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Opportunities for Green H_2 in EU High-Speed-Crafts Decarbonization Through Well-to-Wake GHG Emissions Assessment

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Abstract

This paper introduces a mathematical model to assess the polluting impact of the decarbonization options for medium-sized High-Speed Crafts in the EU, and their consequences in terms of Market-Based Measure costs and Goal-Based Measure compliance under expected regulatory scenarios. This model is applied to a particular European High-Speed Craft operating in the Canary Islands. Considering slow steaming along with High Speed Craft's retrofitting with alternative technologies for its electricity supply, we conclude that green H_2 fuel Cells provide the greatest environmental advantage by comparison with slow steaming alone, achieving a 6.96% improvement in emissions and savings under European Market-Based Measures of 39.76% by 2033. The expected regulative progression involves a 5.90% improvement in the Market-Based Measure costs' convergence with the actual pollution impact of High-Speed Crafts. The findings warn about the pressing need to review the implementation of On-Shore Power Supply emissions into the Fuel EU fines, and about a concerning pull effect for the most polluting European High-Speed Crafts are moved towards the outermost regions of the EU due to their permanent exceptions from the application of the European Market-Based Measures.

Keywords: high-speed-crafts; green H_2 fuel cells; market-based-measures; carbon intensity indicator; maritime decarbonization

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1. Introduction

Traditionally, maritime environmental regulations have been based on the attainment of standards that are compiled as rules to achieve an environmental goal, or functional requirements associated with that goal. These regulatory requirements are called Goal-Based Measures (GBMs). However, in the last decade, initiatives based on the Pollutant Pays Principle (PPP) have gained support in regulatory frameworks due to the recognition that GBMs are insufficient for the effective reduction of greenhouse gas (GHG) emissions. These new tools are named Market-Based Measures (MBMs); they place a price on GHG emissions to incentivise reductions in fuel consumption and investments in mitigation technologies for maritime transport. MBMs were included in the EU's maritime transport policy for the first time in 2021, and they became effective in 2024; therefore, MBMs are very recent tools in comparison to GBMs.

According to the European Maritime Safety Agency (EMSA), nearly half of EU maritime traffic (port call numbers) in 2019 [1] was domestic traffic, mainly comprising Ro-Pax vessels. Between 2016 and 2020, the EU-Ro-Pax fleet expanded by 11.07%, with High-Speed Crafts (Article 10 of SOLAS (The International Convention for the Safety of Life at Sea, 1974)) showing a stronger growth of 16.57% over the same period [2]. This placed the EU as the world leader in this field, with 53% of the World's Ro-Pax fleet (GT) in 2025 [3]. The growth of this traffic pattern has been largely due, on the one hand, to explicit support from the EU's transport policies for Short Sea Shipping (SSS) through the Motorways of the Sea [4] as a preferential mode for ensuring the public service obligations of accessibility for islands, remote locations, peninsulas, etc., and, on the other hand, to the evident advantages provided by high-speed services (short shipping times enable high-frequency calls with the same number of vessels) for the users.

Indeed, the effects of this traffic's pressure on the EU were highlighted not only through 13.4 million tons of CO_2 emissions in 2023 (https://www.emsa.europa.eu/eumaritimeprofile/section-4-environment.html accessed on 13 January 2026), the fourth largest contributing vessel type in the EU (only after container vessels, bulk carriers, and oil tankers), but also through the vessels' consistent classification according to the Carbon Intensity Indicator (CII, MEPC.336(76)): over 40% of EU-Ro-Pax vessels, regardless of their speed, were rated D or E in 2020 [5]. Furthermore, the newest vessels achieved the worst score (D; [5]) due to High-Speed Crafts' prevalence in this segment. According to CII regulations, when a vessel is rated with a score below C (rated as D for three consecutive years, or one year as E (MEPC.339(76)), corrective plans must be introduced to achieve a C score. The enormous difficulty in correcting the classification of Ro-Pax vessels operating at high speeds (High Speed Crafts-HSC-) with the available technology has led to the subsequent inclusion of a specific sub-category for them in the CII reference line guidelines (G2; MEPC.353(78)) with more lax requirements.

Even though the relaxation of this IMO GBM has temporarily eased the environmental pressure on these vessels, there are growing demands from MBMs imposed both by the EU (EU-ETS: European Union Emission Trading System (Directive 2023/959); Fuel EU Initiative (Regulation (EU) 2023/1805); ETD: Energy Taxation Directive (COM/2021/563 (final))) and recently, by the IMO (IMO Net-Zero framework) involving the assessment's progression from CO_2 to CO_{2eq} emissions and from the Tank-to-Wake—TtW—approach to the Well-to-Wake—WtW—approach, which is motivating the search for reliable solutions to make the HSC fleet more sustainable.

Given the current technological maturity of the emerging solutions, the highly demanding requirements of this traffic pattern, and the ageing of the EU-HSC fleet (average remaining service life of 10 years [3]), providing feasible solutions is a challenge for medium-sized HSCs (5000–10,000 GT). While promising innovations in propulsion, such as electric batteries and H_2 fuel cells, have recently been adopted in some newly built HSCs of small to medium size (mainly, 0–5000 GT), these technologies are not currently applicable to most existing vessels in the EU due to their age, size, and general arrangement. This search for solutions is particularly pressing in EU archipelagos, the outermost regions and very short-distance routes (channels and straits), where HSC traffic is intensive, and road alternatives are absent. Likewise, studies into MBM's performance as proportionate incentives for vessel retrofitting are scarce, usually qualitative, and not focused on HSCs' realities.

In light of the above, this paper contributes to covering these knowledge gaps by providing quantitative information to make decisions about the decarbonization of the existing EU-HSCs from two points of view: that of the shipowners, who are forced to comply with CII requirements by ensuring that their vessels achieve a C rating within an evolving regulative framework, and of the policy-makers, who must review progressive "basket measure" effectiveness as an incentive for the adoption of sustainable technologies by the HSC fleet.

To meet this aim, this paper introduces a mathematical model to assess HSCs' actual pollutant impact, along with its consequent effects in terms of Goal- and Market-Based Measures. The model's application enables us to determine the EU-HSCs' level of attainment of the current and incoming environmental policies (GBM and MBM) through a combined solution based on the findings of previous analyses ([5–7]; among others): vessels' retrofitting with sustainable technologies for their electricity supplies, along with slow steaming. The model's application to a particular shipping line in the Canary Islands over a 10 year time period (successive regulatory scenarios) and with sustainable technologies to replace the electricity-generating components (Photovoltaic system—PV system; On-Shore Power Supply—OPS; and green H_2 fuel cells) permits us to broaden our knowledge in quantitative terms within the following research lines:

- From the shipowners' perspective: Evolution of the alternative technologies' performance for HSCs' electricity supply in terms of sustainability and MBM savings with the progressive tightening of the environmental policies (IMO and EU frameworks).
- From the policy-makers' perspective: Progression of MBMs' effectiveness as PPP tools for EU-HSCs when emerging technologies are involved.
- From the policy-makers' perspective: Divergences among IMO and EU approaches for MBMs and their consequences on the promotion of alternative technologies for the EU-HSC fleet's decarbonization. Particular attention is paid to the effects of the regulation's exceptions at the convergence of the outermost regions.

After a brief review of the main contributions from previous research (Section 2), the paper introduces a mathematical model (Section 3) that enables the quantitative assessment of HSCs retrofitted with different alternative technologies by considering the IMO and EU regulations along with the actual pollutant impact of the retrofitted vessels. Section 4 presents the case study of a representative HSC operating inter-island in the Canarian Archipelago, and the adaptation of the mathematical model to this case is explained. The results obtained are collected and analysed in Section 5. Finally, Section 6 and Section 7, respectively, present a discussion and contextualization of the results and the final conclusions of this research.

2. Literature Review

Since the EU basket measures' introduction in July 2021, their performance and shortcomings on a current TtW CO_2 basis have been frequently analysed from both an academic perspective ([7–10]; among others) and through broad-scope reports commissioned by EU institutions [5,11]. Thus, while some studies have tackled the interaction between Carbon Intensity Indicator compliance (by IMO, MEPC 76 in June 2021) and the EU-MBMs [5,7,10] in shipowners' decision-making, other research has specifically addressed the EU-MBMs' performance [8] and their role in fuel choice [9,11].

Even though the implications of possible EU-MBM modifications have previously been studied, with consistent findings, like the evident need to extend the scope of the EU-ETS to vessels from 400 GT instead of 5000 GTs, [12], which was ultimately included into the EU regulations (Directive (EU) 2023/959), the effects of other EU-MBM modifications on the basis of the TtW CO_{2eq} approach (instead of TtW CO_2; Regulation (EU) 2023/2776), which will be enforced from January 2026, and their probable evolution to WtW CO_{2eq} have not been sufficiently tackled yet. In this sense, the Trosvick and Brynolf study [13] is notable, since it analysed several policy scenarios related to Fuel EU and EU-ETS by concluding that there is a need to advance towards WtW CO_{2eq} in EU-ETS to avoid an upstream emissions increase, and estimated that this change will involve duplicating current quantified emissions (in line with Vierth et al. discussion [12]). Likewise, analyses of the incoming IMO Net Zero Framework's (MEPC 83, April 2025) impact on the EU framework, which will price GHG emissions from 2028 by adopting the WtW GHG intensity approach (MEPC.391(81)), are still very scarce in the literature due to its novelty. In this regard, as a result of the EU Commission consultation on the EU-ETS review, Transport & Environment [14] highlighted the limited ambition of the IMO Net Zero Framework, noting that it excludes over 85% of EU shipping emissions from pricing. Thus, the report not only recommended the EU basket measures' coexistence with the IMO initiative but also extending the EU-ETS's scope by covering 100% of extra European Economic Area voyages [14] to cope with the marine e-fuel transition. On the other hand, the report highlighted the need to incentivize clean technologies in SSS by removing the current exemptions in the application of the EU-ETS for small vessels and several routes (like the outermost regions, small islands off the mainland, ports of the same Member State, etc), given the current technological solutions.

Indeed, the recent IMO (MEPC.391(81)) 2024 Guidelines on the life cycle GHG intensity of marine fuels have boosted the search for decarbonization solutions from the life cycle (LC) perspective (WtW approach). As a result, interesting evidence-based insights have been obtained, among them, the key role played by the vessel's speed, beyond TtW, by affecting WtW emissions [15], and the significant dependence of upstream emissions on external conditions to the renewable fuel, not only regarding the regional energy conditions [15], but also the storage tank design [16]. Therefore, although the environmental superiority of a fuel is not fixed, its Global Warming Impact has become a priority in the LC analysis [15–17]. Thus, although batteries are the preferred choice for small ferries—below 5000 GTs—[13] the suitability of green H_2 for SSS is widely accepted [18]. Aside from its technical feasibility, comprehensive reduction insights have supported it as a choice for this traffic pattern: over 84% of WtW GHG emissions were eliminated with e-H_2 power systems [15] versus MDO engines, and they achieved 91.7% better results than HFO engines when fuel cells were involved [17]. Focusing on the decarbonization of medium-sized Ro-Pax vessels, several authors have previously analysed alternative fuels and mitigation options. Again, green H_2 and an ammonia–hydrogen blend have become a preferred fuel for SSS vessel propulsion. Thus, whereas Sánchez et al. [19] achieved decarbonization targets and economic feasibility through an ammonia–hydrogen blend for internal combustion engines [20], LC analysis recommended the preferential use of green H_2 in fuel cells for the on-board electricity supply (instead of generating sets), to minimise the negative effects of the batteries' weight. In this line, Martínez-López et al. [7,21] tackled SSS decarbonization by replacing auxiliary engines with solar photovoltaic systems (PV systems) in the former [7], and with an On-Shore Power Supply, green H_2 fuel cells, and PV systems in the latter [21]. Although the techno-economic results, along with the environmental aim compliance, were favourable, only Martínez-López et al. [7] specifically addressed the technical particularities of High-Speed Crafts (HSCs). Additionally, the analysis only considered the current EU environmental rules on the basis of TtW CO_2 emissions (EU-ETS) as a static scenario.

Finally, it is interesting to note that most of the EU's research projects focused on SSS decarbonization have been addressed at new-building of small ferries operating at moderate speeds, by offering propulsion alternatives using batteries (900 GT 'Ellen' from H2020 project E-FERRY (https://cinea.ec.europa.eu/featured-projects/e-ferry_en accessed on 13 January 2026) at 22 n.m; 228 GT 'MS Medstraum' at 23 kn from the H2020 project TrAM (https://tramproject.eu accessed on 13 January 2026) or hydrogen-driven fuel cells for passenger HSCs at 28 kn from GKP7H2-MoZEES programme (https://mozees.no/wp

-content/uploads/2018/05/Fredrik-Aarskog_for-distribution.pdf accessed on 13 January 2026 by Norway's Climate Action Plan for 2021–2030). The resulting vessels are highly interesting; however, as their operative requirements are far from the average EU medium-sized HSC's (around 8000 GTs when operating with rolled cargo over 35 kn), they have a limited applicability to the fleet's retrofitting.

In this context, this paper attempts to address this knowledge gap by tackling the performance of medium-sized EU-HSC retrofitting solutions for their electricity supply under progressive regulatory scenarios in the EU. This approach enables us to broaden the usefulness of the results beyond the shipowners' interest by also addressing the interests of the policymakers.

3. The Method

This section introduces the calculation method that enables the quantitative assessment of HSCs retrofitted with several technologies in terms of real sustainability (Pollutant Impact-PI-see Section 3.1) and alignment with the regulations imposed by the IMO (Section 3.2) and the EU (Section 3.3). The latter involves not only GBM compliance (Sections 3.2.1 and 3.3.1) but also the quantification of potential savings in terms of the MBMs (Sections 3.2.2 and 3.3.2) associated with each technology proposed. The method assumes, on the one hand, the previous selection of an alternative technology for the sustainable supply of electricity for HSCs. Such a selection must consider the adequacy of these options for the technical and operative features of the vessels and ports involved. On the other hand, the method likewise assumes three regulatory scenarios (see Figure 1) with increasing level of exigency on decarbonization that, according to the regulation trend (comprehensive approach to the life cycle assessment of the activity, see regulation progress collected in Section 2), will be based on the consideration of the following: CO_2 Tank-to-Wake (TtW) emissions (current regulatory scenario), CO_{2eq} Tank-to-Wake (TtW) emissions (the incoming scenario), and CO_{2eq} Well-to-Wake (WtW) emissions (the expected scenario in the medium term). Detailed information about the scenario assumptions (see Figure 1) is provided in Section 3.3 (EU-ETS evolution) and Section 3.3.1 (Fuel EU evolution).

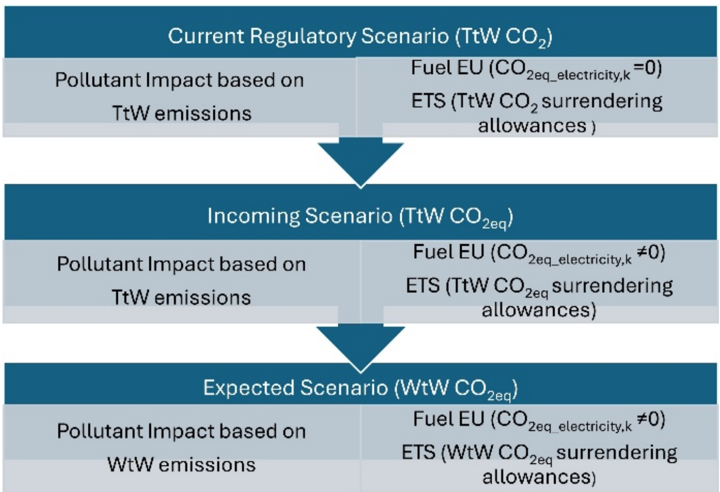

Figure 1. Expected progression of regulatory scenarios.

3.1. Pollutant Impact

Pollutant Impact (PI in EUR/trip) quantifies the vessel's sustainability performance. To achieve this aim, the PI model must go beyond GHG emissions by including additional pollutants that enable a comprehensive assessment of the retrofitted vessels with alternative technologies.

Given the expected regulatory evolution (see Figure 1), the PI models, which were previously published [22], have been necessarily modified by limiting their scope to air quality [7] and including N_2O pollutant and WtT emissions in the evaluation. In this way, the new annual $PI_y|_{WtW}$ model (∀y∈Y; in EUR/trip and year,) integrates both emission stretches (TtW and WtT, see Equation (1)) for each year (∀y∈Y, see Appendix A) in all navigation stages per trip: (SS = {1, . . . , s}, see Appendix A) free sailing, manoeuvring, berthing, and hoteling time—see Appendix A—in compliance with the successive approaches of the maritime environmental regulations (IMO and EU).

$$\text{PIy} \mid \text{WtW} = \sum_{s=1}^{4} PI_{sy} \;|_{TtW} + \sum_{s=1}^{4} PI_{sy} \;|_{WtT} \qquad \forall \text{s} \in \text{SS} \wedge \forall \text{y} \in \text{Y} \tag{1}$$

- Tank-to-Wake component (TtW).

Downstream emissions collect the impact of eight air pollutants (U = {1, . . . , *u*}, see Appendix A)—SO_X, NO_x, $PM_{2.5}$, PM_{10}, CO_2, CH_4, N_2O and NH_3—emitted by the main engines and the technology selected for the electricity supply (L = {1, . . . , *l*}) during the time invested in each navigation stage (TVB_{sky}, ∀s∈SS∧∀k∈K∧∀y∈Y in hours) through TtW emission coefficients (EG_{suly}; ∀s∈SS∧∀u∈U∀l∈L∧∀y∈Y in Kg/h). Whereas the free sailing evaluation (s = 1, see Equation (2)) considers the kind of sea (K* = {1. . ., *k*}) to determine the unitary cost of every pollutant (CU_{skuvy}; ∀s∈SS∧∀k∈K∀u∈U∀v∈V∧∀y∈Y in EUR/kg pollutant), the remaining navigation stages (∀s∈SS*, see Equation (3)) take into account, aside from the port's country (K = {1. . ., *k*}), the population density in the port hinterland (V = {1, . . . , *v*}).

- ○ Free sailing stage (s = 1):

$$\text{PI}_{1y} \;|_{\text{TtW}} = \sum_{l=1}^{L} \sum_{u=1}^{8} \left(EG_{1uly} \times CU_{1kuy} \times TVB_{1y} \right); \quad \forall \text{k} \in \text{K}^* \wedge \forall \text{y} \in \text{Y} \tag{2}$$

- ○ Remaining navigation stages (∀s∈SS*):

$$\text{PI}_{sy} \;|_{\text{TtW}} = \sum_{k=1}^{k} \sum_{l=1}^{L} \sum_{u=1}^{8} \left(EG_{suly} \times CU_{skuvy} \times TVB_{sky} \right); \quad \forall \text{s} \in \text{SS}^* \wedge \forall \text{v} \in \text{V} \wedge \forall \text{y} \in \text{Y} \tag{3}$$

- Well-to-Tank component (WtT).

Upstream emissions are quantified via the method specified in the 2024 LCA guidelines [23], wherein WtT GHG intensity factors (WtT_EG_{jly} in g CO_{2eq}/MJ), along with the lower calorific values (CVj; ∀j ∈ J in MJ/g fuel), are provided for every marine fuel used on board (J = {1, . . . , *j*}), as shown in Appendix A. Therefore, this emissions stretch (see Equations (4) and (5)) only considers GHG emissions in aggregated terms through CO_{2eq} (CO_2, CH_4, and N_2O pollutants (using the global warming potential over a 100-year time-horizon (MEPC 391 (81)); 100 GWP: CO_2 = 1; CH_4 = 28; N_2O = 265)). For this assessment, besides the aforementioned variables, the specific fuel consumption of the engines ($SFOC_{sjl}$; ∀s ∈ SS∧ ∀j ∈ J ∧ ∀l ∈L in g fuel/kWh) and the power developed by the vessel's engines (PB_{sly};∀s ∈ SS∧∀l ∈L∧ ∀y ∈ Y in kW) are necessarily considered in the calculations (see Equations (4) and (5)).

- ○ Free sailing stage (s = 1):

$$\text{PI}_{1y} \;|_{\text{WtT}} = \sum_{l=1}^{L} \left(WtT_{EG_{jly}} \times CV_{jl} \times SFOC_{sjly} \times PB_{sly} \times CUeq_{1ky} \times TVB_{1ky} \right); \quad \forall \text{k} \in \text{K}^* \wedge \forall \text{y} \in \text{Y} \tag{4}$$

- ○ Remaining navigation stages (∀s∈SS*):

$$\text{PI}_{sy} \;|_{\text{WtT}} = \sum_{k=1}^{k} \sum_{l=1}^{L} \left(WtT_{EG_{jly}} \times CV_{jl} \times SFOC_{sjly} \times PB_{sly} \times CUeq_{skvy} \times TVB_{sky} \right); \quad \forall \text{s} \in \text{SS}^* \wedge \forall \text{j} \in \text{J} \wedge \forall \text{v} \in \text{V} \wedge \forall \text{y} \in \text{Y} \tag{5}$$

WtT emissions from OPS use deserves special mention, since on-shore emission factors (EFG_{uky};$\forall u \in U \wedge \forall k \in K \wedge \forall y \in Y$ in kg/KWh, see Appendix A) can be obtained for all pollutants considered in TtW emissions from the regular information published by regional and EU institutions (Gross Electricity Generation per type of generation and the electric power generating plants' pollutant emissions). For that reason, the WtT pollutant impact component from OPS can be estimated with greater accuracy (see Equation (6)) by considering the on-shore electrical power ($PB2_{sy}$; $\forall s \in SS^{**} \wedge \forall y \in Y$ in kW) and lag in the connection time (CT_{sk}; $\forall s \in SS^{**} \wedge \forall k \in K$ in hours).

- On-shore electricity grid ($\forall s \in SS^{**}$):

$$PI_{sy}\ |_{WtT} = \sum_{k=1}^{k}\sum_{u=1}^{8}\left(EFG_{uky} \times PB2_{sy} \times CU_{skuvy} \times (TVB_{sky} + CT_{sk})\right); \forall v \in V\ \wedge \forall s \in SS^{**} \wedge \forall y \in Y \quad (6)$$

3.2. IMO Measures

Despite the wide debate about MBMs' suitability, IMO, until 2025, exclusively enforced GBMs, mainly through the Carbon Intensity Indicator from 2021 (CII, see Section 3.2.1). However, at the 83rd session of the Marine Environment Protection Committee (MEPC 83, April 2025), IMO finally announced its intention to include MBMs (see Section 3.2.2) through new requirements for WtW-GHG fuel intensity coupled with a pricing and reward mechanism collected in the IMO Net-Zero Fund (IMO Circular Letter No. 5005; 11 April 2025). Even though CII is currently calculated on the basis of TtW CO_2 emissions, its transition to a WtW CO_{2eq} approach could be shortly tackled, along with specifications of the consequences for CII non-compliance (expected review of GHG strategy short-term measures in January 2026). This involves a significant push towards maritime transport sustainability, but also disruptions in the expected EU scenarios in the medium-term.

3.2.1. GBM: Annual Operational Carbon Intensity Indicator

The Carbon Intensity Indicator (CII) was approved in the MEPC 76 (June 2021) as a GBM with compulsory application from January 2023 for vessels over 5000 Gross Tonnage (GT). Apart from vessel size, no exception to its application was specified, therefore CII regulations are enforced regardless of the geographic location of a route. This indicator provides information about the CO_2 (grams) per distance covered (D in nautical miles) and the vessel's cargo capacity (C, see Equation (7)). The CO_2 emissions are those recorded in the IMO Data Collection System—IMO DCS—according to MEPC.278(70), where fuel-specific carbon conversion factors (conversion factors are available in MEPC.308(73)) (CFF_{jl}; $\forall j \in J \wedge \forall l \in L$ in t CO_2/t fuel) are applied to this purpose.

$$CII\_A_y = \sum_{s=1}^{s}\sum_{k=1}^{k}\sum_{l=1}^{l}((SFOC_{sjly} \times PB_{sly} \times CFF_{jl}) \times TVB_{sky})/(C \times D); \quad \forall j \in J \wedge \forall y \in Y \quad (7)$$

Although several guidelines were published in 2021 for the application of CII (MEPC.336(76), MEPC337(76), MEPC338(76), and MEPC339(76)), most were modified afterwards.

The measure defines the CII attained by the vessel (CII_A_y, $\forall y \in Y$; see Equation (7)) for each year (g CO_2/t and n.m) (MEPC.336(76) revoked by MEPC.352(78) and modified by MEPC.355(78)), which is compared to the Required Annual Operational CII (CII_Ry see Equation (8)).

$$CII\_R_y = a \times C^{-c} \times \left(1 - \frac{Zy}{100}\right); \quad \forall y \in Y \quad (8)$$

The latter is determined on the basis of a CII reference line (MEPC337(76) revoked by MEPC.353(78)) for every kind of vessel (a, c parameters in Equation (8)), which is corrected by a progressive reduction factor over time $-Zy$; $\forall y \in Y$—(MEPC.338(76) revoked by MEPC.400(83)). The vessel is finally classified with an A to E score by considering the CII classification attained within the bounds of the CII rating system (MEPC.339(76) revoked by MEPC.354(78)). Thus, when a vessel is rated a D for three consecutive years, or an E in one year, the vessel must develop a correction plan (Ship Energy Management Plan-SEEMP-) to return to a C score.

Among the most relevant changes on the initial guidelines (MEPC 76, June 2021), we highlight the following:

- The inclusion of a sub-category in High-Speed Crafts to include Ro-Ro passenger ships for the CII reference line guidelines (G2; MEPC.353(78)).
- Despite the rating boundaries' extension to Ro-Ro passenger ships in the CII Rating Guidelines (G4, MEPC.354(78)), no specific considerations were included for HSCs.
- The inclusion of more restrictive reduction factors in the 2026 aftermath in comparison to the previous period (2023–2026).

The main consequence of the aforementioned changes is a significant increase in the Required Annual Operational CII along with an extension of the rating boundaries. This has led to an evident relaxation of the environmental requirements for HSCs in contrast to the 2021 CII regulations.

3.2.2. MBM: The IMO Net-Zero Framework

This section collects the requirements for the annual GHG fuel intensity (GFI in g CO_{2eq}/MJ) compliance and the non-compliance consequences (IMO Circular Letter No.5005, 11 April 2025), with expected application commmencing from 2028 for vessels over 5000 GT. However, these regulations open the door to exclude domestic traffic (like the most HSC activity) from the regulation's scope if Member States adopt consistent measures that ensure an equivalent sustainability level. IMO Net-Zero Framework is based on the annual WtW GHG emissions per energy unit consumed by the vessel, according to the 2024 Guidelines on life cycle GHG intensity of marine fuels (MEPC.391(81)). It is worth pointing out the evolution presented by the IMO approach by widening the environmental scope: whereas CII considers TtW CO_2 emissions per nautical mile and cargo unit, the IMO Net-Zero fund is based on WtW CO_{2eq} emissions per energy unit.

The GFI_attained (see Equation (9)) shows annual GHG vessel intensity (g CO_{2eq}/MJ) by considering, on the one hand, the energy produced by the vessel across several fuels (E_{sjly}; ∀s∈S∧∀j∈J∧∀l∈L ∧∀y∈Y in MJ, see Equation (10)), the on-shore power supply (EC_s; ∀s∈SS), and the energy obtained from renewable sources like photovoltaic energy, wind, etc., (ES_s; ∀s∈SS). On the other, the WtW GHG intensity in gCO_{2eq}/MJ (EI_{sjly}; ∀s∈SS∧∀j∈J∧∀l∈L∧∀y∈Y) is the result of the addition of WtT GHG intensity and TtW GHG intensity (see Equation (11)). Whereas the former ($CO_{2eqWtT,j}$ ∀j∈J in gCO_{2eq}/MJ) can be directly taken from the default emission factors collected in the 2024 Guidelines on life cycle GHG intensity of marine fuels (Appendix A), the latter must be calculated (see Equations (11) and (12)) by considering the GWP [23] along with the default WtT emissions factors[6] (CFF_{jl}, CFM_{jl}, CFN_{jl} in g CO_2/g fuel). WtW GHG intensity for OPS (EIC_{ky}; ∀k∈K∧∀y∈Y) merits particular mention since, aside from being equivalent to WtT GHG intensity, its value is the result of the 'mixed energy' involved in electricity production for the onshore network (share of renewable sources). Therefore, its value is highly dependent on the geographical location and the year (progressive decarbonization of the EU's electricity networks).

- Attained annual GHG fuel intensity (GFI_attained).

$$\mathrm{GFI\_attained_y} = \sum_{s=1}^{s}\sum_{k=1}^{2}\sum_{l=1}^{L}\sum_{j=1}^{j}\left(E_{sjly} \times EI_{sjly} + EC_s \times EIC_{ky}\right)/\left(\sum_{s=1}^{4}\sum_{l=1}^{L}\sum_{j=1}^{j}\left(E_{sjly} + EC_s + ES_s\right)\right);\forall \mathrm{y} \in \mathrm{Y} \quad (9)$$

$$\mathrm{E_{sjly}} = \sum_{k=1}^{k}\left(CV_{jl} \times SFOC_{sjly} \times PB_{sly} \times TVB_{sky}\right); \qquad \forall \mathrm{s} \in \mathrm{SS} \wedge \forall \mathrm{j} \in \mathrm{J} \wedge \forall \mathrm{l} \in \mathrm{L} \wedge \forall \mathrm{y} \in \mathrm{Y} \quad (10)$$

$$EI_{sjly} = (CO_{2eqWtT,j} + (CO_{2eqTtW,j,l} \times E_{sjly})/CV_{jl})/E_{sjly}; \qquad \forall s \in SS \wedge \forall j \in J \wedge \forall l \in L \wedge \forall y \in Y \tag{11}$$

$$CO_{2eqTtW,j,l} = (CFF_{jl} \times GWP_{CO2} + CFM_{jl} \times GWP_{CH4} + CFN_{jl} \times GWP_{N2O}); \qquad \forall j \in J \wedge \forall l \in L \tag{12}$$

The regulation evaluates the GFI compliance balance by comparing the target annual GHG fuel intensity with the GFI_attained. The former is corrected through progressive annual reduction factors from two perspectives: direct compliance target (ZTD_y; ∀y∈Y, see Appendix A) and base target (ZTB_y; ∀y∈Y). Consequently, two target levels exist: Direct compliance target annual GFI (GFI_TD, see Equation (13)) and Base target annual GFI (GFI_TB, see Equation (14)).

- Target annual GHG intensity

$$GFI\_TD = 93.3 \times \left(1 - \frac{ZTDy}{100}\right) \quad ; \qquad \forall y \in Y \tag{13}$$

$$GFI\_TB = 93.3 \times \left(1 - \frac{ZTBy}{100}\right) \quad ; \qquad \forall y \in Y \tag{14}$$

Table 1 collects the management of the compliance deficit through tier levels and their quantification as a contribution to the IMO Net Zero fund in monetary units (remedial units in EUR/year). Due to the current research aims, even though the regulation contains several possible approaches to balance the compliance deficit, GHG emissions pricing contributions are considered as the sole form of non-compliance compensation.

Table 1. Assessment of the compliance deficit and remedial units for IMO Net Zero fund.

GFI Compliance Balance	TIER I (g CO_{2eq})	TIER II (g CO_{2eq})	IMO Net Zero Fund (EUR/Year) *
$GFI\_TD \geq GFI\_attained_y$	0	0	0
$GFI\_TD < GFI\_attained_y \leq GFI\_TB$	$(GFI\_TD - GFI\_attained_y) \times (\sum_{s=1}^{4}\sum_{l=1}^{L}\sum_{j=1}^{j}(E_{sjly} + EC_s + ES_s))$	0	$(GFI\_TD - GFI\_attained_y) \times (\sum_{s=1}^{4}\sum_{l=1}^{L}\sum_{j=1}^{j}(E_{sjly} + EC_s + ES_s) \times 0.85)$
$GFI\_TB < GFI\_attained_y$	$(GFI\_TD - GFI\_TB) \times (\sum_{s=1}^{4}\sum_{l=1}^{L}\sum_{j=1}^{j}(E_{sjly} + EC_s + ES_s))$	$(GFI\_TB - GFI\_attained_y) \times (\sum_{s=1}^{4}\sum_{l=1}^{L}\sum_{j=1}^{j}(E_{sjly} + EC_s + ES_s))$	$(GFI\_TD - GFI\_TB) \times (\sum_{s=1}^{4}\sum_{l=1}^{L}\sum_{j=1}^{j}(E_{sjly} + EC_s + ES_s) \times 0.85) + (GFI\_TB - GFI\_attained_y) \times (\sum_{s=1}^{4}\sum_{l=1}^{L}\sum_{j=1}^{j}(E_{sjly} + EC_s + ES_s) \times 3.23)$

* USD 1 = 0.85 EUR.

3.3. EU Measures

In 2021 the EU published three regulation proposals to achieve significant reductions in the CO_2 emitted by maritime transport between EU Member States and third countries: the Fuel EU maritime initiative (COM (2021)562 final), the restructuring of the Energy Taxation Directive (COM (2021)563 final), and the inclusion of shipping in the EU Emission Trading system (COM (2021)551 final). Whereas the former involved a GBM (aside from MBM) based on WtW CO_{2eq} emissions (WtW GHG intensity) the remaining proposals involved MBM with taxation of the energy developed by the vessel (EUR/GJ) and TtW CO_2 emissions (EUR/CO_2 t), respectively.

While the Energy Taxation Directive's restructuring proposal awaits committee decisions (up to date, see Section 3.3.2), remaining proposals were solidified in the Regulation (EU) 2023/1805 for the Fuel EU initiative (see Section 3.3.1) and the Directive 2023/959 for the inclusion of maritime transport in the EU-ETS (see Section 3.3.3).

The final regulations include some modifications of the initial proposals, mainly the following:

- Fuel EU: inclusion of a fixed reference value of 91.16 g/CO_2eq to define the WtW GHG intensity target, tightening of the Fuel EU non-compliance penalty through a recidivism mechanism and a modification of the reduction schedule of the WtW GHG intensity target.

- EU-ETS: a delay in enforcement from 2023 to 2024 and therefore a modification of the progressive inclusion of TtW CO_2 emissions from vessels.

The application of EU-ETS involves the liability of offering allowances for TtW CO_2 emissions as reported through the EU-MRV system (Regulation (EU) 2015/757). In 2023, the EU-MRV was also amended to widen its scope to vessels over 400 GT (initially 5000 GT) and to include the CH_4 and N_2O emissions record in the EU-MRV from January 2025 (Regulation (EU) 2023/957). In such a way, EU-ETS will take the additional GHG emissions from EU-MRV (Regulation (EU) 2023/2776) to extend the offering of allowances to verified WtT CO_{2eq} emissions from January 2026.

Finally, it is worth highlighting the regulations' exception to application in the outermost regions (defined in article 349 of the Treaty on the Functioning of the EU); although the regulations' enforcement encompasses the entire EU, implementation in these regions has been postponed until December 2029 for Fuel EU and December 2030 for EU-ETS. Additionally, only half of the energy used by the vessels in the outermost regions must be taken into account under the Fuel EU assessment.

3.3.1. GBM: Fuel EU Maritime Initiative

The Fuel EU maritime initiative (Regulation (EU) 2023/1805) can be considered a GBM, since it limits the WtW GHG intensity of the energy used by a vessel (g WtW CO_{2eq}/MJ) to target value ($(GHGIE_{target})_y$; $\forall y \in Y$, see Equation (15)) with an annual progressive reduction (μy; $\forall y \in Y$). However, the Fuel EU initiative exceeds a GBM, as it imposes a non-compliance penalty ($Fuel\_EU_y$; $\forall y \in Y$ in EUR/year; see Equation (16)) that is based on compliance divergency between the actual WtW GHG intensity ($(GHGIE_{actual})_y$ $\forall y \in Y$, see Equation (17)) and the target one; the recidivism (n); and the percentage of the vessel's energy considered depending on the ports involved: EU Member States, EU outermost regions, or third countries (γ_i; $\forall i \in I$, see Appendix A). The $GHGIE_{actual}$ calculation considers default values ($CO_{2eqWtT,j}$; $\forall j \in J$, in g CO_{2eq}/MJ collected in the Annex II, Regulation (EU) 2023/1805; see Equation (18)) in the WtT GHG emissions calculation (see Equation (18)), and for TtW GHG emissions calculation (see Equation (19)), it considers the TtW CO_{2eq} emissions of combusted fuel ($CO_{2eqTtW,j,l}$ in gCO_{2eq}/g fuel, see Equation (12)) with the same approach as the IMO Zero Net Framework, but taking the GWP (using the global warming potential over a 100-year time-horizon (Directive (EU) 2018/2001); 100 GWP: CO_2 = 1; CH_4 = 25; N_2O = 298.) values and default WtT emission factors (CFF_{jl}, CFM_{jl}, CFN_{jl}) from Directive (EU) 2018/2001 and Regulation (EU) 2023/1805, respectively.

$$(GHGIE_{target})_y = 91.16 \times \mu_y; \qquad \forall y \in Y \tag{15}$$

$$Fuel\_EU_y = \frac{2.4}{41} \times \gamma_i \times \left(\sum_{s=1}^{s} \sum_{k=1}^{k} \sum_{l=1}^{l} \left(TVB_{sky} \times \left(SFOC_{sjly} \times PB_{sly} \times CV_{jl}\right)\right) + EC_s\right) \times \left(\frac{(GHGIEtarget)y - (GHGIEactual)}{GHGIEactual}\right) \times \left(1 + \left(\frac{n-1}{10}\right)\right); \quad \forall i \in I \wedge \forall j \in J \wedge \forall y \in Y; \tag{16}$$

$$GHGIE_{actual} = f_{wind} \times \left(EWtT_y + ETtW_y\right) / \left(\left(\sum_{s=1}^{s} \sum_{l=1}^{l} \left(E_{sjly} \times RWD_{jl}\right)\right) + EC_s + ES_s\right); \qquad \forall y \in Y \tag{17}$$

$$EWtT_y = \sum_{s=1}^{s} \sum_{l=1}^{l} \left(E_{sjly} \times CO_{2eqWtT,j}\right) + \sum_{s=1}^{s} \sum_{k=1}^{k} EC_s \times CO_{2eq\_electricity,k}; \quad \forall j \in J \wedge \forall y \in Y; \tag{18}$$

$$ETtWy = \sum_{s=1}^{s} \sum_{l=1}^{l} E_{sjly} \times \left(CO_{2eqTtW,j,l} \times \left(1 - \frac{1}{100} \times C_{engine\_slip,l}\right) + CO_{2eqTtWslippage,j,l} \times \frac{1}{100} \times C_{engine\_slip,\ l}\right); \forall j \in J \wedge \forall l \in L \wedge \forall y \in Y \tag{19}$$

This regulation, aside from incorporating the compulsory use of OPS or zero-emission technologies for container and passenger vessels at berth from January 2030, significantly supports this option by permitting the WtT GHG emission factor associated with OPS to be made null ($CO_{2eq\_electricity,k}$ ∀k ∈ K, see Equation (18)). Even though this exception is a reality in the current regulatory scenario (see Figure 1), the latest approaches to the OPS emissions impact [24] recommend a comprehensive assessment (MEPC.391(81)). For this reason, whereas $CO_{2eq\_electricity,k}$ is zero in the current regulatory scenario, the remaining scenarios (the incoming scenario and expected scenario) consider its value in Fuel EU calculations (see Figure 1).

There are several differences between the Fuel EU and IMO Zero-Net frameworks' approaches to WtW GHG intensity calculation for vessels. Beyond the aforementioned exception for OPS emissions, Fuel EU includes reward factors for wind energy use (f_{wind}, see Equation (15)) and for non-biological fuels (RWD_{jl}; ∀j ∈ J ∧∀l ∈L; see Equation (18) and Appendix A) by reducing the $GHGIE_{actual}$ (g CO_{2eq}/MJ) value when sustainable options are involved. In addition, the WtT GHG emissions default values ($CO_{2eqWtT,j}$), collected under both regulations for all fuels, are not allways coincident, again, the IMO Zero-Net framework (MEPC.391(81)) assumes higher values. Finally, the GWP for the GHG emissions are also different between both regulations; even though the values taken by the IMO Zero-Net framework (MEPC.391(81)) are the same as the EU-MRV regulation (CO_2 = 1; CH_4 = 28; N_2O = 265 in Regulation (EU) 2023/2776), they are different from those specified in the Fuel EU regulation (CO_2 = 1; CH_4 = 25; N_2O = 298 in Directive (EU) 2018/2001).

3.3.2. MBM: Energy Taxation Directive

The COM/2021/563 (final) widens the Energy Taxation Directive's (ETD) scope related to energy products and electricity taxation by including EU maritime transport. However, the current proposal also introduces a zero-taxation rate for on-board electricity generated over 10 years and OPS electricity is excluded from the application of ETD. Consequently, only the energy developed by propulsion engines is taken into account for these calculations (l = 1, see Equations (20) and (21) and Appendix A).

Thus, annual energy taxation (ETD_y; ∀y ∈ Y in EUR/year, see Equation (20)) is calculated by considering the annual trips (N, see Appendix A) and the energy taxation per trip and year (ETU_y; ∀y ∈ Y in EUR/trip, see Equation (21)), where the energy developed by the vessel (in GJ) is taxed according to the type of fuel used for its generation. The taxation rate (TL_j; ∀j ∈ J in EUR/GJ, see Equation (21) and Appendix A) is updated by yearly increasing its minimum level by one tenth, beginning in 2023.

$$ETD_y = N \times ETU_y; \qquad \forall y \in Y \qquad (20)$$

$$ETU_y = \sum_{s=1}^{s} \sum_{k=1}^{k} \left(TL_j \times CV_{jl} \times SFOC_{sj1y} \times PB_{s1y} \times TVB_{sky} \right); \qquad \forall j \in J \wedge \forall y \in Y; \qquad (21)$$

Although the current COM/2021/563 (final) status is awaiting committee decision, the voting time is scheduled for November 2025.

3.3.3. MBM: EU Emission Trading System

Directive 2023/959 enforced the inclusion of EU shipping in the EU-ETS from 2024 on a general basis, and from December 2030 for shipping within the EU's outermost regions or between these regions and the regular EU region. According to the regulation, the shipping companies are liable to surrender the verified GHG emissions allowances from the EU-MRV system (Regulation (EU) 2015/757) are required to be surrendered by considering the EU Member states' port membership (α_i; $\forall i$ ∈ I) and a schedule of progressive inclusion (β_y; $\forall y$ ∈ Y) over time. The annual cost (ETS_y; ∀y ∈ Y; EUR/year, see Equations (22) and (23)) is highly dependent not only on the EU carbon price (CP_y; ∀y∈Y in EUR/emission tonne), but also on the carbon emission approach reported by the EU-MRV ($(\text{emissions})_y$; $\forall y \in Y$, see Equations (24)–(26)). As was mentioned before (see Figure 1), even though the current regulatory scenario involves TtW CO_2 emissions (see Equation (24)), the incoming scenario (from 2026) considers TtW CO_{2eq} emissions (see Equations (12) and (25) with $CO_{2eqTtW,j,l}$; $\forall j \in J \,\hat{}\, \forall l \in L$ in TtW $gCO_{2eq}/gFuel$) and the expected scenario will assess WtW CO_{2eq} emissions (see Equations (10) and (26), with $CO_{2eqWtT,j}$; $\forall j \in J$ in WtT gCO_{2eq}/MJ and E_{sjly}; $\forall s \in S \wedge \forall j \in J \wedge \forall l \in L \wedge \forall y \in Y$ in MJ).

$$ETS_y = N \times ETSU_{y;} \qquad \forall y \in Y \tag{22}$$

$$ETSU_y = CP_y \times \alpha_i \times \beta_y \times (\text{emissions})_y; \qquad \forall i \in I \wedge \forall y \in Y; \tag{23}$$

- Current regulatory scenario (TtW CO_2 emissions, Regulation (EU) 2015/757):

$$(\text{emissions})_y = \sum_{s=1}^{s} \sum_{k=1}^{k} \sum_{l=1}^{l} ((SFOC_{sjly} \times PB_{sly} \times CFF_{jl}) \times TVB_{sky}); \quad \forall j \in J \wedge \forall y \in Y \tag{24}$$

- Incoming scenario (TtW CO_{2eq} emissions; Regulation (EU) 2023/957):

$$(\text{emissions})_y = \sum_{s=1}^{s} \sum_{k=1}^{k} \sum_{l=1}^{l} \left(SFOC_{sjly} \times PB_{sly} \times TVB_{sky} \times CO_{2eqTtW,j,l} \right); \quad \forall j \in J \wedge \forall y \in Y \tag{25}$$

- Expected scenario (WtW CO_{2eq} emissions; MEPC.391(81)):

$$(\text{emissions})_y = \sum_{s=1}^{s} \sum_{k=1}^{k} \sum_{l=1}^{l} (SFOC_{sjly} \times PB_{sly}\, TVB_{sky} \times CO_{2eqTtW,j,l} + E_{sjly} \times CO_{2eqTtW,j,l}) \forall j \in J \wedge \forall y \in Y \tag{26}$$

4. Case Study

A representative High-Speed Craft from the Canarian archipelago (see Table 2 and [25]) with inter-island activity was selected as a case study. The exemptions to the EU-MBM's application in the outermost regions, the high pollution impact of medium-sized HSCs, and the increasing percentage of this traffic in the Canarian Islands makes it interesting to analyse as a particular case to broaden application of the findings.

Table 2. Technical features for HSC [26].

Length Overall (m)	112.6
Length between perpendiculars (m)	101.3
Beam (m)	26.2
Draft (m)	3.8
Draft max (m)	4.85
Depth to main deck (m)	8.5
Depth to upper deck (m)	15
Gross Tonnage	10,369
Deadweight Max(t)	10,000
Cars/Pax (capacity)	357/1400
Main engine (BHP kW)	36,000 (4 × 9 MW)
Auxiliary engines (kWe)	4 × 393
Service speed (kn)	38
Bow thruster (kW)	2 × 300
Waterjets	4 × 125KaMeWaSIINP

Thus, the case focuses on a vessel that has a service speed of 38 kn on a regular line between Gran Canaria and Fuerteventura (maritime distance of D = 55 n.m) with four calls per day (i.e., two in each direction) offering 1100 trips per year.

The vessel is propelled by four MAN 20V28/33D STC main engines (MMPP) and the electricity plant is made up of four generating sets (MMAA) VOLVO PENTA MARINE

GENSET D16-MG. Due to the route's short distance, in order to meet Directive 2005/33/EC (max 0.1%S content in fuels for port operations) LSMGO is assumed to be the only fuel used by all on-board engines.

Table 3 shows the most habitual operating pattern for this regular line. There is a significant under-use of the on-board electricity generation capacity (just two of the four generating sets—MMAA—are operating in the most demanding navigation stage with a 57% rating). The information in Table 3 was tested by comparing the annual CO_2 emissions reported by THETIS-MRV (IMO 9557848) with those obtained by introducing the technical and operative information from Tables 2 and 3 into an emissions calculation tool (SHIP-DESMO-Ro-Ro Passenger from the Danish Ro-RoSECA project (https://gitlab.gbar.dtu.dk/oceanwave3d/Ship-Desmo/-/find_file/master, https://danishshipping.dk/en/policy/climate/ship-design-calculation-tool/ (accessed on 13 January 2026); [27]) along with the required Effective Horse Power (Maxsurf Resistance tool) to operate under the assumed navigation stages. The deviation was found to be 0.99% by assuming a current 1100 trips/year by this vessel (34,139.89 tCO_2/year reported in THETIS-MRV, 2023 [28] versus the estimated 34,286.25 tCO_2/year), which validates not only the operating information (Table 3) but also the emissions calculation approach. Consequently, this emissions estimation will be used for further pollutant impact assessments and the vessel's CII calculation.

Table 3. Current operating features for the HSC vessel.

Navigation Stage	Speed (kn) VB_s	Propulsion Requirements (kW)	Capacity Planning MMPP * (%BHP)	Electricity Requirements (kW)	Capacity Planning MMAA ** (%kWe)	Times (h/Trip) TVB_s
Free Sailing	38	33.757	4xMMPP 93.73%	400	2xMMAA 51%	1.6
Manoeuvring	4	43.2	1xMMPP 4.8%	450	2xMMAA 57%	0.5
Berthing	0	0.00	0.00%	400	2xMMAA 51%	1
Hoteling	0	0.00	0.00%	250	1xMMAA 64%	11.6 ***

* MMPP: Main engines; ** MMAA: Auxiliary engines (generating sets); *** Aggregated time per day: sleeping time and idle times between trips.

According to the initial CII rules (MEPC.337(76); MEPC.339(76); MEPC.338(76)), the HSC operating under the pattern shown in Table 3 in 2023 was rated E; therefore, it should provide a rectification plan to obtain a C score. Taking into account the oversized capacity of the current on-board electricity plant and the zero-emission technologies at berth requirement implemented beginning in 2030 (Regulation (EU) 2015/757), this study analyzes the performance of several combined solutions that are technically feasible for this kind of vessel [7]: slow steaming along with the vessel's retrofitting, focused on the electricity generating plant. Given the limited relative weight of the emissions from the electricity supply on the total vessel's emissions (5.24% in 2023, see Table 3), speed moderation (operational solution) not only enables it to reach the CII target but also reduces the propulsion power requirements (voyage cost savings). In such a way, the vessel's retrofitting scope might achieve a reduction in the number of main engines by involving an additional sustainability boost, which could be gained from the consequent decrease in the vessel's weight [7].

Taking into account the maturity of the sustainable alternative technologies, the technical suitability of the vessel's features (detailed technical information about vessel retrofitting can be found in Martínez-López et al. [7]) and the accomplishment of the operating scheduling (slow steaming is only viable when the additional time can be balanced by reducing idle time, with a minimum vessel inactive time of 8.5 h from 22.00 h to 6.30 h), this study considers the following alternatives to meet CII requirements over a time range from 2024 to 2033:

- Slow steaming. Operative solution, which means no vessel retrofitting is necessary.
- Photovoltaic system (PV system) for electricity supply together with slow steaming: Retrofitted vessel. The Global Horizontal Irradiance (GHI) in the Canarian Archipelago is 6.98 $kWh/m^2/day$ (NASA Resources from Homer Pro microgrid software).
- Fuel cell system (green H_2 fuel cell; this is a proton-exchange membrane fuel cell—PEMFC—[7]) for electricity supply along with slow steaming. Retrofitted vessel.
- Onshore power supply system (OPS) for electricity supply in port (berthing and hoteling, see Table 2) together with slow steaming. Retrofitted vessel.

4.1. Pollutant Impact

The PI calculation follows the method presented in Section 3.1 where eight pollutants (U = {1, . . ., u}) are evaluated in all scenarios (see Figure 1) and for every navigation stage (SS = {1, . . ., s}) from a TtW perspective: CO_2, CHEUR, N_2O (greenhouse gases), SO_X (acidifying substances), NO_x (ozone precursors), $PM_{2.5}$, PM_{10} (particulate mass) and NH_3. The unitary cost for air pollutants (CU_{skuvy}; ∀s∈SS∧∀k∈K∀u∈U∀v∈V∧∀y∈Y in EUR/kg pollutant, see Appendix A) were updated to 2024 by using a CPI (Consumer Price Index) = 23.4% (2016–2024; National Statistics Institute of Spain, 2024) on the pollutants' costs for maritime transport, published by Van Essen et al. [29], and a 2% constant inflation rate was assumed for further interannual updates. In this regard, it is necessary to highlight the frequent difference between carbon dioxide's unitary costs [29] and the carbon allowance price. Whereas the former involves the climate change avoidance cost (CU_{sk1v1} = 123.4 EUR/t CO_2, central value for 2024), the latter fluctuates depending on the market. For that reason, with the intention of assessing the EU-MBM divergence with the vessel's actual pollutant impact (EU-MBMs' performance as a PPP tool), the pollutant impact (PI) is calculated by assuming the unitary cost (CU_{sk1v1} = 123.4 EUR/t CO_2, central value for 2024), and PI2 by taking the carbon allowance price from the EU carbon permits (CP = 76.09 EUR/t in December, 2024 (https://tradingeconomics.com/commodity/carbon accessed on 13 January 2026) as carbon dioxide's unitary costs.

Likewise, TtW emission coefficients (EG_{suly}; ∀s∈SS∧∀u∈U∀l∈L∧∀y∈Y in Kg/h) were taken from the calculation emission tool (SHIP-DESMO-Ro-Ro Passenger from the Danish RoRoSECA project; [30]) by considering the operative and technical pattern of the HSC (Tables 2 and 3). However, this calculation emission tool does not include CH_4 and N_2O emissions, which is why these TtW emission coefficients were estimated by considering the Pavlenko et al. [31] information for the engines in this particular case, and fuel types (LSMGO) involved in every technological alternative ($7.5.10^{-4}$g CH_4/MJ; 3.9. 10^{-3}g N_2O/MJ, and 7.37 MJ/kWh for LSMGO medium-speed four stroke). The TtW CO_{2eq} emissions (incoming scenario) are estimated from the CO_2, N_2O, and CH_4 emission factors by considering the GWP ((Regulation (EU) 2023/2776) and (MEPC.391(81)).

The PI estimation under the WtW approach (expected scenario, see Figure 1) adds WtT CO_{2eq} emissions to the previous TtW emissions calculated, where lower calorific values and WtT GHG intensity default values are taken from MEPC.391(81) and COM (2021) 562 final for the fuels involved in the alternatives: LSMGO (CV_{jl} = 0.0427 MJ/g; $WtT_{EG_{jly}}$ = 17.7 gCO_{2eq}/MJ) and green H_2 (CV_{jl} = 0.12 MJ/g; $WtT_{EG_{jly}}$ = 3.6 gCO_{2eq}/MJ). Finally, the WtT pollutant impact for OPS considers the emission factors of on-shore electricity networks on the islands (EFG_{uky};∀u∈U∧∀k∈K ∧∀y∈Y in kg/KWh, see Equation (6) and Table S1 from Supplementary Materials). These factors are estimated from the pollutant emissions of the electric power-generating plants (European Pollutant Release and Transfer Register-E-PRTR (Regulation (EC) No 166/2006; https://www.eea.europa.eu/en/datah ub/datahubitem-view/9405f714-8015-4b5b-a63c-280b82861b3d accessed on 15 January 2025) along with the Gross Electricity Generation per type of generation [32,33]. Moreover, due to the lack of $PM_{2.5}$ emission in the previous sources, this factor was obtained by considering its relationship with PM_{10} emission (EMEP/EEA air pollutant emission inventory guidebook–2009 [34]). Finally, the annual updating of these emission factors is addressed by the Sustainable Energy Strategy in the Canary Islands [35], where the full decarbonization of the grid is expected by 2040 (100% share of renewable sources).

4.2. Goal and Market-Based Measures

All measurements have considered the carbon dioxide emissions obtained for every solution by taking the operative and technical features of the vessel (Tables 2 and 3) as inputs in the emission calculation tool, as mentioned in the previous section. When a green H_2 fuel cell is evaluated as an option, the rewards factor in Fuel EU initiative archives RWD = 2 (RWD = 1 in other cases, see Equation (17)), and the default value for H_2 WtT GHG intensity is assumed to be $CO_{2eqWtT,2}$ = 3.6 gCO_{2eq}/MJ (COM/2021/562 final) for the IMO Net-Zero Framework as well as the Fuel EU initiative (see 11 and 18, respectively). Likewise, the WtT GHG intensity approach for the OPS assessment is also notable; this was calculated through the actual 'mix energy' involved in the islands' electricity production (Table S1 from Supplementary Materials). Thus, this estimation for the islands' electricity grids ($CO_{2eqWtT,j}$) was used for the GFI calculation attained (see Equation (9), IMO Net-Zero Framework) as well as the $GHGIE_{actual}$ calculation ($CO_{2eq\_electricity,k}$, see Equations (17) and (18)) for the Fuel EU initiative under all regulatory scenarios except for the current scenario, where its value is null (see Figure 1). Given the high dependence of the current on-shore electricity generation on the islands' fossil fuels (over 79% and 81% for Gran Canary and Fuerteventura islands in 2021, respectively; data from [32,33]), $GHGIE_{actual}$ is also calculated by assuming the OPS Euro-mix 2020 ($CO_{2eq\_electricity,k}$ = 106.3 gCO_{2eq}/MJ (COM (2021)562 final)) to widen the scope of the analysis. With the same aim, EU-MBMs are estimated by assuming both the EU regular region's conditions and the outermost region's conditions. The latter involves a delayed enforcement for the EU-ETS and Fuel EU initiative, and only half the energy used by the vessel is considered for non-compliance fines under Fuel EU. Finally, noting that the same Carbon Allowance Price (CP_1 = 76.09 EUR/t emissions for 2024 with interannual updating of 2% of the inflation rate in 2024 and thereafter) is assumed for every regulatory scenario for EU-ETS calculation (TtW CO_2, TtW CO_{2eq} and WtW CO_{2eq}, see Figure 1) to enable its comparison with PI2 in terms of PPP performance, the convergence with the actual pollutant impact of the vessel is as follows.

5. Results

5.1. Carbon Intensity Indicator (Current Situation and Evolution)

The HSC's non-compliance with CII requirements in 2023 (under the guidelines published in 2021) led to an operative feasibility analysis of slow steaming to return the vessel to a C score. This analysis necessarily involved testing whether the additional free sailing time could be balanced by a reduction in port times [36,37] to maintain the accomplishment of the ship's schedule. Table 4 shows the current speed (38 kn) as an unfeasible option under the initial and final CII regulation guidelines (D and E scores). However, a progressive reduction in the speed until 2033 (from 28.11 kn in 2024 to 25.24 kn in 2033, see Figure 2) would enable it not only to meet CII regulations (see Equations (7) and (8) in Section 3.2.1) but also the operative requirements: the increased shipping time per trip (up to 41.87 min in 2033 over an initial 96 min) can be balanced by shortening idle times (see Table 3) and keeping the minimum inactivity time (8.5 h from 22.00 h to 6.30 h of vessel sleeping time, see Table 3). Therefore, slow steaming as the sole operative measure (no vessel retrofitting is necessary) can be considered a viable option for the CII accomplishment, although this involves a drastic reduction in the initial speed (from 38 kn to 25.24 kn in 2033, see Figure 2).

Table 4. HSC scores and required speeds to meet the CII regulations for the initial vessel (no retrofitting).

	HSC (38kn)				Slow Steaming HSC		
Year	*Shipping Time (min)*	*Regulation* (1)	*Regulation* (2)	*Speed (kn)*	*Increasing Shipping Time (min)*	*Regulation* (1)	*Regulation* (2)
2024	*96*	E	C	28.11	29.16	C	A
2025	*96*	E	D	27.81	30.38	C	A
2026	*96*	E	D	27.50	31.64	C	A
2027	*96*	E	**D**	27.19	32.93	C	A
2028	*96*	E	D	26.88	34.28	C	A
2029	*96*	E	D	26.56	35.70	C	A
2030	*96*	E	E	26.24	37.14	C	A
2031	*96*	E	E	25.91	38.64	C	A
2032	*96*	E	E	25.58	40.25	C	A
2033	*96*	E	E	25.24	41.87	C	A

(1) MEPC.337(76); MEPC.338(76); MEPC.339(76) (2) MEPC.353(78); MEPC.354(78); MEPC.400(83).

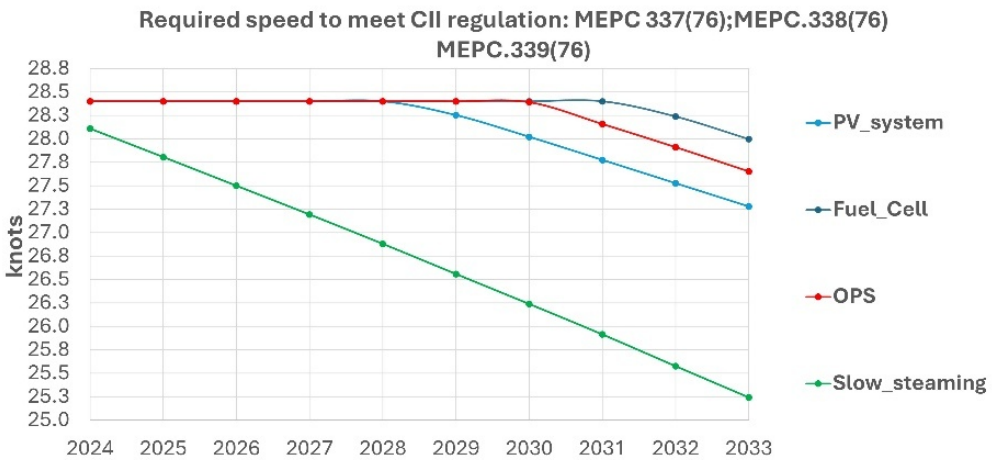

Figure 2. Required HSC speed to meet CII requirements when alternative technologies for electricity supply are considered.

The combination of slow steaming with the vessel's retrofitting allows for moderate and late reductions in the speed (beginning from 2029) to meet CII requirements; this produces C and A scores under the initial and final CII regulations (see Figure 2). These reductions are inversely proportional to the technology's sustainability, as assessed, but are also conditional on the consequent modifications of the vessel to be more lightweight (vessel retrofitting [7]).

5.2. Pollutant Impact Evolution

Aside from providing HSC sustainability information when a decision is made about decarbonization options, the PI (unitary cost assumed in 2024 for carbon dioxide is 123.4 EUR/ton; see also Section 3.1) assessment permits us to offer further information for different stakeholders.

Thus, Figure 3 shows the performance of the retrofitted HSC with the analysed technologies for electricity supply by assuming the necessity of slow steaming to meet CII requirements (speeds shown in Figure 2) for the expected and incoming scenarios. Since the final PI is the addition to emissions from propulsion and electricity generation (L = {1, . . ., l}, see Equations (2)–(6)), Figure 3 shows, not including the final PI for the mitigation alternatives (continuous lines), the contribution of the propulsion's emissions (PIp, dotted lines) to the final PI (see Section 3.1). Regardless of the regulation approach (WtW CO_{2eq} in the expected scenario versus the TtW CO_{2eq} in the incoming scenario), the most sustainable solution is achieved through the use of green H_2 fuel cells (lower PI, continuous line in Figure 3), whereas the most polluting solution is found for slow steaming only (no retrofitting of the vessel).

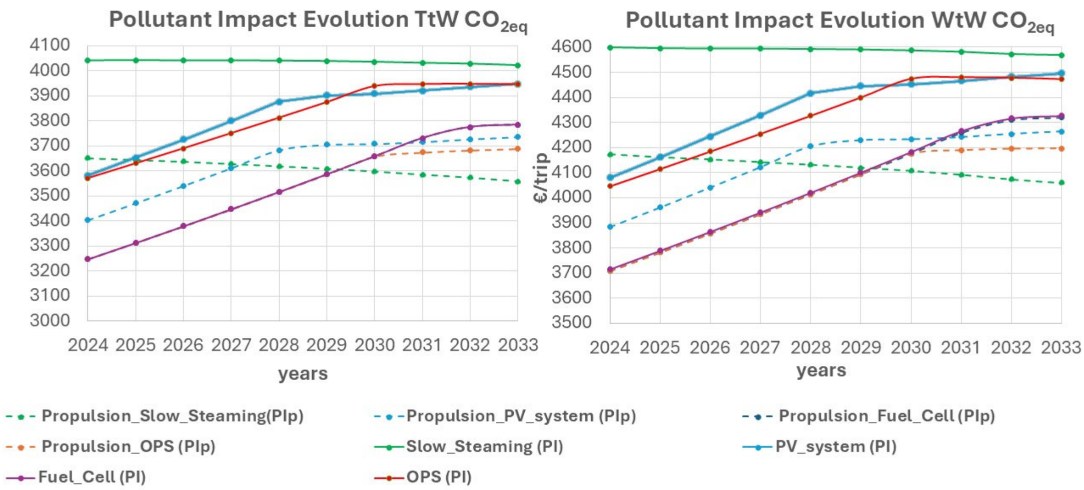

Figure 3. HSC pollutant impact evolution (EUR/trip) when several alternative technologies are analysed under different regulatory scenarios.

As expected, the contribution of electricity generation to the total pollutant impact is practically null for the green H_2 fuel cell (continuous and dotted lines are practically coincident in Figure 3) and achieves its maximum contribution with the pure slow steaming option (the widest gap between the continuous and dotted lines in Figure 3).

In all cases, the main contributors to PI are obviously the main engines (propulsion service plotted by dotted lines); however, the evolution of this contribution varies according to the required service speed (see Figure 2). Thus, whereas the propulsion's contribution is constantly decreasing for slow steaming only (no retrofitting) to meet CII requirements, the remaining options' contributions rise (due to the PI inflation rate per EUR/trip) until the starting year of the service speed reductions (see Figure 2). This is when the emissions reductions from the generating parts' replacement are insufficient to meet CII requirements (2029, 2032, and 2030 for the PV system, green H_2 fuel cell, and OPS, respectively).

Since the contribution from the electricity generation's emissions to PI is counter to the propulsion's contributions, its relative weight (PI from electricity generation/total PI) increases over time (from 2024 to 2033, see Table 5) for slow steaming and PV system options (a constant electricity supply is assumed versus an annual variation in propulsion requirements), whereas it is practically constant for the green H_2 fuel cells (low variations in the required speed in the last two years, see Figure 2) and it is lightly reduced for OPS (from 2024 to 2033, see Table 5). The latter point is due to the large influence of the progressive decarbonization plan assumed for the on-shore electricity networks on the islands ($EFG_{uky};\forall u \in U \wedge \forall k \in K \wedge \forall y \in Y$ in kg/KWh, see Equation (6)). It is also noteworthy that the electricity supply emissions lose weight against the propulsion in a WtW scenario, except for the green H_2 fuel cell (0% and 0.17% in Table 5), whose contribution is zero only in the TtW approach ($WtT_{EG_{jly}}$ = 3.6 gCO_{2eq}/MJ; COM (2021) 562 final; see Equations (4) and (5)). This fact also explains the advantages in sustainability terms (PI) of the green H_2 fuel cell compared to the remaining options ($(PI_{FC} - PI_{remaingoptions})/PI_{remaingoptions}$ %) when a WtW regulatory scenario, the expected scenario, is assumed (see Table 6).

Table 5. Contribution from the electricity generation's emissions to PI in 2024 and 2033 under different regulation approaches.

	PV_System	Fuel_CELL	OPS	Slow_Steaming
Approach		**2024**		
CO_{2eq} **TtW**	4.97%	0.00%	9.08%	9.68%
CO_{2eq} **WtW**	4.77%	0.17%	8.35%	9.28%
		2033		
CO_{2eq} **TtW**	5.38%	0.00%	6.49%	11.54%
CO_{2eq} **WtW**	5.16%	0.17%	6.13%	11.14%

Table 6. Environmental advantage of green H_2 fuel cell versus the remaining solutions in 2033 under different regulation approaches.

Approach	PV_System	OPS	Slow_Steaming
CO_{2eq} **TtW**	−4.16%	−4.09%	−5.91%
CO_{2eq} **WtW**	−3.77%	−3.23%	−5.27%

The broadening of the PI analysis scope, from TtW to WtW emissions, involves total PI values increasing (see Figure 3) between 14.84 and 15.42% (see Figure 3 and Table S2 from the Supplementary Materials) in the HSC's environmental assessment. Nevertheless, this relative increase is not directly transferred to the MBM and GBM values because these measures only consider GHG emissions, whereas the PI model (see Section 3.1) additionally evaluates acidifying substances, ozone precursors, and particulate mass. Consequently, with the aim of identifying the impact of the regulatory progression on the MBMs' performance (PPP tools), Table 7 collects the relative weight of the GHG emissions on the total PI under both regulation approaches (PI_{GHG}/PI, see U = {1, . . . , u} in Section 3.1 and Appendix A). A significant speed reduction is the main driver of the progressive decrease in the total GHG contribution to the total PI (see Table 7). This is true because, even though the PI value (EUR/trip) lightly increases over time due to the inflation rate updating (CPI = 2%), abrupt speed reductions sufficiently shorten the emissions to overcome this increase. This can be seen in Table 7 through the evolution of the PV system option from the starting year for speed reduction (from 2029, see Figure 2) and especially in the slow steaming option (from 2024, see Figure 2). In contrast, green H_2 fuel cells and OPS options enlarge the relative GHG contributions from the starting year of speed reductions (2032 and 2030) due to lower and later speed reductions (See Figure 2). As Table 7 shows, GHG emissions represent more than 50% of total emissions in all cases by increasing their relative weight (5.61–5.90%, see Table 7) from the CO_2 TtW emissions approach (current scenario) to the CO_{2eq} WtW approach (expected scenario, see Figure 1). This improvement in the vessel's pollution representation under the regulations necessarily leads to an enhancement of the proportionality principle for both the GBMs and MBMs because they are only based on GHG emissions.

Table 7. Contribution of GHG emissions to the total PI from different regulation approaches.

	CO_2 **TtW Approach**				CO_{2eq} **WtW Approach**			
Year	**PV_System**	**Fuel_Cell**	**OPS**	**Slow Steaming**	**PV_System**	**Fuel_CELL**	**OPS**	**Slow Steaming**
2024	58.97%	60.02%	58.58%	58.04%	64.81%	65.86%	64.23%	63.94%
2025	58.97%	60.02%	58.65%	58.02%	64.81%	65.86%	64.31%	63.87%
2026	58.97%	60.02%	58.72%	58.01%	64.81%	65.86%	64.39%	63.82%
2027	58.97%	60.02%	58.80%	57.97%	64.81%	65.86%	64.47%	63.83%

Table 7. *Cont.*

	CO_2 TtW Approach				CO_{2eq} WtW Approach			
Year	**PV_System**	**Fuel_Cell**	**OPS**	**Slow Steaming**	**PV_System**	**Fuel_CELL**	**OPS**	**Slow Steaming**
2028	58.97%	60.02%	58.87%	57.92%	64.81%	65.86%	64.56%	63.78%
2029	58.97%	60.02%	58.95%	57.88%	64.81%	65.86%	64.64%	63.75%
2030	58.95%	60.02%	59.03%	57.85%	64.79%	65.86%	64.73%	63.71%
2031	58.94%	60.02%	59.08%	57.82%	64.77%	65.86%	64.76%	63.68%
2032	58.92%	61.49%	59.14%	57.79%	64.76%	67.17%	64.79%	63.60%
2033	58.91%	61.52%	59.20%	57.75%	64.74%	67.20%	64.81%	63.60%

5.3. Market-Based Measures

According to Figure 1, only two EU-MBMs are affected by regulation approaches: EU-ETS (see Section 3.3.3), which considers the THETIS-MRV records with a progressive scope, and the Fuel EU initiative (see Section 3.3.1) in the OPS assessment ($CO_{2eq\_electricity,k}$ $\forall k \in K$, see Equation (18)).

Whereas WtT emissions from OPS are ignored for Fuel EU calculations in the current scenario ($CO_{2eq\_electricity,k} = 0$; $\forall k \in K$, see Equation (18)), these emissions are considered in the remaining regulation approaches. Accordingly, Figure 4 shows the total EU-MBM composition (the addition of EU-ETS, Fuel EU, and ETD, see Section 3.3) by taking into account the emissions determined in the assumed scenarios for 2033 (see Figure 1), where EU-ETS gains relative weight with the tightening of the regulatory scenarios, especially in the WtW CO_{2eq} scenario, at the expense of the remaining measures. In fact, EU-ETS clearly becomes the main EU-MBM in monetary terms (Figure 4). Retrofitted vessels with green H_2 fuel cells and OPS deserve particular attention. Due to its sustainability, the Fuel EU fine is zero for this option; consequently, only ETD and EU-ETS have an impact on it. Regarding the OPS option, the inclusion of its WtT CO_{2eq} in the Fuel EU calculations in the TtW CO_{2eq} and WtW CO_{2eq} approaches significantly increases the Fuel EU fine's relevance to it.

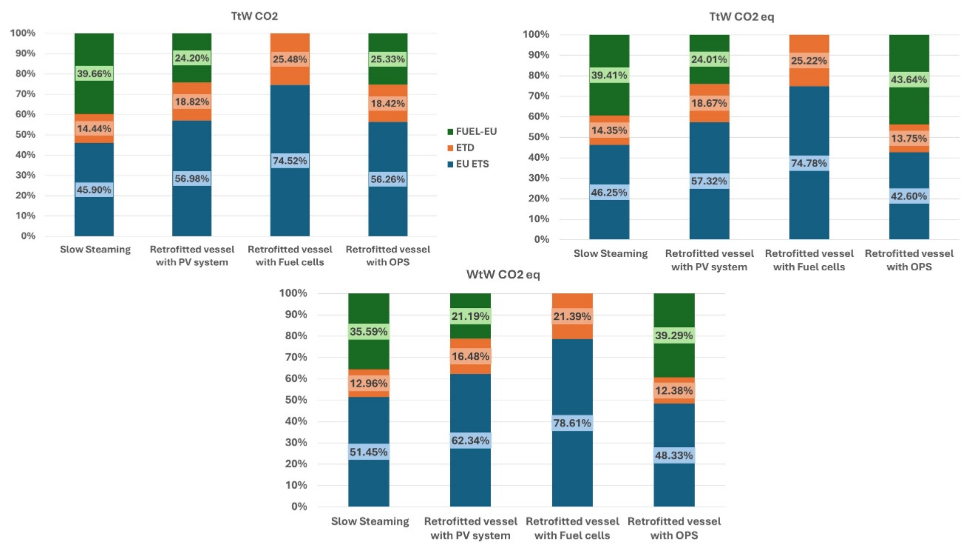

Figure 4. Total EU-MBM composition in 2033 for HSCs with every mitigation alternative by operating in a regular EU region under different regulation scenarios.

Figures 5–8 show the MBM evolution versus the pollutant impact for every technical solution operating under every regulatory scenario. IMO-Zero-Net shows an inflexion point in 2030 owing to the reduction factors tightening from this year onwards (ZTB_y and ZTD_y; $\forall y \in Y$, see Equations (13) and (14) and Appendix A). Total EU-MBM (aggregated value of all EU measures, see Section 3.3) is shown by a blue line whose shape, in steps, is determined by the measures phased in (β_y; ∀y∈Y, achieves 100% emissions in 2026 for EU-ETS and μ_y: ∀y∈Y, progressive implementation in the Fuel EU with constant values per steps: 2024, 2025–2029; 2030–2034, etc., see Appendix A).

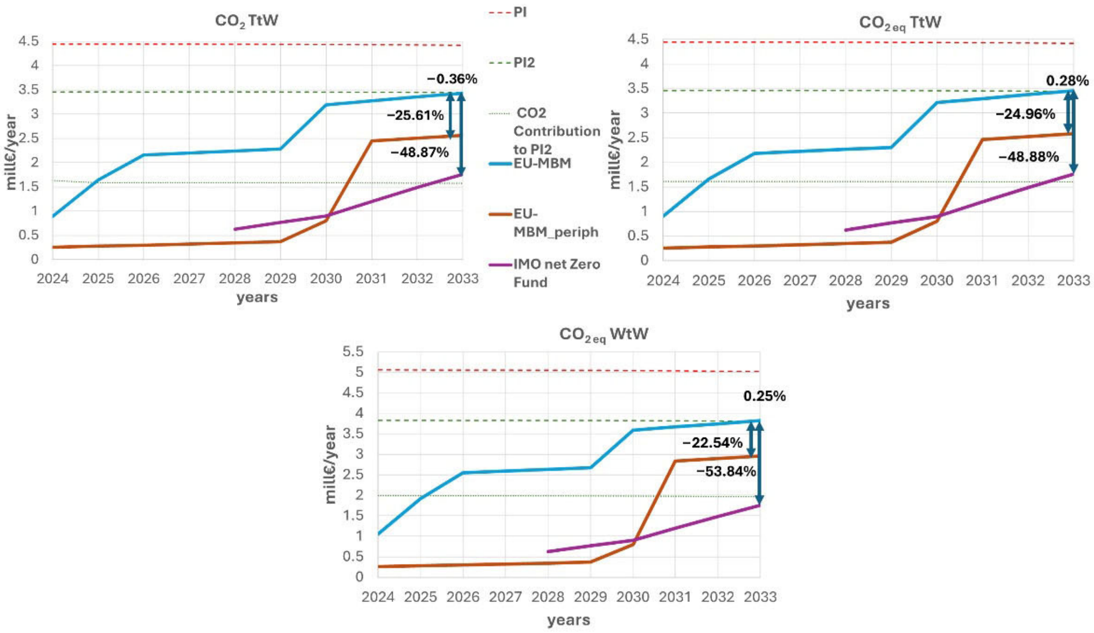

Figure 5. MBM versus PI evolution for the initial vessel with slow steaming.

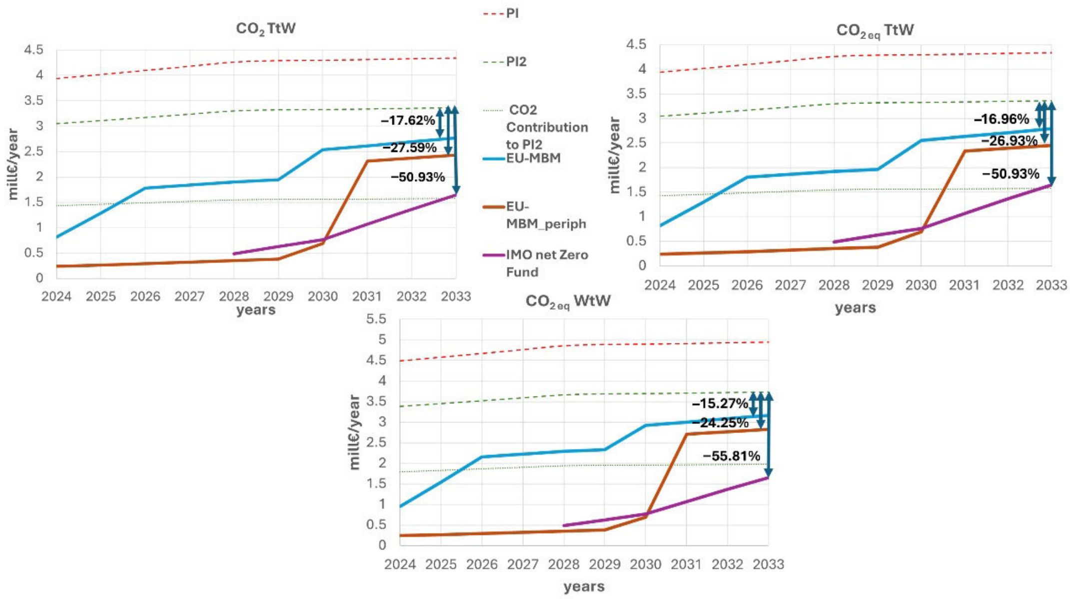

Figure 6. MBM versus PI evolution for the retrofitted vessel: PV system with slow steaming.

The same reason also explains the total EU-MBM shape for the outermost region (brown line), although this is delayed to December 2029 (Fuel EU initiative) and December 2030 (EU-ETS). In this regard, it is necessary to highlight that, beyond the delay in implementation, a constant divergence exists from the regular regions' EU-MBM when full implementation is reached (see Figures 5–8), since 50% of the vessel's energy is exempted under the Fuel EU initiative for shipping in the outermost regions. The greatest differences between both types of regions in 2033 (the gap between blue and brown lines) reach 31% with the OPS option when the incoming scenario is assumed (CO_{2eq} TtW, see Figure 8).

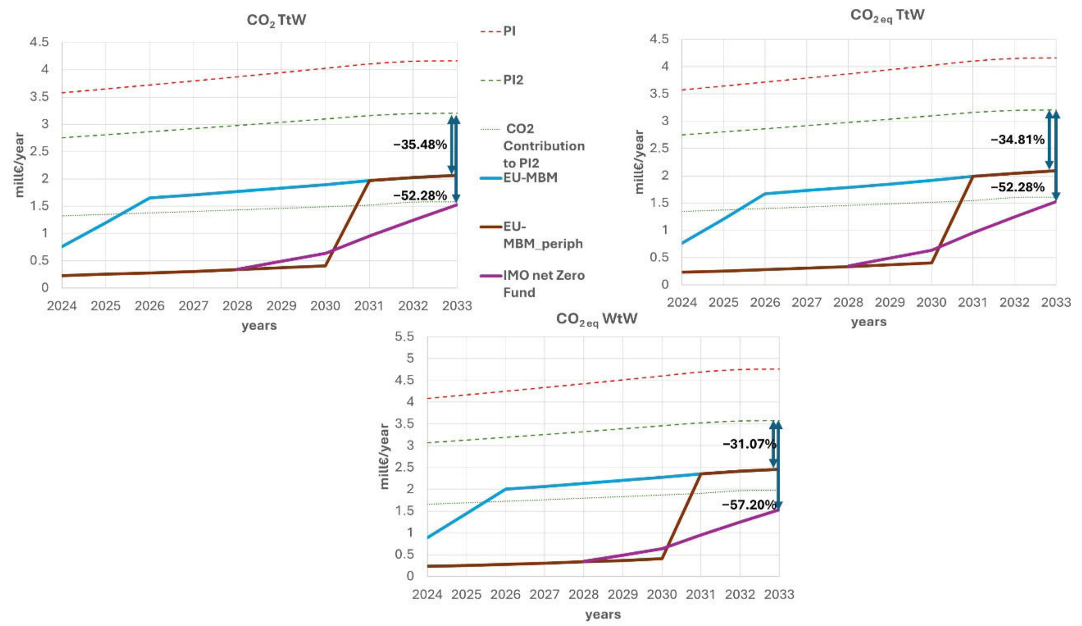

Figure 7. MBM versus PI evolution for the retrofitted vessel: green H_2 fuel cell with slow steaming.

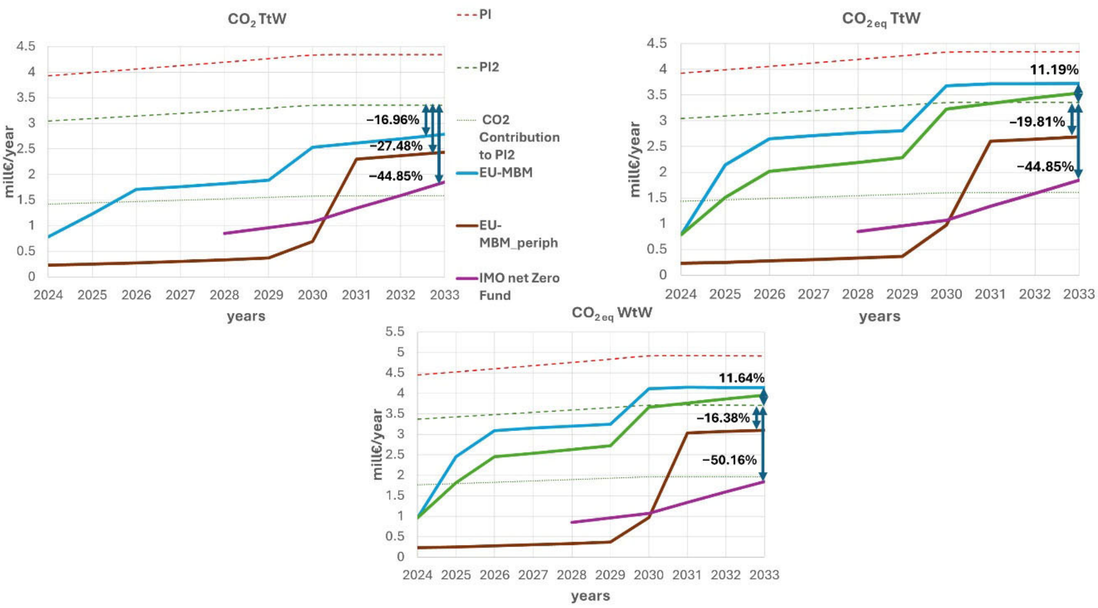

Figure 8. MBM versus PI evolution for the retrofitted vessel: OPS with slow steaming.

However, as the Fuel EU fine is null for the green H_2 fuel cell in any EU region (high sustainability), the convergence between EU-MBMs in both regions (coincident blue and brown lines) is achieved from the start of the EU-MBM's full implementation (2031, see Figure 7).

In order to assess the MBMs' effectiveness as PPP tools, the figures show in dotted lines, aside from the actual vessel's pollutant impact (PI on the basis of an unitary cost for carbon dioxide emissions CU_{sk1v1} = 123.4 EUR/t CO_2, for 2024, see Section 3.1), the resulting pollutant impact, PI2, when the carbon allowance price (CP = 76.09 EUR/t in December 2024 (https://tradingeconomics.com/commodity/carbon accessed on 13 January 2026) taken for EU-ETS is also assumed to be a unitary cost for carbon dioxide emissions (CU_{sk1v1} = CP = 76.09 EUR/t).

This fact permits us to evaluate the MBMs' proportionality to the actual vessel's pollutant impact. In this regard, the results show a progressive approach from EU-MBM to PI2 with the tightening of the regulatory scenario (from TtW CO_2 to WtW CO_{2eq} approach, see Figures 5–8), this is true despite the fact that the PI2 is higher under the WtW approach in comparison with the TtW scenarios.

This higher value for PI2 also explains the larger gap found in this scenario for the IMO net zero, found in all cases to achieve 57.20% when the green H_2 fuel cell is assessed (see Figure 7). Even though the fitness level found for the EU-MBMs regarding PI2 is significantly higher than the IMO initiative's convergence, significant differences exist among the technologies evaluated. Whereas the EU-MBMs achieve the highest convergence with PI2 when no retrofitting is involved (−0.36% to 0.28% deviation, see Figure 5), the deviation increases with the sustainability of the technology installed, consequently achieving the maximum deviation with the green H_2 fuel cells (35.48%, see Figure 7). This is mainly due to the regulating effect of the Fuel EU fines on the sustainable technologies. Thus, when the Fuel EU fines' relevance is substantial (see Figure 4), EU-MBM's proportionality with PI2 increases.

Except for the OPS retrofitted vessel evaluation, all cases provide an EU-MBM score in 2033 below PI2 (several pollutants beyond GHG emissions are assessed) by overcoming carbon dioxide emissions' contribution to PI2 (see Figures 5–8). However, this does not occur with the IMO initiative when the WtW CO_{2eq} scenario is assumed, or when the green H_2 fuel cell is involved. Finally, it is necessary to analyse the OPS solution assessment under the incoming and expected scenarios, where WtT GHG emissions from onshore electricity networks are included in the Fuel EU calculations ($CO_{2eq\_electricity,k} \neq 0; \forall k \in K$, see Equation (18)). Figure 8 shows an overestimation of the EU-MBM regarding PI2 for this option by reaching 11.19% and 11.64% for the incoming and expected scenarios, respectively. Given the high polluting level of the islands' electricity network ($CO_{2eq\_electricity,k}$ = 368.67 g CO_{2eq}/MJ in 2024, and $CO_{2eq\_electricity,k}$ = 150.12 g CO_{2eq}/MJ in 2033; see Table S1 from Supplementary Materials). Figure 8 also records the EU-MBMs' behaviour (see the green line) when a conventional electricity network from the continental region is involved (EuroMix 2020: $CO_{2eq\_electricity,k}$ = 106.3 gCO_{2eq}/MJ (COM (2021) 562 final)). The results also show, in this case, an overestimation of 5.64% and 6.62% by the EU-MBM for every scenario.

From the shipowners' perspective, it is interesting to quantify the possible advantages of making decisions based on vessel retrofitting versus slow steaming only. Focusing on this point, Table 8 shows that, despite the progressive convergence of the total pollutant impact among all alternatives over time (see Figure 3), the advantage in monetary terms for EU-MBM savings ($(\text{EU-MBM}_{remainingalternatives} - \text{EU-MBM}_{slowsteaming})/\text{EU-MBM}_{slowsteaming}$) does not move in the same direction by increasing its value over time.

Uniquely, under the IMO framework approach (see IMO net Zero Fund in Table 8, further information about this trend can be found in Tables S3–S5 from the Supplementary Materials), the advantage provided by the retrofitted vessel proportionally decrease over the time. This is mainly due to the Fuel EU architecture's effect on EU-MBM framework; this initiative integrates, on the one hand, reward measures for sustainable energies (like RWD_{jl}; $\forall j \in J \wedge \forall l \in L$, see Equation (17) and Appendix A) and on the other, a recidivism mechanism for fines. This significantly affects slow steaming due to its Fuel EU non-compliance from 2024. Again, the OPS behaviour is different, especially in the incoming and expected scenarios, due to the decarbonization plan for the islands and the consideration of their WtT CO_{2eq} emissions. Thus, despite the progressive polluting convergence among alternatives (PI2, see Table 8), the green H_2 fuel cell increases EU-MBM savings regarding slow steaming over time, and the PV system option maintains them in all scenarios (see Table 8 and Tables S3–S5 from the Supplementary Materials).

Table 8. Saving in monetary terms by vessel retrofitting versus slow steaming only according to several scenarios.

		TtW CO_2		TtW CO_{2eq}		WtW CO_{2eq}	
		2028	**2033**	**2028**	**2033**	**2028**	**2033**
Retrofitted vessel with PV system	*EU-MBM*	−15.07%	−19.30%	−14.94%	−19.18%	−13.16%	−17.29%
	Pollutant Impact (PI2)	−4.56%	−2.39%	−4.56%	−2.39%	−4.35%	−2.13%
	IMO net Zero Fund	−21.87%	−6.31%	−21.87%	−6.31%	−21.87%	−6.31%
Retrofitted vessel with fuel cells	*EU-MBM*	−21.15%	−39.76%	−21.04%	−39.52%	−19.09%	−35.60%
	Pollutant Impact (PI2)	−13.87%	−6.96%	−13.87%	−6.96%	−13.36%	−6.34%
	IMO net Zero Fund	−44.76%	−13.16%	−44.76%	−13.16%	−44.76%	−13.16%
Retrofitted vessel with OPS	*EU-MBM*	−18.56%	−18.83%	22.26%	8.00%	21.46%	8.35%
	Pollutant Impact (PI2)	−6.09%	−2.60%	−6.09%	−2.60%	−6.17%	−2.70%
	IMO net Zero Fund	35.20%	5.07%	35.20%	5.07%	35.20%	5.07%

6. Discussion

The results reveal that the broadening of the regulatory scope from TtW CO_2 to WtW CO_{2eq} will improve the proportionality of the EU-MBMs to the actual pollutant impact of these vessels from between 5.61 and 5.90%. This fact is relevant because an additional difficulty exists for SSS operations to meet the PPP through MBMs due to the limited weight of GHG emissions, in monetary terms, on the total PI of this traffic (57.75–67.20% for the particular case). This is due to the long periods spent in port (up to 75.3% of each day in this particular case), near population centres where other pollutants with more severe harmful effects are becoming more relevant (the unitary cost for particulate matters in 2024 for PM2.5 = 429.43 EUR/kg in Spanish metropolitan areas versus 8.88 EUR/kg in the Atlantic Ocean and 123.4 EUR/kg for carbon dioxide, [29]). The aforementioned improvement in the representativeness of the whole HSC pollutant impact through the EU-MBM involves a progressive convergence between the actual pollutant impact and the EU-MBM with an excellent fitness level when only fossil fuels are involved (from −0.36% to 0.28% deviations).

The analysis of the EU-MBM composition confirms the Fuel EU's buffer effect, not only as a promotion tool for sustainable technologies but also as an effective punishment mechanism for non-compliance recurrence. Despite its good performance, significant disruptions were found in Fuel EU's fine calculations when TtW CO_{2eq} emissions from OPS are considered. The proof of this is that, even though improvements between 2.6% and 6.17% in the HSC's pollutant impact are achieved from OPS use versus only the slow steaming alternative, penalties from the EU-MBM are higher than the slow steaming option by between 8% and 22.26% (see Table 8). Given the progressive level of demands in the regulations (trend towards WtW approach) and the heterogeneity of the share of renewable sources in the EU electricity networks, appropriate consideration of these emissions in the Fuel EU architecture should be a priority for policy-makers.

The IMO net zero fund initiative only covers a maximum percentage of 55.15% of the total pollutant impact of the HSCs, and even then, in the WtW CO_{2eq} scenario, this measure is insufficient to cover GHG emission contributions (2028–2033). Its current architecture does not provide incentives for promoting the choice of emerging technologies beyond the benefits that result from consequent emissions reductions. Therefore, the IMO net Zero fund does not seem to be significant regarding the current EU-MBMs.

Although the incoming MBM integration with the IMO within the EU framework is not the subject of this research, notable inconsistencies have been detected in their assumptions that should be homogenised. Among others, different GWP sources are applicable for every measure; whereas Fuel EU assumes a 100-year horizon GWP: CO_2 = 1; CH_4 = 25; N_2O = 298 (Directive (EU) 2018/2001); EU-ETS and IMO initiative take CO_2 = 1; CH_4 = 28; N_2O = 265 (Regulation (EU) 2020/1014) and (MEPC.391(81)). Inconsistencies in WtT CO_{2eq} emission default values were also found; LSMGO under the IMO regulation achieves 17.7gCO_{2eq}/MJ (MEPC.391(81)) and 14.4 gCO_{2eq}/MJ (Regulation (EU) 2023/1805) under the Fuel EU initiative.

Despite the limited contribution of electricity generation to HSCs' whole pollutant impact (5.24% in 2023), the assumed strategy to meet CII requirements through progressive speed reduction with a replacement of the generating sets by more sustainable technologies has resulted in being not only feasible operationally but also advantageous in terms of MBM savings.

Among the evaluated options, green H_2 fuel cells provide the greatest advantage both in terms of sustainability and MBM savings, since this option results in being the most favoured one over time under all regulatory scenarios (deviations between PI2 and EU-MBM: 31.07–35.48% and with IMO net-zero fund: 52.28–57.20%). From the shipowners' opportunity cost standpoint, the choice of green H_2 fuel cells versus no vessel retrofitting (slow steaming only) involves an environmental improvement range of 6.34–6.96% in 2033 and an EU-MBM savings range of 35.6–39.76%.

Delays and permanent exemptions arising from EU-MBM application for the outermost regions merit particular attention (article 349 of the Treaty on the Functioning of the EU), as they were included with the aim of ensuring accessibility and connectivity for these regions. In light of these results, continuous EU-MBM divergence among these regions will extend after full implementation of the measures. Additionally, the more polluting the vessel is, the greater the gap between EU-MBMs' regions becomes. This fact suggests not only a 'call effect' for non-compliant vessels, most likely old vessels, from the remaining EU zones to the outermost regions, but also concerning adverse incentives for the local fleet's retrofitting with sustainable technology. A special warning is the fact that, according to STEAM-modelled data [38], outermost regions like the Canary Islands experience intense CO_2 emissions pressure versus other European shipping areas [18]. This reality not only challenges the policy-makers' arguments for the numerous exceptions applied to EU outermost regions in terms of environmental policy [39] but also departs from preserving the equality of rights of all EU citizens to environmental justice.

7. Conclusions

Even though the maritime transport environmental regulation has undergone frequent modifications in recent years, a progression map can be drawn from an analysis of the successive regulations and proposals. Assuming the most probable regulatory scenarios, this paper quantifies the performance of possible technical solutions to ensure GBM compliance by medium-sized HSCs. The results reveal that the incoming broadening of the regulatory scope from TtW CO_2 to WtW CO_{2eq} involves significant improvements in the representativeness of the whole HSC pollutant impact through EU-MBM. This means a progressive convergence between the actual pollutant impact and EU-MBM in the WtW CO_{2eq} scenario over time.

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In light of the results, Fuel EU plays a key role in making investment in HSCs' retrofitting with emerging technologies reliable since it results in significant savings over time, in contrast to other, more polluting options. However, the lack of TtW CO_{2eq} emissions' consideration from OPS has resulted in a significant weak point in the current Fuel EU fines' calculation by perturbing the accurate assessment of this alternative against others. Therefore, its correct inclusion should be a priority for the policy makers.

The IMO net Zero fund initiative (currently, its vote was postponed to October 2026-MEPC 83) has not resulted in significant progress against EU-MBM, and its architecture is not effective enough to push sustainable technologies.

The benefits of a strategy based on a vessel's retrofitting for the electricity supply, along with slow steaming, gain importance over time (electricity emission contributions increase compared to the propulsion) regardless of the regulation approach used, and additionally, they go beyond the MBM savings by achieving fuel expense reductions from propulsion. According to the results, green H_2 fuel cells arise as the most suitable option in terms of sustainability and MBM savings among the technical alternatives analysed in this research.

Despite the good performance found for the incoming and expected EU-MBM trend, the insights of this paper recommend that policy-makers remove their current EU-MBM exemptions for SSS in the outermost regions, since the rights to mobility and environmental cohesion could be maintained by addressing additional efforts to ensuring that green H_2 facilities and supply points for vessels in ports (specific inclusion in Regulation (EU) 2023/1804 is required) and activating financial support (revenues from Fuel EU fines and EU-ETS) to address local HSC fleets' retrofitting in line with the Renewable Energy Directive's targets.

The insights drawn from this research are applicable beyond the particular case, since the analysis's scope was widened to EU regular regions, and both the HSC's characteristics and the operational requirements are frequent in EU-SSS. However, the performance of PV systems and the results linked to it are highly conditioned by the solar Global Horizontal Irradiance—GHI—resource [21]. Consequently, aside from the Canary Islands, the scope of these findings is constrained to locations with close solar GHI: the Archipelago of Azores, Madeira, the Mediterranean, the Adriatic Sea, and Atlantic routes from Portugal up to France (La Roche).

Finally, given the good results obtained under all regulatory scenarios for the retrofitted HSC with green $H_{2\,f}$uel cells along with slow steaming, further analysis should be carried out to ascertain if the consequent reductions in EU-MBM and fuel consumption provide sufficient leverage to compensate for the initial investment and high price of the green H_2 involved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse14020190/s1, Table S1. Forecast average WtT emission factors for OPS from Gran Canaria and Fuerteventura. Table S2. Increase of HSC's pollutant impact from TtW to WtW regulation approach. Table S3. Saving in monetary terms by vessel's retrofitting versus slow steaming only in the current regulatory scenario (TtW CO2). Table S4. Saving in monetary terms by vessel's retrofitting versus slow steaming only in the incoming scenario (TtW $CO_{2\,eq}$). Table S5. Saving in monetary terms by vessel's retrofitting versus slow steaming only in the expected scenario (WtW CO_2 eq).

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Appendix A

Subscripts:

I = {1, . . ., *i*}: Port localization: All ports are placed in an EU Member State; only one port belongs to an EU Member State; one port belongs to an EU outermost region; no port belongs to the EU region.

J = {1, . . ., *j*}: Marine fuels. For the case study: 0.1%S MGO (LSMGO) and green H_2.

K = {1. . ., *k*}: Country of port.

K* = {1. . ., *k*}: Kind of Sea/Ocean.

L = {1, . . ., *l*}: Main and auxiliary engines for the vessels; two- and four-stroke.

SS = {1, . . ., s}: Navigation stages: free sailing, manoeuvring, berthing (loading/unloading, bunkering, and anchoring operations), and hoteling time (idle time).

SS* = {2, . . ., s}: Navigation stages: manoeuvring, berthing and hoteling time.

SS** = {3, . . ., s}: Navigation stages:, berthing and hoteling time

U = {1, . . ., *u*}: SO_X (acidifying substances), NO_x (ozone precursors), $PM_{2.5}$, PM_{10} (particulate mass), CO_2, CH_4, N_2O (greenhouse gases), and NH_3.

V = {1, . . ., *v*}: Population density in the hinterland. Rural, suburban, and urban area [29]. Every assessment's year. This research collects a time range from 2024 to 2033.

Variables:

α_i: Percentage of CO_2 emissions to be considered in EU-ETS according to the localization of the port calls (%): Both ports belong to a EU Member State ($\alpha_i = \alpha_1 = 100\%$); only one port belongs to a EU Member State ($\alpha_i = \alpha_2 = 50\%$); no port belongs to a EU Member State ($\alpha_i = \alpha_3 = 0\%$);

β_y: Percentage of CO_2 emissions to be considered in EU-ETS according to the implementation year: 2024 ($\beta_y = \beta_1 = 40\%$); 2025 ($\beta_y = \beta_2 = 70\%$); 2026 and subsequent years ($\beta_y = \beta_3 = 100\%$);

γ_i: Percentage of energy to be considered in the Fuel EU regulation according to the nature of the ports (%): Both ports belong to a EU Member State ($\gamma_i = \gamma_1 = 100\%$); only one port belongs to a EU Member State or is located in a EU outermost region ($\gamma_i = \gamma_2 = 50\%$); no port belongs to a EU Member State ($\gamma_i = \gamma_3 = 0\%$);

μ_y: Percentage of maximum target emissions to be considered for Fuel EU according to the activity year-implementation schedule-: 2024 ($u_y = u_1 = 0\%$); 2025–2029 ($u_y = 98\%$); 2030–2034 ($u_y = 94\%$); 2035–2039 ($u_y = 85.5\%$); 2040–2044 ($u_y = 69\%$); 2045–2049 ($u_y = 38\%$); 2050-thereafter ($u_y = 20\%$);

C: Ship's cargo capacity according to the ship type (MEPC.352 (78)). It is measured in gross tonnage (GT) for Ro-Pax vessels.

$C_{engine\_slip,l}$: Engine fuel slippage is the non-combusted fuel measured as a percentage of the mass of every kind of fuel (%); $\forall l \in L$.

CF_{skuvy}: Unitary costs for air pollutants in port operations (EUR/kg pollutant) ∀s∈SS* ∧∀k∈K∧∀u∈U ∧∀v∈V∧∀y∈Y.

CFF_{jl}: Carbon conversion factor collected in the resolution MEPC.308(73) and Regulation (EU) 2023/1805 (tonne CO_2/tonne fuel); ∀j ∈ J∧∀l ∈L.

CFM_{jl}: Emission factor for CH_4 (tonne CH_4/tonne fuel) included in MEPC.391(81)); ∀j ∈ J∧∀*l* ∈L

CFN_{jl}: Emission factor for N_2O (tonne N_2O/tonne fuel) included in MEPC.391(81)); ∀j ∈ J∧∀*l* ∈L

CII_A_y: Attained Carbon Intensity Indicator for every year (CO_2 g/nm and tonne); ∀y ∈Y.

CII_R_y: Attained Carbon Intensity Indicator for every year (CO_2 g/nm and tonne); ∀y ∈Y.

$CO_{2eq\_electricity,k}$ = WtT GHG emission values for OPS (gCO_{2eq}/MJ); ∀k ∈ K

$CO_{2eq\ TtW,j,l}$: TtW GHG emissions values for every kind of combusted fuel and engine (gCO_{2eq}/gFuel); ∀*j* ∈ J∧∀*l* ∈L.

$CO_{2eqTtW\_slippage,j,l}$: CO_2 equivalent emissions for every kind of slippage fuel and engine (gCO_{2eq}/gFuel); ∀*j* ∈ J∧∀*l* ∈L.

$CO_{2eqWtT,j}$: WtT GHG emission values for every kind of combusted fuel(gCO_{2eq}/MJ); ∀j ∈ J. Default values are collected in Annex II of Regulation (EU) 2023/1805 (Fuel EU) and in Appendix 2 of MEPC.391(81)) for IMO Net-Zero Framework

CP_y: EU Carbon Pricing (EUR/tonne Carbon emissions and year); ∀*y* ∈ Y.

CT_{sk}: Connection/disconnection times for the OPS use (h). This operation is only undertaken during the berthing/unberthing operations (s = 3); therefore, its value is assumed to be null in the hoteling stage (CT_{k4} = 0); ∀s ∈ SS**∧∀k∈K.

CU_{1kuy}: Unitary costs for air pollutants in free sailing (EUR/kg pollutant); ∀k∈K*∧ ∀u∈U ∧ ∀y∈Y.

$CU_{eq\ skvy}$: Unitary costs for CO_{2eq} in port operations (EUR/kg CO_{2eq}) ∀s∈SS*∧∀k ∈K∧∀v∈V∧∀y∈Y.

$CU_{eq\ 1ky}$: Unitary costs for CO_{2eq} in free sailing (EUR/kg CO_{2eq}) ∀k∈K∧∀y∈Y.

CV_{jl}: Lower Calorific Value of the fuel in every engine (GJ/g fuel); ∀j ∈ J∧∀l∈L.

D: total distance travelled (in nautical miles) reported in IMO DCS.

E_{sjly}: Energy developed by the vessel through engines or technologies by using fuels, for every navigation stage and year (MJ). ∀s∈S∧∀j∈J∧∀l∈L ∧∀y∈Y;

EC_s: Electricity delivered to the vessel at berth per connection point through OPS (MJ); ∀s ∈ SS**

EFG_{uky}: Emission factors per pollutant emitted by OPS; in every port and year (kg/kWh) ∀u∈U∧∀k∈K ∧∀y∈Y;

EG_{suly}: Tank to Wake emission factors per pollutant; for every navigation stage, type of engine and year (kg/h) ∀s∈S∧∀u∈U∧∀l∈L ∧∀y∈Y;

EI_{sjly}: WtW GHG intensity involved in GFI attained (IMO Circular Letter No.5005, 11 April 2025) in gCO_{2eq}/MJ; ∀s∈S∧∀j∈J∧∀l∈L ∧∀y∈Y;

EIC_{ky}: WtW GHG intensity for OPS involved in GFI attained (IMO Circular Letter No.5005, 11 April 2025) in gCO_{2eq}/MJ; ∀s∈S∧∀j∈J∧∀l∈L ∧∀y∈Y;

ES_s: Renewable energy delivered by the vessel (MJ); ∀s ∈ SS. In the case study this refers to solar energy.

ETD_y: Energy Taxation per year (EUR/year);∀y ∈ Y

ETS_y: European Trading System's cost per year (EUR/year); ∀*y* ∈ Y

$ETSU_y$: European Trading System's cost per trip (EUR/trip); ∀*y* ∈ Y

ETU_y: Energy Taxation per trip (EUR);∀y ∈ Y.

f_{wind}: Reward factor for wind-assisted propulsion.

$FuelEU_y$: Annual penalty for non-compliance with Fuel EU (EUR/year); ∀y ∈ Y

$GFI\_attained_y$: GHG intensity of the vessel per year and route according to IMO Circular Letter No. 5005, 11 April 2025 (g CO_{2eq}/MJ); ∀y∈Y

$(GHGIE_{actual})_y$: Greenhouse gas intensity of the energy used on-board for a year (g CO_{2eq}/MJ); ∀y ∈ Y.

$(GHGIE_{target})_y$: Maximum greenhouse gas intensity of the vessel's energy permitted per year, it is limited by Regulation (EU) 2023/1805 (g CO_{2eq}/MJ); ∀y ∈ Y.

GFI_TD: Direct compliance target annual GFI in g WtW CO_{2eq}/MJ

GFI_TB: Base target annual GFI in g WtW CO_{2eq}/MJ

GWP: Global warming potential for CO_2, CH_4 and N_2O. 100 GWP: CO_2 = 1; CH_4 = 25; N_2O = 298 (Directive (EU) 2018/2001); CO_2 = 1; CH_4 = 28; N_2O = 265 Regulation (EU) 2020/1014) and (MEPC.391(81))

N: Trips per year.

n: number of consecutive non-compliance periods under the Fuel EU regulation.

PB_{sly}: Power for the vessel's engines for every navigation stage (kW) in every year; $\forall s \in SS \wedge \forall l \in L \wedge \forall y \in Y$.

$PB2_{sy}$: On-shore electricity power for the vessel (kW) in every year and possible navigation stage; ∀s ∈ SS**∧∀y ∈Y.

$PI_y|_{WtW}$: Wake to well pollutant impact (EUR/trip) for every year; ∀y ∈ Y.

PI_{sy}: Pollutant impact in terms of air quality (EUR/trip) for every navigation stage and year; ∀s ∈ SS^∀y ∈ Y. This term can be referred to Tank to Wake ($PI_{sy}|_{TtW}$) or Well to Tank ($PI_{sy}|_{WtT}$) emissions.

RWD_{jl}: Reward factor for non-biological origin's fuels with value of 2 from 1 January 2025 to 31 December 2033. Otherwise, value RWD_{jl} = 1. $\forall j \in J \wedge \forall l \in L$.

$SFOC_{sjly}$: Specific Fuel Consumption for engines in every navigation stage, year and fuel type (g fuel/kWh); $\forall s \in SS \wedge \forall j \in J \wedge \forall l \in L \wedge \forall y \in Y$.

TL_j: Taxation applicable to fuels (EUR/GJ); ∀j ∈ J.

TVB_{sky}: Time invested in every navigation stage per trip (h/trip) for every year by taking into account the geographical location of ports involved; ∀s ∈ SS∧ ∀k ∈K ∧ ∀y ∈Y.

WtT_EG_{jly}: Well to Tank GHG emission factors for every fuel, type of engine and year (kg $CO_{2\ eq}$/MJ) ∀u∈U∧∀l∈L ∧∀y∈Y. See Appendix 2 of MEPC.391(81).

Z_y: Annual reduction factor for CII relative to the 2019 reference line; ∀y ∈ Y: 2024 ($Z_k = Z_1$ = 7%); 2025 ($Z_k = Z_2$ = 9%); 2026 ($Z_k = Z_3$ = 11%); 2027 ($Z_k = Z_4$ = 13.625%); 2028 ($Z_k = Z_5$ = 16.25%); 2029 ($Z_k = Z_6$ = 18.875%); 2030 ($Z_k = Z_7$ = 21.5%); MEPC.400(83)).

ZTB_y: Annual GFI reduction factors over the GFI 2008 from 2028 for Base target (%). ∀y ∈ Y: 2028 ($Z_k = Z_5$ = 4%); 2029 ($Z_k = Z_6$ = 6%); 2030 ($Z_k = Z_7$ = 8%); 2031 ($Z_k = Z_8$ = 12.4%); 2032 ($Z_k = Z_9$ = 16.8%); 2033 ($Z_k = Z_{10}$ = 21.2%); IMO Circular Letter No. 5005, 11 April 2025.

ZTD_y: Annual GFI reduction factors over the GFI 2008 from 2028 for direct compliance target (%).∀y ∈ Y: 2028 ($Z_k = Z_5$ = 17%); 2029 ($Z_k = Z_6$ = 19%); 2030 ($Z_k = Z_7$ = 21%); 2031 ($Z_k = Z_8$ = 25.4%); 2032 ($Z_k = Z_9$ = 29.8%); 2033 ($Z_k = Z_{10}$ = 34.2%); IMO Circular Letter No. 5005, 11 April 2025

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