ALTERNATIVE TECHNOLOGIES' ROLE IN FAST FERRIES' ACCOMPLISHMENT WITH EUROPEAN GREEN DEAL REGULATIONS

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Abstract

This study evaluates the techno-economic feasibility of combining slow steaming with emerging retrofitting solutions for electricity supply onboard to ensure Fast Ferries' compliance with the Carbon Intensity Indicator (CII). A case study focused on 10,000 GT ferry operating under short sea shipping conditions analyzes two activity scenarios: outermost regions and remaining zones based on the implementation of European Union Market-Based Measures (EU-MBM). The results identify as the most sustainable solution, green hydrogen fuel cells, coupled with a 25.3% speed reduction. However, this option leads to a low Internal Rate of Return and high Marginal Abatement Costs, by reducing their appeal from shipowners' standpoint. The analysis also highlights significant inconsistencies in EU-MBM frameworks, particularly with retrofitting projects involving renewable energy and alternative fuels, where excessive subsidies are observed for onshore power solutions. Additionally, Fuel-EU regulations are identified as a key variable impacting the financial viability of retrofitting initiatives. Despite this positive influence, current Fuel-EU policies aggravate inequalities between EU regions, hindering the widespread adoption of emerging decarbonization technologies in remote areas. The study underscores the need for harmonized regulatory frameworks to address these challenges and support sustainable transitions in maritime transport.

Keywords

Fast Ferries, Carbon Intensity Indicator, EU-Market Based-Measures, Decarbonization Emerging technologies, Short Sea Shipping,

1 Introduction

Since adoption of the International Maritime Organization’s (IMO) Initial Strategy on the Reduction of Greenhouse Gas (GHG) Emissions in April 2018, and the "European Green Deal" commitment to reduce the European Union’s (EU's) net GHG emissions by at least 55% by 2030, stakeholders involved have made significant efforts in reducing the negative impact of maritime transport by concluding that no single response is sufficient. Rather, it is the combination of different emission reduction measures (technological, operational, and economic) that will lead the industry to a truly effective and sustainable solution for regulatory compliance and achieving the set objectives (Tadros et al., 2023).

Medium-sized Fast Ferries (Fast Ro-Pax vessels) are designed to transport Ro-Ro cargo and passengers, frequently used for short to medium distances to connect two nearby ports. There are several reasons to justify the use of Fast Ferries in SSS, given that they achieve speeds 50% higher than those of conventional ships (24 to 30 knots; IMO (2020)). In SSS, this speed advantage allows for a reduced number of vessels covering the same route to maintain service frequency. However, it requires doubling the power requirements of conventional fast vessels as higher speed translates into more power and, thus, higher operational and emission costs, particularly considering conventional propulsion plants using fossil fuels, such as Marine Diesel Oil (MDO) (Martínez et al. (2005)).

Taking into account the progressive stringency of the regulatory framework in terms of sustainability, fast ferries’ features involve a real challenge for the accomplishment with the Goal Based Measures (GBMs) imposed by IMO and the EU. From the former, the Carbon Intensity Indicator (CII) adopted by the Marine Environment Protection Committee (MEPC) in June 2021 and in effect since January 1, 2023, establishes formulas for measuring the carbon intensity of vessels and a grading system (from A to E, with A being the best and E the worst). Vessels graded as D for three consecutive years or E for one year must develop a plan for corrective action to comply with the annual operational CII through retrofitting, operative pattern changes (Hua et al. 2024), the Ship Energy Efficiency Management Plan (SEEMP), or a combination of measures. Regarding EU, this has established not only stringer GBM than those ones imposed by IMO (through Fuel-EU) but also Market Based Measures (MBMs) like EU Emissions Trading System (EU-ETS), the Energy Taxation Directive (ETD), and Fuel-EU for maritime transport. MBMs based on the “Polluter Pays Principle”, present a different scenario for the operational costs of Fast Ferries within the EU, influencing not only shipping companies’ decision-making on technological and operational patterns but also impacting ports and logistics chains in EU countries (Chen et al., 2023). This is especially relevant since the regulations collect heterogenous applications for GBMs and MBMs for the EU zones: outermost and regular regions.

While mature technologies exist to meet the desulphurisation of maritime transport, such as the use of open- and closed-loop scrubbers, low-sulphur fossil fuels, and alternative fuels like Liquefied Natural Gas (LNG) (Marrero and Martínez-López, 2023), decarbonization technologies are still emerging by forcing to assess technological combinations and fuels that could enable complete decarbonization across the value chain (Tank-to-Wake-TtW- and Well-to-Tank -WtT-). Given that SSS vessels' electricity supply can reach 30% of total on-board power developed (Martínez-López et al., (2023)), Renewable Energies Sources (RES), alternative fuels and emerging technology, which are not available for propulsion yet, can be however suitable as decarbonization solutions through their application to the electricity supply onboard.

Based on the above, the objective of this paper is assessing the technical and financial feasibility (Net Present Value and Internal Rate of return) of retrofitting medium-size Fast Ferries with emerging technologies for on-board electricity supply to meet the CII requirements under the EU regulatory framework by operating in SSS regime for a 10-years' time-range. The study considers two operative scenarios in the EU: regular and outermost region. The paper attempts to provide knowledge beyond the performance of the solutions analyzed by evaluating: the proportionality of EU-MBMs and the actual environmental impact of decarbonization emerging technologies applied to Fast Ferries, the operative feasibility of slow steaming and the effectiveness of the EU policies to decarbonize the shipping in remote regions.

2 Literature Review

2.1 Decarbonization regulations research

Yang (2018) pointed out the environmental regulations' role to boost SSS companies to adopt various technological and process changes by including energy-efficient systems, alternative fuels, slow steaming, and optimized route plans. However, Raza (2020), afterwards, contended that, despite numerous studies carried out to comply with the 'sulphur cap' regulation, no empirical research had examined the impact of environmental regulations on the adoption of green innovations and the resulting impact of such innovations on the environmental and economic performance in the EU Short Sea Shipping (SSS) industry.

Research by Lagouvardou et al. (2020) and Psaraftis et al. (2021) have focused on the qualitative analysis of MBMs. They conclude that technical and operational measures to achieve carbon emission reduction objectives alone will not achieve this goal, as stated in the studies by Xing et al. (2020) and Chen et al. (2023).

Separately, Psaraftis et al. (2021) contended that the combination of different MBMs in the medium term (EU ETS) - along with short-term measures, such as the Energy Efficiency Existing Ships Index (EEXI), SEEMP and CII -, have a long way to go in achieving the desired emission reductions. Further, the authors highlight that a fuel levy might be more effective than incorporating maritime transport emissions into EU ETS.

2.2 Mitigation alternatives

Under the current regulatory framework, Renewable Energies Sources (RES) such as solar and wind energies have come into a new play role in the SSS pattern due to their potential to replace or reduce the on-board electric generators' use. Previous operative research has shown promising results for SSS: a CO_2 abatement capacity of 3.38% in Car-carriers (Martínez-López et al., (2023)), ships using photovoltaic solar energy increase energy efficiency by 6.9% compared to those using fossil fuels (Arief and Fathalah (2022)) suggested that the Photovoltaic system (PV system) involves potential in short routes and is considered a new trend in eco-friendly ship construction. However, Perčić et al. (2022) warmed about PV systems have a significant disadvantage in terms of maintenance costs due to their exposure to a salty atmosphere, which can trigger corrosion if the PV panels are not properly protected.

On the other hand, alternative fuels such as ammonia and hydrogen have sparked great interest as solutions for emissions reduction (Ampah et al., 2021). Hydrogen fuel cells are considered to be one of the most promising solutions at a technological level (Van Biert et al., 2016), gaining a significant advantage in short-distance maritime transport, especially in Ro-Ro and Ro-Pax vessels, where hydrogen fuel demands can be predicted much more accurately than for other vessels that could potentially use hydrogen (Melideo and Desideri, 2024).

Regarding the operational measures that shipping companies can implement to meet emission targets (GBMs), slow steaming (speed reduction) has significant potential to reduce atmospheric emissions from vessels.

In order to meet the European Green Deal objectives, the Directive 2014/94/EU forced to EU ports to provide facilities enough for On Shore Power Supply (OPS) in 2025, afterwards Regulation (EU)

2023/1805, collects the compulsory use of OPS by ferries at berthing from 2030 or equivalent zero-emissions technology for electricity supply at berthing from 2030. However, the environmental effectiveness of this measure is strongly conditioned by the RES level involved in the electricity generation on land (Martínez-López et al. (2021)), therefore, its performance is dependent on the geographical placement of the port.

In the light of foregoing, fast ferries introduce a real challenge for the accomplishment of the GBMs, beyond the technological limitations for the vessel's decarbonization, the new EU-MBMs condition the taking decisions for retrofitting with emerging technologies. This research attempts to tackle this problem evaluating a medium-sized fast ferry by operating with several emerging technologies in combination with slow steaming. This permits to rank the possibilities by considering not only their environmental performance but also their attractiveness level for the shipowners.

3 Methodology

This study explores the technical and operative feasibility of achieving CII compliance by medium size fast-ferries through slow steaming with the replacement of conventional on-board generators with emerging technologies since, they have proved to offer significant environmental benefits. These are in commercial state for this purpose, since on-board electricity generation requires less power compared to propulsion, and the operative pattern of Fast Ferries involves long periods at berth. Based on prior research, technological maturity, and installation feasibility, three technological options are assessed along with slow steaming: PV systems, green hydrogen-based fuel cells (preferred over ammonia due to easier storage), and onshore power supply (OPS). The selection of the appropriate technology for retrofitting influences the required reduction in service speed, directly impacting on the operational feasibility of the solution (calls scheduling). Once the technological solution is operative viable, the economic feasibility of retrofitting is assessed using the Internal Rate of Return (IRR) and Net Present Value (NPV), to provide a comprehensive evaluation from the shipowner's perspective.

3.1 IMO GBM: the Carbon Intensity Indicator (CII)

The CII, effective since January 2023, requires annual evaluation of over 5,000 Gross Tonnage (GT) vessels based on their CO_2 emissions per nautical mile (D) and transported cargo (C). The attained CII (CII_Ay, see equation 1) is compared to the required CII (CII_Ry, see equation 2) for each vessel type, calculated using specific fuel oil consumption (SFOC), engine power (PB), and operational time (TVB) across different navigation stages. Slow steaming is identified as a practical solution for Fast ferries to achieve a C rating, provided the vessel maintains its schedule and daily port calls, ensuring sufficient propulsion power (PB) while meeting emissions targets (see equation 2).

$$CII\_Ay=\sum_{s=1}^{s}(TVBsy(\sum_{l=1}^{l}(SFOCjls \times PBlsy \times CFFjl))/(C \times D); \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS^\wedge \forall y \in Y \quad (1)$$

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

3.2 Pollutant Impact (PI)

The Pollutant Impact (PI) model published by Martínez-López et al. (2022) will be taken as a base-reference but adapted to this research's aim, focusing the assessment on annual air quality (CEM_{sy}; $\forall s \in SS^\wedge \forall y \in Y$; in €/trip ; see equation 3), by considering the following pollutants (U={1,..,u}, see Annex): acidifying agents (SOx), ozone precursors (NOx), particulate matter (PM2.5 and PM10), greenhouse gases (CO2, CH4), and ammonia slip (NH3). These pollutants are assessed in equations 4-7 by considering their emission factors (EG_{suly}; $\forall u \in U \wedge \forall l \in L \wedge \forall y \in Y$ and EFG in kg/h for vessel and kg/KW.h for OPS respectively, see Annex), unitary costs (CF_{sukvy};$\forall s \in S \wedge \forall u \in U \wedge \forall f \in F \wedge \forall v \in V \wedge \forall y \in Y$; CF_{suy}; $\forall s \in S \wedge \forall u \in U \wedge \forall y \in Y$; in €/kg pollutant), and time spent (TVB_{sy}; $\forall s \in S \wedge \forall y \in Y$) in navigation stages (SS = {1,..,s}). The model has been expanded to include the hoteling stage (s=4) and WtT emissions from land-based grids (OPS). While emissions during free sailing (s=1) depend on the ocean type, emissions during other stages (($\forall s \in SS^*$; $SS^*=\{2,3,4\}$) are heavily influenced by the geographical location of ports. This influence is even more significant with OPS, as the share of Renewable Energy Sources (RES) in the grid affects emissions during berthing and hoteling stages. Additionally, connection and disconnection times (CT) for OPS use further impact the evaluation. This comprehensive approach enables detailed assessments of technological alternatives for emission reduction.

$$PIy=\sum_{s=1}^{4} CEM_{sy}\ ; \forall s \in S \wedge \forall y \in Y \quad (3)$$

$$CEM1y=\sum_{l=1}^{L}\sum_{u=1}^{7}(EG_{1uly} \times CF_{1uy} \times TVB_{1y});\ \forall u \in U \wedge \forall l \in L \wedge \forall y \in Y \quad (4)$$

$$CEMsy= \frac{1}{2} \times \sum_{k=1}^{2} CEM_{sky}\ ; \forall k \in K \wedge \forall s \in SS^* \wedge \forall y \in Y \quad (5)$$

- On-board electricity supply:

$$CEMsky=\sum_{l=1}^{L}\sum_{u=1}^{7}(EG_{suly} \times CF_{sukvy} \times TVB_{sy}); \forall k \in K \wedge \forall v \in V \wedge \forall s \in SS^* \wedge \forall l \in L \wedge \forall y \in Y \quad (6)$$

- On-shore electricity grid (OPS):

$$CEMsky=\sum_{u=1}^{7}(EFG_{uky} \times PB_{2sy} \times CF_{sukvy} \times (TVB_{sy} + CT));\ \forall k \in K \wedge \forall v \in V\ \wedge \forall s \in SS^{**} \wedge\ \forall y \in Y \quad (7)$$

3.3 EU-MBM

3.3.1 EU-Emission Trading system (EU-ETS)

European Union Emissions Trading System (Directive 2023/959), requiring the surrender of allowances based on CO2 emissions from 2023, reported through the EU-MRV system (Regulation (EU) 2015/757) under a progressive inclusion schedule. However, postponed the inclusion of shipping in the EU-ETS to 2024 and extended the deadline to December 2030 for shipping activities within the EU's outermost regions or between these regions and continental Europe, as per Article 349 of the Treaty on the Functioning of the EU. The proposed equations 8 and 9 respectively estimate the annual cost (ETS_y; $\forall y \in Y$, €/year) and cost per trip ($ETSU_y$; $\forall y \in Y$, €/trip) of surrendered allowances, accounting for the EU carbon price (CP, €/ton CO2) and CO2 emissions reported through the MRV system, adjusted by port location (inside/outside the EU) and year of inclusion according to Directive 2023/959.

$$ETSy = N \times ETSUy \ \forall y \in Y \tag{8}$$

$$ETSUy = CP \times \alpha i \times \beta y \times \sum_{s=1}^{s} \left(TVBsy \left(\sum_{l=1}^{l} \left(SFOCjls \times PBlsy \times CFFjl \right) \right) \right); \ \forall j \in J \wedge \forall \ \wedge \forall l \in L \wedge \forall s \in SS \wedge \forall y \in Y; \tag{9}$$

3.3.2 Energy Taxation Directive (ETD)

The ETD initiative is based on the framework proposed in COM/2021/563 (final), which aims to overhaul the EU's approach to taxing energy products and electricity. Currently awaiting a decision at the committee stage, the proposal includes exemptions from taxation for both on-board electricity generation and electricity supplied via Onshore Power Supply (OPS). The annual energy tax (ETD_y; $\forall y \in Y$ €/year) and the tax per trip (ETU_y; $\forall y \in Y$ €/trip), are calculated using the number of trips per year (N) through equations 10 and 11. The tax rate (TL_j; $\forall j \in J$ €/GJ) is applied to the energy output of the vessel, expressed in gigajoules, and is derived from the fuel consumed and its net calorific value (CVj $\forall j \in J$ GJ/g fuel GJ/g fuel). Starting in 2023, the minimum tax rate will increase incrementally, with an annual adjustment of one-tenth of the base level.

$$ETDy = N \times ETUy; \ \forall y \in Y \tag{10}$$

$$ETUy = \sum_{s=1}^{s} (TLj \times CVj \times SFOCjls \times PB1sy \times TVBsy); \ \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \wedge \forall y \in Y; \tag{11}$$

3.4 EU-GBM

3.4.1 Fuel-EU maritime initiative

The FuelEU Maritime initiative, formalized in Regulation (EU) 2023/1805, introduced a progressive reduction schedule of annual GHG intensity for vessels by taking a fixed reference value of 91.16 g for CO2eq (see equation 13). Non-compliance penalties ($Fuel\_EU_Y$; ∀y∈Y in €/year, see equation 12) are observed, with increased fines for frequent breaches. For this reason, Fuel-EU is, aside from a GBM, also considered as a MBM. Special provisions for outermost regions account for only half the energy used on voyages and delay enforcement until December 2029. The initiative also promotes sustainable energy, integrating measures like onshore power supply, wind-assisted propulsion, and non-biological fuels. Additionally, container and passenger vessels must compulsory adopt onshore power or zero-emission technologies at berth, starting January 2030, with an extension to 2035 for smaller ports (the variables used in equations 12-18 can be found in the Annex)

$$\mathrm{Fuel\_EUy} = \frac{2.4}{41} \times \gamma i \times \left(\sum_{s=1}^{s} TVBsy\left(\sum_{l=1}^{l} (\mathrm{SFOCjls} \times \mathrm{PBlsy} \times \mathrm{CVj})\right) + \sum_{c=1}^{c} Ec\right) \times \left(\left(\frac{\mathrm{GHGIEtarget)y} - \mathrm{GHGIEactual)}}{\mathrm{GHGIEactual}}\right) \times \left(1 + \left(\frac{n-1}{10}\right)\right); \forall i \in I \wedge \forall j \in J \wedge \forall l \in L \wedge \forall c \in CC \wedge \forall s \in SS \wedge \forall y \in Y; \tag{12}$$

$$\mathrm{(GHGIEtarget)y} = 91.16 \times \mu y;\ \forall y \in Y \tag{13}$$

$$\mathrm{GHGIEactual} = \mathrm{fwind} \times (\mathrm{WtTy} + \mathrm{TtWy})\ \forall y \in Y \tag{14}$$

$$\mathrm{WtTy} = \left(\frac{1}{\mathrm{Vessel\_energyy}}\right) \times \left[\sum_{s=1}^{s} TVBsy\left(\sum_{l=1}^{l} (\mathrm{SFOCjls} \times \mathrm{PBlsy} \times \mathrm{CVj})\right) \times \mathrm{CO2eqWtT,j}\right];\ \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \wedge \forall y \in Y; \tag{15}$$

$$\mathrm{TtWy} = \left(\frac{1}{\mathrm{Vessel\_energyy}}\right) \times \left(\sum_{s=1}^{s} \sum_{l=1}^{l} \left[(TVBsy \times (\mathrm{SFOCjls} \times \mathrm{PBlsy} \times \mathrm{CVj})) \times (\mathrm{CO2eqTtW,j,l} \times (1 - \frac{1}{100} \times \mathrm{Cengine\_slip,l}) + \mathrm{CO2eqTtWslippage,j,l} \times \frac{1}{100} \times \mathrm{Cengine\_slip,l}\right)\right];\forall j \in J \wedge \forall l \in L \wedge \forall s \in S \wedge \forall y \in Y; \tag{16}$$

$$\mathrm{Vessel\_Energyy} = \left(\sum_{s=1}^{s} TVBsy\left(\sum_{l=1}^{l} (\mathrm{SFOCjls} \times \mathrm{PBlsy} \times \mathrm{CVj} \times \mathrm{RWDjl}) + \sum_{c=1}^{c} \mathrm{Ec}\right);\ \forall j \in J \wedge \forall l \in L \wedge \forall c \in CC \wedge \forall y \in Y \wedge \forall s \in SS; \tag{17}$$

$$\mathrm{CO2\ eq\ TtW,j,l} = \mathrm{CFFjl} \times \mathrm{GWPCO2} + \mathrm{CFMjl} \times \mathrm{GWPCH4} + \mathrm{CFNjl} \times \mathrm{GWPN2O};\ \forall j \in J \wedge \forall l \in L \tag{18}$$

3.5 Internal Rate of Return and Net Present Value

Feasibility analysis of retrofitting investments is carried out through the Internal Rate of Return (IRR, see equation 19) and Net Present Value (NPV, see equation 21) to determine the possible shipowners' willingness to adopt technological alternatives. These calculations consider the differential cash flow (see equation 20) between retrofitting options and the baseline scenario of slow steaming (without retrofitting) to meet CII requirements. Key factors include capital costs (CAPEX), operational cost (OPEX), the latter considers EU-MBM, such as emission trading (ETS), energy taxation (ETD), and Fuel-EU penalties. Additional operational costs encompass maintenance, replacement, and fuel expenses, with cash flow savings arising when retrofitting options reduce costs compared to the baseline. Positive NPV, influenced by the discount rate (R, see Annex), signals economic viability, making retrofitting an advantageous alternative when it provides cost savings over time.

$$\text{CAPEXq}=\sum_{y=1}^{y}\left(\frac{\Delta(\text{NCFq})y}{(1+\text{IRRq})^{y}}\right);\ \forall q\in Q\forall\wedge y\in Y \tag{19}$$

$$\Delta(\text{NCFq})y=\Delta\ (\text{MCq})y+\Delta\ (\text{RCq})y+\Delta\ (\text{BCq})y+\Delta\ (\text{BACq})y+\Delta\ (\text{MBMq})y;\ \forall q\in Q\ \wedge\forall y\in Y \tag{20}$$

$$\text{NPVq}=-\ \text{CAPEXq}+\sum_{y=1}^{y}\left(\frac{\Delta(\text{NCFq})y}{(1+R)^{y}}\right);\ \forall q\in Q\forall\wedge y\in Y \tag{21}$$

4 Application case

The method was applied to a particular case of inter-islands shipping of 55 nautical miles: Gran Canaria -Fuerteventura (Canarian Archipelago) which is covered by a Ro-Pax catamaran operating under high-speed conditions (Fast ferry): 38 knots and high-frequency operations (4 trips/day, 2 calls/direction). Additionally, the vessel offers a large open upper deck suitable for PV system installation. This is highly interesting in this application case, since Canary Islands present a maximum Global Horizontal Irradiance (GHI) of 6.98 kWh/m2/day make PV systems particularly advantageous. According to the scheduling, the Fast Ferry spends 1.6 hours per trip in free sailing (TVB1), 0.5 hours maneuvering at 4 knots (TVB2), and 1 hour berthing per port (TVB3). Additionally, the accumulated idle time per day arises to 11.6 hours at berth (TVB4) due to meet schedule plan (hoteling time is also considered). These conditions highlight the potential benefits of installing PV systems to reduce emissions and improve energy efficiency during extended port stays. The combination of technical features and operational patterns offers a robust case study for assessing sustainable retrofitting solutions for fast ferries.

The vessel assumed by this research is a medium size catamaran1(10,369 GT with capacity to carry 357 cars and 1,400 passengers) its technical characteristics include a total length of 112.6 m, beam of 26.2 m and design draft of 3.8 m, and a GT. It is powered by four diesel engines (MAN 20V28/33D STC) with a total output of 36,000 kW (4x9 MW), complemented by auxiliary generators (4x393 kWe) and waterjets for propulsion.

Four technological alternatives are analyzed to meet CII requirements (Q ={1,..,q}, see Annex): slow steaming without vessel retrofitting(*q*=1), PV system combined with slow steaming (*q*=2), a green hydrogen (H2) fuel cell system with slow steaming (*q*=3), and OPS system integrated with slow steaming (*q*=4). For retrofitting options, the process involves removing the two main engines and installing alternative systems for electricity supply. This includes modifying the engine room arrangement, and the cargo space, when this is necessary, to accommodate the new components by ensuring compliance with stability requirements (Maxsurf Stability) through recalculating the ship lightweight. The latter is used to determine new requirements for propulsion power (Maxsurf Resistance). Thus, the alternative systems' environmental performance and the new propulsion power determine the vessel's new CO2 emissions (calculated using SHIP-DESMO-Ro-Ro Passenger methodology (Kristensen and Psaraftis, 2016a)). Afterwards, the vessel pollutant impact is reassessed, and the new requirements on sailing speed reduction are estimated to accomplish with CII standards. This comprehensive evaluation ensures that the selected retrofitting options are both technically and operationally feasible for GBM compliance.

Several assumptions have been considered in the evaluation to ensure zero emissions during at berth and sleeping stages. Low Sulphur Marine Gas Oil (LSMGO) for main and auxiliary engines during the whole navigation time (55 nm) to comply with the 0.1% Sulphur content limit required in EU ports (Directive 2005/33/EC). Sufficient green hydrogen fuel is available in port for Fuel Cell and likewise, OPS facilities are provided in the ports involved. PV systems can operate 48.16% of the daily time according to the information provided by NASA Resources from Homer software (average of 4,219 hours/year and 5.40 kWh/m2 /day of Global Horizontal Irradiance (GHI)). The WtT emission factors from OPS have been yearly estimated (2023-2033) through projections from the Pollutant Release and Transfer Register's trends (PRTR; 2017-2019, pre-COVID) and aligned with the Sustainable Energy Strategy for the Canary Islands (Government of the Canary Islands, 2022).

The unitary costs of pollutants (CF_{sukvy};$\forall s\in S\wedge\forall u\in U\wedge\forall f\in F\wedge\forall v\in V\wedge\forall y\in Y$; CF_{suy}; $\forall s\in S\wedge\forall u\in U\wedge\forall y\in Y$; in €/kg pollutant) were taken for Spain from the European Commission's latest Handbook on the External Costs of Transport (Van Essen et al., 2019), updated through the aggregated

Consumer Price Index (CPI) of 19.4% (National Statistics Institute of Spain). CO2 unitary cost deserves special attention, since CO2 (CP) price is set at €119.2/t for 2023 by considering the climate change avoidance cost (Van Essen et al. ,2019) whereas the Carbon Allowance Cost used by EU-ETS achieved €82.87/t in December 2023. This has forced the realization of two pollutant impact analysis: The first one (PI) assumes the CP as the CO2 price, and the second one (PI2) considers the CO2 price Carbon Allowance Cost. In such a way, the proportionality between MBMs and the actual pollutant impact of Fast Ferries can be analyzed when the vessels operate with different technological alternatives. To evaluate PI and PI2, the emission factors for all pollutants were estimated through SHIP-DESMO-Ro-Ro methodology (Kristensen and Psaraftis, 2016a), accounting for electricity demand and operational patterns. Moreover, a constant 2% inflation rate was applied in this research over the time range to all cost updates, including OPEX and CAPEX. This approach provides a comprehensive evaluation of economic and environmental impacts across scenarios.

European regulations were applied for both regular and outermost regions by considering that, in the latter, Fuel-EU implementation is delayed to 2029 and EU-ETS compliance to 2031, with adjusted penalties based on onboard energy use. Default emission factors and reward adjustments for green hydrogen and OPS were also considered in their application.

The analysis of investment projects on vessel retrofitting (IRR and NPV) assumes 2023 as the investment year, with an evaluation period from 2024 to 2033 and a 10% discount rate. This includes differential cash flow ($\Delta(NCF_q)_{y;}\ \forall y \in Y \wedge \forall q \in Q$) calculations, incorporating CAPEX and OPEX for each retrofitting alternative compared to the base case (slow steaming without retrofitting). Operational adjustments, such as navigation times during free sailing and hoteling stages, significantly impact costs, particularly for fuel and electricity supply. Loan costs were also included in the analysis; 70% of CAPEX is financed over 5 years at a 6% interest rate. To address variability in CAPEX and market factors like fuel and carbon prices, Monte Carlo simulations were used in a sensitivity analysis. This approach evaluates the economic and environmental impacts of retrofitting Fast Ferries under diverse regulatory and market conditions.

5 Results

The analysis shows that slow steaming increases the influence of electricity generation on total vessel's emissions, rising from 9.5% in 2023 to 11.58% in 2033, due to proportional speed reductions, and therefore, the consequent reduction of emissions from the propulsion power.

Figure 1 shows that H2 green fuel cells clearly the best environmental performance, eliminating whole emissions from electricity generation and offering the lowest pollutant impact costs (PI: 3,418,783–4,062,023 €/year), this permit maintaining a high service speed (28.4 kn) during all operation years. Intermediate performances were found for, OPS (service speed: 28.4 – 27.6 kn) and PV systems (PI:3,772,450–4,236,264 €/year), see Figure 1). Even though these technological solutions have proved to offer similar environmental benefits, OPS (minimum service speed 27.6 kn) still shows a higher contribution from electricity generation (6.5% by 2033) compared to PV (5.38%) (minimum service speed 27.3 kn). Since the OPS use involves the lightest vessel after retrofitting (1114.74 t vs. 1152.4 t for PV) PV system introduces a higher mitigation efficiency. Hence, green H2 fuel cells are the most sustainable alternative, followed by PV and OPS, while slow steaming (without retrofitting) offers the highest pollutant impact costs (PI: 4,341,369–4,319,092 €/year), emphasizing the advantages of advanced retrofitting technologies.

Figure 1

MBM evolution versus Pollutant Impact for Fast ferry with several technological solutions by operating in a regular region.

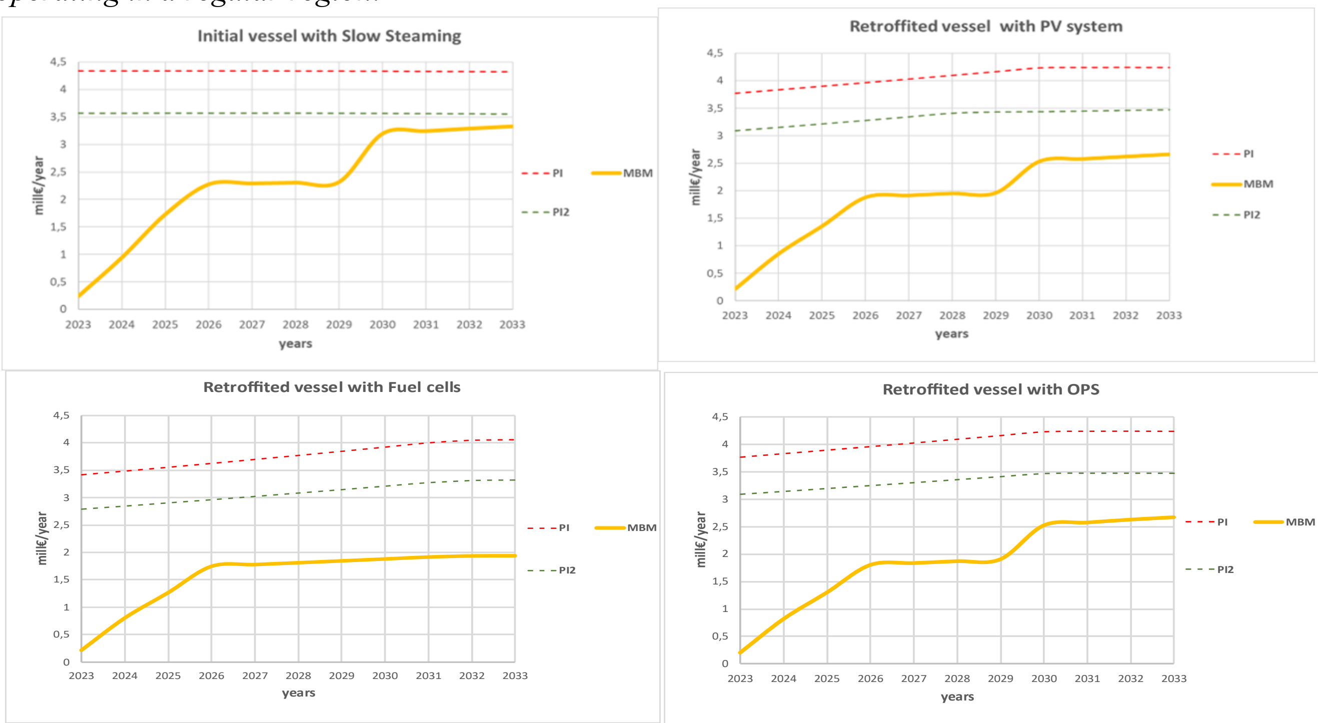


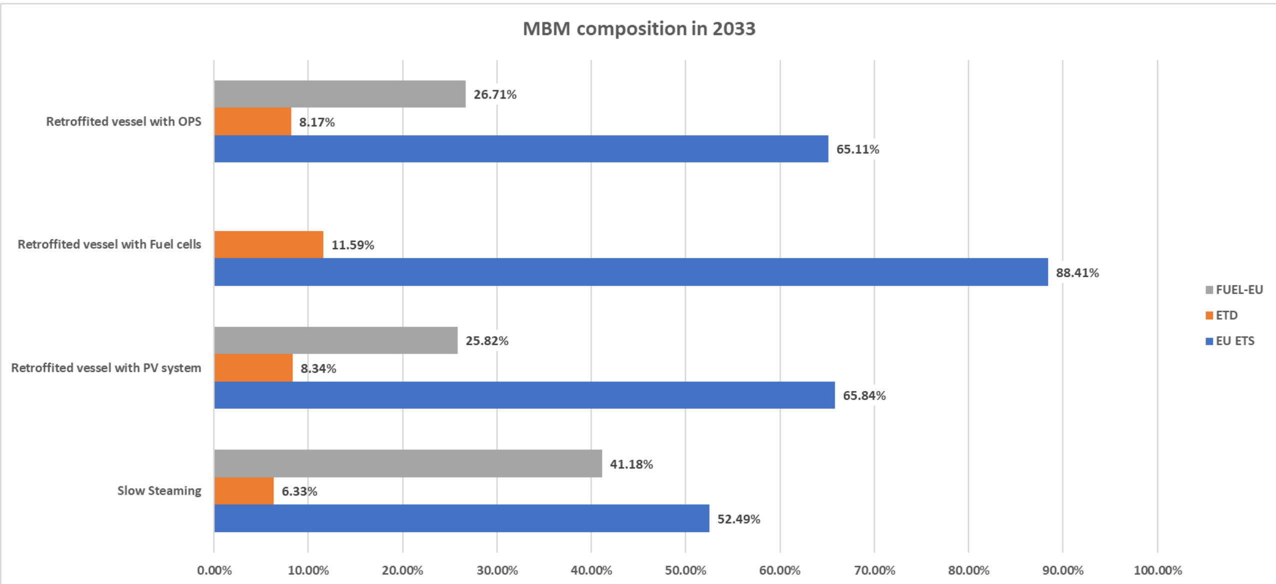
Figure1 also shows the MBM shape due to its temporal evolution through progressive integration of CO2 emissions under the EU-ETS until 2026, when 100% of emissions are included. From 2030, the Fuel-EU scheme tights the reductions in GHG intensity targets, impacting additional non-compliance fines (see step shape in Figure 1). Whereas slow steaming incurs constant Fuel-EU non-compliance fines from its enforcement in 2025, PV systems and OPS avoid fuel-EU fines until 2030, creating a significant cost step that year. In contrast, green hydrogen fuel cells remain fully Fuel-EU compliant throughout 2023–2033, resulting in no steps for its MBM curve.

Additionally, MBM alignment with actual pollutant impact (PI2, see Figure 1) positively progress over time for all cases, but their effectiveness as a "polluter pays principle" (PPP) tool varies according to the technologies involved. Whereas slow steaming achieves in 2033, the highest alignment, MBMs covers 93.76% of PI2, (CO2 price is equivalent to carbon allowance cost), MBMs for fuel cells cover only 58.39% of PI2, and OPS (77.09%) and PV systems (76.62%) achieve intermediate alignment. This highlights the varying proportionality of MBM in reflecting actual environmental impact of Fast ferries retrofitted with emerging technology.

Thus, the most convergent MBMs with PI2 belong to the solution where the Fuel EU penalties have the highest relative percentage on total MBMs (Figure 2), this is, slow steaming (41.18% see Figure 2), opposite to this, Fuel EU fines have null influence on MBMs for green H2 fuel cells (0% see Figure 2) by leading to the highest divergence between PI2 and MBMs. Consequently, Fuel-EU fines are the most significant tool to achieve high proportionality between actual pollutant impact of the vessels and MBMs.

Figure 2

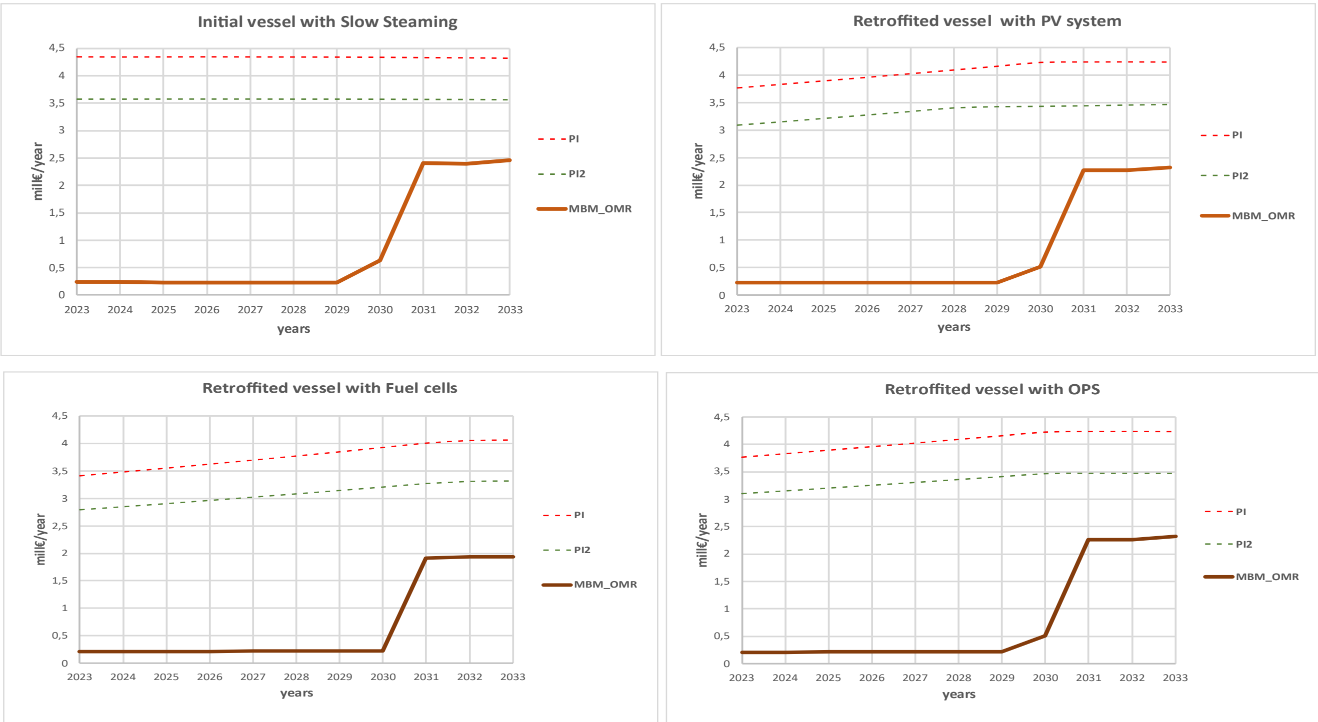
MBM Composition for 2033 when the Fast Ferry is retrofitted



For outermost regions (see Figure 3), MBM enforcement delays to 2029 (Fuel-EU) and 2030 (EU-ETS) create a temporary gap between peripheral and regular regions during the exemption years (2024–2031, see Figures 1 and 3). Additionally, a permanent divergence exists afterward, since, on the one hand, only half the onboard energy is considered in these regions for Fuel-EU evaluation and on the other hand the exemption reduces recurrent non-compliance penalties, therefore, further amplifying MBM cost differences across EU territories. Again, the Fuel EU influence on MBMs determines the divergence among MBM territories. Thus, while the fuel cell alternative achieves total convergence across regions as soon as the EU-ETS is fully implemented in the outermost regions (2030, see Figure 1 and 3), slow steaming, with the highest Fuel-EU weight (41.18%), shows a 15.15% deviation by 2033.

Figure 3

MBM evolution versus Pollutant Impact for Fast Ferry with several technologies by operating in an outermost region.



The study reveals an overallocation of MBM benefits compared to the actual environmental advantages offered by non-fossil fuel alternatives, particularly solar energy and green hydrogen fuel cells. For example, while fuel cells provide 41.93% savings in MBM costs, they only account for a 6.76% reduction in environmental costs, highlighting a significant mismatch. This issue, previously identified for OPS, is now shown to extend to other emerging technologies as well. In the case of OPS, preferential treatment under Fuel-EU regulations further skews the alignment between MBM savings and actual pollutant reductions. These findings raise critical questions about the effectiveness and equity of current MBM frameworks, suggesting they may not adequately reflect the true environmental costs associated with different technologies, particularly when non-CO2 pollutants, such as particulate matter, are considered.

Table 1

Feasibility analysis and Monte Carlo Simulation for the scenarios

	PV system		Fuel Cells		OPS	
Inputs for the base scenario						
Capital cost (€)*	1,323,255		1,323,632		691,762	
Replacement_cost(€/year)**	---		542,168		---	
Maintenance_cost(€/year)[1]***	71,277		25,437		180,334	
Fuel_saving_generating_sets[2] (%)***	54.30%		-73.38%		-12.80%	
LSMGO(€/t)***	766		---		766	
GreenH_2-electricity_generation (€/MWh)***	---		224.67		---	
Port electricity supply(€/kWh)[3]***	---		---		0.13	
Feasibility analysis						
	PV system		**Fuel Cells**		**OPS**	
	Regular region	Outermost region	Regular region	Outermost region	Regular region	Outermost region
IRR (%)	144%	88%	124%	23%	281%	186%
NPV (€)	4,202,678	1,567,810	4,144,255	218,290	3,776,310	870,203
Recovery time (years)	1	1	2	5	1	1
Monte Carlo Simulation for regular region						
Statistics						
Mean (IRR (%))	145%		125%		283%	
Coeff. Variation (IRR (%))	11.18%		12.16%		9.89%	
Mean (NPV (€))	4,197,419		4,140,656		3,525,224	
Coeff. Variation (NPV (%))	9.40%		9.10%		13.01%	
Contribution to the variance (IRR (%))						
Capital cost	-86.70%		-84.20%		-91.30%	
LSMGO	4.10%		---		0.00%	
Maintenance cost	-0.70%		-0.10%		-5.60%	
Fuel_saving generating sets (%)	5.90%		9.50%		-0.20%	
Contribution to the variance (NPV (%))						
Capital cost	-6.90%		-7.60%		-1.50%	
LSMGO	7.50%		---		0.00%	
Maintenance cost	-1.00%		-0.10%		-6.20%	
Fuel_saving generating sets (%)	12.90%		14.70%		-34.80%	
Unitary Price for Fuel-EU penalty(€/MJ)	70.6%		77.00%		57.3%	

*2023;** 2030;***2024 [1] On-board generating set costs are added to OPS technology costs (€) [2] In monetary terms due to the systems performance [3] Connection/unconnection:8.45€ (Las Palmas Port, 2024)

The misalignment underscores the need for more comprehensive measures that better balance economic incentives with environmental impact reduction.

As Table 1 shows, all retrofitting alternatives show significant advantages over slow steaming in terms of economic feasibility, with IRRs exceeding 120% and recovery times of one to two years for under regular regions' framework. OPS emerges as the option with the highest IRR (281% and 186% for regular and outermost regions, respectively) due to its low capital cost (€691,762) and substantial MBM savings, while the PV system alternative provides the highest NPV (€4,202,678 and €1,567,810, see Table 1) closely followed by H_2 fuel cell, despite having the latter, the lowest IRR (124% and 23% for every region's framework) due to its high initial cost (€1,323,632) and mid-life replacement expense (€542,168 in 2030, see Table 1).

The PV system demonstrates unique advantages, such as positive savings in auxiliary engine bunkering from operational solar panels (48.16% of daily time) and reduced maintenance costs. However, it is also the most sensitive to external variables, such as LSMGO price fluctuations, with impacts of 4.10% on IRR and 7.5% on NPV (see Table 1).

Monte Carlo simulations validate these findings (see means of the distributions achieved in Table 1), showing that capital costs and the systems' performance (fuel saving generating sets, see Table 1) are the most influential variables. Fuel-EU penalties play a crucial role in generating positive NPV across alternatives (57.3% - 77% contribution to NPV variance), highlighting, once again, their importance in incentivizing retrofit investments. This can be seen in the shortening of NPV for the investment projects analyzed under outermost regions' regulation (see Table 1 and Figure 2) in comparison to the regular regions.

Overall, while OPS offers immediate economic advantages, the fuel cell alternative stands out as the most sustainable option with long-term value, balancing environmental and economic considerations effectively

6 Discussion and conclusions

The CII and remaining EU GBM compliance by Fast ferries requires solutions to be both effective and aligned with the European Union's MBM. This study shows that combining slow steaming with retrofitting ships to use emerging technologies for on-board electricity supply is an effective and feasible way forward. This approach not only meets the Fuel-EU demanding about zero emissions while berthing since 2030, but also it reduces emissions caused by electricity generation during slower sailing and maneuvering stages. Finally, these results confirm earlier findings about the importance of acting on onboard electricity systems in SSS vessels to reduce the total emissions.

The analysis found a mismatch between the MBMs imposed to Fast ferries and their actual environmental impact when they are operating with renewable energies and alternative fuels technologies. This fact involves implicit over-grants from MBMs for the investments in emerging technologies, thus, 20.15% MBM savings when PV system is set up in the Fast Ferries versus 2.29% actual pollutant impact reduction, and 41.93% MBM savings for green hydrogen fuel cells in Fast Ferries versus 6.76% current pollutant impact reduction. These divergences are mainly due to missing Well-to-Tank (WtT) emissions in the MBM calculations and the lack of penalties for Fuel-EU non-compliance in the emerging technologies. Therefore, the adjustments' need in the MBM architecture exists to improve the effectiveness of MBM as a tool to meet PPP in the SSS.

Although green hydrogen fuel cells are sustainable, they are a less attractive option for shipowners (in terms of NPV and IRR) due to their high costs, short lifespan, and the high price of green hydrogen. PV systems and OPS are more cost-effective, but whereas PV systems provide significant CO_2 emissions reductions (55.17%), the OPS reductions are more constrained (35.39%) by offering the latter better results in terms of economic feasibility. However, this feasibility is strongly determined by the exemption of the WtT emissions, by underestimating total emissions from OPS by 3.22% per trip and 8.53% in monetary terms for short sea routes.

Current exemptions for EU MBMs and GBMs application in the outermost regions deprive them of the incentives previously found for the EU regular regions to meet CII requirements through emerging technologies' investments. Fuel EU has proved to contribute between 57-71% to NPV variance for the mitigation alternatives' investments. This involves significant reductions for NPV and IRR in the retrofitting of the outermost regions' vessels. These regions depend heavily on maritime transport and public service obligations to maintain their connectivity; therefore, the current derogation of EU policies are putting them at a significant disadvantage compared to other EU areas. This raises concerns about the fairness and effectiveness of EU policies in supporting decarbonization equally across all regions.

Future studies should be addressed to determine the impact on Fast Ferries of connection/disconnection time for OPS, the availability of green hydrogen in port, and risks related to not meeting regional energy goals. Combining different sustainable technologies could also be explored. While this study focuses on one specific case, the results and data are strong enough to apply to similar cases across the EU.

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Annex

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 H2.

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

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

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 and hoteling time.

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

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

U={1,..,u}: SOX (acidifying substances), NOx (ozone precursors), PM2.5, PM10 (particulate mass), CO2 ,CH4 (greenhouse gases) and NH3 (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

αi: Percentage of CO2 emissions to be considered in EU-ETS according to the localization of the port calls (%): Both ports belong to an EU Member State (αi = α1 = 100%); only one port belongs to an EU Member State (αi = α2 = 50%); no port belongs to an EU Member State (αi = α3 = 0%);

βy: 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 ($\beta y = \beta 3 = 100\%$);

γi: 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 ($\gamma i = \gamma 3 = 0\%$);

μy: Percentage of maximum target emissions to be considered for Fuel-EU according to the activity year-implementation schedule-: 2024 (uy = u1= 0%); 2025-2029 (uy = 98%); 2030-2034 (uy = 94%); 2035-2039 (uy = 85.5%); 2040-2044 (uy =69%); 2045-2049 (uy = 38%); 2050-thereafter (uy =20%);

BACq: Bunker cost for the electricity supply through several systems (€); $\forall q \in Q$

BCq: 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).

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

CEMsy: Vessel impact on air quality (€/trip) for every navigation stage and year; $\forall s \in SS$^$\forall y \in Y$.

CFsukvy: Unitary costs for air pollutants in port operations (€/kg pollutant) $\forall s \in S \wedge \forall u \in U \wedge \forall f \in F \wedge \forall v \in V \wedge \forall y \in Y$.

CFsuy : Unitary costs for air pollutants in free sailing (€/kg pollutant);$\forall s \in S \wedge \forall u \in U \wedge \forall y \in Y$.

CFFjl: Conversion factor collected in the resolution MEPC.308(73) and in the Commission Regulation (EU) No 601/2012 (tonne CO_2/tonne fuel) ; $\forall j \in J \wedge \forall l \in L$.

CFMjl: Emission factor for CH_4 (tonne CH_4/tonne fuel); $\forall j \in J \wedge \forall l \in L$

CFNjl: Emission factor for N_2O (tonne N_2O/tonne fuel); $\forall j \in J \wedge \forall l \in L$

CII_Ay: Attained Carbon Intensity Indicator for every year (CO_2 grams/nm and tonne); $\forall y \in Y$.

CII_Ry: 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(gCO2eq/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 (gCO2eq/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 (gCO2eq/MJ); $\forall j \in J$.

CP: EU Carbon Pricing (€/tonne CO_2).

CVj: Lower Calorific Value of the fuels (GJ/g fuel); $\forall j \in J$.

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

Ec: Electricity delivered to the vessel at berth per connection point through OPS (MJ); $\forall c \in CC$

EGsuly : Emission factors per pollutant; for every navigation stage, type of engine and year (kg/h) $\forall s \in S \wedge \forall u \in U \wedge \forall l \in L \wedge \forall y \in Y$;

EFGuky: Emission factors per pollutant emitted by OPS; in every port and year (kg/KW.h) $\forall u \in U \wedge \forall k \in K \wedge \forall y \in Y$;

ETDy: Energy Taxation per year (€/year);$\forall y \in Y$

ETSy: European Trading System's cost per year (€/year); $\forall y \in Y$

ETSUy: European Trading System's cost per trip (€/trip); $\forall y \in Y$

ETUy: Energy Taxation per trip (€);$\forall y \in Y$.

fwind: Reward factor for wind-assisted propulsion.

FuelEUy: Annual penalty for non-compliance with Fuel-EU (€/year); $\forall y \in Y$

GBM: Goal Based Measures (€)

(GHGIEactual)y: Greenhouse gas intensity of the energy used on-board for a year (g CO_2 eq/MJ); $\forall y \in Y$.

(GHGIEtarget)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.

IRRq: 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.

NCFqy: Net Cash Flow for every alternative and year (€); $\forall y \in Y \land \forall q \in Q$.

NPVq: Net Present Value for every alternative (€); $\forall q \in Q$.

MBM: Market Based Measures (€)

MCq: Maintenance costs for the electricity supply systems (€); $\forall q \in Q$

PBlsy: Power for the vessel's engines for every navigation stage (kW); $\forall l \in L \land \forall s \in SS \land \forall y \in Y$.

R: Discounting rate for the investment that is demanded by the shipowner (%)

RCq: Replacement costs for the electricity supply systems $\forall q \in Q$)

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

SFOCjls: Specific Fuel Consumption for engines in every navigation stage and fuel type (g fuel/kW.h); $\forall j \in J \land \forall l \in L \land \forall s \in SS$.

TLj: Taxation applicable to fuels (€/GJ); $\forall j \in J$.

TVBsy: Time invested in every navigation stage in a trip (h/trip) per year; $\forall s \in SS \land \forall y \in Y$.

Zy= Annual reduction factor from 2019 values applied over reference line for calculation of the required carbon intensity indicator; $\forall y \in Y$: 2024 (Zk =Z1=7%); 2025 (Zk =Z2=9%); 2026 (Zk =Z3=1

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