Current performance of sulphur mitigation technologies in Short Sea Shipping vessels in the context of market and goal-based measures

Africa Marrero
Oceanic Platform of the Canary Islands (PLOCAN)
Las Palmas, Spain
Department of Naval and Industrial Engineering, University of A Coruña
A Coruña, Spain
africa.marrero@plocan.eu

Alba Martínez-López
Department of Mechanical Engineering, New shipbuilding unit,
University of Las Palmas de Gran Canaria
Las Palmas, Spain
alba.martinez@ulpgc.es

Abstract

In January 2020, the Global Sulphur Cap - forced a massive retrofitting of vessels with SOx emissions abatement technologies. This involved a particular challenge for short sea shipping, as they are barely able to take advantage of economies of scale to mitigate the additional capital and operational cost derived from investments in abatement measures. Despite this, these investments do not ensure short sea shipping vessels' compliance with the forthcoming environmental normative in the European Union since this is focused on Greenhouse Gas mitigation. In January 2023, the Carbon Intensity Indicator regulation came into force along with the European Market-Based Measures and the regional Goal-Based Measures to meet the European Green Deal objectives. Given this context, this paper firstly attempts to determine if the new Market-Based Measures are sufficient to cover the environmental costs of current short sea shipping vessels, and secondly if today's abatement technologies can comply with the forthcoming regulation when it is applied to short sea shipping vessels. To achieve these aims, the external costs of a short sea shipping feeder vessel - employing several Global Sulphur Cap mitigation technologies - are analysed and compared with the additional economic cost of Market-Based Measures over a 10-year term. In turn, Carbon Intensity Indicator values are calculated over the period by assuming the mature mitigation technologies installation to assess its compliance's level with new Goal-Based Measures.

Keywords: Short Sea Shipping, Maritime Sustainability, Market Based Measures, Abatement technology performance, Environmental costs model.

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I. INTRODUCTION

Global Sulphur Cap enforcement (2020 GSC) in January 2020, which led to large-scale vessel retrofitting, took advantage of previous research insights and mitigation technologies offered by the industry, such as: open and closed-loop scrubbers, low-sulphur content fuels and Liquified Natural Gas (LNG) propulsion. Even though these solutions had lacks (methane slip for LNG propulsion; ammonia slip for Selective Catalytic Reduction (SCR) to meet permitted NOx emissions; the environmental impact of wash waters from scrubbers, among others), these options are commercially available and, therefore they could be assumed by the shipowners as technologically mature options.

In this context, several studies analyzed the expected performance of 2020 GSC mitigation alternatives (retrofitting vessel investments) that were suggested by decision models by assuming uncertain conditions. These works often analyzed scenarios by focusing on key variables, such as: high variations on fuel prices in the post-2020 horizon [1-2]; significant modifications of cargo rates [3], and modifications of foreseeable operation times (increases of port times due to On-Shore Power Supply-OPS- connections- [4-5]). However, the influence of the forthcoming decarbonization regulation (reduction of Greenhouse Gas -GHG- emissions) on the decisions around 2020 GSC abatement technology was barely analyzed. This is so because, although several regulatory measures have been discussed by the International Maritime Organization (IMO) and European Union (EU) in recent years, agreement was not found until mid-2021, with enforcement in 2023, of: IMO Goal-Based-Measures-GBMs- (mainly, MEPC.336, 337 and 338(76)), which were strengthened in the EU by additional schemes (COM (2021) 562 final), and Market Based Measures (MBMs) (COM (2021) 551 final, COM (2021) 563 final). Thus, even though there is robust empirical evidence about the suitability of 2020 GSC abatement solutions for every kind of fleet, a knowledge gap exists regarding the impact of the new decarbonization regulation on the expected feasibility of 2020 GSC abatement investments.

MBMs necessary involve higher Operational Cost (OPEX) for vessels in the short-term to ensure fulfilment of the Polluter Pays Principle-PPP- and in turn, the Goal-Based Measures (GBMs) demand progressive CO2 reductions over time. In order to meet the latter, new retrofitting to improve fuel-efficiency and service speed moderation on vessels is the most expected response from shipping in the medium-term. Consequently, vessels will incur additional Capital Cost (CAPEX) and OPEX, which will lead to new working scenarios and call into question the feasibility of investments in mitigation systems implemented under the 2020 GSC umbrella.

The need for a comprehensive review is even greater in the case of Short Sea Shipping (SSS) fleets, as the small capacity of these vessels along with the high speed requirements to offer frequent transport services involve not only low-sustainability vessels (higher polluting indicators MEPC.336 (76)-) but also, 'low-advantageous ships' due to the effects of economy of scale to support the additional costs of implementing MBMs and GBMs [6]. Moreover, slow steaming, which has been suggested as the easiest GHG compliance solution (negligible CAPEX; [7-8]), is unfeasible for SSS, as moderating vessel speed would lead to operate with more vessels in SSS routes and assuming possible modal shifts for the load to the trucking [9-11].

Considering the above, the purpose of this paper is to determine the influence of the incoming decarbonization regulation on the feasibility of 2020 GSC abatement technology investments for European SSS vessels and its environmental effectiveness. An assessment of vessels performance, following MBM and GBM's requirement to operate with different abatement technologies, demands not only a review of the suitability of 2020 GSC mitigation decisions (i.e., the robustness of the reached knowledge to date) but also to test whether - and if so to what extent - SSS vessels' compliance with the new regulation can lead to a trade-off between actual environmental costs and the additional costs incurred by shipping from MBM to meet the PPP.

To achieve this aim, this paper introduces a calculation model to quantify the additional OPEX resulting from MBMs. These results are firstly compared with the costs of pollutant emissions and marine environment damage (ecotoxicity and eutrophication) estimated through an environmental cost model [12], by assuming different abatement options. Next, an estimation of the GBM's enables us to assess SSS compliance over time and therefore identify the need for new investments when several mitigation systems are installed.

To provide quantitative data, the analysis is applied to a particular SSS case: a feeder vessel operating under Maritime EU regulation on a linear route between the Canary Islands and the Iberian Peninsula. The feeder has a 10-year payback period and employs the following 2020 GSC mitigation technology: Heavy Fuel Oil (HFO), with an open- and closed-loop scrubber; low-sulphur content Marine Gas Oil (MGO), and Liquified Natural Gas (LNG), with a dual fuel marine engine.

This study addresses the knowledge gap regarding current SSS fleet performance in the 2020 GSC aftermath by considering, on the one hand, fulfilment of the new decarbonization regulation over time (GBMs) and, on the other, the proportionality of the incoming MBMs to cover the SSS fleet's external costs. The paper's approach enables policymakers to understand more about the effectiveness of different regional and international policies related to emissions reduction on SSS vessels. In fact, the results will also be useful for ship-owners, not only for making decisions about future vessels' retrofitting under the new decarbonization regulation, but also for improving the social uptake of this regulatory framework.

II. Methodology

The following paragraphs introduce the calculation models that enable assessment of MBM effectiveness (see sections 2.1 and 2.2) and the performance of the 2020 GSC abatement systems to meet the new GBM (see section 2.3). Section 2.4 shows the calculation of Pollutant Impact (PI in €/trip,) for SSS vessels with several mitigation alternatives to meet the 2020 GSC regulation. The comparison of PI of SSS vessels versus the OPEX increase due to MBM, allows to assess the effectiveness of the normative. Additionally, analysis of GBM compliance by SSS vessels equipped with 2020 GSC mitigation systems enables to determine their performance and additional investment needs.

A. MBM: Energy Taxation

Equations (1) and (2) show the Energy Taxation; this MBM is a yearly value (ET in euros) and a value per trip (ETU) respectively (N involves the annual trips, see Appendix A), because of enforcement of COM/2021/563 final. Aside from the Taxation Level for kind of fuel (J = {1,...,j}) used by the vessel (TLj; ∀j ∈ J in €/GJ), Eq. (2) estimates the energy developed (Gigajoules) at all navigation stages (SS={1,...,s}) by considering their operational times (TVBs; ∀s ∈ SS), along with the calorific values of the fuels (CVj; ∀j ∈ J in GJ/g), the propulsion power developed by the main engine at every navigation stage (PB1s ; ∀s ∈ SS in kW), and its specific fuel consumption (SFOCjs1; ∀j ∈ J∧∀s ∈ SS). The latter is dependent not only on fuel type and navigation stage (%MCR of the engine), but also on the type of engine (2-stroke or 4-stroke).

$$ET=N\times ETU \quad (1)$$

$$ETU=\sum_{s=1}^{s}(TLj\times CVj\times SFOCj1l\times PB1s\times TVBs);\quad \forall j\in J\wedge\forall s\in SS; \quad (2)$$

B. MBM: Carbon Allowance Cost

Equations (3) provide the annual carbon allowance cost (ETS in euros) for a SSS vessel, operating under EU-ETS (see Appendix A), whereas Eq. (4) offers this cost per trip (ETSU) by considering EU carbon price (CP in €/CO2 ton). Since the proposed EU-ETS (COM2021 (551) final) takes the CO2 emissions from EU-MRV, Eq. (4) assumes the CO2 emissions' estimation by considering fuel consumption and conversion factors (CFFjl; ∀j ∈ J∧∀l ∈ L in t CO2/t fuel), from Annex VI of the EU Commission Regulation No 601/2012. Fuel consumption is estimated by considering - aside from the power of the on-board engines (PBls; ∀l ∈ L∧ s ∈ SS) - their specific consumption (SFOCjls; ∀j ∈ J∧∀l ∈ L ∧∀s ∈ SS) and time invested in all navigation stages (TVBs; ∀s ∈ SS). Additionally, the influence of the port calls' jurisdiction (from/to Member State I = {1,...,i}, see also Appendix A) on emissions quantification for EU-ETS is also considered (αi; ∀i ∈ I) along with the progressive inclusion of the emissions over the years, collected in COM2021 (551) final (βk; ∀k ∈ K, see Nomenclature).

$$ETS=N\times ETSU \quad (3)$$

$$ETSU=CP\times \alpha i\times \beta k\times \sum_{s=1}^{s}(TVBs(\sum_{l=1}^{l}(\mathrm{SFOCjls}\times \mathrm{PBls}\times \mathrm{CFFjl})); \forall j\in J\wedge\forall k\in K\wedge\forall l\in L\wedge\forall s\in SS; \quad (4)$$

C. GBM: Carbon Intensity Indicator accomplishment

In order to identify vessels' fulfilment of GBM, imposed by the IMO over time, the Carbon Intensity Indicator (CII)(MEPC 336(76)) is evaluated by considering the attained CII (CII_A) and required CII (CII_Rk; ∀k ∈ K) for every year. The CII_A calculation (Resolution MEPC.336(76) - 2021 Guidelines on Operational Carbon Intensity Indicators and the Calculation Methods (CII Guidelines, G1)) considers CO2 grams per nautical mile and transported cargo tonnes (with C representing the vessel's cargo capacity and D the trip distance, see Appendix A) and is shown in Eq. (5). Whereas the CII_Rk, that is modified over time (K= {1,...,k}) according to a yearly reduction factor (Zk; ∀k ∈ K) relative to 2019 emissions (MEPC337(76)-CII Reference line guidelines, G2), is estimated in Eq. (6). Moreover, Eq. (6) collects the factors a and c that are constant and dependent on the vessel's type (MEPC337(76)).

$$CII\_A=\sum_{s=1}^{s}(TVBs(\sum_{l=1}^{l}(SFOCjls\times PBls\times CFFjl))/(C\times D);\forall j\in J\wedge\forall l\in L\wedge\forall s\in SS \quad (5)$$

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

Guidelines on the operational carbon intensity rating of ships (CII Rating Guidelines- MEPC.339(76) – 2021-) collects vessels' classification over time by highlighting their obligation to introduce an energy efficiency strategy under SEEMP (-Ship Energy Efficiency Management Plan, see MEPC.346(78)), and to return to C or a superior level, when the vessels achieve a score of D for three years or an E rating in one year. 2021 Revised MARPOL Annex VI includes in the regulations 26-28 the compulsory application of CII from January 2023.

D. Pollutant Impact

Pollutant Impact (PI, see Appendix A) offers a tool to evaluate a vessel's sustainability (see Eq. (7); [12]) when it operates with several 2020 GSC mitigation systems. PI provides information in terms of external costs (€/trip), by considering climate change and air quality (CEMs; ∀s ∈ SS) along with the ecotoxicity (EMEs; ∀s ∈ SS) and marine eutrophication (ETRs; ∀s ∈ SS) of scrubbers' wash waters.

$$PI = \sum_{s=1}^{n} CEM_s + \sum_{s=1}^{n} EME_s + \sum_{s=1}^{n} ETR_s\ ; \forall s \epsilon SS \quad (7)$$

The CEMs (∀s ∈ SS) calculation considers the unitary costs and emission factors from different abatement systems for SSS vessels [12] by considering the following pollutants: acidifying substances (SOX), ozone precursors (NOx), particulate mass (PM2.5 and PM10), Greenhouse Gases (CO2, CH4) and the ammonia slip (NH3). In turn, the contaminants collected in Appendix 3 of the 2021 Guidelines for Exhaust Gas Cleaning Systems – (MEPC.340(77)), mainly PAHs and metals, are considered for the ecotoxicity evaluation of the scrubbers' wash water (EMEs; ∀s ∈ SS). Regarding the marine eutrophication assessment (EMEs; ∀s ∈ SS), the nitrogen concentrations from scrubber discharges are considered.

The environmental impact of scrubbers' wash waters in terms of ecotoxicity (EMEs; ∀s ∈ SS) is estimated by assuming, the ecotoxicological midpoint characterization factor to ocean water for every contaminant in kg 1,4 DCB-eq/kg pollutant [13] and the monetary value of marine ecotoxicity (€/kg1,4 DCB-eq), following the approaches from [12-14], among others. Thus, whereas the Environmental Price Method [15] can be taken to monetize eutrophication and ecotoxicity on the marine environment from the scrubbers' discharges, for the EU context, the Handbook on the External Costs of Transport (last updated in 2019; [16]) published by the European Commission, collects the unitary cost for pollutant emissions (per country, by considering the pollution density of the geographical locations).

III. APPLICATION CASE

The method introduced above is applied to a particular feeder vessel (see Table 1) operating between Cadiz port (at 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 TVB1=37.14 hours in free sailing; TVB2=0.5 hours (per port) in manoeuvring, and TVB3=3 hours (per port) in loading/unloading operations. However, due to sleeping time (scheduling requirements), every trip involves 14 additional hours at berth (TVB4=7 hours -per port-).

To comply with 2020 GSC, four possible abatement alternatives are assessed for the vessel [12]: HFO fuel with open-loop scrubber, HFO fuel with closed-loop scrubber, MGO and LNG fuelled engine. Even though the MGO option does not involve vessel retrofitting (see Table 1), the other alternatives mean significant CAPEX. It is necessary to bear in mind that Power Take Off (PTO) will generate the full electrical power during free sailing (1,570), and therefore the generating sets (MAN 5L23/30DF) only operate in port (2,400 kW for manoeuvring, and 1,470 kW for berthing).

During free sailing, the assumed sulphur content is 0.5%S for MGO whereas for HFO, three possible scenarios are analyzed: 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, mean that open-loop scrubbers and MGO alternatives take as 0.1%S MGO for main and auxiliary engines in port (manoeuvring and berthing navigation stages).

Abatement capacity of 98% for SO2 emissions and 55% for PM2,5 for all scrubbers is assumed for emission calculations (Ship Design Programs for Emission Calculations, DTU).

The PI calculation follows the [12] approach (see section 2.4) by using Spanish CPI (12.7% from 2016-2022, National Statistics Institute of Spain, 2022) to update air pollutants' unitary costs [16], and the EU-27 countries' average CPI (13.3% from 2016-2022, Eurostat, 2022) to calculate monetary values for ecotoxicity and eutrophication [15].

Table 1. Feeder vessel´s characteristics

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* (BHP kW)	8,300
TEUs/ (reefer)	869/234
Auxiliary engines (kWe)	3X590
PTO (kw)	1800
Bow thruster (kW)	880
Lightweight (t)	4,666.21

** MAN B&W G50ME-C9.6-LPSCR*

For the calculation of GBM and MBM, the engines power (PBls; ∀l ∈ L∧∀s ∈ SS) and other engines' features (SFOCjls; ∀j ∈ J∧∀l ∈ L ∧∀s ∈ SS) were taken by assuming a free sailing speed of 18.5 kn and 4 knots for manoeuvring speed (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).

Regarding MBM, the taxation level applicable to fuels (TLj; ∀j ∈ J) is updated from 2023 to the next years by considering a projection of the expected average CPI for EU-27 countries in the next 10 years- (at an annual increase of 0.83%; Eurostat, 2022). The same updating ratio is applied to the Carbon Price (CP) for the Carbon Allowance Cost (EU-ETS (COM2021 (551) final). For this case, a base value CP=67€/tCO2 [17-18], is considered for 2022. At this point, it is interesting to highlight the difference between the carbon cost for the calculation of the MBM based on the EU-ETS (CP=67€/tCO2, for 2022) and the unitary cost for CO2 in the PI calculation (see section 2.4 and [16]). The latter takes the central value for the climate change avoidance cost; that is 100€/tCO2 for 2016 in the short and medium term (up to 2030; [16]). On the other hand, the Handbook on the External Costs of Transport [16] also collects a low value of 60€/tCO2 for 2016, while the standard PI estimation for vessels considers the central value. To establish a realistic comparison between the vessel's environmental impact and de MBM in monetary terms, the PI will be calculated assuming, aside from the central values (PI), the low value (PI2) for the CO2 (climate change avoidance cost) with their corresponding update over the time.

IV. RESULTS

Table 2 collects the MBM, disaggregated by kinds (ET and ETS), against the pollutant cost calculated through the pollutant impact (PI and PI2) for several mitigation systems that fulfill 2020 GSC. This table shows the evolution of costs from 2022 to 2031 by because - despite the decarbonization regulation being effective from January 2023 (CII included in new Regulations 26-28 of MARPOL Annex VI) – their requirements (Resolution MEPC.338(76)), and therefore its stringency levels (Z_k; $\forall k \in K$; see Eq. (6) and Nomenclature), progress over time. This is also the case of ETS (COM2021 (551) final), in which surrender allowances are gradually phased in (2023-2025); it is only from 2026 that the total CO2 emissions recorded by EU-MRV ($\beta_k = \beta_4 = 100\%$; see Eq. (4) and Nomenclature) will be considered for surrendered allowances.

Table 2 shows that only LNG-fuelled engines met the CII class requirements over the whole period analyzed (at least a C score, MEPC.339(76)) and therefore, no additional investment would be required in mitigation systems for decarbonization.

The opposite occurs when the scrubbers operating with 3.5%S HFO (where this is allowed), regardless of their mode (open- or closed-loop), were selected as 2020 GSC mitigation systems. In this case, from 2025, ship-owners need to evaluate possible retrofitting or severe modification of vessel's operational pattern (that is, a corrective action plan to show how the required rating of C or higher can be achieved after a D score has been registered for three consecutive years) to fulfil the GBM (Regulation 26, MARPOL Annex VI). The same need is found for the MGO 0.5%S option, but in 2028.

Figure 1 shows the evolution of MBM's effectiveness in ensuring PPP by evaluating the vessel's pollutant impact with scrubbers. Both closed- and open-loop scrubbers show the MBM level (the thickest line) to be considerably lower than the vessel's pollutant impact. The latter was estimated by assuming several possible Sulphur concentrations for HFO (3.5%S, 2%S, and 1%S, see Figure 1).

Table 2. SSS vessels' performance under the decarbonisation normative compliance; operating with several 2020 GSG abatement systems.

	OPEN-LOOP SCRUBBERS (€/year)									
	2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
ETS	0	304.892	691.724	1.084.982	1.562.891	1.575.915	1.589.047	1.602.289	1.615.642	1.629.106
ET	0	235.132	237.239	239.366	241.511	243.676	245.859	248.063	250.286	252.529
MBM	**0**	**540.024**	**928.963**	**1.324.348**	**1.804.402**	**1.819.590**	**1.834.907**	**1.850.352**	**1.865.928**	**1.881.635**
PI	**4.124.049**	**4.161.011**	**4.198.304**	**4.235.931**	**4.273.896**	**4.312.201**	**4.350.849**	**4.389.843**	**4.429.187**	**4.468.884**
PI2	3.085.411	3.113.064	3.140.965	3.169.116	3.197.519	3.226.177	3.255.091	3.284.265	3.313.700	3.343.399
CII (Class)	C	D	D	**D**	D	D	E	E	E	E
	CLOSED-LOOP SCRUBBERS (€/year)									
	2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
ETS	0	306.647	695.706	1.091.227	1.571.887	1.584.986	1.598.194	1.611.513	1.624.942	1.638.483
ET	0	236.560	238.680	240.820	242.978	245.156	247.353	249.570	251.806	254.063
MBM	**0**	**543.207**	**934.386**	**1.332.047**	**1.814.865**	**1.830.142**	**1.845.547**	**1.861.082**	**1.876.748**	**1.892.546**
PI	**4.156.567**	**4.193.820**	**4.231.407**	**4.269.331**	**4.307.595**	**4.346.202**	**4.385.155**	**4.424.457**	**4.464.111**	**4.504.120**
PI2	3.113.996	3.141.905	3.170.065	3.198.476	3.227.143	3.256.066	3.285.248	3.314.692	3.344.400	3.374.375
CII (Class)	C	D	D	**D**	D	D	E	E	E	E
	MGO 0.5%S (€/year)									
	2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
ETS	0	288.069	653.557	1.025.116	1.476.655	1.488.960	1.501.368	1.513.880	1.526.495	1.539.216
ET	0	225.691	227.713	229.754	231.813	233.891	235.987	238.102	240.236	242.389
MBM	**0**	**513.760**	**881.270**	**1.254.870**	**1.708.468**	**1.722.852**	**1.737.356**	**1.751.982**	**1.766.732**	**1.781.606**
PI	**4.063.043**	**4.099.458**	**4.136.200**	**4.173.270**	**4.210.673**	**4.248.411**	**4.286.488**	**4.324.906**	**4.363.668**	**4.402.777**
PI2	3.088.574	3.116.255	3.144.185	3.172.365	3.200.797	3.229.484	3.258.428	3.287.632	3.317.097	3.346.827
CII (Class)	C	C	C	C	D	D	**D**	D	E	E
	LNG (€/year)									
	2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
ETS	0	236.887	537.438	842.982	1.214.295	1.224.414	1.234.617	1.244.906	1.255.280	1.265.741
ET	0	160.646	162.086	163.538	165.004	166.483	167.975	169.481	171.000	172.532
MBM	**0**	**397.533**	**699.524**	**1.006.520**	**1.379.299**	**1.390.897**	**1.402.593**	**1.414.387**	**1.426.280**	**1.438.273**
PI	**3.110.225**	**3.138.100**	**3.166.225**	**3.194.603**	**3.223.234**	**3.252.123**	**3.281.270**	**3.310.678**	**3.340.350**	**3.370.288**
PI2	2.308.896	2.329.589	2.350.468	2.371.534	2.392.789	2.414.234	2.435.872	2.457.703	2.479.731	2.501.955
CII (Class)	A	A	B	B	B	B	B	C	C	C

The central value for the climate change avoidance cost was also considered for the calculation (PI, continuous lines, see Figure 1), along with its low value (PI2, see interrupted lines in Figure 1) to ensure correct analysis of the results. In all cases the difference between the MBM and pollutant impact is relevant; in 2025 (the last accomplishment year without additional measures or investments) MBM cost only covers the 41.79% of PI2 value (31.26% of PI) when open-loop scrubbers are installed, and for closed-loop scrubbers, MBM covers 41.65% of PI2 value (31.20% of PI).

assesses the compliance statement with the decarbonization regulations (GBM) for retrofitted SSS vessels with several 2020 GSC mitigation systems (and checks the robustness of previous findings about 2020 GSC mitigation alternatives for SSS fleets) and secondly, it provides quantitative information about the proportionality of the new measures (MBM) against the environmental damage actually caused by SSS. From the application case, we can conclude that only the LNG, as expected, is effective: not only to mitigate the sulphur emissions (2020 GSC compliance) but also to fulfil the GBM (CII rating) in the time range considered.

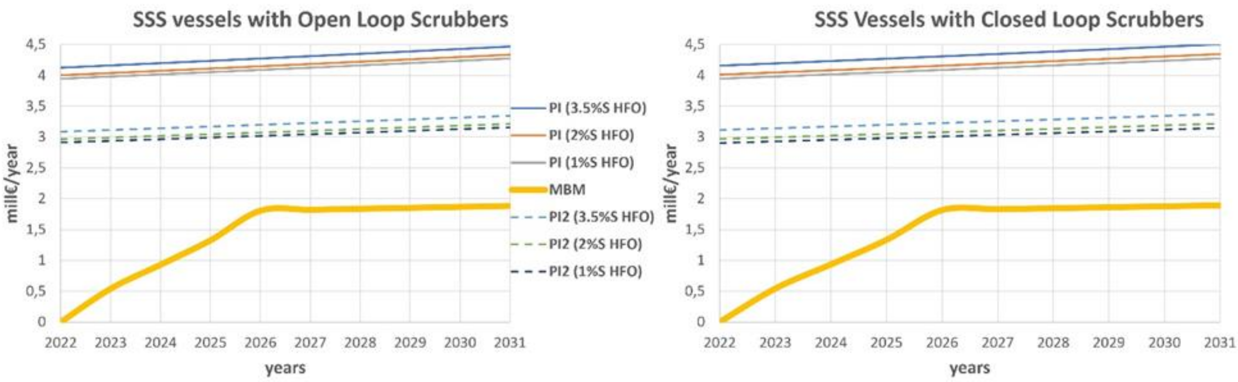

Figure. 1. MBM versus PI in SSS vessels with scrubbers by assuming central and low avoidance cost for CO2 in climate change

Likewise, Figure 2 collects the adequation of MBM to the feeder vessel's pollutant impact, when MGO and LNG were selected as 2020 GSC mitigation alternatives. For the former the MBM covers 53.32% of the PI2 value (40.53% of PI) in 2028, the last accomplishment year (see Table 2), whereas with the latter, in 2031, the MBM achieves 57.49% of the PI2 value (42.7%PI).

The other 2020 GSC mitigation options require an additional investment or assume an operative modification in 2028 for the MGO alternative, and in 2025 for the scrubbers' alternative. This would involve a new retrofitting or a different operational scenario only five or eight years after GSC has come into force.

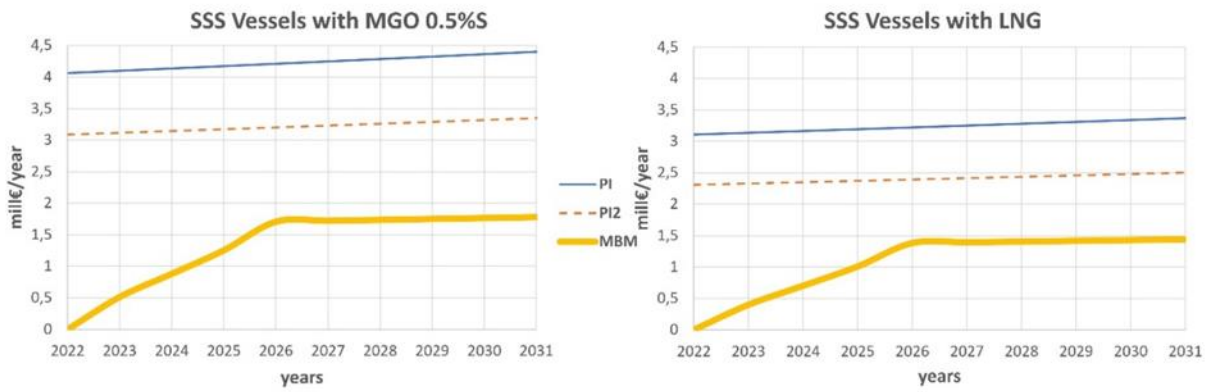

Figure. 2. Adequation of MBM to the feeder vessel's pollutant impact

V. CONCLUSIONS

Maritime academic research has often focused on the implications of the evolution of the emissions regulations on shipping. Firstly, considering the Emission Control Areas' statement and then the Global Sulphur Cap implementation (2020 GSC) in January 2020. The massive retrofitting of vessels in 2020 to fulfil the 2020 GSC was preceded by numerous techno-economic studies about possible mitigation systems. Even though this analysis considered forecasts for future scenarios, they hardly ever evaluated an early implementation of decarbonization regulations based on MBM along with additional GBM as it is taking place. Consequently, previous insights about the feasibility of the 2020 GSC mitigation systems are currently under discussion. This paper contributes to deepening knowledge in this regard, with two objectives: it firstly

Therefore, further techno-economic studies of decisions about mitigation alternatives should include the additional costs derived from this new framework. Finally, even though generalization of results from application cases should be avoided, there is evidence that MBM applied to SSS feeder vessels are far from the pollutant impact of these vessels by only covering from 41.79% to 57.49%of the environmental costs (minor differences, PI2). Indeed, the possible Carbon Price fluctuation could have a significative impact on the ETS value and therefore on MBM; however, the wide differences that were found, suggest that these measures are insufficiently effective for an environmental trade-off. This key insight requires to complete the assessment through further research by including, aside from MBM, the total costs incurred by vessels for decarbonization: especially regarding the increase of OPEX and the initial CAPEX.

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VII. APPENDIX A

αi Percentage of emissions to be considered according to the nature of the ports (%): Both ports belong to an EU Member State (αi = α1 = 100%); only one port belongs to an EU Member State (αi = α2 = 50%); no ports belong to an EU Member State (αi = α3 = 0%);

βk Percentage of emissions to be considered according to the activity year-implementation schedule-: 2023 (βk = β1 = 20%); 2024 (βk = β2= 45%); 2025 (βk = β3= 70%); 2026, and each year thereafter (βk =β4= 100%);

C Vessel's capacity (DWT or GT, see MEPC.336(76)). For a container vessel C=DWT.

CEMs A vessel's impact on climate change and air quality (€/trip) for every navigation stage; ∀s ∈ SS

CFFjl Conversion factor (tonne CO2/tonne fuel); ∀j ∈ J ∧ ∀l ∈L

CII_A Attained Carbon Intensity Indicator, grams CO2/n.m×tonne

CII_R Required Carbon Intensity Indicator

CP EU Carbon Price, €/tonne CO2

CVj Net Calorific Values for the fuels, GJ/g fuel; ∀j ∈ J.

D Total distance travelled in a trip (nautical miles)

EMEs Ecotoxicity of scrubbers' wash water (€/trip) for every navigation stage; ∀s ∈ SS

ET Energy Taxation per year, €

ETRs The Marine eutrophication of scrubbers' wash water (€/trip) for every navigation stage; ∀s ∈ SS

ETS European Trading System's cost per year, €

ETSU European Trading System's cost per trip, €

ETU Energy Taxation per trip, €

N Number of yearly trips

PBls Power for the vessel's engines (kW) at every navigation stage; ∀l ∈L∧ ∀s ∈ SS

PI Pollutant Impact of vessel (€/trip), by assuming a central value for carbon allowance cost.

PI2 Pollutant Impact of vessel (€/trip), by assuming a low value for carbon allowance cost.

SFOCjls Specific Fuel Consumption for engines at every navigation stage for every fuel (g fuel/kW.h); ∀j ∈ J ∧ ∀l ∈L∧ ∀s ∈ SS

TLj Taxation level applicable to fuels (€/GJ); ∀j ∈ J. TL1=TL2=0.9€/GJ; TL3=0.6€/GJ (2023 values, COM/2021/563 final)

TVBs Time invested in every navigation stage, h; ∀s ∈ SS.

Zk Annual reduction factor for the calculation of the required annual operation from 2019 values; ∀k ∈ K: 2023 (Zk =Z1=5%); 2024 (Zk =Z2=7%); 2025 (Zk =Z3=9%); 2026 (Zk =Z4= 11%); and an increase of 2% for each year thereafter (Resolution MEPC.338(76)).

A. Subscripts

I = {1,...,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,...,j} Motor fuels under taxation; HFO; MDO and LNG

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

L= {1,...,l} A vessel's engines: main and auxiliary engines.

M= {1,...,m} Investment project's years for 2020 GSC abatement systems, by assuming 2019 as the retrofitting date for a SSS vessel.

SS = {1,...,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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