

Can conventional energy-saving technologies keep ships operating in European waters compliant with maritime climate regulations? A simulation-based assessment

Joost Hobbie^{*} , Ishan Sontakke[✉] , Martin Bergström[✉] , Sören Ehlers[✉] 

German Aerospace Center (DLR e.V.), Institute of Maritime Technologies and Propulsion Systems, Düneberger Straße 108, Geesthacht, 21502, Germany

ARTICLE INFO

Keywords:

Fleet decarbonization
Carbon Intensity Indicator (CII)
EU Emissions Trading System (EU ETS)
FuelEU Maritime
Techno-economic assessment
Bottom-up emission modelling
Energy efficiency measures

ABSTRACT

Maritime transport is subject to increasingly strict emission regulation. Ships operating in European waters must comply with the International Maritime Organization's Carbon Intensity Indicator, the European Union Emissions Trading System, and the FuelEU Maritime regulation, raising regulatory and financial pressure on the existing fleet. To stay compliant, shipowners can adopt conventional energy-saving technologies, such as hull and propeller upgrades. They offer an attractive short-term option, because they can be retrofitted to existing ships without switching fuels. How far such measures can keep individual ships within the tightening limits, and what they achieve across the fleet, remain unclear. To answer this, a model combining bottom-up emission estimation, regulatory compliance assessment, and techno-economic optimization is developed and applied to 12,908 vessels operating in European waters, projecting their outcomes from 2025 to 2030. Without technical or operational change, more than half of the fleet would become non-compliant under the Carbon Intensity Indicator by 2030. Under central assumptions on measure effectiveness and cost, conventional retrofits restore compliance for 27.6% of the affected vessels, rising to just under half in an optimistic case. This succeeds for most containerships, only rarely for cruise and passenger ships, and never for small tankers. Where feasible, the investment pays off within a few years, so cost is rarely the obstacle. For most ships, however, the reduction from these measures is too small to close the widening gap to the emission targets. Meeting them will therefore require options beyond conventional efficiency, such as advanced technologies or alternative fuels.

1. Background

International shipping accounted for approximately 2.9% of global anthropogenic GHG emissions in 2018, and without structural intervention this share is expected to increase as global trade continues to expand (IMO, 2021a). In response, the IMO adopted its revised GHG Strategy in 2023, committing the sector to net-zero emissions by around 2050 and to a reduction in carbon intensity of at least 40% by 2030 relative to 2008 levels (IMO, 2023).

Achieving these targets requires shipowners to comply with an increasingly stringent and multi-layered regulatory framework. At the global level, the IMO's CII, mandatory for vessels above 5,000 GT since 2023, introduces an annual rating system linking operational performance directly to regulatory compliance (IMO, 2021b). In parallel, the EU has extended its ETS to maritime transport from 2024 (EU, 2023a) and introduced FuelEU Maritime (EU, 2023b), which imposes WtW GFI

limits on energy used on board vessels sailing in EU waters from 2025. Taken together, these instruments impose overlapping and interacting constraints on vessel operations, effectively linking fuel consumption and technical performance to escalating regulatory and financial risks.

These overlapping requirements create an urgent need for near-term compliance strategies that can be implemented across the existing fleet. In this context, conventional ESDs represent a technically mature and readily deployable option. By reducing fuel consumption through retrofitable design and propulsion improvements, ESDs can improve a vessel's emission footprint without requiring fuel switching or fundamental changes to propulsion systems (Bouman et al., 2017). However, despite their practical relevance, whether conventional ESDs can support compliance with all three regulations jointly, and for which vessel segments they fall short, has not yet been examined in an integrated, fleet-level assessment.

This paper addresses this gap by evaluating whether conventional ESDs constitute a viable compliance pathway under the current

^{*} Corresponding author.

E-mail address: joost.hobbie@dlr.de (J. Hobbie).

<https://doi.org/10.1016/j.ets.2026.100085>

Received 15 April 2026; Received in revised form 19 September 2026; Accepted 21 September 2026

Available online 29 September 2026

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Nomenclature			
AE	Auxiliary Engine	MARPOL	Marine Pollution
AIS	Automatic Identification System	MCR	Maximum Continuous Rating
CAPEX	Capital Expenditure	MDO	Marine Diesel Oil
CH ₄	Methane	ME	Main Engine
CII	Carbon Intensity Indicator	MEPC	Marine Environment Protection Committee
CO ₂	Carbon Dioxide	MMSI	Maritime Mobile Service Identity
DWT	Deadweight Tonnage	MRV	Monitoring, Reporting and Verification
EEA	European Economic Area	N ₂ O	Nitrous Oxide
ESD	Energy-Saving Device	NM	Nautical Mile
ETS	Emissions Trading System	NPC	Net Present Cost
EU	European Union	OPEX	Operational Expenditure
GFI	Greenhouse Gas Fuel Intensity	RoPax	Roll-on/roll-off passenger (ship)
GHG	Greenhouse Gas	RPM	Revolutions Per Minute
GT	Gross Tonnage	SFOC	Specific Fuel Oil Consumption
GWP ₁₀₀	Global Warming Potential over a 100-year time horizon	TEU	Twenty-foot Equivalent Unit
HFO	Heavy Fuel Oil	TtW	Tank-to-Wake
IMO	International Maritime Organization	VLSFO	Very Low Sulphur Fuel Oil
LNG	Liquefied Natural Gas	WFR	World Fleet Register
LPG	Liquefied Petroleum Gas	WtT	Well-to-Tank
		WtW	Well-to-Wake

regulatory framework. Specifically, three research questions are examined: (i) how severe is the regulatory compliance challenge facing the EU fleet under the current trajectory? (ii) to what extent can conventional ESDs restore compliance for non-compliant vessels, and where do their technical limits emerge? and (iii) what determines the economic viability of ESD adoption, and how robust is the technical and economic case under uncertainty?

To answer these questions, this paper develops and applies an integrated fleet-level assessment framework to 12,908 vessels operating in European waters over the period 2025–2030. By integrating bottom-up emissions modelling with regulatory compliance assessment and techno-economic optimization, it identifies for each fleet segment where conventional ESDs can restore compliance and where they reach their limits. These segment-resolved results can serve industry stakeholders as a basis for technology prioritization. For policymakers, they show which fleet segments will require measures beyond energy efficiency, such as alternative fuels or fleet renewal, and which can comply through retrofits but depend on shipyard capacity, material supply, and access to technology and expertise.

2. Related work

The literature on maritime climate regulation has grown quickly, and much of it now examines compliance strategies and decarbonization pathways. A recurring finding is that outcomes depend less on any single instrument than on the interaction of the IMO CII with regional measures such as the EU ETS and FuelEU Maritime (Park et al., 2024). This work falls into three branches, covering operational measures, economic and regulatory instruments, and technical measures, which are increasingly studied together rather than in isolation.

The first branch concerns operational measures, which have received considerable attention in the maritime climate context. Optimization studies show that compliance can often be achieved through speed reduction, routing, or changes in fleet deployment, although these steps may reduce transport efficiency or capacity utilization (Bergström et al., 2023) (Yuan et al., 2023) (Zhang et al., 2024) (Sun et al., 2023). Such approaches offer useful insight into compliance in the short term, but they generally assume a high degree of operational flexibility and do not fully capture the technical constraints of existing vessels. Conceptual work points to structural limitations of intensity indicators, showing that the CII can produce unintended outcomes and needs careful empirical

testing (Wang et al., 2021). Analyses of individual segments add that compliance dynamics differ across vessel types (Bayraktar and Yuksel, 2023), especially for vessels with high auxiliary loads such as cruise ships (Braidotti et al., 2023). What these studies leave aside is the physical efficiency measures that can be retrofitted to the fleet.

A second branch examines economic and regulatory instruments. Studies on the inclusion of shipping in the EU ETS identify carbon pricing as a key driver of mitigation incentives, with effects that differ across vessel segments and operating profiles (Flodén et al., 2024) (Kotzampasakis, 2025). Analyses that combine IMO and EU regulations show that the interplay between policy instruments can markedly change cost-optimal decarbonization strategies (Lehmann et al., 2025). Much of this work operates at the vessel level: integrated assessments quantify how the cost-optimal fuel choice shifts with a ship's degree of EU exposure under the EU ETS, FuelEU Maritime, and an IMO net-zero framework scenario (Rofifah et al., 2026), and techno-economic assessments rank alternative fuel configurations for dual-fuel ships under FuelEU Maritime (Wang et al., 2025). Some studies also reveal uneven regulatory treatment of abatement options, for instance the undervaluation of wind-assisted propulsion (Kwon et al., 2025), or describe a staged transition in which efficiency gains precede fuel switching under tightening limits (Sontakke et al., 2026a). Here too, the work stays largely at the vessel level and concentrates on fuel switching, leaving efficiency retrofits in the background.

The third branch turns to technical measures. Empirical evidence confirms that conventional ESDs can improve vessel performance (Fadaie et al., 2025) (Rehmatulla et al., 2017). Hull cleaning, for instance, has been shown to cut fuel consumption based on operational data (Adland et al., 2018), while large-scale analyses highlight the substantial impact of hull fouling on emissions (Kim and Ozyurt, 2025). However, the uptake of such measures remains uneven and often limited to low-impact technologies, reflecting barriers beyond economic considerations (Rehmatulla and Smith, 2015). These studies confirm that individual ESDs are effective, but assess them largely in isolation and do not quantify to what extent combinations of them can close a potential regulatory compliance gap at fleet scale.

Overall, existing work emphasizes operational strategies, the interaction of economic and regulatory instruments, and the effectiveness of individual technical measures, but it does so mostly at the level of single vessels and with an eye on operational change or fuel switching. What remains less explored is a fleet-scale assessment of how far combinations

of conventional, retrofittable ESDs can secure regulatory compliance under tightening thresholds and jointly under the CII, EU ETS, and FuelEU Maritime regimes. This paper provides that assessment by applying a validated bottom-up emissions model and a techno-economic optimization of conventional ESDs to a large fleet operating in European waters over the period 2025–2030. It quantifies for each segment how far such measures can restore compliance, where their technical limits lie, and whether the required investment is economically justified.

3. Materials and methods

For this study, a Python-based model was developed to assess vessel-level compliance with maritime climate regulations and to quantify the potential impact of conventional ESDs on fleet compliance over 2025–2030. Operational measures such as slow steaming or optimized routing were excluded from the scope, as were advanced system-level technologies, such as wind-assisted propulsion systems, that require detailed individual vessel assessment and cannot be represented through generalized efficiency factors applicable across vessel classes.

The framework comprised three sequential modules. First, vessel-level emissions were estimated using a bottom-up approach. Second, regulatory performance was evaluated by assessing compliance with the IMO CII regulation, EU ETS, and FuelEU Maritime. Third, vessels projected to receive a non-compliant CII rating entered an optimization module that identified the cost-minimizing set of conventional ESDs required to restore CII compliance by 2030, accounting for CAPEX, OPEX, and fuel and regulatory cost savings. Where a feasible solution was found, vessels were assigned the corresponding measure combination; where no combination of applicable measures proved sufficient, vessels were flagged accordingly. To reflect uncertainty in technology performance and costs, the ESD adoption analysis was conducted under three scenarios (pessimistic, central, and optimistic) with the central scenario serving as the reference case. The model structure is illustrated

in Fig. 1, and the individual steps are described in the following subsections.

3.1. Input data and fleet definition

Technical and operational ship data were obtained from the Clarksons WFR database as of 20 January 2026 (Clarksons Research, 2026). A total of 24 vessel attributes were selected to characterize the fleet's composition and its technical and operational specifications, as summarized in Table 1.

Table 1

Vessel attributes from the Clarksons WFR (Clarksons Research, 2026) and their role in the analysis.

Category	Clarksons fields	Role in analysis
Identification	IMO Number, Name, MMSI	Vessel identification and data integration
Classification	Status, Fleet Type, Type, Built	Fleet filtering and ship type assignment
Capacity	GT, DWT, TEU, Capacity (cu m)	Size assignment and regulatory applicability
Propulsion and fuel	Power Type, Engine Derived Total Main Engine Mechanical kW, Engine Derived Total Mechanical Generated (kW), Main Engine Fuel Type, Main Engine Detail, Main Engine 1 RPM, Main Engine 1 SFOC g/kWh, Auxiliary Engine Fuel Type, Auxiliary Engine 1 SFOC g/kWh	Power and fuel consumption estimation
Operations	Speed (knots), Operational speed (knots)	ME load factor estimation
Technology	EST Detail (Energy Saving Technologies)	Identification of existing ESDs
Regional exposure	Time in EU (ETS) National Waters (Last 12 Months, %)	EU exposure for EU ETS/FuelEU Maritime scope

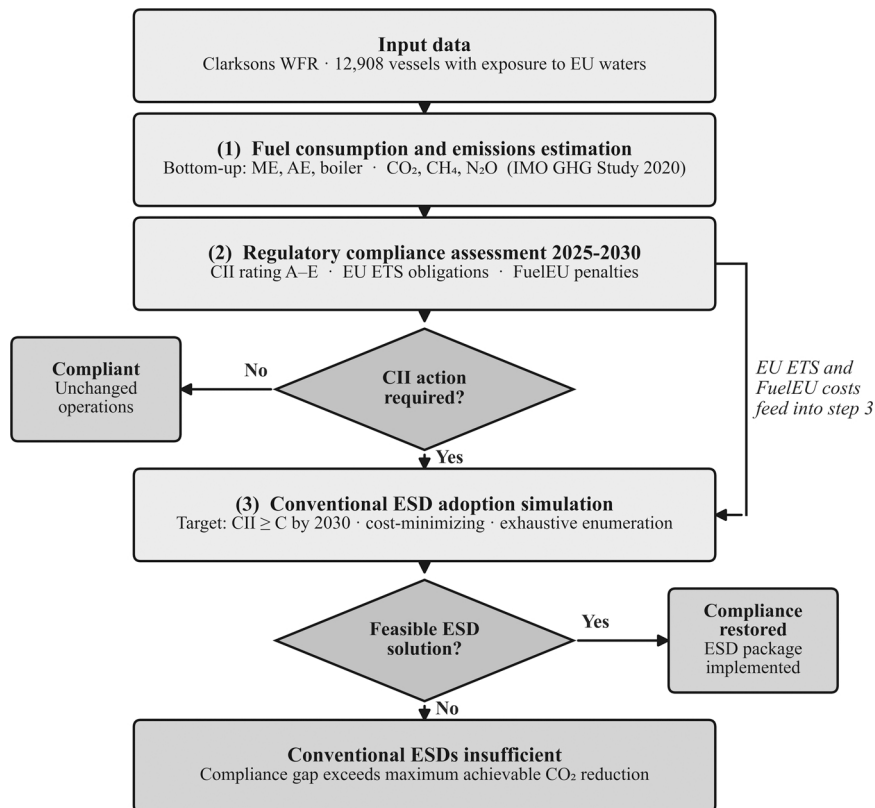


Fig. 1. Model structure for fleet-wide fuel consumption and emission estimation, regulatory compliance assessment, and ESD adoption simulation for 12,908 vessels sailing in EU waters, analysed over 2025–2030.

To ensure consistency with the regulatory and geographical scope of the work, a sequential filtering procedure was applied. Starting from an initial global fleet dataset of 116,050 vessels, non-operational ships (e.g. laid-up, abandoned, or under arrest), non-applicable vessel types (e.g. service vessels, offshore units, fishing vessels), vessels with non-conventional propulsion systems (e.g. wind, nuclear, or fully electric), and vessels lacking key technical parameters (e.g. propulsion power or capacity) were excluded, reducing the dataset to 62,331 vessels. The dataset was subsequently restricted to vessels above 5000 GT, the applicability threshold under the IMO CII regulation (IMO, 2021b), that had spent time in EU national waters during the twelve months to 20 January 2026, as recorded by Clarksons. This yielded 14,613 vessels. For the ESD adoption module, a final filter was applied to retain only vessels mappable to the six ship type categories defined in the DNV energy-efficiency guidance (DNV, 2025a), resulting in a sample of 12,908 vessels. The composition of this fleet is summarized in Table 2. Unless otherwise noted, all subsequent analyses refer to this sample of 12,908 vessels.

3.2. Fuel consumption and emissions estimation

Based on the Clarksons input data, vessel-level emissions were estimated using a bottom-up approach following the Fourth IMO GHG Study (IMO, 2021a); unless stated otherwise, all emission estimation steps and underlying assumptions described below follow this reference. The modelling procedure comprised five steps: (i) assignment of vessel-specific technical parameters, (ii) derivation of operational profiles, (iii) estimation of energy demand, (iv) fuel consumption, and (v) emissions.

Each vessel was assigned to one of 70 ship type and size classes defined in the Fourth IMO GHG Study Table 8. This classification serves as the common reference framework throughout the modelling

Table 2

Composition and key characteristics of the analysed fleet.

Ship type	Size class/category	n (%)	Median capacity	Median build year
Bulk carriers	Small (<35000 DWT)	1016 (7.9%)	30,006 DWT	2010
	Medium (35,000–99,999 DWT)	3572 (27.7%)	61,158 DWT	2014
	Large (≥100,000 DWT)	383 (3.0%)	179,816 DWT	2012
Tankers	Small (<20,000 DWT)	273 (2.1%)	8154 DWT	2010
	Medium (20,000–119,999 DWT)	2741 (21.2%)	49,930 DWT	2011
	Large (≥120,000 DWT)	765 (5.9%)	157,738 DWT	2016
Gas carriers	LNG carriers	445 (3.4%)	174,000 m ³	2019
	LPG/other gas	403 (3.1%)	37,300 m ³	2015
Containerships	Small (<5000 TEU)	1219 (9.4%)	1781 TEU	2007
	Medium (5000–14,499 TEU)	707 (5.5%)	8800 TEU	2012
	Large (≥14,500 TEU)	341 (2.6%)	17,292 TEU	2021
Vehicle carriers	All sizes	479 (3.7%)	60,118 GT	2010
Cruise/RoPax	All sizes	564 (4.4%)	33,324 GT	2004
Total	-	12,908 (100%)	-	-

Note: Ship capacity is expressed as DWT for bulk carriers and tankers (including oil, chemical, and other liquids tankers), GT for vehicle carriers and cruise/RoPax vessels, TEU for containerships, and cargo volume (m³) for gas carriers.

procedure: it provides default operating-mode-specific power outputs for AE and boiler systems (as per Fourth IMO GHG Study Table 17), determines representative operating profiles assigned to each vessel (based on Hobbie et al. (2026)), and forms the basis for imputing missing technical parameters where vessel-level data are unavailable.

Installed ME power was determined based on propulsion type, using shaft power for conventional mechanical propulsion systems (diesel 2-stroke, diesel 4-stroke, steam turbine, gas turbine) and generator output for diesel-electric systems, in which prime movers drive generators rather than directly coupling to the propulsion shaft (cf IMO, 2018).

Fuel types for ME, AE, and boiler systems were assigned using a priority-based approach to resolve multi-fuel entries (where Clarksons records more than one fuel for a vessel) by selecting a single primary fuel according to the hierarchy LNG > Methanol > HFO > MDO > LPG. Missing ME fuel types were imputed using the modal value within each ship type and size class (99.0% directly assigned). AE fuel types were derived analogously (74.9% directly assigned), with MDO applied as default where absent. Boiler fuel type was assumed equal to the AE fuel type. While in reality ships may operate AE and boiler on different fuels, the underlying fleet-level data do not allow for a systematic distinction.

SFOC values were assigned separately for ME, AE, and boiler systems. Reported values were used where available (ME: 86.6%; AE: 37.4%); missing values and all boiler SFOC values, which Clarksons does not report, were imputed following the Fourth IMO GHG Study Table 19, based on engine category, fuel type, and build year class. Engine categories were determined from propulsion type, fuel type, engine specifications (e.g. RPM), and build year.

The ME load factor was calculated from operational and service speed using the cubic propeller law, which describes the non-linear relationship between vessel speed and propulsive power demand, according to Eq. (1):

$$LF_{ME} = \left(\frac{V_{ops}}{V_{service}} \right)^3 \quad (1)$$

where $V_{service}$ denotes the reference (service) speed and V_{ops} the actual operating speed. Service speed was available for 80.5% of vessels and otherwise imputed by ship type and size class median; operational speed was available for all vessels. The resulting load factor was used to adjust the baseline $SFOC_{ME,base}$ to reflect the increase in fuel consumption at partial engine load, following the empirical relationship defined in the Fourth IMO GHG Study:

$$SFOC_{ME,adj} = SFOC_{ME,base} \cdot (0.455 \cdot LF_{ME}^2 - 0.710 \cdot LF_{ME} + 1.280) \quad (2)$$

where $SFOC_{ME,base}$ is the baseline SFOC and LF_{ME} the ME load factor from Eq. (1). The term in parentheses is the ME load correction factor; its empirical coefficients (0.455, −0.710, and 1.280) describe how the SFOC depends on engine load: it is highest at low load, falls to a minimum near the most efficient load (around 80% MCR), and rises again towards full load.

Annual hours in four operating modes (sailing, manoeuvring, at anchor, and at berth) were derived from an AIS-based analysis of vessel activity. Since individual activity records were not available for the fleet, representative operating profiles were assigned at the level of each of the 70 IMO ship type and size classes. The underlying methodology follows Hobbie et al. (2026), originally developed for a regional dataset and extended in this paper to a global AIS dataset for the year 2019 covering 72,371 vessels. Operating mode definitions follow the Fourth IMO GHG Study Table 16, with normal cruising and slow transit aggregated into a single sailing category. For each class, time shares were derived as the average proportion of time spent in each mode across all vessels within the class, then converted into annual operating hours assuming 8760 hours per year. For illustration, bulk carriers of size bin 3 were assigned 51.2% to sailing, 1.2% to manoeuvring, 37.8% to anchoring, and 9.9% to berth operations. Because these shares are

averaged over all vessels in each class, they represent typical operating patterns of a ship type and size class rather than the activity of a specific vessel in a given year. Although the underlying data are from 2019, the resulting sailing hours agree with the MRV-reported time at sea for 2025 at fleet level (Section 4.1), indicating that the profiles remain representative of current activity.

Based on these parameters, annual energy demand was estimated separately for ME, AE, and boiler systems. ME energy demand was calculated according to Eq. (3):

$$E_{ME} = P_{ME} \bullet LF_{ME} \bullet h_{sailing} \quad (3)$$

where P_{ME} is the installed ME power (kW), LF_{ME} the ME load factor from Eq. (1), and $h_{sailing}$ hours in sailing mode, giving E_{ME} in kWh. ME operation during manoeuvring, anchored, and at berth was excluded, as the associated ME loads are negligible in those modes. AE and boiler energy demand was calculated across all operating modes, as auxiliary and hotel loads persist throughout all phases of vessel operation, according to Eq. (4):

$$E_j = \sum_m P_{j,m} \bullet h_m, \quad j \in \{AE, \text{Boiler}\} \quad (4)$$

where $P_{j,m}$ denotes the ship-and-mode-specific power output (kW) of system j in operating mode m , taken from the Fourth IMO GHG Study Table 17, and h_m the AIS-derived ship-and-mode-specific annual operating hours in mode m , giving E_j in kWh.

Annual fuel consumption (t) for each system i was calculated following Eq. (5):

$$F_i = \frac{E_i \bullet SFOC_i}{10^6} \quad (5)$$

where E_i is the annual energy demand (kWh) and $SFOC_i$ the system-specific SFOC (g/kWh), giving F_i in t. For the ME, $SFOC_i$ corresponds to the load-adjusted value defined in Eq. (2); for AE and boiler systems, reported or imputed values were applied. For LNG engines, an additional MDO pilot fuel consumption was assumed depending on the combustion cycle (LNG-Otto: 0.8 g/kWh; LNG-Diesel: 6.0 g/kWh), reflecting the ignition requirement of gas-fuelled engines.

CO₂ emissions (t) were calculated according to Eq. (6):

$$CO_2 = \sum_i F_i \bullet CF_i \quad (6)$$

where F_i is the annual fuel consumption (t) and CF_i the fuel-specific carbon conversion factor (Fourth IMO GHG Study Table 21: HFO: 3.114; MDO: 3.206; LNG: 2.750; Methanol: 1.375; LPG: 3.030 t CO₂/t fuel). Total vessel-level CO₂ emissions were obtained by aggregating contributions from ME, AE, and boiler systems. CH₄ and N₂O emissions were estimated using energy-based emission factors (g/kWh) from the Fourth IMO GHG Study Annex Tables 55–56 and 59–60, applied to the energy demand of each system.

3.3. Regulatory compliance assessment

Regulatory compliance was assessed based on vessel-level fuel consumption and emissions derived in Section 3.2, covering the IMO CII regulation, EU ETS, and FuelEU Maritime.

The attained CII was calculated for each vessel following MEPC.352 (78) (IMO, 2022a) as shown in Eq. (7):

$$CII_{att} = \frac{CO_2 \bullet 10^6}{Capacity \bullet Distance} \quad (7)$$

where CO_2 denotes annual CO₂ emissions (t), $Capacity$ the ship-type-specific reference capacity (DWT for bulk carriers, tankers, gas carriers, and containerships; GT for vehicle carriers and cruise/RoPax vessels), and $Distance$ the annual sailing distance (NM), approximated as

the product of V_{ops} and $h_{sailing}$.

The required CII was derived from the ship-type-specific reference line following MEPC.353(78) (IMO, 2022b), in accordance with Eq. (8):

$$CII_{req} = a \bullet W^{-c} \bullet r_y \quad (8)$$

where a and c are given ship-type-specific regression coefficients, W the reference ship capacity, and r_y the year-specific required CII factor relative to the 2019 reference line, as provided in Table 4.

Vessel performance was assessed by comparing attained and required CII values. Based on this comparison, vessels were assigned ratings A-E using boundary multipliers defined in MEPC.354(78) (IMO, 2022b), where a rating of E in any single year, or D in three consecutive years, triggers a mandatory corrective action plan under MARPOL Annex VI (IMO, 2021b). To project compliance over 2025–2030, the attained CII was held constant, assuming unchanged technical and operational performance, while required CII values tighten annually, yielding an upper-bound estimate of the non-compliant fleet share. Under this projection, the Dx3 trigger first activates in 2027 at the earliest, as the study period commences in 2025.

Following Directive (EU) 2023/959 (EU, 2023a), annual EU ETS surrender obligations were calculated by multiplying vessel-level CO₂ emissions derived in Section 3.2 by the fraction of time spent in EU ETS-covered waters and the applicable phase-in factor (70% in 2025, 100% from 2026 onwards). From 2026, CH₄ and N₂O emissions were included and converted to CO₂-equivalents using GWP₁₀₀ values of 28 and 265, respectively (Greenhouse Gas Protocol, 2024). Monetary compliance costs were derived by multiplying surrender obligations by the EU carbon prices provided in Table 4.

Compliance with FuelEU Maritime (Regulation (EU) 2023/1805 (EU, 2023b)) was assessed using the vessel-level GFI, expressed in g CO₂-equivalent emissions per MJ of energy consumed. Building on the annual fuel masses derived in Section 3.2, WtW CO₂-equivalent emissions were calculated for each fuel stream, i.e. ME, pilot fuel, AE, and boiler, by applying fuel-specific WtT and TtW emission factors from Regulation (EU) 2023/1805 (EU, 2023b). The GFI was then calculated as the ratio of total WtW emissions to total onboard energy consumption, aggregated across all four fuel energy system components. Geographic exposure was approximated by each vessel's share of time in EU ETS-covered waters, consistent with the EU ETS assessment. The compliance balance, i.e. the difference between the vessel's GFI and the applicable regulatory target, expressed in VLSFO-equivalent energy (41,000 MJ/t), was used to quantify non-compliance and derive penalties at a rate of 2400 EUR/t (Table 4).

Although assessed separately above, the three instruments apply to the same vessels and interact. The CII is based on a ship's total annual emissions worldwide, whereas the EU ETS and FuelEU Maritime cover only the fraction associated with EU/EEA-related activity, which varies across the fleet. A ship's EU-related emissions therefore affect all three instruments, while the remainder affects only its CII. Because all three instruments ultimately respond to how much fuel a ship burns and emits, they reinforce each other: an ESD that reduces fuel consumption lowers both a ship's total emissions and its EU-related share, improving the CII rating and lowering the ETS and FuelEU costs at the same time. This interaction is reflected in the study model: a non-compliant CII rating triggers the adoption of ESDs, and Eq. (14) determines when a measure package is sufficient, while the resulting fuel and emission savings lower the ship's EU ETS and FuelEU burden, which is included in the economic assessment via Eq. (15).

3.4. ESD adoption simulation

As described above, vessels receiving a CII rating of E in any single year, or D in three consecutive years, are required to develop a corrective action plan. In this paper, such regulatory triggers were interpreted as decision points for technical intervention: the vessel implements a

conventional ESD package in the year following the trigger, with the objective of restoring a CII rating of C by 2030, subject to at most one intervention per vessel over the study horizon. Triggers were identified based on each vessel's unmitigated CII trajectory through 2030, assuming unchanged technical and operational performance.

The ESD catalogue was based on DNV (DNV, 2025a) and aligned with the ship type classification defined in Table 2. Measures were considered eligible for a specific vessel if they (i) applied to existing vessels, (ii) matched vessel type and size class, and (iii) were not already installed, as indicated by Clarksons (Clarksons Research, 2026). To avoid partial applicability, only measures exhibiting full retrofit applicability and full suitability for the respective vessel type and size class in accordance with DNV were retained. The final set comprised eleven conventional measures, summarized in Table 3, covering the affected energy system component, efficiency and cost ranges, and vessel applicability. Three scenarios were applied to reflect uncertainty in measure effectiveness and costs: pessimistic (low η , high CAPEX and OPEX), central (mid-range values), and optimistic (high η , low CAPEX and OPEX), corresponding to the lower bound, midpoint, and upper bound of the ranges specified in Table 3, respectively. The central scenario serves as the primary reference; the pessimistic and optimistic variants quantify how sensitive compliance and economic outcomes are to the assumed technology performance and cost levels.

Each measure was assigned to one of three ship energy system components: ME, AE, and boiler. For ME systems, measures were further distinguished by whether they affect energy demand or fuel efficiency; for AE and boiler systems, all measures were modelled as direct proportional reductions in fuel consumption.

For ME systems, energy and fuel measures were treated separately. Energy measures were assumed to reduce required shaft power at constant vessel speed, and thus the load factor:

$$LF_{ME,adj} = LF_{ME} \bullet (1 - \eta_{ME,energy}) \quad (9)$$

where LF_{ME} is the baseline ME load factor from Eq. (1), and $\eta_{ME,energy}$ the efficiency gain of the applied measure. The adjusted load factor $LF_{ME,adj}$ was then used to recompute the load-dependent $SFOC_{ME,adj}$ according to Eq. (2). As this correction term is a non-linear function of load, a feedback effect arises: at lower load, SFOC increases slightly, partially offsetting the reduction in energy demand. Consequently, the resulting fuel savings are smaller than the nominal efficiency gain $\eta_{ME,energy}$ alone would imply.

Fuel measures were assumed to act directly on fuel efficiency and adjust SFOC according to Eq. (10):

$$SFOC_{ME,adj} = SFOC_{ME,adj}^{(2)} \bullet (1 - \eta_{ME,fuel}) \quad (10)$$

where $SFOC_{ME,adj}^{(2)}$ denotes the load-adjusted SFOC from Eq. (2) and $\eta_{ME,fuel}$ the efficiency gain of the fuel measure. The reduction in fuel consumption is therefore directly proportional to $\eta_{ME,fuel}$, without additional feedback effects. For dual-fuel LNG engines, pilot fuel consumption was affected only by energy-demand-side measures, as it was assumed to scale with mechanical energy demand rather than thermal efficiency.

AE and boiler measures were modelled as proportional reductions in fuel consumption according to Eq. (11):

$$FC_{j,adj} = FC_j \bullet (1 - \eta_j), j \in \{AE, Boiler\} \quad (11)$$

where FC_j is the baseline fuel consumption of system j and η_j the corresponding efficiency gain of the measure.

Where multiple measures affect the same energy system component, efficiencies were combined multiplicatively according to Eq. (12):

$$\eta_k = 1 - \prod_{i \in S_k} (1 - \eta_i), k \in \{ME \text{ energy}, ME \text{ fuel}, AE, Boiler\} \quad (12)$$

where S_k denotes the set of measures affecting component k and η_i the efficiency gain of measure i . This ensures that efficiency gains are combined only within the same system component, preventing unintended interactions across ME energy, ME fuel, AE, and boiler systems.

Adjusted CO₂ emissions were obtained by propagating the modified fuel consumption of each energy system component through the emission model described in Section 3.2. The resulting annual CO₂ reduction directly determines the adjusted attained CII under the assumption of constant transport work:

$$CII_{att,adj}(S) = CII_{att} \bullet (1 - \frac{\Delta CO_2(S)}{CO_{2,total}}) \quad (13)$$

where $\Delta CO_2(S)$ is the emission reduction achieved by measure set S , and $CO_{2,total}$ the baseline emissions.

A measure set S was considered feasible if it achieves at least a CII C rating in 2030:

$$CII_{att,adj}(S) \leq d_3 \bullet CII_{req,2030} \quad (14)$$

where d_3 is the upper boundary multiplier for rating C as defined in MEPC.354(78) (IMO, 2022b) and $CII_{req,2030}$ the required CII for 2030, derived from Eq. (8). Enforcing the constraint in 2030 is sufficient, as the required CII tightens gradually over the study horizon; a measure set achieving compliance in the most stringent year therefore implies

Table 3
Selected ESDs, their estimated efficiency ranges, cost parameters, and applicability by vessel type, based on DNV (DNV, 2025a).

ESD	Affected component	η (%)	CAPEX (kEUR)	OPEX	Applicable vessels
Hull and propeller cleaning	ME energy	4–12	9–44	-	All
High performance coatings	ME energy	2–8	44–531	-	All
ESDs aft of the propeller	ME energy	0–5	22–106	-	All
Bulbous bow retrofit	ME energy	2–15	443–1328	-	Containerships (all)
Windshields and aerodynamic optimization	ME energy	1–2	443–1505	-	LNG carriers, LPG/other gas, containerships (all), vehicle carriers
Propeller measures	ME energy	2–7	177–2213	-	Containerships (medium, large)
Electronic auto-tuning	ME fuel	0.5–2	4–9	1–3% of CAPEX/year	Bulk carriers (large), tankers (large), containerships (medium, large), vehicle carriers
Engine performance testing and tuning	ME fuel	1–4	44–133	1–3% of CAPEX/year	All
Variable frequency drives	AE	0.5–2	62–266	0.2–2% of CAPEX/year	All
Optimization of cargo handling systems	AE	0.5–1	4–27	-	Tankers (all), containerships (all)
Steam plant operation improvement	Boiler	0.5–1.5	44–266	0.2–1% of CAPEX/year	Tankers (medium, large), cruise/RoPax

Note: Costs were converted from USD to EUR at a rate of 1 USD = 0.885 EUR (European Central Bank, 2025).

compliance in all preceding years.

For each triggered vessel, all feasible measure combinations were evaluated through exhaustive enumeration, and the cost-minimizing solution was selected. If no combination of applicable conventional ESDs proved sufficient to restore a CII rating of C by 2030, the vessel was flagged as having a compliance gap, indicating that the maximum achievable CO₂ reduction through conventional energy-saving technology is insufficient to meet the regulatory requirement. The cost-optimal measure package was identified by minimizing the NPC over the vessel's remaining service life, subject to the feasibility constraint in Eq. (14). The NPC was calculated as:

$$NPC(S) = CAPEX + \sum_{t=1}^T \frac{OPEX - \Delta C_{fuel,t} - \Delta C_{ETS,t} - \Delta C_{FuelEU,t}}{(1+i)^t} \quad (15)$$

where T is the remaining vessel lifetime in years and i is the discount rate (Table 4). T is set to 25 years minus the vessel's age at the trigger year, 25 years being a typical economic life for a merchant ship, but not less than five years, so that even old vessels are assessed over a plausible remaining period. The discount rate is set to a moderate 5% representing the time value of money. The three savings terms, i.e. lower fuel costs and reduced EU ETS and FuelEU Maritime obligations, are each evaluated year by year considering the prices and targets in Table 4 and discounted at i . The EU ETS carbon price, for example, rises to 110.6 EUR/t by 2030 and is then held constant, since vessel lifetimes can extend beyond 2030; this is a conservative choice that may understate ETS savings and affects only the economics, not whether a package is actually feasible, which depends solely on the CO₂ reduction it achieves as per Eq. (14). In addition to the NPC, the simple payback period was reported as the ratio of CAPEX to first-year gross savings, defined as the combined fuel and regulatory cost reductions in the first year after implementation.

4. Results

This section presents the main findings of the fleet-level assessment. It first validates the modelled emissions against verified data reported under the EU MRV Regulation. It then characterizes the fleet's baseline fuel consumption and emission profile and examines the resulting regulatory exposure under the CII, EU ETS, and FuelEU Maritime. Building on this baseline, it assesses the technical feasibility and economic performance of conventional ESD adoption and finally evaluates the sensitivity of the results to uncertainty in measure effectiveness and costs.

Table 4
Regulatory and economic input parameters applied in the model.

Parameter	2025	2026	2027	2028	2029	2030	Unit	Source
Regulatory parameters								
CII reduction factor r_y	0.91	0.89	0.864	0.838	0.811	0.785	-	(IMO, 2021b), (IMO, Resolution MEPC, 2025)
EU carbon price	70.8	76.4	81.4	88.5	99.4	110.6	EUR/t CO ₂ equivalent	(DNV, 2025b)
FuelEU GFI target	89.34	89.34	89.34	89.34	89.34	85.69	g CO ₂ equivalent/MJ	(EU, 2023b)
FuelEU penalty	2400	2400	2400	2400	2400	2400	EUR/t VLSFOeq	(EU, 2023b)
Fuel prices								
HFO	470	461	452	443	434	425	EUR/t	(IMO/DNV, 2024), (Sontakke et al., 2026b)
MDO	651	644	637	629	622	615	EUR/t	(IMO/DNV, 2024), (Sontakke et al., 2026b)
LNG	540	533	527	520	514	507	EUR/t	(IMO/DNV, 2024), (Sontakke et al., 2026b)
Methanol	378	350	322	293	265	237	EUR/t	(IMO/DNV, 2024), (Sontakke et al., 2026b)
Economic assumptions								
Discount rate	5	-	-	-	-	-	%	Authors
Vessel lifetime	25	-	-	-	-	-	Years	Authors
Min. vessel lifetime	5	-	-	-	-	-	Years	Authors

Note: Fuel prices are taken from (Sontakke et al., 2026b) and linearly interpolated between 2025 and 2030. The underlying projections in (Sontakke et al., 2026b) are based on (IMO/DNV, 2024). EU carbon prices were converted from USD to EUR at 1 USD = 0.885 EUR (European Central Bank, 2025). The discount rate, vessel lifetime, and minimum remaining lifetime are constant over the study period, so only a single value is given. All prices and targets are held at their 2030 values for years beyond 2030.

4.1. Model validation

The model estimates fuel use and emissions from each ship's technical and operational characteristics rather than from direct measurements, so it is important to check whether its results agree with reported data. For this, the modelled emissions were compared with vessel-level figures reported under the EU MRV Regulation (EMSA, 2026). For each available ship and year since 2018, MRV reports metrics such as total annual CO₂ emissions, CO₂ emissions per distance, and time spent at sea. Of the 12,908 modelled ships, 10,480 (81%) could be matched to the latest MRV report (2025) via IMO number. The comparison focuses on CO₂, which accounts for 97% of the fleet's GHG emissions (Table 6) and determines the CII rating.

The first comparison uses total annual CO₂ emissions. It is only meaningful for ships that sail almost entirely within the EEA, since MRV captures a full year of activity only for these ships, matching the modelled annual estimate. Since MRV reports where each ship's CO₂ emissions occurred, the EEA share could be determined for every ship, and 409 ships whose share reached at least 95% were selected for the comparison. A 95% rather than 100% threshold keeps a larger and more representative sample (409 ships rather than 254, of which 63% would be cruise/RoPax) while still capturing almost the full annual activity of each ship. Fig. 2a shows the modelled against the reported CO₂ emissions for these ships. As a further check on the operating profiles applied in the model, the modelled sailing hours were compared with the MRV-reported time at sea for the same 409 ships (Table 5).

The second comparison uses CO₂ emissions per distance and can be applied to all 10,480 matched ships. Unlike total emissions, this measure does not depend on which part of a voyage is reported, as a ship emits at a similar rate of CO₂ per distance inside and outside EEA waters. MRV reports it directly, while the modelled value is the annual CO₂ divided by the annual distance from Eq. (7). This is the more relevant of the two comparisons, since it reflects the same emission-per-distance term that determines the CII rating. Fig. 2b shows the modelled versus the reported values for all matched ships.

Table 5 reports the comparisons broken down by ship type: total annual CO₂ and annual sailing hours ratios for the ≥ 95% intra-EEA ships, and CO₂ per distance ratios for all matched ships.

At the median, the model reproduces the reported values well: total annual CO₂ is about 10% high (1.10), CO₂ per distance matches almost exactly (1.00), and sailing hours are close (0.93). These medians are also stable in the 2024 MRV data and across intra-EEA thresholds of 90–100%. At the level of individual ships, the agreement is looser: 54% of ships are within ± 25% for annual CO₂, 71% for CO₂ per distance, and 61% for sailing hours. Although the model uses ship-specific technical

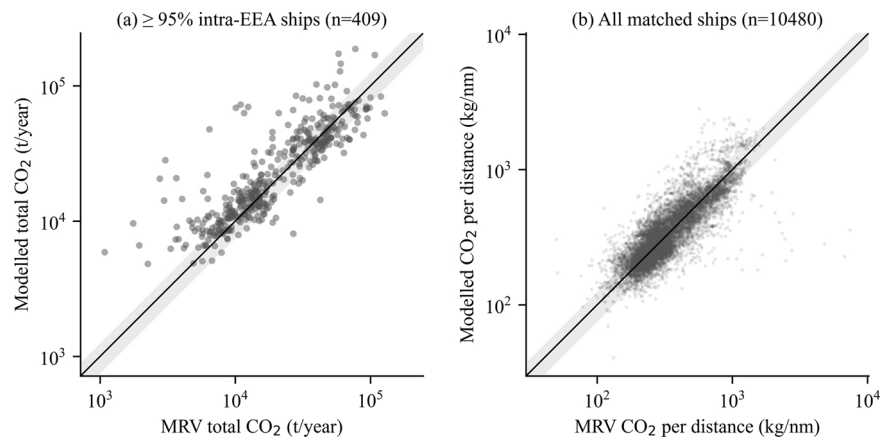


Fig. 2. Modelled versus MRV-reported CO₂ emissions for 2025: (a) total annual CO₂ for 409 ships with $\geq 95\%$ of their reported CO₂ within the EEA, and (b) CO₂ per distance sailed for all 10,480 matched ships. Each marker represents one ship; the solid line denotes the 1:1 relationship and the shaded band a $\pm 25\%$ deviation.

Table 5

Model validation against EU MRV reported emissions, by ship type, reporting period 2025.

Ship type	$\geq 95\%$ intra-EEA - n	$\geq 95\%$ intra-EEA - CO ₂ ratio	$\geq 95\%$ intra-EEA - sailing hours ratio	All matched - n	All matched – CO ₂ per distance ratio	All matched – within $\pm$ 25%
Bulk carriers	8	0.88	0.95	3754	0.95	78%
Tankers	64	1.27	0.99	2978	1.16	61%
Gas carriers	22	1.04	0.99	719	1.10	66%
Containerships	101	1.02	0.99	2053	0.90	78%
Vehicle carriers	2	0.77	0.75	469	0.85	71%
Cruise/RoPax	212	1.05	0.85	507	1.21	50%
Total	409	1.10	0.93	10,480	1.00	71%

Note: Each ratio is the median of the modelled value divided by the MRV-reported value. The sailing hours ratio compares modelled annual sailing hours with the MRV-reported time at sea.

data such as installed power, speeds, capacity, and fuel types, it assigns representative operating profiles by ship class, imputes parameters that are not reported for every ship, and approximates each ship's sailing distance, so it does not reproduce individual vessels exactly. As these differences are largely unbiased, they average out in the fleet- and segment-level results on which the study relies. The one systematic bias observed is an overestimation of tankers and cruise/RoPax vessels (about 16% and 21% in CO₂ per distance); for these segments the attained CII is overstated, so their projected non-compliance should be

interpreted as an upper bound. Overall, the modelled inputs are reliable at the fleet and segment level, while estimates for individual ships are more uncertain.

4.2. Fleet fuel consumption and emissions

The fleet operates on four fuel types (HFO, LNG, MDO, and methanol) with a total annual consumption of 105.2 Mt/year. HFO dominates the fuel mix, accounting for 78.4% (82.5 Mt/year), followed by LNG

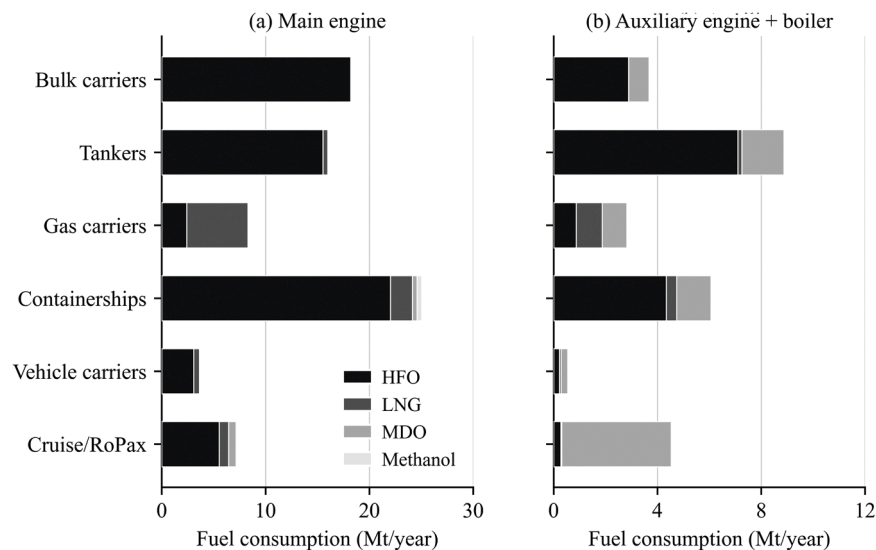


Fig. 3. Annual fuel consumption of the fleet by ship type and energy system component, disaggregated by fuel type: (a) ME, including pilot fuel for LNG-fuelled engines, and (b) AE and boiler combined.

(11.0%; 11.6 Mt/year), MDO (10.1%; 10.6 Mt/year), and methanol (0.5%; 0.5 Mt/year). This dominance of HFO reflects the age structure of the fleet: 61.5% of vessels were built before 2015 and designed around conventional propulsion systems. Fig. 3 presents fuel consumption across ship types by energy system component and fuel type; while the ME accounts for 74.8% of total consumption (78.7 Mt/year), AE and boiler systems contribute 25.2% (26.5 Mt/year), warranting separate representation in the figure.

Containerships account for the largest share of fleet-wide fuel consumption (29.6%; 31.1 Mt/year), disproportionate to their 17.6% vessel count and reflecting their high installed power and operational speeds. Bulk carriers, despite forming the largest segment by vessel count (38.5%), rank third in total consumption (20.9%; 21.9 Mt/year), behind tankers (23.8%; 25.0 Mt/year). Cruise/RoPax vessels account for a further 11.1% (11.7 Mt/year), while gas carriers contribute 10.6% (11.2 Mt/year), and vehicle carriers 4.0% (4.2 Mt/year).

The breakdown by energy system component reveals an important structural difference between these rankings. When ME consumption alone is considered, bulk carriers move ahead of tankers (18.3 vs. 16.1 Mt/year), as tankers carry a substantially higher auxiliary and boiler load driven by thermal energy demands of cargo heating; AE and boiler systems account for 35.5% of tanker fuel use, well above the fleet average of 25.2%. Gas carriers exhibit a distinct fuel profile, with LNG dominating ME consumption in line with the widespread adoption of dual-fuel propulsion in this segment; the use of pilot fuel (MDO) in LNG engines remains negligible at fleet scale (<1% of gas carrier ME consumption).

Translating the observed fuel consumption into a GHG profile of the fleet requires accounting for CH₄ and N₂O alongside CO₂, as these three gases are covered under the EU ETS and FuelEU Maritime frameworks. Table 6 presents the resulting emission inventory by ship type in CO₂-equivalents.

CO₂ accounts for 97.1% of total GHG emissions and therefore largely determines the overall emission profile of the fleet. Its distribution across ship types closely follows the observed fuel consumption patterns. A notable exception occurs for gas carriers: despite the lower carbon intensity of LNG, CH₄ slip from LNG engines results in gas carriers accounting for 64.7% of fleet-wide CH₄ in CO₂-equivalent terms, while representing only 6.6% of the fleet. N₂O emissions are more evenly distributed and broadly proportional to fuel consumption across ship types.

4.3. Fleet regulatory compliance and cost exposure

Under unchanged technical and operational conditions, regulatory exposure increases substantially over the study period. With attained CII values held constant, progressively tightening IMO thresholds lead to a systematic deterioration of vessel ratings, triggering mandatory corrective action for an increasing share of the fleet. Fig. 4 shows the cumulative share of vessels subject to corrective action by ship type and

Table 6

Annual GHG emissions by ship type (CO₂, CH₄ and N₂O in CO₂-equivalents) for the fleet.

Ship type	CO ₂ (Mt/year)	CH ₄ (Mt CO ₂ eq/year)	N ₂ O (Mt CO ₂ eq/year)	Total GHG (Mt CO ₂ eq/year)
Bulk carriers	68.4	0.03	1.01	69.4
Tankers	77.7	0.20	1.11	79.0
Gas carriers	32.5	3.33	0.43	36.3
Containerships	95.3	0.65	1.36	97.3
Vehicle carriers	13.0	0.10	0.19	13.3
Cruise/RoPax	36.5	0.82	0.54	37.9
Total	323.5	5.14	4.65	333.3

Note: CH₄ and N₂O converted to CO₂-equivalents using GWP₁₀₀ values of 28 (CH₄) and 265 (N₂O) (Greenhouse Gas Protocol, 2024).

size class over 2025–2030.

Across the fleet, 14.5% of vessels (1870 ships) trigger mandatory action in 2025 – exclusively via the E-rating mechanism, as the Dx3 pathway cannot commence before 2027. A pronounced step-change consequently occurs in 2027, when the first cohort of ships that held a D rating throughout 2025 and 2026 reaches its third consecutive year: the fleet-wide cumulative triggered share nearly doubles from 16.6% to 34.1% in a single year. By 2030, 50.8% of the fleet (6554 ships) will have been subject to a corrective action plan, with Dx3 accounting for 60.1% of all triggers, making it the dominant compliance mechanism fleet-wide.

The distribution across segments is notably heterogeneous. Small tankers are the most exposed, with 68.1% triggering mandatory action already in 2025, rising to 94.9% by 2030. Cruise/RoPax vessels follow a similar trajectory (56.2% in 2025, 84.2% in 2030), with the E-rating mechanism accounting for 74.9% of triggers in that segment. LNG carriers are the least affected, 11.5% triggered in 2025 and 27.4% by 2030, consistent with the lower carbon intensity of LNG combustion.

The financial dimension of regulatory exposure arises from two concurrent instruments: EU ETS obligations and FuelEU Maritime penalties. Table 7 reports the year-by-year and cumulative cost burden projected under unchanged technical and operational conditions.

The combined regulatory cost escalates markedly over the study horizon. In 2025, ETS obligations, assessed at the 70% phase-in rate, account for 74.9% of the total burden, with FuelEU Maritime penalties contributing the remainder. Unlike the ETS, FuelEU carries no phase-in provision; penalties therefore remain stable through 2029, as the GFI reference target is unchanged over that period. The first notable step-change occurs between 2025 and 2026, when the ETS phase-in fraction advances to 100%. Combined with rising EU carbon prices, this lifts annual ETS costs by 59.1%. The largest single-year increment occurs between 2029 and 2030, when the GFI target tightens from –2% to –6% relative to the 2020 baseline, causing FuelEU penalties to increase by 181.1%. Combined with concurrent EU carbon price increases, this produces an overall annual cost increment of 35.0%. Notably, containerships and cruise/RoPax vessels together account for 55.0% of combined ETS and FuelEU obligations (15.5 billion EUR of 28.2 billion EUR cumulative). At the median, combined regulatory costs rise from 75.6 kEUR per vessel in 2025 to 180.8 kEUR in 2030, with cumulative median obligations of 734.6 kEUR per vessel.

A further noteworthy aspect is the role of CH₄ and N₂O. The treatment of these gases differs across the regulations, which is most relevant for LNG carriers. The CII counts only CO₂, so LNG's comparatively low carbon content makes them the least exposed segment here, and the CH₄ slip of their engines does not count against them. The EU instruments, however, do count it: from 2026 it raises their EU ETS cost by about a sixth, and its effect under FuelEU Maritime is even more pronounced. On CO₂ alone the median LNG carrier would rank well below the FuelEU GFI limit, so without the CH₄ slip almost none would incur a penalty. The CH₄ slip lifts their median GFI to 85.4 gCO₂eq/MJ, which is just under the 2025 limit of 89.3 gCO₂eq/MJ and pushes about a third of LNG carriers into the penalty zone. As the limit tightens to 85.7 gCO₂eq/MJ by 2030, this further rises to about 40%, and the penalties roughly triple.

The projected mandatory corrective action obligations and cumulative burden of 28.2 billion EUR for more than half the fleet by 2030 highlight the urgency of viable compliance pathways. Whether conventional ESDs can meet this challenge across the heterogeneous vessel types documented above is examined in the following section.

4.4. ESD adoption and economic outcomes (central scenario)

To assess whether conventional ESDs can restore compliance, each of the 6554 triggered vessels is evaluated to establish whether a combination of applicable measures can achieve a CII rating of C by 2030 and, where feasible, at what cost. Fig. 5 presents the resulting feasibility

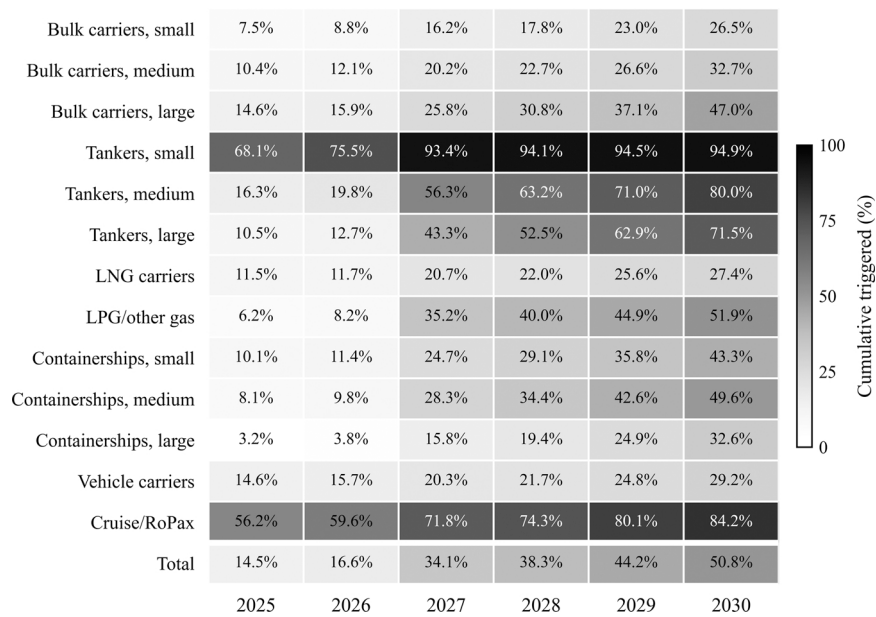


Fig. 4. Cumulative share of vessels triggering CII corrective action under unchanged technical and operating conditions, by ship type and size class.

Table 7

EU ETS and FuelEU Maritime costs under unchanged technical and operating conditions, 2025–2030.

Year	EU ETS (million EUR)	FuelEU Maritime (million EUR)	Total (million EUR)
2025	2149	721	2870
2026	3420	721	4141
2027	3644	721	4365
2028	3961	721	4682
2029	4449	721	5170
2030	4952	2027	6979
Cumulative	22,575	5632	28,207

Note: The values are the fleet totals of the vessel-level EU ETS and FuelEU Maritime obligations calculated as described in Section 3.3, using the regulatory and economic parameters in Table 4 (EU carbon prices, phase-in factors, FuelEU GFI targets, and FuelEU penalty rates).

assessment by segment for the central scenario.

Fleet-wide, a feasible ESD solution is identified for 1809 vessels (27.6%), while for the remaining 4745 ships (72.4%) no combination of conventional measures proves sufficient. The results reveal pronounced segment heterogeneity. Containerships exhibit a clear size gradient, with feasibility rising from 55.5% for small to 92.8% for large vessels. This reflects the broader measure portfolio available to larger vessels, which can stack up to nine measures in the largest size class. They are also the only segment in which the majority of triggered ships can be served across all size classes. At the other extreme, no feasible solution is identified for any triggered small tanker, and Cruise/RoPax vessels show a rate of only 6.1%. For vessels with no feasible solution, the compliance gap systematically exceeds what the full portfolio of applicable measures can deliver. This is clearest for small tankers, whose median maximum achievable CO₂ reduction across all applicable measures is only 7.6%.

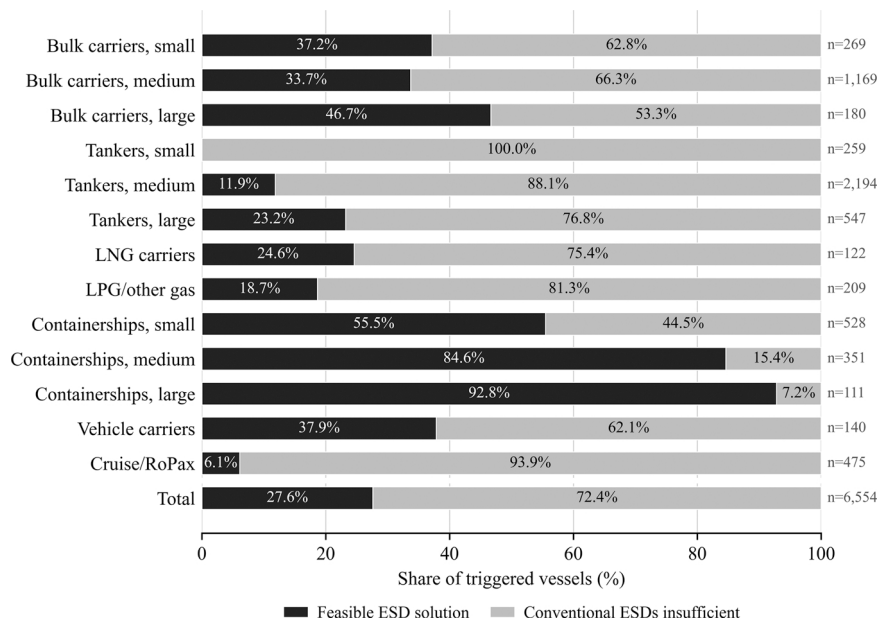


Fig. 5. Share of triggered vessels with a feasible ESD solution by ship type and size class, central scenario.

For the 1809 vessels with a feasible ESD solution, Table 8 summarizes median CO₂ reduction and economic outcomes by segment.

Together, the vessels undergoing ESD measures achieve a combined annual CO₂ reduction of 7.34 Mt, equivalent to 2.3% of total fleet emissions. Across all segments, the economic case for conventional ESDs is strong: the median payback period is 1.3 years and the median NPC is -3088 kEUR, indicating that savings from reduced fuel consumption and lower regulatory obligations outweigh investment costs for the large majority of vessels. More broadly, 95.8% of all vessels with a feasible solution record a negative NPC, confirming that the financial incentive is not confined to a subset of the fleet. Across the 1809 vessels, the total required investment amounts to approximately 1.4 billion EUR, against which the aggregate NPC of -7.3 billion EUR reflects the scale of the economic case at fleet level. The relative contribution of fuel and regulatory savings varies across segments: while fuel savings dominate for most vessel types, regulatory cost reductions account for approximately 40% of total annual savings for Cruise/RoPax vessels, reflecting the disproportionate ETS and FuelEU Maritime exposure of this segment.

Behind these aggregate outcomes lies a concentrated set of ESD measures. Fig. 6 shows the fleet-wide frequency of each measure implementation, disaggregated by ship type.

Across all vessels receiving ESD packages, a total of 9613 individual measure implementations were recorded. Hull and propeller cleaning, engine performance testing and tuning, and high-performance coatings are the three most frequently implemented measures, together accounting for 5289 of these implementations (55.0%); the top five measures account for 79.3%, underscoring how concentrated the distribution is. Their dominance reflects broad applicability across all vessel categories and comparatively low investment requirements. On average, each vessel with a feasible ESD solution incorporates 5.3 measures, indicating that solutions are typically assembled from combinations of complementary low-cost interventions rather than a single high-impact measure. Containerships, bulk carriers, and tankers account for the majority of implementations across most measures, consistent with their combined dominance of the triggered fleet. Cargo handling system optimization is the only measure with a substantial tanker share alongside containerships, reflecting its specific applicability to cargo pump and loading equipment. Steam plant operation improvement is

Table 8
CO₂ reduction and economic outcomes of feasible ESD solutions by ship type and size class, central scenario.

Segment	n	Median CO ₂ reduction (%)	Median CAPEX (kEUR)	Median Payback (years)	Median NPC (kEUR)
Bulk carriers, small	100	13.0	467	2.4	-536
Bulk carriers, medium	394	12.6	467	1.6	-1158
Bulk carriers, large	84	14.5	473	0.8	-2847
Tankers, small	-	-	-	-	-
Tankers, medium	260	9.8	482	1.8	-981
Tankers, large	127	10.9	489	1.0	-3337
LNG carriers	30	12.8	1604	1.0	-13,741
LPG/other gas	39	11.1	631	3.2	-748
Containerships, small	293	15.2	1367	2.8	-950
Containerships, medium	297	21.1	2505	1.0	-10,073
Containerships, large	103	22.1	3642	1.0	-37,336
Vehicle carriers	53	14.4	473	0.7	-2414
Cruise/RoPax	29	10.9	467	0.5	-3775
Total	1809	14.4	1303	1.3	-3088

Note: CO₂ reduction is the percentage reduction in annual vessel-level CO₂ emissions achieved by the selected ESD package relative to the vessel's baseline annual emissions. Tankers, small: no feasible solution identified.

implemented in only 52 cases (almost exclusively on tankers) reflecting its low effectiveness, which limits its selection to vessels where every marginal reduction contributes to meeting the compliance threshold.

4.5. Sensitivity of results to ESD effectiveness and cost assumptions

The feasibility and economic performance of ESD adoption are highly sensitive to assumptions on measure effectiveness. Fig. 7 shows how feasibility, CO₂ savings, and economic outcomes vary across pessimistic, central, and optimistic variants.

The sensitivity of feasibility to effectiveness assumptions is substantial: the share of triggered vessels with a feasible solution ranges from 1.3% under pessimistic to 49.9% under optimistic assumptions, reflecting that even marginal changes in η determine whether a vessel can close the compliance gap to a CII rating of C. The cumulative CO₂ savings amplify this effect: the difference between variants is not driven by η alone but by the compound of fewer vessels reaching feasibility and lower per-vessel effectiveness simultaneously, resulting in a 4,600-fold spread between pessimistic (0.01 Mt) and optimistic (46.0 Mt) cumulative savings over the study period. The economic case undergoes a qualitative shift across variants: under pessimistic assumptions the median NPC turns positive (+1089 kEUR), indicating that at low effectiveness levels the fuel and regulatory savings generated are insufficient to recover investment costs, a threshold effect that disappears entirely under central and optimistic assumptions, where 95.8% and 100% of vessels record negative NPCs respectively.

Moreover, the three variants set all eleven measures to the low, mid, or high end of their efficiency ranges at the same time. Since it is unlikely that every measure is simultaneously at its worst or best, the resulting 1.3–49.9% spread is a best-to-worst scheme rather than a realistic error margin. To describe the uncertainty more realistically, the efficiency η of each measure was instead drawn randomly and independently from its respective range, using a triangular distribution centred on the central-scenario value, and the feasibility share was recomputed. Repeating this 10,000 times gives a median of 27.5%, which is essentially the central-scenario value of 27.6%, and places 90% of the outcomes between 18.2% and 35.4%. The share of vessels that can be restored to compliance is therefore fairly stable and remains a minority of the triggered fleet.

A further insight concerns the role of investment costs: whether a vessel achieves a feasible solution is entirely unaffected by CAPEX assumptions. Across all three cost scenarios within each effectiveness variant, the results are identical: the same vessels pass or fail the compliance threshold regardless of whether costs are assumed high, central, or low. This is because compliance depends solely on how much CO₂ a measure package can deliver, not on what it costs. Investment costs matter for the economic attractiveness of the solution (shifting NPC up or down) but not for whether one exists in the first place. The key uncertainty in ESD compliance assessment is therefore not cost, but effectiveness.

5. Discussion

The results highlight the magnitude of the compliance challenge: under unchanged technical and operational conditions, more than half of the fleet is projected to fall into CII non-compliance by 2030. While all segments are affected, exposure varies considerably. Segments characterized by older fleet structures and higher carbon intensity, such as small tankers and cruise/RoPax vessels, show particularly high vulnerability, whereas segments with newer fleets and lower-carbon fuels, such as LNG carriers, are comparatively less affected. This indicates that compliance risks are unevenly distributed and shaped by both technological characteristics and historical investment cycles. Against this background, conventional ESDs are insufficient to restore compliance for the majority of affected vessels. Even under optimistic assumptions, more than half of the triggered fleet cannot be brought back to

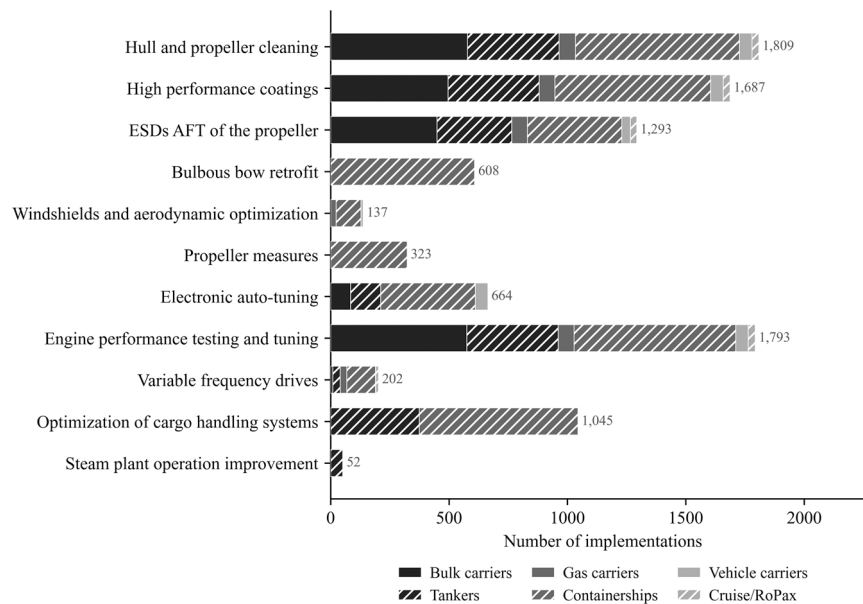


Fig. 6. ESD measure implementation frequency by ship type, central scenario.

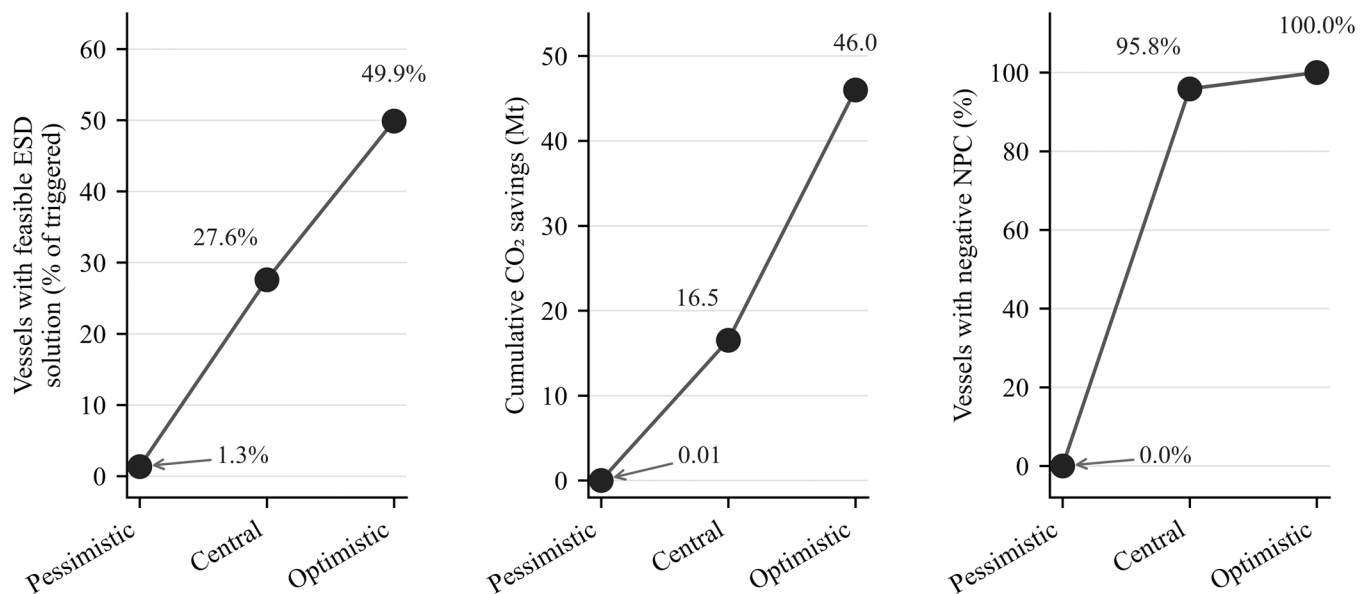


Fig. 7. Sensitivity of ESD feasibility, cumulative CO₂ savings, and economic viability to measure effectiveness and cost assumptions.

compliance, pointing to substantial compliance gaps that cannot be addressed through incremental efficiency improvements alone.

This limit is most apparent for small tankers, the segment where not a single triggered vessel can be brought back to compliance by the ESDs considered. The main reason lies in their emissions profile: small tankers use 52.5% of their fuel for AE and boiler systems, i.e. the highest of any tanker category and well above the tanker average of 35.5%. The applicable measures for small tankers act mainly on the ME and therefore reach less than half of their fuel consumption, while the dominant AE and boiler load can barely be reduced, as the applicable auxiliary measures are comparatively weak and the only relevant boiler measure is restricted to larger tankers. This is compounded by the applicability of ESDs: small tankers are also excluded from a number of measures, including the effective bulbous bow retrofit and propeller measures, leaving them fewer options to combine than other segments. As a result, even combining all applicable measures yields a median reduction of only 7.6%, against a median 32.2% required to restore a C rating by

2030. This gap cannot be closed for any of the 259 triggered small tankers, so the 0% feasibility is a structural technical limit that follows consistently from the model.

Cruise and RoPax vessels are limited in a similar way. On a cruise ship, almost half of the fuel (median 46.6%) is used by the AE and boiler systems that serve the hotel load, and because the available measures act mainly on the ME, this part can barely be reduced. Cruise ships can therefore cut only 8.5% of their emissions, against the 33.9% they would need to reach CII compliance by 2030, which is the widest gap of any segment. RoPax vessels have a lower AE load, but they are the oldest ships in the fleet (median build year 2000). Their age gives them a higher carbon intensity than modern, more efficient ships, so they need a large reduction (median 23.5%) that the available measures cannot provide. This picture holds across all scenarios: even under optimistic assumptions, only 6.8% of cruise ships and 30.4% of RoPax vessels can be brought back into compliance.

The other segments fall between these extremes. Containerships

stand out as the only segment where the measures can, for most ships, exceed the required reduction, giving the highest feasibility (70% under central assumptions). Bulk carriers, vehicle carriers and gas carriers are intermediate (36%, 38% and 21%), and tankers stay low even at the larger sizes (medium 12%, large 23%).

For the vessels that are projected to become non-compliant, alternative transformation pathways must be considered. Operational measures, such as speed reduction, can improve environmental performance without capital investment but introduce trade-offs in transport capacity (Degiuli et al., 2024). Advanced technologies, including wind-assisted propulsion and battery-based solutions, offer additional potential but require vessel-specific assessment and involve higher uncertainty (Thies and Ringsberg, 2023). For the 4745 vessels without a feasible ESD solution, the remaining gap is generally manageable. Even after all applicable measures, half of the ships still need about an 11% further CO₂ reduction, and 84% need less than 25%. Reductions of this dimension are typically within reach of a fuel switch, which delivers larger reductions than conventional ESDs (ABS, 2025). The choice between fuel switching and fleet renewal then depends mainly on a vessel's age: about half of these vessels were built in 2010 or earlier and are near the end of their typical economic lifetime by 2030, so replacing them through fleet renewal seems to be the more sensible pathway, whereas newer vessels, with many years of service left, appear to be better suited to a fuel switch.

Where a feasible ESD solution exists, the economic case is generally favourable. Fuel savings and reduced regulatory exposure typically outweigh investment costs, suggesting that financial constraints are unlikely to be the primary barrier to adoption. The more relevant barrier appears to be timing. Because the regulatory targets tighten over time, a large part of the fleet will most likely reach non-compliance within a few years; in this study, more than half by 2030. This figure need not correspond exactly to reality, but the trend is clear. Retrofit capacity, by contrast, is typically limited, since each vessel is scheduled for dry-docking only every few years. A near-term retrofit demand of this scale therefore risks overwhelming the available yard slots, and is compounded by potential supply-chain bottlenecks and the availability of technologies and expertise. Two actionable insights follow for policymakers. The first is to spread the demand rather than let it pile up: incentives for early retrofits, ideally during a ship's already scheduled dry-docking, could flatten the peak and avoid extra downtime, and building some timing flexibility into the regulations could have a similar effect. The second is to expand and secure the supply side: shipyard capacity, material supply chains, and skilled labour should be strengthened so that more vessels can be handled at once. Because the economic case for the retrofits is already favourable, these system-level measures may be the more important lever for delivering fleet-wide compliance.

Overall, the results underline that decarbonization in shipping is a multidimensional challenge that extends beyond efficiency improvements. While conventional ESDs can contribute to compliance for a subset of vessels, they are insufficient to close the broader structural gap. Achieving sustained compliance will therefore require a combination of measures, including operational adjustments, advanced technologies, alternative fuels, and fleet renewal.

Several limitations of this work should be acknowledged. First, operational measures such as slow steaming or voyage optimization were excluded, as the study focuses on technical retrofits. These measures are of a different nature: they require no CAPEX and do not fit the techno-economic optimization used in this work. In addition, they can be reversed rather than providing a permanent fix, and they may involve commercial trade-offs, since, for example, slow steaming reduces a ship's effective transport capacity (Bergström et al., 2023). Because such measures can lower a vessel's emissions and thereby the attained CII (Degiuli et al., 2024), the reported share of non-compliant vessels in this study should be interpreted as an upper bound.

Second, advanced technologies such as wind-assisted propulsion or

battery-based systems were also excluded, because it is difficult to draw generalized conclusions on their applicability across the fleet. They are not suitable for every ship, and their effect depends strongly on, for example, route, wind conditions, deck layout, and operating profile (DNV, 2025a), so they cannot be captured by the general, class-level efficiency factors used in this work and would instead require a ship-by-ship assessment. As a result, the reported compliance gap should be read as an upper bound: some vessels counted as having no feasible ESD solution could be served by these technologies, although the size of this effect is not quantified in this study. Taken together, the exclusions of operational and advanced technical solutions make the results conservative: adding these measures could improve compliance, which reinforces the main finding that conventional ESDs alone are not enough for most affected vessels to stay compliant with maritime climate regulations.

Third, implementation constraints were not explicitly modelled. Efficiency measures are assumed to be implemented without delay in the year following the compliance trigger, and drydock scheduling as well as shipyard capacity constraints are not considered. In addition, installation downtime, i.e. reducing operational availability and thus first-year fuel savings, was not accounted for. Consequently, the timing and economic performance of these measures may be somewhat optimistic.

Fourth, the share of time spent in EU waters was approximated using a twelve-month average from the Clarksons database rather than voyage-level tracking. While this approach provides a consistent fleet-wide proxy, it may introduce vessel-level inaccuracies in EU ETS and FuelEU Maritime exposure and associated cost estimates.

Fifth, the AIS-derived operating profiles are based on 2019 data. Shipping patterns may have shifted since then, and changes in trade patterns, routing, or speeds could affect the representativeness of the modelled activity over the 2025–2030 period. This concern is mitigated by the validation in Section 4.1, where the modelled sailing hours closely match the MRV-reported time at sea at the fleet level for 2025, indicating that the profiles still reproduce current fleet activity; nevertheless, further shifts over the projection period cannot be ruled out.

The findings of this work point to several directions for future research. A first priority is the integrated assessment of compliance pathways. In this paper, conventional efficiency measures, operational strategies, advanced technologies, and fuel switching were either analysed in isolation or excluded from scope. In practice, however, compliance strategies are likely to rely on combinations of these options. Modelling their interactions within a unified framework would therefore provide a more holistic and realistic representation of available pathways and their combined effectiveness.

Within such a framework, several sources of uncertainty warrant further attention. First, the wide efficiency ranges associated with conventional measures represent a key source of analytical uncertainty, as reflected in the sensitivity results. More granular, vessel-class-specific performance data would improve the robustness of fleet-level assessments. Second, future fuel price trajectories remain a critical determinant of the economic viability of both efficiency measures and fuel switching. Incorporating stochastic price dynamics would enable a more realistic evaluation of investment decisions under uncertainty. Third, implementation constraints (particularly drydock scheduling, shipyard capacity, and access to critical resources) remain largely unexplored, yet may significantly influence the feasibility and timing of technology adoption.

Finally, extending the analytical framework beyond the EU fleet to a global scale would allow the results to be placed in a broader context and support a more comprehensive assessment of compliance dynamics under international regulatory regimes.

6. Conclusion

This paper set out to determine how far conventional energy-saving technologies can keep the fleet operating in European waters compliant

as the CII, EU ETS, and FuelEU Maritime requirements tighten. The answer, across the fleet and broken down by segment, is that they help, but only in part: they restore compliance for a minority of the affected vessels, cheaply and reliably, while the majority stay out of reach.

Where retrofits work they pay off within a few years, so the obstacle is not financing but the technical reach of the measures and the capacity to install them in time. Moreover, the outcome is strongly segment-dependent. Containerships can be restored to compliance in most cases, whereas cruise ships, RoPax vessels, and small tankers cannot: in cruise ships and small tankers, a large share of fuel serves auxiliary and boiler loads that the measures acting on the ME cannot reduce; in RoPax vessels, an old fleet with correspondingly high carbon intensity requires a larger reduction than the measures can deliver.

The near-term compliance problem is therefore less a question of investment incentives than of matching the right measure to each segment, and of ensuring that shipyards, supply chains, and skilled labour can deliver the retrofits in time. For the segments that conventional efficiency cannot reach, the transition will need to draw earlier on advanced energy-saving technologies as well as alternative fuels and, for the oldest vessels, on fleet renewal.

CRedit authorship contribution statement

Joost Hobbie: Writing – original draft, Visualization, Software, Methodology, Conceptualization, Formal analysis. **Ishan Sontakke:** Writing – review & editing, Validation, Methodology, Conceptualization, Formal analysis. **Martin Bergström:** Writing – review & editing, Validation, Methodology, Conceptualization, Formal analysis. **Sören Ehlers:** Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

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