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Research paper

Assessment of emerging technologies for high-speed-crafts decarbonization under the European Union regulation

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ABSTRACT

In order to ensure the Carbon Intensity Indicator (CII) compliance by High-Speed-Crafts (HSCs), this paper provides a quantitative analysis of the techno-economic feasibility of a combined solution with slow steaming and vessels' retrofitting with emerging technologies for their electricity supply. Given the varying introductory dates for the EU Market Based Measures (EU-MBM) application for the outermost regions and remaining zones, both scenarios are analyzed through an application case for inter-island 10,000 GT HSCs in the Canarian Archipelago. The results reveal that the most sustainable solution is the green H2 Fuel-Cells use in HSCs' electricity generation, along with 25.3% speed reduction by maintaining their daily calls. However, this solution is less attractive for shipowners due to its Internal Rate of Return and Marginal Abatement Costs. Additionally, EU-MBM shows a deficient convergence with HSC's pollutant impact when renewable energies and alternative fuels are involved in retrofitting, by evidencing significant over grants, especially for on-shore power supply. Fuel-EU fines prove to be the most influent variable on Net Present Value for HSC retrofitting projects, however the current Fuel-EU architecture motives permanent EU-MBM's divergences among EU regions by prejudicing HSC retrofitting with emerging technologies in the outermost regions.

1. Introduction

Fast Ro-Pax vessels frequently are habitual to cover inter-insular shipping and Short Sea Shipping (SSS) routes in the European Union (EU). These vessels are classified as High Speed Crafts (HSC), according to article 10 of SOLAS (The International Convention for the Safety of Life at Sea, 1974), when they are able to reach speeds of over 3.7. $\nabla^{0.1667}$ (m/s).[1] Aside from their high speed, these vessels are characterized by a small-medium size (5000–10,000 GTs) and their lightness; they often are aluminum catamarans or trimarans. Their advantages are undoubled by allowing to meet two highly demanding requirements of connectivity: high frequency in calls and short sailing times; therefore, enabling a reduced number of vessels in operation. This operating pattern is especially appreciated not only by the hinterland's residents but also by the institutions, who present this transport service as an efficient way to meet public service obligations by preserving accessibility to remote locations. In such a way, high-speed shipping has been institutionally introduced as the suitable seaborne stretch in intermodal transport and even promoted as a desirable alternative to the airplane for passengers' transport.

However, THETIS-MRV[2] reports (Regulation (EU) 2015/757) have evidenced a well-known reality: CO_2 emissions dramatically arise with the marine propulsion power and the latter does with the required speed. Therefore, high speeds in SSS can only be an acceptable solution under the European Green Deal framework when a speed reduction forces to compensate longer sailing times by including more vessels on the route to enable schedules to be met, making slow steaming collectively non-cost effective (Psaraftis et al., 2009; Zis & Psaraftis, 2021). Despite the collective accomplishment's approach (fleet-level compliance) to decarbonization trough Goal Based Measures (GBM), having been previously suggested as a possible bridge-solution (Faber et al., 2021), the truth is that the current form of these measures uniquely

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[1] ∇ = volume of vessel displacement at the design draught.

[2] https://mrv.emsa.europa.eu/#public/emission-report.

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evaluates each vessel, resulting in HSCs to be very impaired.

The International Maritime Organization's (IMO's) Marine Environment Protection Committee (MEPC 76) approved a relevant GBM in June 2021: the Annual Operational Carbon Intensity Indicator -CII- (MEPC.352(78)) that is applicable from January 1, 2023, to vessels with over 5000 Gross Tonnage (GT). Beyond establishing yearly limitations for CO_2 emissions over time (in a progressive reduction schedule), this GBM classifies the vessels from A to E according to their yearly accomplishment level (MEPC337(76), MEPC338(76) and MEPC339 (76)). Thus, C score is required when the vessel is classified as D (during three consecutive years), or an E (in one year), by being obligated to make corrective actions to achieve C score (Ship Energy Management Plan -SEEMP- (MEPC.339(76)).

In a first approach, over 40% of the EU Ro-Pax fleet, regardless of speed and age, achieved a D or E score in 2019 (Nelissen et al., 2023). Further research showed that the HSCs, by sailing in ultra-short-shipping in 2023, frequently reached E rates (Martínez-López et al., 2023) therefore, corrective actions are demanded, not only for the HSC fleet, but also for numerous EU Ro-Pax vessels. The EU's introduction of Market Based Measures (MBM), to boost the Polluter Pays Principle -PPP- through the internalization of the polluting costs, favors the adoption of alternative technological solutions that would not be otherwise economically viable (Psaraftis et al., 2021). Likewise, one of these measures, the Fuel-EU normative (Regulation (EU) 2023/1805), also collects the compulsory use of On Shore Power Supply (OPS) or equivalent zero-emissions technology for electricity supply at berthing from 2030.

Therefore, emission payments through MBM, along with their accompanying requirements, emerge as an important incentive to adopt ambitious solutions to meet the CII normative (Nelissen et al., 2023). However, the situation is different in the outermost regions: despite the fact that SSS is especially intensive in these regions and the CII regulation enforcement (IMO scope) affects them, the main EU-MBM were temporary postposed, thus depriving the outermost fleet of this inducement for its possible retrofitting.

Given this context, this paper focused on providing a quantitative analysis about the feasibility of HSCs' retrofitting with emerging technologies for its electricity supply to reach CII compliance under the EU framework by operating in a SSS regime. To broaden this paper's scope, the selected application case analyzes the performance of HSCs operating in an EU outermost region. Thus, this study attempts to respond to the following research questions.

- Are EU-MBMs able to reflect HSCs' actual Pollutant Impact when decarbonization technology is used for its electricity production?
- How does decarbonization technology for HSC electricity production impact on required speeds to meet the CII regulation, and therefore on SSS's schedule accomplishment?
- Would additional subsidies be necessary to promote HSCs' retrofitting with the most sustainable technologies on the basis of their environmental advantages?
- Are EU policies suitable to boost HSCs' decarbonization in the outermost regions?

In this manner, this paper contributes not only to support the ship owners' decision-making for CII compliance, but also to broad existing knowledge about EU-MBM performance when emerging technologies are involved in HSCs' retrofitting, by addressing existing gaps about the joint impact of the IMO and EU decarbonization policies on HSCs operating in several EU regions.

The rest of the paper is organized as follows. Section 2 briefly reviews the main contributions from previous research. Next, the paper introduces a mathematical model (Section 3) that quantifies, on the one hand, the costs of EU decarbonization normative compliance (MBM) for HSCs when retrofitted with different alternative technologies for electricity generation. On the other hand, the model reflects the actual pollutant impact of these options to meet the CII regulation. This model's application to HSCs operating in inter-insular shipping in the Canarian Archipelago (in an EU outermost region) is shown in Section 4 by enabling a quantitative analysis of the results in Section 5. Finally, whereas Section 6 identifies the main findings with application to broader contexts, Section 7 compiles learning lessons for stakeholders, suggestions for policy makers, and pending research lines, on the basis of both the insights and shortcomings of this research.

2. Literature review

2.1. Decarbonization regulations in EU shipping, and shortcomings

MEPC 72 approved in 2018 the 'Initial IMO Strategy on Reduction of Greenhouse Gas (GHG) emissions from Ships' (updated in 2023 in MEPC 80) which collected, among other goals, a minimum GHG emission reduction target of 50% by 2050 (in relation to 2008) for shipping. Several measures were defined to meet this objective, among them CII (GBM), that is based on the base of Tank to Wake (TtW) emissions perhaps considered to be the most promising. In 2021 Fit for 55 package was adopted by the European Commission (EC) as a set of policy measures to meet the objective of reducing to 55% by 2030 (from the 1999 base) of total EU GHG emissions. As part of this strategy, shipping is included in the EU-Emission Trading System (EU-ETS) from 2024 (Directive 2023/959) by initiating, in this manner, the widely discussed MBM for the shipping (Psaraftis et al., 2021). Likewise, the Fuel-EU Maritime initiative (Regulation (EU) 2023/1805) is also due to be enforced in 2025. This measure offers a double dimension: on the one hand, it is a stricter GBM than CII since it attempts to include Well-to-Wake emissions (WtW) and, on the other, it is an MBM, because it collects a non-compliance penalization. Finally, the proposal to restructure the Energy Taxation Directive (ETD) by integrating the taxation of energy products and electricity from intra-EU shipping (COM/2021/563) becomes an additional MBM.

From the academic perspective, several studies have addressed these measures' effectiveness, however studies assessing EU-MBM performance on HSCs have not been found. Nelissen et al. (Nelissen et al., 2023) and Braidotti et al. (Braidotti et al., 2023) have focused on CII's role and its suitability. The former considered EU-MBM and GBM interdependencies on the CII label for EU-vessels and concluded that Fuel-EU could have a significant impact on CII label ships if biofuels were considered as zero-emission fuels by the CII normative. Additional improvements for CII were suggested: a differentiation between renewable fuels, fossil fuels and hydrogen through the WtW approach instead of the current consideration of TtW emissions. Braidotti et al. (Braidotti et al., 2023) analyzed the deficiencies of the CII application to passenger vessels, mainly due to their high-demand energy requirements during berthing and hoteling, since no cargo is transported during these stages. This is aggravated where the time invested in port in relation to the whole navigation period is elevated (20–69%), so the authors propose CII corrections for this traffic segment. From the MBM standpoint, whereas Psaraftis et al. (Psaraftis et al., 2021) analyzed the strongest and weakest points of several MBMs, Marrero and Martínez-López (Marrero & Martínez-López, 2023) concluded a good fitness level of EU-MBM with the actual pollutant impact of the EU-SSS traffic by operating with conventional mitigation technologies to meet ECA (Emission Control Area) requirements.

2.2. High speed crafts and pollution

Nelissen et al. (Nelissen et al., 2023) found that more than 40% of Ro-Pax vessels and over 35% of passenger vessels of the EU-Monitoring, Reporting, and Verification (EU-MRV) fleet were unable to achieve C score from CII in 2019, regardless of their HSC classification, and the situation was worse in 2020 for passenger vessels by achieving a non-compliance share of 65% (due to COVID year). The same report provided a significant insight: E score was achieved by the Ro-Pax vessels with the lowest average age. This can be explained from the information published by EMSA (European Maritime Safety Agency), which warned about HSCs' increase to 19.65% of passenger vessels under the EU-MS flag in 2020, in relation to 2016 (18.7%).

Despite this situation, very few studies have analyzed the environmental impact of medium-sized HSCs and possible solutions. In this regard, Seddiek, I.S. et al. (Seddiek et al., 2013) delighted OPS as an attractive option to reduce effectively atmospheric emissions from HSCs vessels. Psaraftis et al. (Psaraftis et al., 2009) advanced the slow steaming as a feasible solution for fast ferries when the idle time could be reduced in port to mitigate the consequent extra-time during free sailing. The authors highlighted an additional advantage of this solution for EU-SSS: the reduction of the elevated low-sulphur fuel costs (0.1%S, Directive 2005/33/EC). Zincir (Zincir, 2023) concluded the same positive impact from slow steaming on the SSS voyage expenses when this option was chosen to meet CII. However, Raza et al. (Raza et al., 2019) found that expenditure on these costly fuels in the North and Baltic Seas were being transposed to the freights via the Bunker Adjustment Factor (BAF) and this revealed Ro-Pax companies' low willingness to adopt slow steaming as a mitigation option, mainly due to extremely high competition among companies, based on two key factors valued by transport customers: reliability and precision.

Conscious of this reality, Norway stated in 2020 that new ferries and fast ferries should be low or zero emissions for 2023 and 2025, respectively (Norway's Climate Action Plan for 2021–2030 — Meld. St. 13 (2020–2021)). Under this framework, the GKP7H2-MoZEES program (since 2019) and the Horizon 2020 TrAM project (2018–2023) were developed. Both tackled the decarbonization of small high speed passenger vessels. Whereas the former designs hydrogen-driven high speed passenger ferries (1200 kW LT-PEMFC), the latter aimed to develop zero-emission fast going passenger vessels, through advanced modular production, to minimize engineering and production costs. As a result of the TrAM project, the electricity battery-driven fast catamaran ("Medstraum") is currently operating with success in Norway. Despite the relevance of this projects' success, it is necessary to consider target vessels' features: small-size vessels without rolled cargo: 150 passenger vessels, 30m length overall, 1524 kWh capacity batteries for TrAM project (Boulougouris et al., 2021) and 100 passenger vessels, 30m length overall, 2 × 600 kW of propulsion engines for the GKP7H2-MoZEES program. These features are in fact representative of HSC requirements in Norway (Ianssen et al., 2017), however, they seem to be far from the predominant fleet's characteristics of Fast Ro-Pax vessels (bigger vessels with rolled cargo and average capacity 1000 Pax).

Due to the technological maturity of emerging solutions, special attention was paid to the application of fuel cells and photovoltaic systems (PV systems) for small vessels' decarbonization operating under SSS requirements but miss attending again, medium-size HSCs. Thus, whereas fuel cells are mostly analyzed as a propulsion alternative for these small vessels, solar panels are usually evaluated as an alternative to supply on-board electricity rather than as a propulsion solution. Klebanoff et al. (Klebanoff et al., 2017) found 75.8% savings in GHG emissions against Marine Gasoil (MGO) when green H_2 was used in a Proton-Exchange Membrane (PEM) fuel cell for a high-speed catamaran (150 passengers). Likewise, Dall'Armi et al. (Dall'Armi et al., 2021) not only obtained zero-local emissions through a hybrid Low Temperature Proton-Exchange Membrane Fuel Cell (LT-PEMFC)/lithium-ion battery power plant but also achieved an efficiency improvement of over 10% in relation to the MGO for small-size Ro-Pax ferry propulsion (42m length overall and 2x200 kw propulsion engines). Regarding solar energy research, the good performance of PV systems has been highlighted by Atkinson (Atkinson, 2016) in a medium-size high speed Ro-Pax vessel (2400 passengers and 430 vehicle cargo capacity) operating in the Aegean Sea. Quantitative approaches are in line with these results; whereas Martínez-López et al. (Martínez-López et al., 2023) identified savings of 15.5% on fuel for a medium-sized car-carrier (2057 car cargo capacity) between the Canary Islands and Iberian Peninsula, Karatuğ and Durmuşoğlu (Karatuğ & Durmuşoğlu, 2020) achieved 7.38% fuel reduction for a Ro-Ro vessel (283 trailers cargo capacity) between Turkey and Italy.

2.3. Mitigation options for the decarbonization normative compliance

From the standpoint of comprehensive solutions, we can highlight the MAC (Marginal Abatement Cost) studies, which tackle mitigation technologies' cost-effectiveness, and global fleet studies. The latter analyze fleet segments' environmental situation by suggesting improvement solutions in coherence with the regulatory framework. Regarding the first group, studies on the basis of the expert-based MAC approach are especially notable, since they enable not only inclusion of the environmental policies' interdependences in the calculation but also ranking of the mitigation options by addressing shortcomings from the MAC model-based approach (Faber et al., 2021; IMO, 2020). Thus, Lagouvardou et al. (Lagouvardou et al., 2023) analyzed the alternative fuels' MAC by including MBM impact to determine the carbon price threshold to make them feasible (versus conventional fuels). Likewise, Psaraftis et al. (Psaraftis et al., 2021) used the MAC as a base tool to show the advantages of the bunker levy (versus other MBMs) in boosting the adoption of emerging technologies with initial positive MAC.

In the second group, Faber et al. (Faber et al., 2021) proposed fleet-level compliance with CII instead of individual assessments to improve the uptake of zero-emissions fuels by shipping companies. They argued that the retrofitting of just one vessel might mitigate the disadvantages associated to these low cost-effective fuels by allowing collective emissions were equivalent to the C ship label achieved individually. Later, Faber et al. (Faber et al., 2023) concluded that, a maximum abatement potential (24–47% emissions from 2008 to 2030) for the 2018–2030 fleet could be achieved through a 20–30% speed reduction (wind-assisted propulsion and the use of zero carbon emissions' fuels for generating energy (5–10%)). Likewise, Nelissen et al. (Nelissen et al., 2023) also noted that by considering the Fuel-EU impact, a 22% average speed reduction from D to E label vessels (2019 EU MRV fleet) would allow fulfilment of the CII requirements by 2030. Focusing on the SSS fleet, no studies were found that offered solutions for HSC compliance with the decarbonization normative. However, Nielsen et al. (Nelissen et al., 2023) warned, in line with Raza et al.'s (Raza et al., 2019) findings, about the possible loss of competitiveness of SSS vessels in relation to others when they employed slow steaming. Marrero and Martínez-López (Marrero & Martínez-López, 2023) found that Liquefied Natural Gas (LNG) propelled vessels was the best mature mitigation option for the GBM and MBM accomplishment (until 2031) for SSS feeder vessels. The authors also identified the OPS as a significant compliance-tool within the EU decarbonization normative. Finally, Martínez-López et al. (Martínez-López et al., 2023) evidenced that, even though the MAC for PV systems significantly improves due to the EU-MBM effect, this solution applied to the electricity supply of SSS car-carriers was insufficient on its own to ensure CII accomplishment in the medium term.

3. The method

In the light of conclusions obtained by previous research (see section 2), this paper assumes as effective solution to return HSC to CII compliance by reducing vessels' service speed along with the replacement of their on-board generating sets by more sustainable technologies. Since the electricity supply's power is moderated in relation to a vessel's propulsion power, emerging technologies in commercial state can currently be installed in the vessels with good environmental performances. The available technologies' selection determines the required reduction for the service speed (slow steaming) and therefore, this affects not only the vessel's technical feasibility but also their operative feasibility (schedule accomplishment). Once the feasibility of the technological alternative is confirmed, investment in the vessel's retrofitting is evaluated by taking not only the differential Internal Rate of the Return (IRR) but also the differential Net Present Value (NPV) into account to analyze all alternatives from the shipowner's standpoint.

Next, this section introduces the decision-making method about alternative technologies to the generating sets, based on two steps.

- Step1: Each alternative's feasibility is analyzed by considering its technical consequences in terms of propulsion power requirements (modifications of vessel's lightweight), stability's penalty (deviations from the initial centre of gravity) and available space in a machine room to arrange the new systems. When the technical feasibility is verified, environmental performance must be estimated through the real Pollutant Impact (PI). Additionally, CII compliance is tested in the assessed time range along with the suitability of the new speed patterns to meet the required scheduling of the routes.
- Step2: The investment analysis for the vessel's retrofitting involves evaluation of their Capital Expenditure (CAPEX) and Operating Expense (OPEX) with the intention of assessing the IRR and NPV linked to the alternative technologies. The EU context is taken as an assumption in this research, consequently, EU-GBM and EU-MBM belonging to the EU decarbonization of shipping are calculated as essential items of the OPEX estimation. This latter approach permits also evaluating the measures' proportionally regarding the real PI of the emerging technologies and their capacity to boost their choice on HSC.

3.1. Step1: technical and operative feasibility of the decarbonization options

3.1.1. The Carbon Intensity Indicator (CII) and required speed (slow steaming)

The CII has been in force since January 2023. This GBM (IMO) compels annual evaluation of vessels over 5000 GT by considering their CO_2 grams emitted (reported under IMO DCS[3] conditions) per nautical mile (*D*) and transported cargo (*C*); this involves calculation of the yearly attained CII (CII_A_y, $\forall y \in Y$; see equation (1)) versus the required CII (CII_R_y, $\forall y \in Y$; see equations (2) and (3)) for every kind of vessel (*a* and *c* are dependent on the vessel type, see Annex). CII_A_y (CII Guidelines, G1; resolution MEPC.352 (78)) is calculated by estimating CO_2 emissions according to IMO DCS through specific fuel consumption ($SFOC_{jls}$; $\forall j \in J \wedge \forall l \in L \wedge \forall s \in SS$; in gr/KWh) for the fuels ($J = \{1, ..., j\}$) of the engines ($L = \{1, ..., l\}$, see Annex), their required powers (PB_{lsy}; $\forall l \in L \wedge s \in SS \wedge y \in Y$; in kW), the conversion factors (CFF_{jl}[4]; $\forall j \in J \wedge \forall l \in L$ in t CO_2/t fuel) and the times (TVB_{sy}; $\forall s \in SS \wedge \forall y \in Y$; in hours) invested in every navigation stage ($SS = \{1, ..., s\}$; free sailing ($s = 1$); manouvring ($s = 2$); berthing/unberthing($s = 3$); hoteling time ($s = 4$), see Annex as well) for every year $Y = \{1, ..., y\}$.

$$CII\_A_y = \sum_{s=1}^{s} \left(TVB_{sy} \left(\sum_{l=1}^{l} \left(SFCO_{jls} \times PB_{lsy} \times CFF_{jl} \right) \right) \Big/ (C \times D); \right. \quad \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \wedge y \in Y \tag{1}$$

$$CII\_R_y = \left(1 - \frac{Z_y}{100}\right) \times a \times C^{-c}; \ \forall y \in Y \tag{2}$$

$$CII\_A_y = CII\_R_y; \ \forall y \in Y : \tag{3}$$

The CII_A_y (CII Guidelines, G1; resolution MEPC.352 (78)) must be compared with CII_R_y (CII Reference line guidelines, G2; MEPC337(76)) to determine the accomplishment level; in such a way that the vessel achieves score from A to E (CII Rating Guidelines, G4; MEPC.339(76)). This classification is annual as, on the one hand, CII_R_y ($\forall y \in Y$) value is affected by a progressive reduction factor (Z_y; $\forall y \in Y$) over 2019 emissions (CII Reduction factor guidelines, G3; Resolution MEPC.338(76)) that is applicable every year, according to a schedule. On the other hand, the powers developed at every navigation stage can change yearly (PB_{lsy}; $\forall l \in L \wedge s \in SS \wedge y \in Y$) and consequently their times (TVB_{sy}; $\forall s \in SS \wedge \forall y$) by modifying the CII_A_y value (see equation (1)). So, E score for one year, or three consecutive D scores force action to be taken to return the vessel to C score via a Ship Energy Management Plan -SEEMP- (MEPC.339(76)).

Slow steaming is understood to be an operative solution to reach C score in an HSC vessel, insofar as the vessel can meet the route's schedule; this is, the required number of daily calls to maintain current connectivity among the involved ports. To jointly meet these aims, the speed reduction during free sailing ($s = 1$) should be as little as possible. In other words, the service speed should be able to demand the necessary propulsion power ($PB_{1,1}$, see equation (1)) to make the attained CII is the yearly equivalent to the required CII (see equation (3)).

Indeed, when the generating sets' activity for the electricity supply of the vessel is replaced by a more sustainable technology, the necessary speed to achieve C score through slow steaming (equation (3)) will be higher, by facilitating the operative feasibility of this solution.

3.1.2. Alternative technologies' design, arrangement, and consequences

As was forementioned, this research assumes as the most reliable solution to meet CII by HSCs, a combination of slow steaming with an emerging technology (renewable energy, alternative fuels and mitigation devices (IMO, 2020)) to replace the generating sets for the electricity supply (Nelissen et al., 2023). For this replacement, three possibilities are parsed due to previous research findings, technological maturity and installation feasibility in HSCs: photovoltaic systems (Martínez-López et al., 2023); green hydrogen-based fuel cells (which are preferred in this case over ammonia, due to storage advantages (Kim et al., 2023)); and OPS (Marrero & Martínez-López, 2023).

Slow steaming: as noted, this operational measure is widely recommended when it is compatible with the operating schedule because it leads to lower fuel consumption [1; 10] and therefore lower emissions (Farkas et al., 2023; Hua et al., 2024). Therefore, slow steaming is assumed as a highly effective short-term measure insofar as the number of vessels in the route can be kept (Gospić et al., 2022). However, the recommended speed reductions of 20–30% (Faber et al., 2023; Nelissen et al., 2023) involves moving away from design points for the operation of engines, shaft lines and propellers, resulting in significant inefficiencies for the whole propulsion system. Therefore, to implement this measure, a new vessel's resistance analysis must be undertaken by assessing possible HSC retrofitting to remove main engines or adjust the current ones. The former action offers an additional advantage since it also reduces the HSC's lightweight and this is per se an abatement measure (IMO, 2020).

PV system: the photovoltaic system is based on the solar energy captured 's use through solar panels which are designed for maritime environments by being integrated with the ship's diesel generators. Obviously, the first requirement to maintain system feasibility is the geographical localization of the expected routes, because the availability of the solar resource strongly determines system performance (Martínez-López et al., 2023). Likewise, the upper deck must be open enough to place the panels with the following requirements: they should be installed at an angle of 5–10° from the horizontal and are limited to 10 per string to avoid exceeding a height of 3 m. A clearance of 0.8 m between rows is also required to allow crew passage for maintenance. The panels are connected to the ship's electrical system via inverters, which are sized on the basis of the maximum number of panels and the peak power they can generate. Additionally, a battery storage system can be implemented to store excess energy, providing power during port stays. Both batteries and inverters can be installed below the main deck, potentially in the auxiliary machinery space, if room allows. Thus, aside

[3] Data Collection System (MEPC. 278(70)).

[4] Resolution MEPC.308(73) and Commission Regulation (EU) No 601/2012.

from the available space for the arrangement, the PV system involves a challenge in terms of extra-weight and stability penalization (elevation of the panel arrangement's centre of gravity on the upper deck). Therefore, careful evaluation of this trade-off is required to ensure the PV system's feasibility.

Green H_2 Fuel Cell: This solution includes a diesel engine paired with a proton exchange membrane fuel cell -PEMFC-. This low temperature Fuel Cell is selected due its high-power density (Wang et al., 2022) that demands less installation space (Fu et al., 2023) by maintaining high electrical efficiency, especially for short routes' requirements (Van Biert et al., 2016). The fuel cell is supplied by hydrogen stored in independent type-C tanks ,[5] with a capacity calculated according to the consumption ship's requirements. Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations (MSC.1/Circular.1647, June 15, 2022), along with The International Code of Safety for Ships using Gases or other Low flashpoint Fuels (IGF Code, 2017) are required to design green H_2 fuel cell installation. In September 2024, the latter will result in an IMO guideline being implemented for Hydrogen fuelled vessels (expectantly approved in MSC 109). Additionally, the application of specific criteria from Classification Societies are also desirable (Fuel cell installations -Pt.6 Ch.2 Sec.3, DNV-RU-SHIP, 2021-; Requirements for fuel cell power systems for marine and off-shore applications ABS, 2023-1-1-4/1.5 of the ABS Rules for Conditions of Classification (Part 1)-; etc.). The fuel cells will be connected to the ship's electrical system via inverters and a battery storage system to store unused energy. These components should be sized according to the ship's load curves and power needs; likewise, they should be located below the main deck if space allows, preferably in rooms adjacent to the engine room, but never inside it. If permitted by the underdeck space, this would prevent reduction of the main cargo area; alternatively, these systems can also be installed on cargo decks if necessary.

OPS: This solution requires an energy distribution system, control panel, frequency converter, and cable reels.

Finally, to test the technical feasibility of the proposed solutions for HSCs, a vessel's retrofitting alternatives must comply with the criteria collected in the International Code of Safety for High-Speed Craft (HSC 2000 code; MSC.97(73)). The code mandates stability verifications whether there is a deviation from the initial vessel's lightweight over 2% or a modification of the longitudinal center of gravity exceeding 1% of the ship's length. These situations are habitual in the retrofitting of these vessels because many of them are made of aluminium and therefore are ultra-lighted.

3.1.3. *Pollutant impact (PI)*

To offer a broader perspective about the environmental performance of the considered technological alternatives, beyond CII compliance (see section 3.1.1), their PI in monetary terms (€/trip) should be quantified. To this aim, the PI model published by Martínez-López et al. (Martínez-López et al., 2022) will be taken as a base-reference but adapted to this research's aim. Thus, the initial assessment model (Martínez-López et al., 2022) was broadened by including the hoteling stage (s = 4, see Annex) and on-shore emissions from electricity supply by OPS (Well-to-Tank emissions emitted by the land network) to offer a comprehensive evaluation of the technological alternatives. Additionally, the ecotoxicity of the marine environment and marine eutrophication impact (exhaust gas cleaning systems' impact) will not be taken into account by focusing the assessment on the annual pollutant impact due to air quality per navigation stages (PI_{sy}; $\forall s \in SS^\wedge \forall y \in Y$; in €/trip; see equation (4)).

$$\mathrm{PI_y} = \sum_{s=1}^{4} PI_{sy};\ \forall s \in SS \wedge \forall y \in Y \tag{4}$$

[5] ABS Guidance notes on strength assessment of independent type C tanks, 2022.

Consequently, the introduced PI only quantifies in monetary terms the air pollutants (U = {1, …*u*}, see Annex): acidifying substances (SO_X), ozone precursors (NO_x), particulate mass ($PM_{2.5}$ and PM_{10}), greenhouse gases (CO_2, CH_4) and ammonia slip (NH_3). To this aim, the ship emission factors Tank-to-Wake (EG_{suly}; $\forall u \in U \wedge \forall l \in L \wedge \forall y \in Y$ in kg/h), unitary costs (CF_{sukvy};$\forall s \in SS^* \wedge \forall u \in U \wedge \forall k \in K \wedge \forall v \in V \wedge \forall y \in Y$; CF_{1uky}; $\forall u \in U \wedge \forall k \in K^* \wedge \forall y \in Y$; in €/kg pollutant) and times invested in the navigation stages (TVB_{sy}; $\forall s \in S \wedge \forall y \in Y$) must be also deemed (see equations (5) and (7)).

$$\mathrm{PI_{1y}} = \sum_{l=1}^{l} \sum_{u=1}^{7} \left(EG_{1uly} \times CF_{1uky} \times TVB_{1y}\right); \quad \forall k \in K^* \wedge \forall l \in L \wedge \forall y \in Y \tag{5}$$

$$\mathrm{PI_{sy}} = \frac{1}{2} \times \sum_{k=1}^{2} CEM_{sky};\ \forall k \in K \wedge \forall s \in SS^* \wedge \forall y \in Y \tag{6}$$

- On-board electricity supply:

$$\mathrm{PI_{sky}} = \sum_{l=1}^{l} \sum_{u=1}^{7} \left(EG_{suly} \times CF_{sukvy} \times TVB_{sy}\right); \quad \forall k \in K \wedge \forall v \in V \wedge \forall s \in SS^* \wedge \forall l \in L \wedge \forall y \in Y \tag{7}$$

- Vessel is plugged into the on-shore electricity grid (OPS)

$$\mathrm{PI_{sky}} = \sum_{u=1}^{7} \left(EFG_{uky} \times PB_{2sy} \times CF_{sukvy} \times \left(TVB_{sy} + CT_{sk}\right)\right); \quad \forall k \in K \wedge \forall v \in V \wedge \forall s \in SS^{**} \wedge \forall y \in Y \tag{8}$$

Whereas the emissions cost for the free sailing stage (s = 1) is uniquely dependent on the ocean type (CF_{1uky}; $\forall u \in U \wedge \forall k \in K^* \wedge \forall y \in Y$; see equation (5)), for the remaining navigation stage *s* ($\forall s \in SS^*$; $SS^* = \{2,3,4\}$) this value (CF_{sukvy};$\forall s \in SS^* \wedge \forall u \in U \wedge \forall k \in K \wedge \forall v \in V \wedge \forall y \in Y$ is highly conditioned by the geographical localization of the ports ($\forall k \in K$) and their polpulation density ($\forall v \in V$ see Annex), as can be seen in equations (6)–(8). This dependence is even more notable when the OPS is used (Martínez-López et al., 2021), since the port localization and its features not only influence the emission factors in berthing and hoteling stage *s* ($\forall s \in SS^{**}$; $SS^{**} = \{3,4\}$) by the share of Renewable Energy Sources (RES) in the on-shore grids (EFG_{uky};$\forall u \in U \wedge \forall k \in K \wedge \forall y \in Y$ in kg/KWh), but also, connection/disconnection lag times (CT_{sk} ; $\forall s \in SS^{**} \wedge \forall k \in K$, see Annex) for OPS use (see equation (8)).

3.2. *Step2: feasibility analysis for the retrofitting investments*

3.2.1. *OPEX related to environmental performance for decarbonization options*

This section collects the GBM and MBM for shipping, imposed by EU regulations (European Green Deal framework- COM (2019) 640 final-), to meet the decarbonization targets. Obviously, MBM respond to the Polluter Pays Principle (PPP) and therefore, attempt to be an environmental charge for the vessels by being these ones also proportional to their pollutant impact. Consequently, the application of these measures will increase vessels' operative costs (OPEX) and, therefore, these must be considered in the feasibility analysis of the investments for vessels' retrofitting.

3.2.1.1. MBM: EU-emission trading system (EU-ETS). Shipping was firstly included in the EU-ETS in 2021 (COM2021 (551) final) with the liability of surrendering allowances from 2023 CO_2 emissions (reported through the EU-MRV system, Regulation (EU) 2015/757) according to a progressive schedule of inclusion. However, finally the Directive 2023/959 postponed the inclusion of shipping in the EU-ETS to 2024 by extending the delay to December 2030 for shipping in the EU's outermost regions (article 349 of the Treaty on the Functioning of the EU), or between these regions and the continental EU.

$$ETS_y = N \times ETSU_y;\ \forall y \in Y \tag{9}$$

$$ETSU_y = CP \times \alpha_i \times \beta_y \times \sum_{S=1}^{s}\left(TVB_{sy}\sum_{l=1}^{l}\left(SFOC_{jls} \times PB_{lsy} \times CFF_{jl}\right)\right);\quad \forall i \in I \wedge \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \wedge \forall yY; \tag{10}$$

Equations (9) and (10) show respectively the annual cost (ETS_y; $\forall y \in Y$; €/year) and the cost per trip ($ETSU_y$; $\forall y \in Y$; €/trip) due to the surrendered allowances. To this aim, aside from considering the EU carbon price (CP in €/CO_2 ton), equation (10) estimates total CO_2 emissions by following the process collected for the MRV system (Commission Regulation (EU) No 601/2012; Regulation (EU) 2015/757) and that was previously introduced for the calculation of the attained CII (see equation (1)). The CO_2 emissions amount affected by surrendered allowances (EU-ETS) is corrected (α_i; $\forall i \in I$) by the localization of the ports involved in the shipping (inside/outside EU region $I = \{1, \ldots, i\}$) and by the year analyzed (β_y; $\forall y \in Y$), according to the schedule of progressive inclusion over time (Directive 2023/959, see Annex).

3.2.1.2. MBM: Energy Taxation Directive (ETD). This measure is based on the proposal collected in the COM/2021/563 (final) for restructuring the EU framework for the taxation of energy products and electricity (Awaiting committee decision, to date). According to this communication, on-board electricity generation as well as OPS electricity are exempted from taxation.

$$ETD_y = N \times ETU_y;\ \forall y \in Y \tag{11}$$

$$ETU_y = \sum_{s=1}^{s}\left(TL_j \times CV_j \times SFOC_{jls} \times PB_{lsy} \times TVB_{sy}\right);\quad \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \wedge \forall y \in Y; \tag{12}$$

Considering that N collects the number of trips per year, equations (11) and (12) show the annual energy taxation (ETD_y; $\forall y \in Y$ in €/year) and the energy taxation per trip (ETU_y; $\forall y \in Y$ in €/trip) respectively (N involves annual trips, see Annex A). The taxation level (TL_j; $\forall j \in J$ in €/GJ) for every type of fuel ($J = \{1, \ldots, j\}$) must be applied to the energy developed by the vessel in Gigajoules. The latter is estimated through the fuel consumed by the vessel (see equation (12)), and that fuel's net calorific value (CV_j; $\forall j \in J$ in GJ/g fuel). The taxation level is updated by increasing its minimum level, one tenth annually from 2023.

3.2.1.3. GBM: Fuel-EU maritime initiative. Fuel-EU maritime initiative is an additional GBM to CII (MEPC.352 (78)), but whereas CII limits CO_2 emissions, the former limits the GHG intensity of energy used on board (gr CO_{2eq}/MJ). This measure was collected for the first time in the COM (2021) 562 final, where the required reductions started in 2025 according to a progressive schedule, taking as a reference value the 2020 GHG intensity estimated from the EU-MRV report (Regulation (EU) 2015/757). However, the final requirements for this measure were published in Regulation (EU) 2023/1805 with some modifications, among them: the progressive reductions schedule (μ_y; $\forall y \in Y$) was modified and applied on a fixed reference-value 91.16gr/CO_{2eq} to define the GHG intensity target ($(GHGIE_{target})_y$; $\forall y \in Y$, see equation (14)). Additionally, although the COM (2021) 562 (final) also collected a non-compliance penalty (to be MBM as well), this has been tightened by increasing its value ($Fuel\_EU_y$; $\forall y \in Y$) with the recidivism (n: number of consecutive non-compliance periods, see equation (13)). Finally, Regulation (EU) 2023/1805 has included a singular consideration to shipping in the outermost regions: only one half of the energy used on the voyages should be considered (γ_i; $\forall i \in I$; see Annex) for calculations and a delay in the enforcement of this measure until December 2029 is included.

$$Fuel_{EU_y} = \frac{2.4}{41} \times \gamma_i \times \left(\sum_{s=1}^{s}\left(TVB_{sy}\left(\sum_{l=1}^{l}\left(SFOC_{jls} \times PB_{lsy} \times CV_j\right)\right) + \sum_{c=1}^{c}E_c\right)\right) \times \left(\frac{\left(GHGIEtarget\right)_y - GHGIEactual}{GHGIEactual}\right) \times \left(1 + \frac{n-1}{10}\right);\ \forall i \in I \wedge l \in L \wedge \forall c \in CC \wedge \forall s \in SS \wedge \forall y \in Y \tag{13}$$

$$(GHGIE_{target})_y = 91.16 \times \mu_y;\ \forall y \in Y \tag{14}$$

$$GHGIE_{actual} = f_{wind} \times (WtT_y + TtW_y);\ \forall y \in Y \tag{15}$$

$$WtT_y = \left(\frac{1}{\left(Vessel_{energy}\right)_y}\right) \times \sum_{s=1}^{s}\left[TVB_{sy}\left(\sum_{l=1}^{l}\left(SFOC_{jls} \times PB_{lsy} \times CV_j\right)\right) \times CO_{2eqWtT,j}\right];\quad \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \wedge \forall y \in Y \tag{16}$$

$$TtW_y = \left(\frac{1}{\left(Vessel_{energy}\right)_y}\right) \times \sum_{s=1}^{s}\sum_{l=1}^{l}\left[\left(TVB_{sy} \times \left(SFOC_{jls} \times PB_{lsy} \times CV_j\right)\right) \times \left(CO_{2eqTtW,j,l} \times \left(1 - \frac{1}{100} \times C_{engine_{slip,1}}\right) + CO_{2eqTtWslippage,j,l} \times \frac{1}{100} \times C_{engine_{slip,1}}\right)\right];\quad \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \wedge \forall y \in Y; \tag{17}$$

$$(Vessel\_energy)_y = \left(\sum_{s=1}^{s}\left(TVB_{sy}\left(\sum_{l=1}^{l}\left(SFCO_{jls} \times PB_{lsy} \times CV_j \times RWD_{jl}\right)\right) + \sum_{c=1}^{c}E_c\right)\right);\quad \forall j \in J \wedge \forall l \in L \wedge \forall c \in CC \wedge \forall y \in Y \wedge \forall s \in SS; \tag{18}$$

$$CO_{2\ eq\ TtW,j,l} = CFF_{jl} \times GWP_{CO2} + CFM_{jl} \times GWP_{CH4} + CFN_{jl} \times GWP_{N2O};\ \forall j \in J \wedge \forall l \in L \tag{19}$$

Since, non-compliance involves a fine (€/year; see equation (13)), Fuel-EU is also an MBM where the charge value is mainly conditioned by the non-compliance difference between the actual GHG intensity of the energy used ($GHGIE_{actual}$; in g $CO_{2\ eq}$/MJ, see equation (15)) and the target value. The former is estimated by considering GHG emission factors ($CO_{2eq\ WtT,j}$; $\forall j \in J$; see equation (16)) and also $CO_{2equivalent}$ emissions of combusted fuel ($CO_{2\ eq\ TtW},j$; $\forall j \in J$, see equations (17) and (19)). Moreover, the Fuel-EU initiative also takes into account sustainable sources of energy: OPS (E_c; $\forall c \in CC$, in MJ, see equations (13) and (18)) and Reward factors for wind assisted propulsion ($f_{wind,}$ see equation (15)) and for non-biological fuels use (RWD_{jl}; $\forall j \in J \wedge \forall l \in L$; see equation (18)).

Finally, the obligation of using OPS or zero-emission technologies at berth for container and passenger vessels from January 2030 (from 2035 for comprehensive ports; these are not covered by article 9 of Regulation (EU) 2023/1804) was kept in the current regulation from the initial Communication.

3.2.2. Internal Rate of return and Net Present Value

Evaluation of the possible alternatives to generating sets necessary involves assessment of retrofitting investments' feasibility. To this end, IRR (see equation (20)) and the NPV (see equation (22)) are used as evaluating tools for the alternatives ($Q = \{1,..,q\}$) by considering a life span ($Y = \{1,..,y\}$).

$$CAPEX_q = \sum_{y=1}^{y}\left(\frac{\Delta(NCF_q)_y}{(1+IRR_q)^y}\right);\ \forall q \in Q \forall \wedge y \in Y \tag{20}$$

Aside from the capital cost linked to every alternative ($CAPEX_q$; $\forall q \in Q$), equations (20) and (22) consider the differential Cash Flow ($\Delta(NCF_q)_{y;}$ $\forall y \in Y \wedge \forall q \in Q$; see equation (21)) between retrofitting vessel and the reference case; that is, uniquely applying slow steaming to meet the CII requirements (no retrofitting). Differential cash flow is consequently assumed as the difference between two discrete cash flow values; thus, this can achieve a positive or negative value for every particular year. Additionally, NPV is strongly conditioned by the discounting rate (R), this is, the return rate able to ensure project feasibility from the shipowner's standpoint.

$$\Delta(NCF_q)_y = \Delta\ (MC_q)_y + \Delta\ (RC_q)_y + \Delta\ (BC_q)_y + \Delta\ (BAC_q)_y + \Delta\ (MBM_q)_y;\ \forall q \in Q\ \wedge \forall y \in Y \tag{21}$$

Annual cash flow estimations consider several operative costs (OPEX): replacement costs[6] for every technological alternative versus the generating sets (RC_q; $\forall q \in Q$), maintenance costs[7] (MC_q; $\forall q \in Q$), bunker costs related to propulsion power (BC_q; $\forall q \in Q$) and also bunker costs for electricity generation (BAC_q; $\forall q \in Q$). Finally, the operative costs related to the vessels' environmental impact of the vessels under the EU normative ($MBM_{q,}$; $\forall q \in Q$) are also considered, as explained in section 3.2.1, through the emission trading system costs (ETS_q; $\forall q \in Q$, see equation (9)), the European Taxation Directive costs (ETD_q; $\forall q \in Q$, see equation (11)) and Fuel-EU penalties ($Fuel\_EU_q$; $\forall q \in Q$, see equation (13)).

$$NPV_q = -CAPEX_q + \sum_{y=1}^{y}\left(\frac{\Delta(NCF_q)_y}{(1+R_q)^y}\right);\ \forall q \in Q \forall \wedge y \in Y \tag{22}$$

It is worth bearing in mind that the maintenance and replacement costs are dependent on accumulated working hours ($\forall y \in Y$). In fact, the Cash Flow difference will be positive when the retrofitting cases ($q =$ 2,3,4) provide savings in relation to slow steaming ($q = 1$). Since, all Net Cash Flow items are costs (see equation (21)), a positive difference between retrofitting alternative and slow steaming involves an economic advantage towards the former (i.e., savings in terms of costs).

[6] Replacement includes all costs involved in replacing a system when its lifespan is over.

[7] Maintenance costs involve labor costs and part replacement costs to maintain electricity generation systems.

Table 1
Technical features for HSC.[9]

Lo (m)	112.6
Lpp (m)	101.3
B(m)	26.2
Dmain_deck (m)	8.5
Dupper_deck (m)	15
Tmax (m)	4.85
T(m)	3.8
Service speed (kn)	38
Main engine (BHP kW)[a]	36,000 (4 × 9MW)
Cars/Pax	357/1400
Auxiliary engines (kWe)[b]	4X393
GT	10,369
Daedweight Max(t)	10,000
Bow thruster (kW)	2x300
Waterjets	4x125KaMeWaSIINP

[a] MAN 20V28/33D STC Marine Engine.
[b] VOLVO PENTA MARINE GENSET D16-MG.

Table 2
Current operative features for an HSC vessel.

Navigation stage	Speeds (kn) VB_s	%BHP main engines (kW)	Required electrical power (kW)	Capacity planning[a]	Times (h/trip) TVB_s
Free Sailing	38	93.73% (33.757 kw)	400	2xMMAA 51%	1.6
Maneuvring	4	0.12% (43.2 kW)	450	2xMMAA 57%	0.5
Berthing	0	0.00%	400	2xMMAA 51%	1
Hoteling	0	0.00%	250	1xMMAA 64%	11.6[b]

[a] MMAA = Auxiliary engines (generating sets).
[b] Aggregated hoteling time per day (idle times for scheduling adjustments between trips and daily sleeping time).

4. Application case

A Ro-Pax catamaran (see Table 1, and general arrangement[8,9] (Royal Institution of Naval Architects, 2011)), operating under high speed conditions between two islands of the Canarian Archipelago (Gran Canaria and Fuerteventura), was selected as an application case for the following reasons: extra high speed (38kn), very-short-distance (D = 55 n.m; Las Palmas-Morrojable), high frequency in calls (4 trips/day, two calls in each direction, evident oversizing of the electricity generating plant regarding its current needs (see Table 2) and a large upper deck that enables PV system installation. The latter is particularly interesting in the Canarian Archipelago where solar Global Horizontal Irradiance (GHI) was found to be 6.98 kWh/m^2/day (NASA Resources from Homer software).

The data shown in Table 2 collect the vessel's current operating requirements (on-board measurements for electricity supply). Maxsurf Resistance[10] tool was applied to the vessel's model (Maxsurf modeling)

[8] https://www.austal.com/sites/default/files/data-sheet/H24620Leonora20Christina20low20res.pdf.

[9] IMO 9557848 was used as an application vessel (https://www.vesselfinder.com/es/vessels/details/9557848).

[10] Wyman method for resistance prediction applied from Resistance Module of Maxsurf software.

to estimate the Effective Horse Power (EHP) in a first approach. These results along with the technical and operative features of the vessel were used as inputs for estimating necessary Brake Horse Power -BHP of the engine and the annual CO_2 emissions through Ship Design Programs for Emission Calculations- SHIP-DESMO-Ro-Ro Passenger (developed by the Danish RoRoSECA project,[11][12] (Kristensen & Psaraftis, 2016a; Kristensen & Psaraftis, 2016b)). The effectiveness of these estimations was tested by comparing the results achieved with those reported to THETIS-MRV[13] in 2022 (37,746.90 tCO_2/year versus 38,587.27tCO_2/-year); the found deviation is −2.2%. Once the operative information is confirmed and the estimation method for CO_2 emissions is tested, future estimations can be undertaken by predicting CII class evolution over time and assessing the performance of alternative solutions to achieve CII compliance.

Thus, the CII class for 2023 is estimated as E score (CII_A = 63.007gCO_2/t. n.m and CII_R = 31.467 gCO2/t. n.m). This classification, according to the regulation (MEPC.339(76)), compels to propose corrective action to achieve C score. The obligation to use zero-emission technologies at berth from 2030 (Regulation (EU) 2023/1805) along with recommendations from previous research to include OPS as soon as possible in SSS vessels (Marrero & Martínez-López, 2023), leave to assess as first option a vessel's retrofitting focused on the electricity plant's renewable. However, due to the low contribution of electricity generation to the whole CO_2 emissions in the HSC (a 3.53% contribution to whole CO_2 emissions; see propulsion and electrical powers in Table 2), the replacement of the generating sets on its own is insufficient to meet C score. This involves considering actions over propulsion power; slow steaming (operative measure) emerges as an interesting solution insofar as it is feasible in terms of schedule accomplishment: 4 trips/day, two calls in each direction and 8.5 h as a minimum sleeping time (inactive vessel from 22.00 h to 6.30 h).

4.1. Step1: technical and operative feasibility of the decarbonization options for the application case

Fig. 1 shows that HSCs' current speed (38kn) should be reduced to speeds ranging from 28.4kn to 25.24kn (from 2023 to 2033 respectively) to ensure C score until 2033 through slow steaming. These results involve reductions between 25.3% and 33.5% of the initial speed and are in line with previous research (Faber et al., 2023; Nelissen et al., 2023). These target speeds have been obtained by considering the influence on final CO_2 emissions of expected increasing shipping times: from 28 min to 41.87 min per trip (2023–2033, see Table A1 from Supplementary Material_A). Thus, in 2033 the shipping time would reach a maximum in 2.05 h (initial shipping time 1.6 h; see Table A1 from Supplementary Material_A) by reducing the aggregated hoteling time to 8.80 h/day (initial 11.6 h, see Table 2). In such a way, at the cost of reducing the port idle times between trips (buffers for scheduling compliance), the current 8.5 h for sleeping time for the vessel (from 22.00 h to 6.30 h) along with the required two daily calls/direction could be kept. Neither the maximum expected increase in time per trip (41.87 min, see Fig. 1) seems to be a significant obstacle to maintaining current traffic (passengers with cars and inter-insular loads), even in the transport of perishable goods. Consequently, slow steaming can be assumed to be a feasible option in operative terms to reach C score until 2033.

It is interesting to bear in mind two consequences of this option; on the one hand the required propulsion power goes down to 14,483 kW[14] in the most demanding scenario (2023), therefore, two main engines (see Table 1) would be sufficient to provide the required propulsion power. This vessel's retrofitting would reduce the vessel's lightweight (see Tables A2–A5 from Supplementary Material_A) with further decreases on the bunkering needs. On the other hand, the pollutant impact's contribution from the electricity supply to the whole vessel's emissions is increasing in relative terms over the time with the progressive reduction of the speed, in such a way, the electrical generation sustainability becomes more relevant on the vessel.

For this reason, four possible technological alternatives to meet CII requirements are analyzed in this application case.

- Slow steaming: no vessel retrofitting($q = 1$).
- PV system: the photovoltaic system together with slow steaming ($q = 2$).
- Fuel Cell: green H_2 fuel cell system along with slow steaming ($q = 3$).
- OPS: On shore power supply system together with slow steaming ($q = 4$).

The vessel's retrofitting involves, in all options ($q = 2,3,4$), the two main engines' extraction along with the alternative system's installation for the electricity supply. This includes modification of the engine room arrangement to set up the systems' components (see Tables A3–A5 from Supplementary Material_A) in according to the required normative (see section 3.1.2).

- PV system's panels are installed on the bridge deck and at the bow of the upper deck. Batteries and converters are located on the deck just below the main deck, in the workshop room, forward of the auxiliary engine rooms on both sides of the ship.
- Fuel Cells are installed on the deck just below the main deck, in the auxiliary engine room, while battery storage system and converters are placed in the room at the stern of the auxiliary engine room. The H_2 tank is installed at the stern of the bridge deck.
- OPS involves the energy distribution system, control panel, and frequency converter are located on the auxiliary engine room (starboard skid) while the cable reel is placed at aft of the upper deck (starboard side).

Considering the modifications on the initial center of the gravity and lightweight by vessel retrofitting (a deviation from the initial vessel's lightweight over 2% exists in all cases, see Table 3), a stability assessment (calculated through Maxsurf Stability) is required for every alternative technology to meet the 2000 HSC CODE (MSC.97(73)). Despite the rising of the vertical center of gravity (k_G, see Table 3), mainly due to remove the main engines located on bottom deck, every alternative widely passes all stability criteria.

Likewise, removing two main engines (106.4 t, see Table A2 from Supplementary Material_A) is the main cause of the significant lightweight reduction in all retrofitting alternatives regarding the slow steaming without retrofitting (see Table 3). This fact explains the necessary BHP (calculated in kW from EHP- Maxsurf Resistance[13−] by SHIP-DESMO-Ro-Ro Passenger tool(Kristensen & Psaraftis, 2016b)) required for the main engines to meet 28.4 kn at service speed with every alternative under the same load condition (T = 3.8m).New propulsion power requirements, along with the new environment performance of the electricity plant, define new CO_2 emissions (SHIP-DESMO-Ro-Ro Passenger (Kristensen & Psaraftis, 2016a);). The vessel's new pollutant impact requires new sailing speed reduction patterns to meet CII compliance. Fig. 2 shows that, whereas for slow steaming speed reduction must be progressive over time to achieve C score by reaching 25.24 kn in 2033, when this operative solution is combined with alternative technology, the minimum required speed is 27.28 kn. Additionally, the initial 28.4 kn can be maintained until 2028 when the vessel is retrofitted. Likewise, Fig. 2 indicates the most sustainable options based on the required year to reduce the speed: Fuel cell

[11] https://gitlab.gbar.dtu.dk/oceanwave3d/Ship-Desmo/-/find_file/master.
[12] https://danishshipping.dk/en/policy/climate/ship-design-calculation-tool/.
[13] https://mrv.emsa.europa.eu/#public/emission-report.
[14] Wyman method for resistance prediction applied from Resistance Module of Maxsurf software.

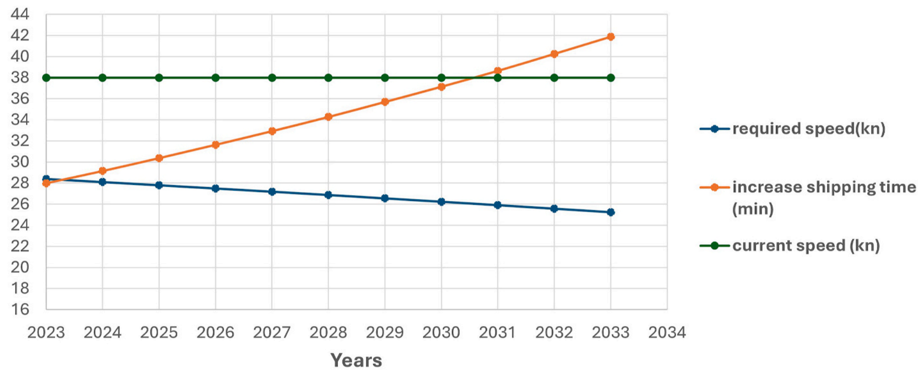

Fig. 1. Required Values to reach C score by slow steaming.

Table 3
HSC retrofitting impact on stability and propulsion power.

	Lightweight (t)	x_G	k_G	y_G	BHP (kW)[a]
Slow steaming (no retrofitting)	1217.39	36.05	7.88	0	14,433.83
PV system retrofitting	1152.4	38.01	8.313	0.009	13,094.00
Fuel Cell retrofitting	1,114,74	36.89	8.27	0.059	12,471.93
OPS retrofitting	1114.19	37.05	8.25	0.059	12,471.93

[a] Required speed for 2023 CII compliance without retrofitting; 28.4 kn and T = 3.8m.

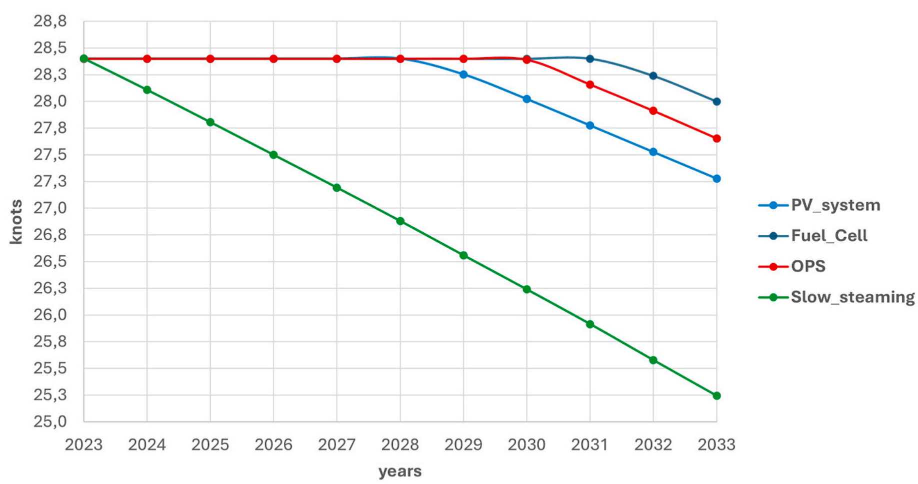

Fig. 2. Speed patterns to reach C score when several technical alternatives are implemented.

shows the latest reduction year (2032), whereas the opposite occurs for the PV system option; the latter also involves the earliest year for speed reduction (2029).

4.1.1. Pollutant impact for the application case

This analysis has assumed LSMGO for main and auxiliary engines by default to avoid fuel shift in such a short distance (55 nm) by meeting the maximum 0.1%S content fuel demanded in EU-ports (Directive 2005/33/EC). Moreover, when Fuel Cells and OPS alternatives are evaluated, the analysis assumes the existence of sufficient green H_2 supply and suitable facilities in the ports involved. Likewise, this analysis has assumed average 4219 h/year of solar time and 5.40 kWh/m^2/day of GHI with 6.98 kWh/m^2/day as a maximum value for the application case (28° 8.3′N, 15° 24.8′W, NASA Resources from Homer software), which consequently involves PV system operation during 48.16% of the daily time (24h). Finally, all retrofitting alternatives are sized to be able to ensure zero-emissions during the berthing and hoteling stage to compliance with Fuel-EU normative (Regulation (EU) 2023/1805). Thus, the most demanding electricity supply scenario was considered to sizing fuel cell system (2033, see Fig. 2 and Table 2) and H_2 tanks capacity by demanding a range enough to operate when the sleeping port has not H_2 facilities. Likewise, the battery storage sizing in PV system must cope with the electricity needs during the longest periods in port (at 28.4kn see Fig. 2 and Table A1 from Supplementary material A) without solar resource or auxiliary engines' supply.

PI calculation (see section 3.1.3) has considered for every year CO_2, SO_x, NO_x, $PM_{2.5}$, as well as PM_{10} emissions, obtained through SHIP-DESMO-Ro-Ro passengers for every possible retrofitted vessel (see Table 3 and Fig. 2). Moreover, CH_4 emissions for engines (5.527.10–3 gCH_4/kWh) were also estimated by considering the factors for Tank to Wake emissions provided by Pavlenko et al. (Pavlenko et al., 2019). These factors are dependent on the engines' technology (7.5.10-4g CH_4/MJ for medium speed-four stroke, see Table 1), the kind of fuel (LSMGO), and the vessel's specific fuel consumption (7.37 MJ/kWh).

Addition to vessel's emissions (EG_{suly}; $\forall u \in U \wedge \forall l \in L \wedge \forall y \in Y$ in kg/h), on-shore emissions factors (EFG_{uky};$\forall u \in U \wedge \forall k \in K \wedge \forall y \in Y$ in kg/KWh, see equation (8)) were also estimated to evaluate the OPS option in every port (see Table 4). The factors value is highly conditioned by the

Table 4
OPS emission factors in Continental Spain, Gran Canaria and Fuerteventura (2021).

	NO_x (g/kWh)	SO_2 (g/kWh)	$PM_{2,5}$ (g/kWh)	PM_{10} (g/kWh)	CO_2 (g/kWh)	CH_4 (g/kWh)	NH_3 (g/kWh)
Continental Spain	0.254	0.042	0.005	0.004	106.195	0.021	0.002
Gran Canaria	1.307	0.281	0.037	0.019	527.164	0.026	0.272
Fuerteventura	11.097	1.594	0.288	0.144	567.742	0.026	0.002

(Data Source: (European Commission, 2023; European Environment Agency, 2009, p. 96; Government of the Canary Islands, 2021; Ministry for Ecological Transition and the Demographic Challenge, 2024))

Table 5
Gross Electricity Generation, by fuel in 2021 (%).

	Hard coal	Brown coal	Oil and petroleum products	Natural gas and manufactured gas	Solid biofuels and renewable wastes	Renewable	Nuclear	Main Activity Electricity Only Plants [TWh]
SPAIN (continental)	1.77%	0.00%	3.67%	26.51%	2.17%	45.23%	20.64%	236.48
GRAN CANARIA ISLAND	0.00%	0.00%	79.44%	0.00%	0.00%	20.56%	0.00%	3.35
FUERTEVENTURA ISLAND	0.00%	0.00%	81.77%	0.00%	0.00%	18.23%	0.00%	0.62

(Data Source: (European Commission, 2023; Government of the Canary Islands, 2021))

share of renewable sources on the on-shore generation electricity plants (Martínez-López et al., 2021). This influence is indeed significant on the emission factors between continental Spain and the Islands (see Tables 4 and 5).

To meet this aim, Gross Electricity Generation per type of generation ((Government of the Canary Islands, 2021) ,[15] (European Commission, 2023), [16]; see Table 5) together with the pollutant emissions of the electric power generating plants (Thermal power stations and other combustion installations) must be considered. The latter was obtained from European Pollutant Release and Transfer Register -E-PRTR- (Regulation (EC) No 166/2006) published by the Spanish Ministry for Ecological Transition and Demographic Challenge (PRTR).[17] However, since the PRTR does not collect the particulate matters $PM_{2.5}$, this pollutant was estimated on basis of its relationship with the PM_{10} (European Environment Agency, 2009, p. 96; Martínez-López et al., 2021)

Nevertheless, the emission factors linked to OPS (see Table 4) are not static, since the Canary Islands are following a decarbonization policy focused on reaching 62% of renewable energy penetration by 2030 and a full decarbonized energy system by 2040. Consequently, a 100% of renewable energising the grid is expected by 2040. For that reason, the emission factors have been annually adapted to the period 2023–2033 (see Supplementary Material_B) by projecting their evolution from the information reported by the PRTR (2017-2019-pre-COVID evolution) and the Sustainable Energy Strategy in the Canary Islands (Government of the Canary Islands, 2022).

Regarding the unitary cost for the pollutants (CF_{sukvy};$\forall s \in SS^* \wedge \forall u \in U \wedge \forall f \in F \wedge \forall v \in V \wedge \forall y \in Y$; CF_{1uky}; $u \in U \wedge \forall k \in K^* \wedge \forall y \in Y$; in €/kg pollutant), the data related to Spain published by the European Commission in the last Handbook on the External Costs of Transport (HECT (Van Essen et al., 2019);) were considered. However, these costs are related to 2016, therefore an update to 2023 was undertaken by considering the aggregated Consumer Price Index -CPI- (19.4%, National Statistics Institute of Spain). For the subsequent updates of the costs (for 2023–2033), a constant CPI = 2% was assumed. This value, beyond PI calculation, was used for all necessary cost updates (OPEX and CAPEX) as an inflation rate in this research. CO_2 unitary cost (CF_{1uky}; $u \in U \wedge \forall k \in K^* \wedge \forall y \in Y$; $CF_{sukvy;}$ $\forall s \in SS^* \wedge \forall u \in U \wedge \forall f \in F \wedge \forall v \in V \wedge \forall y \in Y$) deserves special mention, since 119.2€/t was taken for PI calculation by updating to 2023 the central value provided by the HECT (Van Essen et al., 2019) as the climate change avoidance cost. However, the fact that the same publication (Van Essen et al., 2019) also offers 71.64€/t (2023) as the low value for CO_2 emissions and, the Carbon Allowance Costs for EU-ETS calculation arises to CP = 82.87€/t[18] (December 2023) has motived a further pollutant impact analysis (PI2), where this CP value is taken as CO_2 unitary cost (harmful effect of this pollutant in monetary terms) to offer a realistic comparison between MBM and the real HSC pollutant impact by operating with different technological alternatives (Marrero & Martínez-López, 2023).

4.2. Step 2: feasibility analysis for retrofitting investments in the application case

The IRR and NPV analysis (see equation (20)) takes 2023 as the investment year whereas the evaluation time spreads over 2024 to 2033. In parallel, the differential value of the Cash Flow ($\Delta(NCF_q)_{y}$; $\forall y \in Y \wedge \forall q \in Q$; see equation (21)) requires the estimation of CAPEX and OPEX values for every retrofitting alternative versus the base case (see Tables A.6-A.7 in Supplementary Material_A).

The calculation of bunker and EU-MBM items of OPEX (see equation (21)) considers, aside from the technical characteristics of the initial engines (see Table 1) and the alternative systems for the HSC's electricity generation (see Table A.3-A.6 from Supplementary Material_A), the operative patterns to meet C score under the CII regulation (see Fig. 2); this necessarily involves adjusting the navigation times in free sailing and hoteling stages for every alternative. Beyond the differential costs by electricity supply ($\Delta(BAC_q)_y$; $\forall q \in Q \wedge \forall y \in Y$), these operation patterns mainly influence the differential bunker cost for the HSC propulsion ($\Delta(BC_q)_y$; $\forall q \in Q \wedge \forall y \in Y$).

The European Normative (see section 3.3.1) was applied to EU-MBM calculation, but from two standpoints: by considering the application route as a regular region and as an outermost region. The latter involves, on the one hand, delaying the Fuel-EU application until December 2029 and the EU-ETS to 2031, and on the other, considering only one half of the energy used on-board for estimating the non-compliance Fuel-EU fines (Regulation (EU) 2023/1805). This decision has been made with the intention to widen the scope of this research by analyzing the consequences of these temporary derogations and exceptions collected in the EU decarbonization normative for shipping in the outermost regions.

[15] https://www3.gobiernodecanarias.org/ceic/energia/oecan/files/AnuarioEnergeticoCanarias_2021_v2.pdf.

[16] https://energy.ec.europa.eu/data-and-analysis/eu-energy-statistical-pocketbook-and-country-datasheets_en.

[17] https://en.prtr-es.es/Informes/InventarioInstalacionesIPPC.aspx.

[18] https://tradingeconomics.com/commodity/carbon.

CO_2 emissions were estimated for every technological alternative through SHIP-DESMO-Ro-Ro passengers (Kristensen & Psaraftis, 2016a) by considering the required electricity supply (see Table 2) and the linked operative pattern (see Fig. 2). Additionally, as said, a 2% constant inflation rate is applied for subsequent updates on 2023 values: CP = 82.87€/t[18] (2023) for the EU-ETS calculation.

Default emission factors collected in the Annex II of the Regulation (EU) 2023/1805 were taken to calculate the Fuel-EU compliance balance and their penalties (see equation (13)). Special mention deserves $CO_{2eqWtT,j}$ ($\forall j \in J$ (see equation (16)); and the rewards factor RWD_{jl} ($\forall j \in J \wedge \forall l \in L$, (see equation (18)). Thus, for the former, 3.6 g CO_{2eq}/MJ (COM/2021/562 final) has been assumed for green H_2 whereas this value is zero for OPS use (Annex I of the Regulation (EU) 2023/1805). Parallelly, RWD = 2 is taken for the fuel cells and RWD = 1 in other cases. Moreover, in coherence with the Fuel-EU initiative's aim (GHG intensity of the whole energy used on board by a ship), the energy developed by PV system (MJ) was also integrated in the denominator ($Vessel\_Energy_y$; $\wedge \forall y \in Y$; see equation (18)) for the GHG intensity calculation ($GHGIE_{actual;}$ see equation (15)) even though this is not specifically collected in the Regulation (EU) 2023/1805 (equation (1) of Annex I).

Finally, to offer more realistic IRR and NPV results, on the one hand, the loan's financial costs are included in the Cash Flow (see equation (21)). Thus, a loan by 70% retrofitting CAPEX is assumed for IRR calculation with a repayment period of 5 years at a 6% interest rate. On the other hand, the high dependence of the CAPEX on shipyards and systems' manufacturers factories along with the high volatility of key variables - like the bunker and the carbon allowance prices (daily values) - force to test the robustness of the results achieved through a probabilistic analysis of sensitivity over the base scenario (MonteCarlo simulations).

5. Results

5.1. Step1: environmental and operative performance

The relative weight of the propulsion versus on-board electricity generation on the HSC pollutant impact not only offers information about improvement capacity provided by technological alternatives, but also about the performance, in terms of representativeness, of those environmental measures mainly focused on a unique polluting source: propulsion power (ETD, for example). Fig. 3 shows that, whereas the slow steaming progressively broadens the influence of electricity generation on the HSC total pollutant impact, from 9.5% in 2023 to 11.58% in 2033; this being directly proportional to the speed reduction (see Fig. 2). The influence of the electricity generation on the total pollutant impact of the retrofitted HSC with fuel cells is overridden (the broken line is coincident with the continuous line; see Fig. 3).

Intermediate situations are provided by OPS[19] and PV system options. Even though both show similar environmental performance (see continuous lines in Fig. 3), the contribution of the electricity generation to PI is higher in OPS (from 9.37% to 6.5%) than PV system (from 4.97% to 5.38%) mainly due to the different propulsion power requirements for retrofitted vessels, since OPS leads to a lighter vessel than PV system (1114.74t versus 1152.4t, see Table 3). Likewise, the OPS alternative presents a decreasing tendency in this regard, as far as the progressive inclusion of the on-shore decarbonization policy in the Canary Islands[20] is implemented. Moreover, from an operative standpoint, OPS demands a speed decrease from 2030, one year later than PV system alternative (2029, see Fig. 2). This is so, not only by the different HSC's lightweight, but also due to the fact that the CII calculation does not consider on-shore emissions (see equation (1)) by involving a competitive advantage for OPS. Thus, in absolute terms, the fuel cell offers the best environmental performance (PI = [3107.98€/trip-3692.75€/trip]) during the whole-time range (2023–2033) followed by PV system (PI = [3426.52€/trip-3853.39€/trip]) and OPS (PI = [3429.49€/trip-3851.15€/trip]), and in final position, slow steaming (PI = [3946.69€/trip-3926.45€/trip]).

In light of the above, the fuel cell arises as the most sustainable alternative (minimum PI) not only because of the zero emissions provided from the electricity supply, but also by the low weight of this system (see Table 3). This allows to maintain 28.4 kn as a service speed by meeting CII normative up to 2032 and, in the years thereafter, the speed reduction would be slower than the remaining options (see Fig. 2).

Fig. 4 shows the MBM evolution (continuous blue line) under the schedule implementation published by the EU to date (see section 3.3.1). The increasing tendency until 2026 is due to the progressive integration of CO_2 emissions for EU-ETS calculation (β_y; $\forall y \in Y$; see equation (10)), which achieves 100% of reported CO_2 emissions in 2026. Thereafter, the line shape in steps is mainly determined by the Fuel-EU scheme; that is, step reductions on 91.16 grCO_{2eq}/MJ (2025–2029; u_y = 98%; 2030–2034; u_y = 94%; see equation (14)) for calculating the GHG intensity target ($(GHGIE_{target})_y$; $\forall y \in Y$, see equation (14)) which defines the non-compliance fines ($Fuel\_EU_{y;}$ $\forall y \in Y$; see equation (13)).

It is found that, whereas non-compliance is constant for slow steaming from Fuel-EU enforcement in 2025, compliance exists until 2030 (no fines) for PV system and OPS alternatives, which motives a significant step for them in 2030 (see Fig. 4). This line shape is not shared by the fuel cell alternative due to its Fuel-EU compliance during the whole-time range (2023–2033); in other words, Fuel-EU normative has no impact in monetary terms on the green H_2 fuel cells ($Fuel\_EU_y = 0$; $\forall y \in Y$). Finally, the brown line shows the evolution of MBM when the outermost regions' exemptions are applied: December 2029 and December 2030 as starting dates for Fuel-EU and EU-ETS enforcement, respectively. This MBM delay involves not only a convergence gap between peripherical and non-peripherical regions during the exemption years (2024–2031), but also a permanent divergence after 2031 due to Fuel-EU application: only one half of the total on-board energy must be assessed (γi; $\forall i \in I$; see Annex). Moreover, as the recurrent non-compliance (n; see equation (13) and Annex) is specifically penalized through a surcharge, this delay indeed reduces the non-accomplishment's recurrence for the same year by increasing MBM's divergence between EU territories.

Therefore, MBM divergence among EU regions is directly proportional to the relative weight of the Fuel-EU on the total MBM (see Fig. 5). Thus, whereas a total convergence of MBM (blue and brown lines) is met for fuel cell alternative as soon as EU-ETS is implemented in the outermost regions (2030), the slow steaming solution, with the highest relative weight of Fuel-EU on MBM (41.18%, see Fig. 5), reaches a 15.15% deviation in 2033.

Focusing on the proportionality of MBM (continuous blue lines, see Fig. 4) to the actual pollutant impact (interrupted lines, PI and PI2), progressive alignment among them is found for all cases. However, only MBM obtained from slow steaming results to be a reliable PPP tool in 2033, since 93.76% of pollutant impact would be covered by MBM by assuming the same price for carbon allowance and CO_2 unitary cost (PI2). On the opposite side, the MBM from the fuel cells alternative only would cover 58.39% of the PI2 in monetary terms; intermediate effectiveness would be reached by MBM when these are calculated for OPS (77.09% PI2 in 2033) and PV system (76.62% PI2 in 2033).

The good adjustment of MBM from fossil fuel vessels in SSS to the actual harmful environmental impact had been tested in previous research (Marrero & Martínez-López, 2023). However, the results obtained in the actual research go beyond the previous findings, by revealing a deficient adjustment when no-fossil fuels are used for the electricity supply. The reasons of this fitting lack are several. Firstly,

[19] Propulsion contribution to PI for OPS (broken line), is coincident with the total PI of the fuel cell option until 2030 (see Fig. 3).

[20] Sustainable Energy Strategy in the Canary Islands (Government of the Canary Islands, 2022).

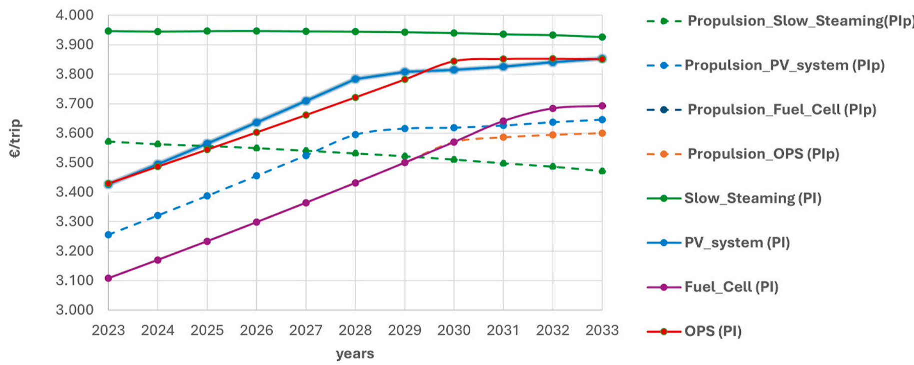

Fig. 3. Contribution of propulsion to pollutant impact of HSC.

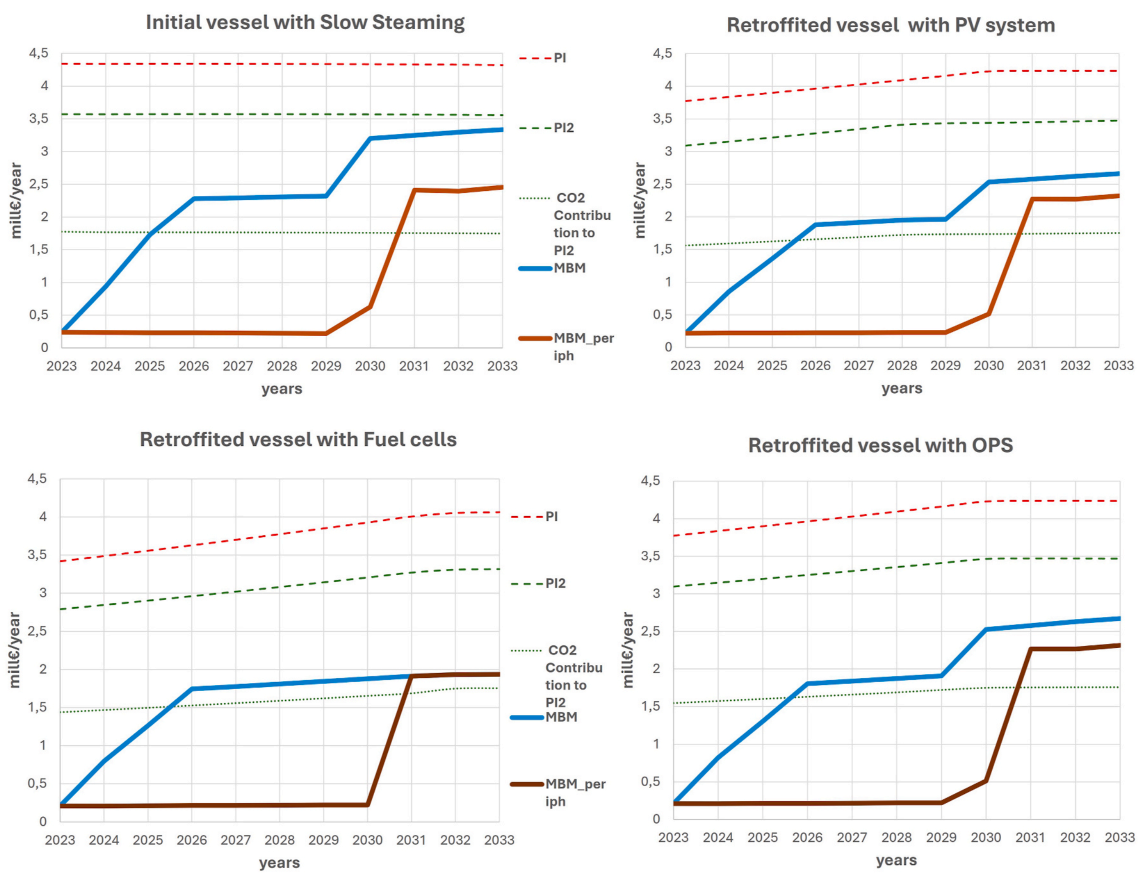

Fig. 4. MBM evolution versus Pollutant Impact.

MBM are mainly calculated on the basis of CO_2 emissions, however, by paying attention to the contribution of these to the total pollutant impact (CO_2 contribution line and PI2, see Fig. 4), they only involve between 49 and 53% of the harmful costs. Indeed, the CO_2 costs are completely covered by MBM in all cases when EU-ETS is fully integrated (2026, see Fig. 4), however, the costs related to other pollutants, like particulate matters (unitary cost in 2023 for $PM_{2.5}$ = 405.52€/kg in Spanish metropolitan areas versus 8.59€/kg in the Atlantic Ocean (Van Essen et al., 2019),), achieve greater relevance in SSS due to the high relative weight of port times in the whole navigation period; 73.5% daily time is port time in the application case by considering hoteling stage (see Table 2).

Likewise, in line with Marrero and Martínez-López's (Marrero & Martínez-López, 2023) results, Fuel-EU fines have been identified as needed to achieve a good fit level between PI2 and MBM. Nevertheless, the emerging technological alternatives fulfil Fuel-EU requirements at least until 2030 (PV system and OPS, see Figs. 4 and 5) by avoiding penalties in monetary terms and consequently, moving away from convergence with the actual pollutant impact. In this regard, it is necessary to note that the OPS gets preferential treatment in the Fuel-EU normative; the normative (Annex I, Regulation (EU) 2023/1805) forces to set to zero WtT emissions (see equation (16)) from the electricity delivered to the ship (OPS). However, this delivered energy in port is in fact considered as part of the whole energy consumed by the vessel (Ec; $\forall c \in CC$; see equation (18)). Equally, OPS emissions from on-shore electricity generation are not considered either in the CII regulation and EU-ETS normative by benefiting the OPS use in relation to the remaining options.

Even though the remaining alternatives do not take advantage of MBM application exemptions, like OPS, the truth is that an evident 'over

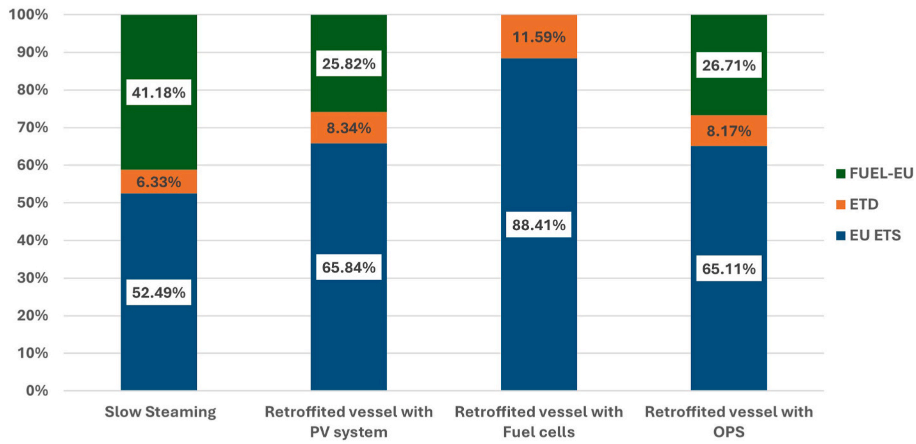

Fig. 5. MBM composition in 2033.

Table 6
Impact of vessel retrofitting in relation to slow steaming (% reduction) under base scenario's conditions.

		2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
PV system	*MBM*	*−8.95*	*−9.19*	*−21.50*	*−17.45*	*−16.44*	*−15.38*	*−15.38*	*−20.82*	*−20.59*	*−20.38*	*−20.15*
	PI2	−13.48	−11.71	−9.99	−8.22	−6.36	−4.47	−3.82	−3.59	−3.21	−2.76	−2.29
Fuel cells	*MBM*	−13.05	−15.42	−27.12	−23.48	−22.54	−21.57	−20.54	−41.31	−41.08	−41.28	−41.93
	PI2	−21.83	−20.23	−18.68	−17.07	−15.40	−13.69	−11.94	−10.13	−8.24	−7.10	−6.76
OPS	*MBM*	−13.05	−12.89	−24.66	−20.75	−19.78	−18.77	−17.70	−21.08	−20.61	−20.13	−19.80
	PI2	−13.24	−11.78	−10.39	−8.97	−7.48	−5.99	−4.45	−2.85	−2.59	−2.53	−2.45

Table 7
Inputs for the base scenario.

	Slow steaming	PV_System	Fuel_Cells	OPS
Capital cost (€)[a]		1,323,255	1,323,632	691,762
Replacement_cost(€/year)[b]	167,827			
Replacement_cost(€/year)[c]			542,168	
Maintenance_cost(€/year)[e d]	214,936	71,277	25,437	180,334
Fuel_saving_generating_sets[f] (%)[d]		54.30%	−73.38%	−12.80%
LSMGO(€/t)[d]	766	766		766
Green H_2-electricity_generation (€/MWh)[d]			224.67	
Port electricity supply (€/kWh)[g d]				0.13
Carbon Allowance Cost(€/t)	82.87	82.87	82.87	82.87

[a] 2023.
[b] 2033.
[c] 2030.
[d] 2024.
[e] On-board generating set costs are added to OPS technology costs (€).
[f] In monetary terms due to the systems performance.
[g] Connection/unconnection:8.45€ (Las Palmas Port, 2024).

grant' exists for all of them by taking into account MBM savings versus the environmental advantage provided by them (see Table 6). This reality had been also highlighted by Marrero and Martínez-López (Marrero & Martínez-López, 2023) for OPS use; nevertheless, in this research, this over fund results to be extensive to solar energy an d green H_2 fuel cells (see Table 6); with the latter being especially significant, according Table 6: 41.93% of MBM savings versus 6.76% of pollutant reduction in monetary terms-PI2- by assuming base scenario's conditions (see Table 7).

5.2. Analysis of the retrofitting investments. Identification of key variables

While the previous section evidenced an implicit grant through MBM reductions for HSC retrofitting with emerging alternatives, this section quantifies these incentives by evaluating if they are sufficient to boost the most sustainable technologies in HSC (see Fig. 3).

As mentioned in section 3.4, the analysis is carried out in relative terms; the advantage of every technological alternative ($Q = \{1,..,q\}$) for HSC retrofitting versus slow steaming for a time range from 2023 to 2033 ($\Delta(CF_q)_y; \forall q \in Q \wedge \forall y \in Y$) by taking as a constant inflation rate 2% per year (see Table 7). Table 7 provides the assumed inputs to assess the base scenario. All capital costs ($CAPEX_q; \forall q \in Q$, see equation (20)) are the result of adding the cost of removing two main engines (350.000€[21]) to the cost of acquisition and installation of the technological alternatives (unitary costs are collected in the Supplementary Material_A; see Tables A.6 and A.7).

Replacement costs ($RC_q; \forall q \in Q$), are closely linked to the system lifespan (substitution year, see Table 7) and in turn, this time is dependent on the working hours (lifetime for generating sets' replacement 75,500 h[22]). Likewise, working hours also determine the annual maintenance costs, although these hours are taken as constant values for every year. It is necessary to note that, despite the short life cycle for the fuel cells (6 years), it is expected that their replacement costs will decrease on the initial costs (75% of initial capital cost, during the first 6 years (Kim et al., 2023),) due to their quick technological development. On the opposite side, assuming the electricity generating requirements (see Table 2), PV system and OPS involve longer lifespans than the time range of this project for all their components by making replacement costs are therefore, negligible ($(RC_q)_y = 0; \forall q \in Q \wedge \forall y \in Y$).

Fuel savings provided by the alternative systems versus the initial generating sets show that an advantage (positive values in Table 7) was obtained under several assumptions for the PV system: an annual

[21] Information supplied by Astican shipyards.
[22] https://www.volvopenta.com/marine/all-marine-engines/d16-mg-rc/.

Table 8
Expected Cash Flow in euros/year and feasibility analysis for the PV system.

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
CAPITAL COST_PV SYSTEM	−1.323.255										
REPLACEMENT											167.827
LOAN	926.279										
LOAN'S PRINCIPAL		−164.318	−174.178	−184.628	−195.706	−207.448					
EXTRA-OPERATIVE NCF	*−396.977*	*−164.318*	*−174.178*	*−184.628*	*−195.706*	*−207.448*					*167.827*
MAINTENANCE		143.659	146.532	149.463	152.452	155.501	158.611	161.784	165.019	168.320	171.686
BUNKERING_AUXILIARY_ENGINES		179.078	182.659	186.313	190.039	193.840	197.716	201.671	205.704	209.818	214.015
BUNKERING_MAIN_ENGINES		323.935	227.075	126.854	22.298	−84.027	−128.000	−156.432	−186.726	−212.745	−240.375
EU-ETS		70.195	100.364	110.140	75.439	40.169	27.349	22.432	14.751	5.985	−3.291
FUEL-EU		0	260.123	280.403	299.629	317.965	335.379	639.594	647.756	651.904	658.688
ETD		16.305	11.385	6.396	1.295	−3.792	−6.420	−7.325	−8.658	−9.768	−10.928
MBM		86.500	371.871	396.939	376.363	354.342	356.309	654.701	653.850	648.121	644.469
LOAN'S INTEREST		−55.577	−45.718	−35.267	−24.189	−12.447					
OPERATIVE NCF		677.596	882.421	824.301	716.962	607.210	584.636	861.723	837.847	813.514	789.795
CASH FLOW (TOTAL NCF)	−396.977	513.277	708.243	639.673	521.256	399.761	584.636	861.723	837.847	813.514	957.622
IRR	144%										
NPV	−396.977	81.827	698.128	1.217.374	1.612.079	1.894.454	2.279.682	2.809.350	3.289.754	3.724.877	4.202.678
RECOVERY TIME (YEARS)	1										

Table 9
Expected Cash Flow in euros/year and feasibility analysis for the fuel cell.

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
CAPITAL COST_FUEL CELL	−1.323.632										
REPLACEMENT								−542.168			167.827
LOAN	926.542										
LOAN'S PRINCIPAL		−164.365,29 €	−174.227,20 €	−184.680,84 €	−195.761,69 €	−207.507,39 €					
EXTRA-OPERATIVE NCF	*−397.090*	*−164.365*	*−174.227*	*−184.681*	*−195.762*	*−207.507*		*−542.168*			*167.827*
MAINTENANCE		189.499	193.289	197.155	201.098	205.120	209.223	213.407	217.675	222.029	226.469
BUNKERING_AUXILIARY_ENGINES		−242.002	−246.842	−251.779	−256.815	−261.951	−267.190	−272.534	−277.985	−283.544	−289.215
BUNKERING_MAIN_ENGINES		534.890	442.249	346.331	246.164	144.317	39.752	−68.681	−180.938	−263.827	−293.934
EU-ETS		119.322	188.055	237.919	205.774	173.110	139.573	104.757	68.687	46.245	38.486
FUEL-EU		0	260.123	280.403	299.629	317.965	335.379	1.220.630	1.274.309	1.325.631	1.373.010
ETD		26.224	21.403	16.514	11.514	6.530	1.514	−3.586	−8.763	−12.113	−13.363
MBM		145.546	469.581	534.836	516.917	497.605	476.466	1.321.801	1.334.233	1.359.763	1.398.133
LOAN'S INTEREST		−55.593	−45.731	−35.277	−24.196	−12.450					
OPERATIVE NCF		572.340	812.546	791.266	683.169	572.641	458.250	1.193.993	1.092.986	1.034.421	1.041.453
CASH FLOW (TOTAL NCF)	−397.090	407.975	638.319	606.585	487.407	365.134	458.250	651.825	1.092.986	1.034.421	1.209.280
IRR	124%										
NPV	−397.090	−16.516	538.938	1.031.326	1.400.400	1.658.316	1.960.265	2.360.917	2.987.612	3.540.891	4.144.255
RECOVERY TIME (YEARS)	2										

Table 10
Expected Cash Flow in euros/year and feasibility analysis for OPS.

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
CAPITAL COST_OPS	−691.762										
REPLACEMENT											
LOAN	484.234										
LOAN'S PRINCIPAL		−85.901,29 €	−91.055,37 €	−96.518,69 €	−102.309,81 €	−108.448,40 €					
EXTRA-OPERATIVE NCF	*−207.529*	*−85.901*	*−91.055*	*−96.519*	*−102.310*	*−108.448*					
MAINTENANCE		34.602	35.294	36.000	36.720	37.455	38.204	38.968	39.747	40.542	41.353
BUNKERING_AUXILIARY_ENGINES		−42.197	−43.041	−43.902	−44.780	−45.675	−46.589	−47.521	−48.471	−49.441	−50.429
BUNKERING_MAIN_ENGINES		534.890	442.249	346.331	246.164	144.317	39.752	−61.191	−85.157	−135.348	−164.166
EU-ETS		95.466	145.472	175.870	142.484	108.554	73.726	37.593	25.473	17.327	8.896
FUEL-EU		0	260.123	280.403	299.629	317.965	335.379	639.594	647.756	651.904	658.688
ETD		26.224	21.403	16.514	11.514	6.530	1.514	−2.651	−3.949	−6.214	−7.463
MBM		121.690	426.998	472.787	453.627	433.049	410.619	674.537	669.280	663.017	660.121
LOAN'S INTEREST		−29.054	−23.900	−18.437	−12.645	−6.507					
OPERATIVE NCF		*619.931*	*837.601*	*792.780*	*679.086*	*562.639*	*441.985*	*604.793*	*575.400*	*518.771*	*486.879*
CASH FLOW (TOTAL NCF)	−207.529	534.030	746.545	696.261	576.776	454.191	441.985	604.793	575.400	518.771	486.879
IRR	281%										
NPV	−207.529	290.633	940.264	1.505.446	1.942.191	2.263.013	2.554.245	2.925.989	3.255.911	3.533.385	3.776.310
RECOVERY TIME (YEARS)	1										

average solar GHI = 5.40 kWh/m^2/day (4219 h/year of solar time, over 59% of sunshine; NASA resources) and 5° for solar panels' angle on deck, with an assumed performance of 226.74 W/m^2 (Solar Tiger Neo JKM570N-72HL4-V). Likewise, a lower calorific value of CV = 0.12MJ/gr (3.6MJ/kWh) was assumed for green H_2 in fuel cells and a constant requirement of 1292.46kWh/day (see Table 2) was taken for the OPS supply.

Regarding variable costs (see Table 7), 2024 was taken as an initial operational year by considering the required vessel speeds' pattern for the CII compliance (see Fig. 2) and a constant generating electricity plan (see Table 2); thus LSMGO (766€/t; January 2024 Rotterdam port)[23] is the fuel considered for main engines working (BC_q;$\forall q \in Q$) and generating sets (BAC_q; $\forall q \in Q$), by operating in slow steaming mode, PV_system (when no sunny hours exist) and OPS (when there are no berthing stages). Additionally, green H_2 price (224.67€/MWh[24] January 2024, see Table 7) and port tariffs (8.45€ as a switch on/off tax along with 0.13€/kWh[25]) are taken for electricity supply costs (BAC_q; $\forall q \in Q$) of fuel cells and OPS at berthing, respectively.

Tables 8–10 show the feasibility analysis for the technological alternatives. Besides the IRR, the NPV was also calculated by assuming a 10% discount rate to determine the value provided by the projects and the investments' recovery time when the projects are financed (see 4.2 section). Paying attention to the results, all retrofitting' alternatives show, versus slow steaming, IRR over 120% by reaching a maximum of 281% for the OPS option. This involves very short recovery times (one year for OPS and PV system and two years for fuel cell system); consequently, there is a low risk in the retrofitting investments versus the slow steaming option.

It is worth highlighting that the good results obtained for OPS in terms of IRR (see equation (20)) regarding the remaining options are mainly due to its low capital cost (691,762€ for OPS versus 1,323,255€ and 1,323,632€ for PV system and fuel cell, respectively; see Tables 8–10). This fact along with significant MBM savings (similar MBM for OPS and PV systems; see Tables 8 and 10) balance its higher cost by port electricity supply versus on-board electricity generation (negative values for bunkering auxiliary engines, see Table 10). In this regard, only PV system offers a clear advantage for the electricity supply; this involves positive values for auxiliary engines bunkering (operative solar panels during 48.16% of daily time) and significant savings in maintenance costs (see Table 8). Both costs are practically self-cancelling in the remaining options (see Tables 9 and 10).

The main engines' bunkering shows annual savings for all alternatives during the initial years due to reduction of the vessel's lightweight by the two removed engines (see Table 3) in the retrofitting. However, this advantage lessens over time, insofar as the required speed patterns for slow steaming and retrofitting alternatives are closing (see Fig. 2). Considering the whole lifespan (aggregated results), an advantage exists for bunker costs in the lightest alternatives: Fuel cells and OPS (see Table 3).

The most sustainable option, the fuel cell alternative (see Figs. 3 and 4), actually offers relevant MBM savings regarding the other options, however this does not result to be enough to compensate for the high initial capital cost (1,323,632€) and its necessary replacement during the project life (542,168€ in 2030), consequently, it provides the lowest IRR (124%). Despite this, the fuel cell offers a higher total NPV (see equation (22)) than that linked to OPS (4,144,255€ against 3,776,310€, see Tables 9 and 10). This contradiction between IRR and NPV is due, on the one hand, to high IRR sensitivity to CAPEX values and, on the other hand, to the NPV's dependence on the assumed discount rate to ensure the project's feasibility.

Thus, discount rates below 14.51% lead to unfavorable NPV for OPS

[23] https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#LSMGO.
[24] https://www.eex-transparency.com/hydrogen/germany.
[25] https://www.palmasport.es/en/commercial-services/.

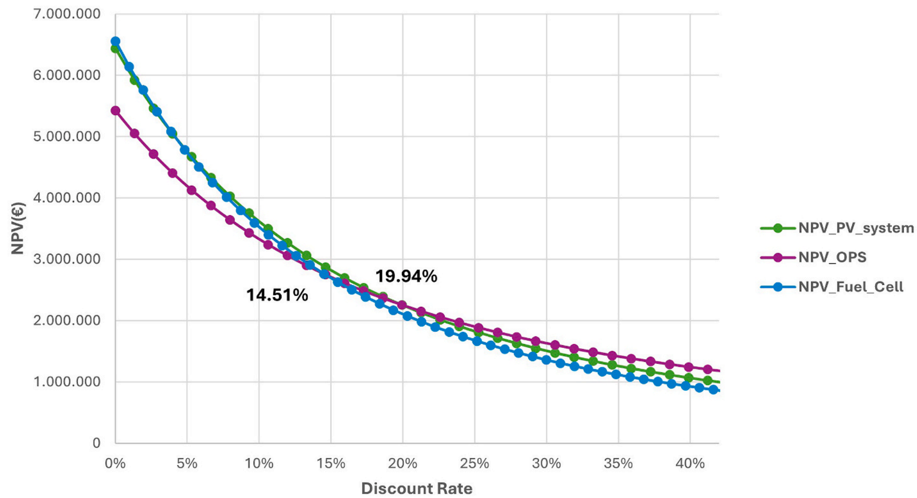

Fig. 6. NPV performance for the technological alternatives through several discount rates.

Table 11
Statistics and sensitivity chart for IRR and NPV obtained through MonteCarlo simulations.

Statistics		PV system	Fuel Cell	OPS		PV system	Fuel Cell	OPS
Base Case	IRR (%)	144%	124%	281%	NPV (€)	4,202,678	4,144,255	3,776,310
Mean		145%	125%	283%		4,197,419	4,140,656	3,525,224
Coeff. Variation		11.18%	12.16%	9.89%		9.40%	9.10%	13.01%
Variables		Contribution to the variance (%)				Contribution to the variance (%)		
Capital cost		−86.7%	−84.2%	−91.3%		−6.9%	−7.6%	−1.5%
Unitary price for Fuel EU penalty (€/MJ)		1.7%	2.7%	0.7%		70.6%	77.0%	57.3%
Replacement cost		–	0.0%	–		–	−0.5%	–
Maintenance cost		−0.7%	−0.1%	−5.6%		−1.0%	−0.1%	−6.2%
Fuel_saving generating sets (%)		5.9%	9.5%	−0.2%		12.9%	14.7%	−34.8%
LSMGO		4.1%	–	0.0%		7.5%	–	0.0%
Carbon Allowance Cost (€/t)		0.8%	3.6%	2.1%		−1.1%	0.1%	−0.2%
H_2-e_electricity generation (€/MWh)		–	0.0%	–		–	0.0%	–
Port electricity supply(€/kWh)		–	–	0.0%		–	–	0.0%

regarding the remaining options; however, the opposite happens when the discount rate surpasses 19.94% (see Fig. 6). Often, the discount rates assumed for evaluating technologies based on GHG emissions (Marginal Abatement Cost framework) are between 3 and 10% (IMO, 2020; Lagouvardou et al., 2023; Martínez-López et al., 2023). Consequently, a return baseline over 14.51% (see Fig. 6) is improbable for the HSC retrofitting project, in such a way that the NPV estimations obtained in Tables 8–10 can be accepted as realistic.

To meet the robustness of the results achieved from the base scenario's inputs (see Table 7) and identify the most influential variables on the results, sensitivity analyses are undertaken by assuming probability functions for the initial inputs of every alternative. Even though the unitary price required for calculating Fuel-EU fines (2.4/41 = 0.0585 €/MJ, see equation (13)) is not expected to vary in the short-term (Annex IV, Regulation (EU) 2023/1805), its influence on the MBM through Fuel-EU will be quantified to broaden the results' contextualization. For this purpose, this variable will be incorporated into the analysis as an additional input to those collected in Table 7.

Thus, Monte Carlo simulations[26] take inputs from triangular functions where their average values are those assumed for the base scenario and a variation range of 20% is taken for the most and least likely values. Table 11 shows the results of the probability distributions obtained for NPV and IRR from the simulations (100,000 trials with 100% certainty level with the highest fit to beta distributions). According to statistics, the distributions are homogeneous (coefficient of variation below 13% in all cases) and therefore, their means are sufficiently representative of the expected feasibility for the investment projects.

Paying attention to the variables' influence on the results, we can highlight a preponderance of the MBM through Fuel-EU (unitary price for the Fuel-EU penalty) on the NPV in all cases, and this is directly proportional to the system's sustainability (57.3% for OPS, 70.6% for PV system and 77% for the fuel cell). This fact contrasts with the low relevance of the carbon allowance cost's variation on the expected results; this is due to the significance of the savings by Fuel-EU in monetary terms versus EU-ETS (see Tables 8–10, in line with Nelissen et al. (Nelissen et al., 2023)). Beyond the MBM impact, the contribution of the systems' performance to the value's generation (NPV) through fuel saving generating sets (see Table 11) is relevant. Indeed, this influence is positive when fuel saving generating sets increases with the variable's value that defines the improvement capacity of the system (total efficiency of the PV system and the assumed green H_2 calorific value; 12.9% and 14.7% contributions respectively, see Table 11) and this influence is obviously negative when the performance system is measured through reductions on an associated attribute (electricity requirements of 1292.46kWh/day for the OPS supply; −34.8%, see Table 11).

In parallel, the capital cost stands out as the most influential variable on the IRR value (over 84% in all cases, see Table 11), as expected, but again, fuel saving generating sets and the unitary price for the Fuel-EU penalty emerge as the following influent variables, although very far from the capital cost.

In general terms, even though in all cases system investment

[26] Crystal Ball software (Oracle).

feasibility is strongly conditioned by its own characteristics (capital costs and system performance) the Fuel-EU penalty has resulted to be a key variable in generating value in the projects, as it is the main driver to reach positive NPV. Likewise, PV system has proved to be the most exposed alternative to external variables owing to its sensitivity to the LSMGO price (4.10% on IRR and 7.5% on NPV, see Table 11).

6. Discussion

This application case studied a route that can be classified as ultra-short (with 55 nm), in which, under a high-speed regime, 11.6 h/day corresponds to the aggregated idle time: hoteling and port-times for meeting the schedule (see Table 2). The analysis has proved that the extra sailing time (up to 41.87 min per trip, see Fig. 1) derived from the necessary speed reduction to reach C score by 2033 could be balanced by shortening idle times without penalizing the vessel's schedule and loaders' willingness to use it. This fact along with the consequent savings in bunker and MBM costs from slow steaming, seriously questions the appropriateness of high speed for ultra-short sea shipping in the EU.

Corrective actions for EU-HSCs to reach the C level required by the CII regulation must consider not only their effectiveness but also their suitability within the EU decarbonization framework. The adequation of a combined solution through slow steaming together with replacing the conventional electricity generation plants has been evidenced. On the one hand, this combined option meets Fuel-EU normative that compels zero emissions to be attained at berthing from 2030. Additionally, it mitigates the relative increase of vessel emissions from electricity generation when slow steaming is adopted (see Fig. 3) and finally, the solution is in line with previous research findings: significant MBM savings can be achieved through on-board electricity generations for SSS (Marrero & Martínez-López, 2023). From the operative research, this combined option favors its uptake from shipping companies and customers since vessel retrofitting also undercuts the vessel's lightweight (see Table 3) by broadening the emissions reduction from the required power propulsion. This offers the possibility of maintaining higher speeds by accomplishing CII requirements during more years (see Fig. 2) by shortening the extra sailing time.

The MBM analysis reveals that whereas high convergence exists between MBM and actual HSC's pollutant impact when the emissions are provided by fossil fuels (see Fig. 6), a deficient adjustment is found when alternative fuels and renewable energies are set up for the electrical generation. The quantification of MBM bonus by using alternative technologies versus environmental advantages provided by them shows a significant over grant for these technologies in 2033 (see Table 6): 20.15% MBM versus 2.29%PI2 for PV system, 41.93% MBM versus 6.76%PI2 for green H2 fuel cells and 19.80% MBM versus 2.45%PI2 for OPS, in terms of reductions. The main reasons for this divergence are: the absence of fines by Fuel-EU non-compliance and a lower dependence of the SSS pollutant impact on the GHG in relation to other pollutants (relevant port times). These results suggest the need of a possible adaptation of the current MBM architecture to ensure its utility as PPP-tool for SSS by operating with alternative technologies.

Despite this distortion, the effects of this over grant on investment projects for HSC's retrofitting are concluded by paying attention to the sensitivity analysis: between 57 and 77% of the added value by the investment projects (NPV, see Table 11) is due to the MBM savings, specifically to the savings on Fuel-EU penalties. In fact, this variable (along with the CAPEX) has resulted to be the most influential on the expected investments' feasibility in alternative technologies for HSC electricity generation.

Despite the over grants and MBM savings' relevance on the results, these have not been sufficient to clearly boost the choice of slow steaming with the most sustainable technology: the green H_2 fuel cells (see Table 12). This is so, mainly owing to the CAPEX, its short-lifespan for replacement and the elevated price for green H_2. This fact can be quantified through MAC estimation (€/CO_2 averted tonnes) for every technology as an alternative to generating sets. Thus, the higher the MAC value is, the less cost-efficient is deemed the technology, so MAC<0 is an indicator of feasible alternatives from the ship owner's point of view (IMO, 2020; Psaraftis et al., 2021)

Aside from calculating this value for year 2033 (MAC*), Table 12 shows the MAC calculated through NPV, where this value for every alternative (see Tables 8–10) is divided by the aggregate CO_2 tonnes averted by them for a time range (IMO, 2020; Lagouvardou et al., 2023). Despite this, all retrofitting options are profitable from the ship owners' standpoint by considering the whole project's lifespan (NPV>0), therefore MAC of NPV is less than zero (see Table 12). Thus, these values give information about the profit obtained by the shipowner per everted CO_2 tonne when the technology is installed. OPS system emerges as the most interesting option for shipowners in relative terms despite its low mitigation capacity (−759.72€/tCO2 versus 35.39% mitigation capacity). PV system proves to be the next most cost-effective alternative by itself (−537.32€/CO_2 tonne with 55.17% mitigation capacity) where the MAC* value 773.41€/tonne CO_2 has been reduced in relation to previous estimations (1186€/tCO_2 in IMO (IMO, 2020) and 813.61€/t CO_2 in Martínez-López et al. (Martínez-López et al., 2023)), mainly due to a full consideration of MBM effects. Table 12 also shows that fuel cell, despite it provides the highest abatement potential (100%), is highlighted as the least cost-effective (MAC* = 1105.09€/tonne CO_2; MAC of NPV = −220.62€/tonne CO_2). Even though the MAC analysis completes the results previously obtained, it is necessary to bear in mind that they offer unitary information about one polluter CO_2, instead all polluters involved in the PI (see Figs. 3 and 4).

Given the relevance of the CAPEX on the results (see Table 11), the possibility of including additional funding focused on this variable to reinforce the most sustainable solution's selection (financial incentives (Nelissen et al., 2023),), slow steaming with fuel cell (see Fig. 3), on the basis of its environmental advantage regarding the remaining options (bonus=(PI-$PI_{fuel.cell}$)-(MBM-$MBM_{fuel.cell}$)), is not plausible given the results achieved (aggregate bonus 2023–2033): −2,858,516 €, −722, 681€ and −264,902€ versus slow steaming, PV system and OPS, respectively. In all cases except OPS, extra-bonuses for fuel cells (negative values) surpasses investment differences between the options, even by including the replacement costs: 1,865,800€, 542,545€, 1,174, 038€ for slow steaming, PV system and OPS, respectively.

Even though over grants have been evidenced for all alternative technologies that were assessed in this research, the OPS currently benefits from an additional exception for GBM and EU-MBM application by significantly distorting its assessment in relation to other decarbonization options.

The omission of onshore emissions (Well-to-Tank -WtT-emissions) in OPS by Fuel-EU and the CII normative in its current format (Nelissen

Table 12
MAC values (€/tonne CO_2) for alternative technologies and CO_2 abatement potential (%) versus conventional generating sets.

PV_system (55.17%)		Green H_2 Fuel Cell (100%)		OPS (48.70%)		OPS[b](35.39%)	
MAC[a]	MAC of NPV	MAC[a]	MAC of NPV	MAC[a]	MAC of NPV	MAC[a]	MAC of NPV
773.41	−542.35	1105.09	−295.08	309.96	−552.16	525.23	−759.72

[a] 2033.
[b] On-shore emissions are included.

et al., 2023), involves that, in ultra-short sea shipping, practically half the day (port times increase to 11.6 h/day, see Table 2) the HSC is assumed to be a zero-emission source by underestimating, in the application case, 3.22% of total CO_2 emissions per trip (propulsion power included) and 8.53% of the total pollutant impact of HSC in monetary terms (PI).

Even though the CII currently does not collect WtT emissions (conversion factors between fuels and CO_2 emissions- CFF_{jl} $\forall j \in J \wedge \forall l \in L$ see equation (1); Resolution MEPC.308(73)), the IMO has implicitly recognized the significance of this deficit by publishing, in July 2023, the 'Guidelines on life cycle GHG intensity of marine fuels', where WtT and finally WtW GHG emission factors are quantified on the basis of a life cycle attributional methodology (MEPC.376(80)). Therefore, it is expected that, in a near future, these procedural improvements are incorporated into the CII calculation and extensively to EU-MBM calculation.

6.1. Outermost regions

The previous findings are applicable to HSC by operating in EU-ultra-short sea shipping. However, as mentioned, the shipping in outermost regions (article 349 of Treaty on the Functioning of the EU), is excluded from EU-ETS and Fuel-EU application until December 2030 and December 2029 respectively and, even then, the Fuel-EU will only consider half of the energy developed by vessels for the GHG intensity calculation. The main reason provided by policy makers is preserving the accessibility to these regions through efficient maritime transport connectivity. However, given the insights drawn in this paper, these exceptions/decisions do not result to be in line with the aforementioned policy targets.

The CII regulation (IMO) does not provide derogations based on geographical shipping localization. Therefore, E score vessel, such as an HSCs in the EU outermost regions, must also fulfil the CII by providing solutions to become C score vessels. However, until 2030 and 2031, these shipping companies will be unable to take advantage of the main EU incentives for vessel retrofitting with more sustainable technologies: EU-MBM, especially from the Fuel-EU normative. This penalization regarding shipping in the remaining EU regions is quantified in Table 13 through the IRR and NPV, which measure the possible interest of shipowners in assuming investment's projects to instal more sustainable technologies in HSCs.

In view of these results, the current derogations collected in the EU normative make more difficult a sustainable transition of the HSC fleet to meet the CII regulation in the outermost regions in comparison to the remaining regions by creating additional barriers to preserve equal rights on shipping decarbonization. Obviously, this is especially relevant in these regions, where total dependence on maritime transport stresses the need for environmental improvements.

The effectiveness of the EU's transport policy in the outermost regions is often in question given their particular characteristics and the need to preserve connectivity in these remote areas by ensuring, at the same time, citizen rights to sustainability standards through public service obligations. Proof of this was the reaction to OPS facility enforcement (Directive 2014/94/EU); this was strongly responded to by arguing lack of adequation, not only in the outermost regional context but also on other state-islands where on-shore electricity grids are scarcely shared by renewable energy sources, unlike in the continental case (Martínez-López et al., 2021; Winkel et al., 2016).

In this regard, the wide-ranging debate on the non-desirable effects of public subsidies for transport in the outermost regions is notable: undermining of the actual demand, loss of competitiveness, the reduction in free competition, among others (Calzada & Fageda, 2014; Rus & Socorro, 2022). Even though the influence of these subsidies on slow steaming's uptake by shipping operators is beyond the scope of this research, this should be assessed in a further step, since the positive impact from the consequent bunker cost reduction (Psaraftis et al., 2009) could be lightened by the subsidies, especially when these take the form of an ad valorem (percentage of discount on the freight price (Rus & Socorro, 2022);) by minimizing the effect of this incentive.

Table 13
IRR and NPV in the base scenario for the EU regions, according to the current EU-MBM framework.

	IRR(%)		NPV[a](€)	
	EU	Outermost_regions	EU	Outermost_regions
PV_System	144%	88%	3.524.391	1.567.810
Fuel Cell	124%	23%	4.144.255	218.290
OPS	281%	186%	3.776.310	870.203

[a] 2023–2033.

7. Conclusions

This paper assesses the feasibility of possible technological alternatives to address HSCs from E to C score according to CII normative in the EU framework. Given the technological maturity of the commercial alternatives, the paper assumes that this objective is reachable through combining slow steaming with sustainable technology for the electricity supply until 2033. The results achieved from an application case in the Canary Islands (an outermost region in the EU) shows that slow steaming is operatively feasible in ultra short sea shipping (55 nm), by calling into question the need for high speed on these routes, even in those protected as a public service obligation.

Likewise, the paper reviews the effectiveness of the EU-MBM in this application's context, HSC operating in SSS with alternative technologies, from two standpoints: firstly, the alignment between MBM and the actual harmful impact of these vessels, since their acceptation as a PPP tool mostly relies on it (payment willingness from shipping companies), and secondly, their utility as an operative leverage to make sustainable technologies economically viable regarding the conventional systems based on burning fossil fuels.

The findings obtained not only enhance the significance of the Fuel-EU normative to ensure the effectiveness of EU-MBM as a PPP tool in SSS, which had been identified in previous research (Marrero & Martínez-López, 2023) but also warn about the need to review the current MBM architecture when ultra short sea shipping, alternative fuels and renewable energies are evaluated since, under this context, significant divergences were found between MBM and the HSC pollutant impact (up to 42% for green H_2 fuel cell alternative). Among the reasons, the absence of WtT emissions in the MBM calculations is notable, especially for OPS.

In fact, this deviation entails excessive 'over grants' for those HSCs equipped with sustainable alternatives in relation to the environmental advantage offered by them, but also a significant incentive to promote HSC retrofitting with sustainable technologies: a contribution between 57 and 71% to the NPV variance was obtained. Given these results, the decision to apply temporal derogations for MBM in the outermost regions deprives these zones, which are especially dependent on maritime transport, of one of the main economic incentives for HSC to return to C score (CII regulation) through retrofitting with sustainable technologies, by placing them in a disadvantageous situation in relation to the other EU regions.

Further attention should be paid in a next step to the possible negative influence of public subsidies on slow steaming implementation for HSC in the outermost regions. In parallel, the main shortcomings of this paper should be also addressed by further research: inclusion of lag times in port by OPS connection and green H_2 bunkering, the existence of green H_2 port facilities, the risk's quantification of non-compliance with the Sustainable Energy Strategy in the Canary Islands (Government of the Canary Islands, 2022) and the analysis of mixed solutions by combining alternative technologies.

Even though insights drawn from a particular case should not be generalizable, the consistency of the results obtained in this paper along with the frequency of the inputs used to build the base scenario allows us to extrapolate the findings to similar frameworks in the EU: HSC operating in ultra short sea shipping. Thus, aside from the Atlantic archipelagos (Azores, Madeira, the Canary Islands, etc), numerous HSCs operate in similar conditions in the continental seas: the Baltic Sea (Sjaellands Odde-Aarhus-IMO: 9561356; Frederikshavn-Roenne-IMO: 9501590), English Channel (Portsmouth- Cherbourg-IMO: 9551363) and the Mediterranean Sea (Pozzallo-LaValeta IMO: 9559743; Pireus-Syros-IMO: 9135896; Santorini-Mykonos IMO: 9151008), among other routes.

CRediT authorship contribution statement

Alba Martínez-López: Supervision, Project administration, Formal analysis, Conceptualization. **África Marrero:** Writing – original draft, Methodology, Investigation, Formal analysis. **Alejandro Romero-Filgueira:** Validation, Software, Resources, Funding acquisition, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.retrec.2024.101497.

Annex

Acronyms

BAF	Bunker Adjustment Factor
BHP	Brake Horse Power
CAPEX	Capital Expenditure
CII	Carbon Intensity Indicator
CPI	Consumer Price Index
ECA	Emission Control Area
EHP	Effective Horse Power
ETS	Emission Trading System
ETD	Energy Taxation Directive
EC	European Commission
EMSA	European Maritime Safety Agency
EU	European Union
GHI	Global Horizontal Irradiance
GBM	Goal Based Measures
GHG	Greenhouse Gas
GT	Gross Tonnage
HSC	High-Speed-Craft
IRR	Internal Rate of the Return
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LT-PEMFC	Low Temperature Pro-ton-Exchange Membrane Fuel Cell
MAC	Marginal Abatement Cost
MEPC	Marine Environment Protection Committee
MBM	Market Based Measures
MGO	Marine Gasoil
MRV	Monitoring, Reporting, and Verification
NPV	Net Present Value
OPS	On Shore Power Supply
OPEX	Operating Expense
PV	Photovoltaic
PI	Pollutant Impact
PRTR	Pollutant Release and Transfer Register
PPP	Polluter Pays Principle
PEM	Proton-Exchange Membrane
PEMFC	Proton-Exchange Membrane Fuel Cell
RES	Renewable Energy Source
SEEMP	Ship Energy Management Plan
SSS	Short Sea Shipping

TtW Tank to Wake
WtW Well to Wake

Subscripts

CC = {*1,.,c*} Connection points for OPS
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 application case: 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
Q = {*1,..,q*}) Alternatives to meet CII normative. For the application case: slow steaming, PV_system, _Fuel cells and OPS
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 (greenhouse gases) and NH_3 (ammonia slip)
V = {*1,..,v*} Population density in the hinterland. Rural, suburban and urban area (Van Essen et al., 2019)
Y = {*1,..,y*} Every assessment year. This research collects the time range from 2024 to 2033 by assuming a possible investment in 2023

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 an EU Member State ($\alpha_i = \alpha_1 = 100\%$); only one port belongs to an EU Member State ($\alpha_i = \alpha_2 = 50\%$); no port belongs to an 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 normative according to the nature of the ports (%): Both ports belong to an EU Member State ($\gamma_i = \gamma_1 = 100\%$); only one port belongs to an EU Member State or is located in an EU outermost region ($\gamma_i = \gamma_2 = 50\%$); no port belongs to an 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 ($u_y = 20\%$)
BAC_q Bunker cost for the electricity supply through several systems (€); $\forall q \in Q$
BC_q Bunker cost for the propulsion power of vessel with several systems installed for electricity supply (€); $\forall q \in Q$
C ship's capacity according to the ship type (CII Guidelines, G1; resolution MEPC.352 (78)). For Ro-Pax is measured in gross tonnage (GT)
$C_{engine\_slip,l}$: 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_{sukvy}: Unitary costs for air pollutants in port operations (€/kg pollutant) $\forall s \in SS^* \wedge \forall u \in U \wedge \forall k \in K \wedge \forall v \in V \wedge \forall y \in Y$
CF_{1uky}: Unitary costs for air pollutants in free sailing (€/kg pollutant); $\forall u \in U \wedge \forall k \in K^* \wedge \forall y \in Y$
CFF_{jl} Conversion factor collected in the resolution MEPC.308(73) and in the Commission Regulation (EU) No 601/2012 (tonne CO_2/tonne fuel); $\forall j \in J \wedge \forall l \in L$.
CFM_{jl} Emission factor for CH_4 (tonne CH_4/tonne fuel); $\forall j \in J \wedge \forall l \in L$
CFN_{jl} Emission factor for N_2O (tonne N_2O/tonne fuel); $\forall j \in J \wedge \forall l \in L$
CII_A_y Attained Carbon Intensity Indicator for every year (CO_2 grams/nm and tonne); $\forall y \in Y$
CII_R_y Attained Carbon Intensity Indicator for every year (CO_2 grams/nm and tonne); $\forall y \in Y$
$CO_{2\ eq\ TtW,j,l}$: CO_2 equivalent emissions for every kind of combusted fuel. Default values are collected in Annex II of Regulation (EU) 2023/1805 (gCO_{2eq}/gFuel); $\forall j \in J \wedge \forall l \in L$.
$CO_{2\ eq\ TtW\_slippage,j,l}$: CO_2 equivalent emissions for every kind of slippage fuel (gCO_{2eq}/gFuel); $\forall j \in J \wedge \forall l \in L$.
$CO_{2\ eq\ WtT,j}$: GHG emission factor for every fuel. Default values are collected in Annex II of Regulation (EU) 2023/1805 (gCO_{2eq}/MJ); $\forall j \in J$
CP EU Carbon Pricing (€/tonne CO_2)
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 as null in the hoteling stage ($CT_{k4} = 0$); $\forall s \in SS^{**} \wedge \forall k \in K$
CV_j Lower Calorific Value of the fuels (GJ/g fuel); $\forall j \in J$
D total distance travelled (in nautical miles) reported in IMO DCS
E_c Electricity delivered to the vessel at berth per connection point through OPS (MJ); $\forall c \in CC$
EG_{suly}: Emission factors per pollutant; for every navigation stage, type of engine and year (kg/h) $\forall s \in S \wedge \forall u \in U \wedge \forall l \in L \wedge \forall y \in Y$
EFG_{uky} Emission factors per pollutant emitted by OPS; in every port and year (kg/kWh) $\forall u \in U \wedge \forall k \in K \wedge \forall y \in Y$
ETD_y Energy Taxation per year (€/year); $\forall y \in Y$
ETS_y European Trading System's cost per year (€/year); $\forall y \in Y$
$ETSU_y$ European Trading System's cost per trip (€/trip); $\forall y \in Y$
ETU_y Energy Taxation per trip (€); $\forall y \in Y$
f_{wind} Reward factor for wind-assisted propulsion
$FuelEU_y$ Annual penalty for non-compliance with Fuel-EU (€/year); $\forall y \in Y$
GBM Goal Based Measures (€)
$(GHGIE_{actual})_y$ Greenhouse gas intensity of the energy used on-board for a year (g $CO_{2\ eq}$/MJ); $\forall y \in Y$

$(GHGIE_{target})_y$ Maximum greenhouse gas intensity of the energy used on-board annually, limited by Regulation (EU) 2023/1805 (g $CO_{2\ eq}$/MJ); $\forall y \in Y$
GWP Global warming potential for CO_2, CH_4 and N_2O
IRR_q Internal Rate of Return for every alternative (%); $\forall q \in Q$
N Trips per year
n number of consecutive non-compliance periods under the Fuel-EU normative.
NCF_{qy} Net Cash Flow for every alternative and year (€); $\forall y \in Y \wedge \forall q \in Q$
NPVq Net Present Value for every alternative (€); $\forall q \in Q$
MBM Market Based Measures (€)
MC_q Maintenance costs for the electricity supply systems (€); $\forall q \in Q$
PB_{lsy} Power for the vessel's engines for every navigation stage (kW); $\forall l \in L \wedge \forall s \in SS \wedge \forall y \in Y$
PI_{sy} Pollutant impact in terms of air quality (€/trip) for every navigation stage and year; $\forall s \in SS\hat{}\forall y \in Y$
$PI2_{sy}$ Pollutant impact in terms of air quality (€/trip) where EU Carbon Pricing is taken as CO_2 unitary cost for every navigation stage and year; $\forall s \in SS\hat{}\forall y \in Y$
R Discounting rate for the investment that is demanded by the shipowner (%)
RC_q Replacement costs for the electricity supply systems $\forall q \in Q$)
RWD_{jl} Reward factor for non-biological origin's fuels with value of 2 from January 1, 2025 to December 31, 2033. Otherwise, value $RWD_{jl} = 1$. $\forall j \in J \wedge \forall l \in L$.
$SFOC_{jls}$ Specific Fuel Consumption for engines in every navigation stage and fuel type (g fuel/kWh); $\forall j \in J \wedge \forall l \in L \wedge \forall s \in SS$
TL_j Taxation applicable to fuels (€/GJ); $\forall j \in J$
TVB_{sy} Time invested in every navigation stage in a trip (h/trip) per year; $\forall s \in SS \wedge \forall y \in Y$
$Z_y =$ Annual reduction factor from 2019 values applied over reference line for calculation of the required carbon intensity indicator; $\forall y \in Y$ 2024 ($Z_k = Z_1 = 7\%$); 2025 ($Z_k = Z_2 = 9\%$); 2026 ($Z_k = Z_3 = 11\%$); 2027 ($Z_k = Z_4 = 13\%$); and a 2% increase for each following year (Resolution MEPC.338(76))

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