision is not imposed by the normative. Because of this, all GBMs are accomplished from inception by avoiding penalties. In this regard, OPS emerges as an efficient tool by considering its cost-benefit (when the share of renewable energy sources in their electricity generation is high, Martínez-López et al., 2021). Although its use is not required by the normative until 2030, its installation in 2024 will involve reductions in MBM (24–50% for the application case) that will lead to highly reduced payback periods for the OPS; only one year in the application case.

On the opposite side to scrubbers, the LNG-fuelled engine arises as a consistent solution not just to meet 2020 GSC requirements (Patricksson and Erikstad, 2017; Martínez-López et al., 2018), but also the GBM from decarbonization regulation (from 2019 to the 2031 aftermath). Although this is in line with previous insights (Bayraktar and Yuksel, 2023), contrary to what was expected, the reduction of MBM in LNG-fuelled engines versus the remaining alternatives (20–30% in the application case) has not proved sufficient to encourage the LNG choice, since the NPC maintains an elevated value due to its initial investment.

Even though the impact of bunker costs on the choice of 2020 GSC mitigation alternatives is not the object of this research, it is necessary to consider its order of magnitude to offer a comprehensive assessment of the decarbonization regulation impact on the SSS mitigation strategy. In 2031 (total implementation) MBM costs will represent between 7 and 9 per cent of total bunker costs (bunker price projections from 2020 November[14]) in the application case. Despite the volatility of bunker prices and carbon allowance costs (CP), it is unlikely that MBMs, on their own, boost an operative leverage towards the choice of more sustainable options. In fact, only with a 17% average price difference between MGO and IFO 380 (the price difference in April 2023[12] was 52.6%), MGO 0.5% would remain the most feasible solution (minimum NPC) in the application case, since MGO 0.5%S represents a compromise solution: minimum NPC, GBM accomplishment beyond 2031 and moderate MBM.

In turn, focusing on GBMs' capacity to change SSS decisions about mitigation options, this research concludes that current non-compliance consequences are not clearly decisive. This is so because - although a breach involves an economic penalty (such as Maritime FuelEU) - it is highly probable that ship operators prefer to pay due to its current weight on vessels' operating costs (MBM magnitude versus bunker costs); thereby undermining GBM effectiveness. This confirms previous researchers' recommendations (Zis and Psaraftis, 2021; Zis et al., 2021) about the need to adopt deterrent fines for GBM non-compliance, in order to boost a change in the mitigation strategies of shipping operators.

7. Conclusions

2021 was a critical year for environmental maritime policy: the CII regulation (MEPC.336(76)) along with several European Communications (EU, 2021b, EU, 2021c and EU, 2021a) definitively opened the door to the widely-discussed use of MBM and GBM in EU shipping. This paper contributes to broadening knowledge about the impact of these measures on SSS by introducing a mathematical model that is able to quantify the OPEX increase, and the CAPEX involved in the accomplishment of the decarbonization regulation in the EU. Thus, application of this model allows to quantify the effectiveness of MBM as a PPP tool for SSS, to assess the performance of 2020 GSC mitigation alternatives (GBM accomplishment) under the EU's decarbonization regulation and consequently, analyzing a possible change in SSS decision-making towards more sustainable options of mitigation. Thus, the approach introduced in this paper overcomes previous analyses, which are mostly qualitative evaluations, since the technical characteristics of SSS vessels (along with 2020 GSC mitigation options) are taken into account to estimate the vessels' pollutant impact, their decarbonization regulation compliance and the costs involved (NPC).

The high adjustment found for MBMs on the pollutant impact of SSS vessels in monetary terms reveals its utility as a tool to ensure the PPP and therefore, this MBM's proportionality should be widely disseminated, in quantitative terms, by policy-making institutions to enhance their uptake in the shipping sector. Efforts in promoting environmental responsibility are especially timely now, when many voices are concerned about a loss of credibility in maritime transport governance caused by situations such as the divergences between the IMO and EU.

Despite the preference for scrubbers' installation in 2019, SSS vessels with scrubbers and those operating with MGO 0.5%S will not be able to meet GBMs until 2031, and only LNG fuelled engines can meet them without any additional investment. In this regard, the inclusion of the compulsory use of OPS (FuelEU regulation) has been found to be a measure in the right direction although, this paper's insights suggest that this must be advanced to 2024. In such a way, OPS installation enables the GBM compliance by SSS vessels up to 2031, regardless of the mitigation systems installed.

This research has also evidenced that, while decarbonization measures will impact on the working scenarios of the SSS vessels by modifying expected 2019 performance for 2020 GSC mitigation systems, the different MBMs involved are insufficient on their own to obtain a trade-off from the higher initial investments in mitigation systems. Neither have MBMs proved to be relevant in readdressing the choice of

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[14] https://shipandbunker.com/prices.

mitigation systems in global terms, since their magnitude in the OPEX is significatively lower than the bunker costs (which is the main driver of shipowners' decisions). Therefore, according to the results achieved, MBMs are insufficient to boost an actual transition to more sustainable investment decisions. In this regard, only GBMs along with deterrent fines for non-compliance are really able to force more suitable mitigation strategies.

The consistency of the results achieved indicates that, the papers' insights are applicable to SSS in the current EU framework beyond the study-case when the carbon allowance costs are between 30 and 150€/tCO$_2$. However, it is necessary to be conscious that the model's suitability is constrained to conventional SSS vessels (i.e., feeder vessels, ro-pax and car-carriers; however, high-speed crafts are beyond the scope of this analysis). Likewise, while the model integrates the current requirements of MBM and GBM (published by European Institutions to date), future amendments to these measures might affect to the papers' insights. To this regard, the MBM adjustment to real pollutant impact of LNG fuelled vessels could be improved. To mis aim, one effective suggestion for ETD policy-makers (2021/0213(CNS)) is permitting the application of the same taxation rate for LNG (as a transitional 'low carbon fuel') in shipping during the transitional period of 10 years (Article 9 of COM (2021) 563).

Finally, in order to deepen these conclusions, further research should be conducted into the impact of GBM and MBM on supply chain costs in EU archipelagos, where a modal shift for SSS traffic is not an option and the aforementioned convenience of OPS is still under discussion, due to the current low share of renewable sources in on-shore electric generation.

CRediT authorship contribution statement

África Marrero: Software, Validation, Investigation, Writing – original draft. **Alba Martínez-López:** Conceptualization, Formal analysis, Supervision.

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

Data will be made available on request.

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Appendix A

Variables

α_i	Percentage of emissions to be considered according to the nature of the ports (%): Both ports belong to an EU Member State ($\alpha_i = \alpha_1 = 100\%$); only one port belongs to an EU Member State ($\alpha_i = \alpha_2 = 50\%$); no ports belongs to an EU Member State ($\alpha_i = \alpha_3 = 0\%$)
β_k	Percentage of emissions to be considered according to the activity year-implementation schedule-: 2023 ($\beta_k = \beta_1 = 20\%$); 2024 ($\beta_k = \beta_2 = 45\%$); 2025 ($\beta_k = \beta_3 = 70\%$); 2026 and each year thereafter ($\beta_k = \beta_4 = 100\%$)
$BUNKER_m$	Fuel cost consumed by the SSS vessel (€) in each year of the investment project lifetime; $\forall m \in M$
C	Vessel's capacity (DWT or GT see MEPC.336(76)). For a container vessel C = DWT
$C_{engine\_sleep,j}$	Engine fuel slippage is the non-combusted fuel measured as a percentage of the mass of every kind of fuel (%). $\forall j \in J$
$CAPEX_m$	Capital cost of additional mitigation systems (€) to meet decarbonization regulation for each year of the project's lifetime; $\forall m \in M$
CAPEX_AB	Capital cost of the 2020 GSC abatement systems (€)
CEM_s	Vessel's impact on climate change and air quality (€/trip) for every navigation stage; $\forall s \in SS$
CF_m	Cash Flow (€) of the investment project for the 2020 GSC abatement technologies for every year of the project lifetime $\forall m \in M$
CFF_{jl}	Conversion factor for CO_2 emissions (tonne CO_2/tonne fuel); $\forall j \in J \wedge \forall l \in L$
CFM_j	Emission factor for CH_4 (tonne CH_4/tonne fuel); $\forall j \in J$
CFN_j	Emission factor for N_2O (tonne N_2O/tonne fuel); $\forall j \in J$
CII_A	Attained Carbon Intensity Indicator (grams CO_2/n.m × tonne)
CII_R	Required Carbon Intensity Indicator
$CO_{2\ eq\ electricity,c}$	GHG emission factor for the electricity delivered to the ship at berth per connection point (gCO_{2eq}/MJ); $\forall c \in CC$
$CO_{2\ eq\ TtW,j}$	CO_2 equivalent emissions for every kind of combusted fuel (gCO_{2eq}/gFuel); $\forall j \in J$
$CO_{2\ eq\ TtW\_slippage,j}$	CO_2 equivalent emissions for every kind of slipped fuel (gCO_{2eq}/gFuel); $\forall j \in J$
$CO_{2\ eq\ WtT,j}$	GHG emission factor for every fuel. Default values are collected in Annex II of EU (2021b) (gCO_{2eq}/MJ); $\forall j \in J$
CP	EU Carbon Pricing (€/tonne CO_2)
CV_j	Net Calorific Values for the fuels (GJ/g fuel); $\forall j \in J$
D	Total distance travelled on a trip (nautical miles)
E_c	Electricity delivered to the vessel at berth per connection point through OPS (MJ); $\forall c \in CC$
EME_s	Ecotoxicity of scrubbers' wash water (€/trip) for every navigation stage; $\forall s \in SS$
ETD	Energy Taxation per year (€)
ETR_s	Marine eutrophication of scrubbers' wash water (€/trip) for every navigation stage; $\forall s \in SS$
ETS_k	European Trading System's cost per year (€); $\forall k \in K$
$ETSU_k$	European Trading System's cost per trip (€); $\forall k \in K$
ETU	Energy Taxation per trip (€)
ESI_k	Environmental Ship Index for every year $\forall k \in K$
$Fuel\_EU_k$	Penalty(€), for a particular year, as laid down in the FuelEU Regulation- EU (2021b)- $\forall k \in K$
GHGIE	Greenhouse gas intensity of the energy used on-board (g $CO_{2\ eq}$/MJ). When this refers to a particular report period GHGIE = $GHGIE_{actual}$, greenhouse gas intensity achieves the limit imposed in this Regulation GHGIE = $GHGIE_{target}$
GWP	Global warming potential for CO_2, CH_4 and N_2O
$LVNO_x$	Limited value for NOx emissions in the engines (g/kWh) related to Tier-I base line (see MARPOL, ANNEX IV, Chapter 3, Regulation 13)
MBM_m	Market Based Measures' costs (€) for each year of the investment project's lifetime; $\forall m \in M$
N	Number of yearly trips
$OPEX_m$	Operating cost (€) of a SSS vessel equipped with a particular 2020 GSC abatement system in every year of the investment project's lifetime; $\forall m \in M$
PB_{ls}	Power for the vessel's engines (kW) at every navigation stage; $\forall l \in L \wedge \forall s \in SS$
PBR_l	Rate Power for the vessel's engines (kW); $\forall l \in L$
PI	Pollutant Impact of vessel (€/trip) when a central value is taken for CO_2 emissions

PI2	Pollutant Impact of vessel (€/trip) when a low value is taken for CO_2 emissions
$PortDues_m$	Cost of port dues (€) for every year of the investment project's lifetime; $\forall m \in M$
$(RVNO_{x})_l$	Rate value for NOx emissions in the vessel's engines (g/kWh) according to their Tier-level (see MARPOL, ANNEX IV, Chapter 3, Regulation 13); $\forall l \in L$.
R	Discount rate (%)
RWD_{ll}	Reward factor for non-biological origin's fuels with value of 2 from January 1, 2025 to December 31, 2033. Otherwise value = 1. $\forall j \in J \wedge \forall l \in L$.
$SFOC_{jls}$	Specific Fuel Consumption for engines in every navigation stage and fuel (g fuel/kW.h); $\forall j \in J \wedge \forall l \in L \wedge \forall s \in SS$
TL_j	Taxation level applicable to fuels (€/GJ); $\forall j \in J$
TVB_s	Time invested in every navigation stage (h); $\forall s \in SS$
X_{ls}	Relative reduction of the average sulphur content of Marine Diesel Oil/Gasoil with a sulphur content equal to or less than 0.50% but greater than 0.10% S
Y_{ls}	Relative reduction of the average sulphur content of Marine Diesel Oil/Gasoil with a sulphur content equal to or less than 0.10%
Z_k	Annual reduction factor for calculation of the required annual operation from 2019 values; $\forall_k \in K$: 2023 ($Z_k = Z_1 = 5\%$); 2024 ($Z_k = Z_2 = 7\%$); 2025 ($Z_k = Z_3 = 9\%$); 2026 ($Z_k = Z_4 = 11\%$); and a 2% increase for each year thereafter (Resolution MEPC.338(76))

Subscripts

$CC = \{1, \ldots, c\}$ Connection points for the OPS

$I = \{1, \ldots, i\}$ Nature of the ports: Both ports belong to EU Member States; only one port belongs to an EU Member State; no ports belongs to an EU Member State

$J = \{1, \ldots, j\}$ Motor fuels under taxation; HFO; MDO and LNG

$K = \{1, \ldots, k\}$ Activity year according to the implementation schedule: 2023, 2024, 2025, 2026 and thereafter.

$L = \{1, \ldots, l\}$ Vessel's engines: main and auxiliary engines

$M = \{1, \ldots, m\}$ Years for the investment project 2020 GSC abatement systems by assuming 2019 as the retrofitting date for an SSS vessel

$SS = \{1, \ldots, s\}$ Stages during maritime transport: free sailing, manoeuvring (pilotage time, towing time, and mooring time), berthing (loading and unloading operations) and sleeping time.

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