

Impact assessment of regulations on container shipping decarbonization: An evidence-based case study

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ABSTRACT

This case study explores the impact of four IMO and EU regulations addressing the green transition challenges of international shipping. The effects of these regulations on a sample fleet are evaluated through an optimization model, and the possibility of replacing the criticized IMO regulation on Carbon Intensity Indicator (CII) with a mid-term measure combination is examined. The results reveal that while current regulations incentivize energy efficiency measures and alternative fuel adoption, more is needed to meet the targets. The study stresses the importance of stronger incentives to encourage investments in green fuels and accelerate the industry's transition. The results imply that an IMO mid-term technical-economic measure combination offers greater flexibility and cost-effectiveness in reduction strategies, potentially overcoming the limitations of the existing CII. Although the study can contribute to the ongoing discourse on the recently agreed IMO Net-Zero Framework, it mainly aims at assisting shipping companies navigate current regulatory frameworks.

1. Introduction

1.1. Background

As the maritime industry emits about 3 % of global greenhouse gas (GHG¹) emissions (IMO, 2020), meeting the goals of the Paris Climate Agreement becomes urgent (UNFCCC, 2015). Following its fourth greenhouse gas study in 2020 (IMO, 2020), the International Maritime Organization (IMO) intensified its efforts to reduce GHG emissions from international shipping. This resulted in a new strategy being released in 2023 (IMO, 2023f). In parallel, the European Union (EU) adopted regional measures to fight carbon emissions within its regulatory scope, leading to the “Fit for 55” package (EC, 2021). These measures include the maritime industry in the EU's Emissions Trading System (EU ETS) (EC, 2023b) and the FuelEU Maritime regulation (EC, 2023c).

As the regulatory framework is being further developed, shipowners and operators face uncertainty over the future path of reducing emissions and are left with unanswered questions on which actions to pursue. IMO's short-term measures, the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), force shipowners to improve their ships' energy efficiency. At the same time, the EU ETS, the FuelEU initiative, and ongoing IMO discussions on midterm measures, such as a global Greenhouse Gas Fuel Standard (GFS) and a levy-like economic instrument, force an uptake of renewable fuels (EC, 2023c; IMO, 2024c). Uncertainty

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¹ A list of abbreviations appears as Appendix 1.

unavoidably accompanies these policy discussions.

Several institutions and industry stakeholders have examined the compliance options for ship operators, developed outlooks of the industry beyond 2030, and studied which policy measures would incentivize the desired behavior. This work includes, among others:

- Alternative fuels (EMSA, 2023; MI, 2023; DNV and Ricardo, 2023; Zou and Yang, 2023; Wang and Iris, 2025)
- CII effectiveness (Faber et al., 2021)
- Effects of different compliance options (Ricardo, 2022; Schroer et al., 2022)
- Impact of EU's regulations (Kleijn et al., 2022; Christodoulou and Cullinane, 2022; T&E, 2022; T&E, 2023; Trosvik and Brynolf, 2024)

Chen et al. (2023) reviewed recent literature regarding market-based measures with an urgent call to carefully design these measures to tackle carbon emissions effectively. On this matter, Kou et al. (2025), Sun et al. (2024), and Koesler et al. (2015) summarize the effects of ETS and carbon taxation while presenting implementation recommendations.

1.2. Policies and regulating authorities

1.2.1. The EU

The recently published regulations affecting shipping decarbonization in the EU are based on two pillars: 1) the inclusion of the maritime industry into the EU ETS and 2) the FuelEU Maritime regulation.

As of 2024, the maritime sector is included in the EU ETS scheme. A 40 % share of its 2024 emissions is already surrendered and paid for, while the corresponding share in 2025 will be 70 %, before 100 % of it must be compensated for from 2026 onwards. Additionally, the GHG scope will change. While considering only CO₂ emissions in 2024 and 2025, methane and nitrous oxide are also included from 2026. Each tonne of CO_{2eq} emissions on a Tank-to-Wake (TtW) basis must be surrendered (EC, 2023a; 2023b).

FuelEU, on the other hand, sets a limit on the GHG intensity of the energy used onboard a ship, thereby promoting the uptake of zero-emission² and near-zero-emission³ fuels. GHG emissions are accounted for on a Well-to-Wake (WtW) basis. Furthermore, the regulation sets benchmarks for the uptake of renewable fuels of non-biological origin (RFNBO) and enforces the usage of onshore power, also called cold ironing, in ports from 2030 onwards (EC, 2023c). The regulation also allows ship operators to pool ships into fleets. Thereby, the compliance unit becomes a group of selected ships rather than an individual ship.

Both the ETS and FuelEU regulations include 100 % of intra-EU trip emissions and 50 % of the emissions of voyages with one port outside of the EU as either origin or destination (EC, 2023a; 2023b; 2023c).

1.2.2. The IMO

As of 1973, IMO adopted the International Convention for the Prevention of Pollution from Ships (MARPOL) to prevent pollution of the marine environment by ships from operational or accidental causes. In May 2005, MARPOL Annex VI (Prevention of Air Pollution from Ships) entered into force. Annex VI sets limits on SOx and NOx emissions, prohibits deliberate emissions of ozone-depleting substances, and designates emission control areas where more stringent standards for SOx, NOx, and PM apply (IMO, 2025d). The first mandatory technical and operational carbon emission reduction measures were adopted in 2011 in the form of the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), respectively.

In 2021, IMO adopted its short-term measures focusing on a ship's energy efficiency. In this context, EEXI compares a ship's energy efficiency to a baseline considering its design parameters (IMO, 2022), while CII measures a ship's operational carbon emissions per transport work (IMO, 2021). The attained CII for a ship, measured through the Annual Efficiency Ratio (AER), is calculated on a yearly basis and must be within a specific rating level. The boundaries of this rating are reduced over time and have, so far, only been defined until 2026. After that, the CII, as a short-term measure, is subject to re-evaluation as part of IMO's 2023 strategy (IMO, 2023f), which introduced more ambitious GHG and emission reduction targets for the shipping industry.

Discussions are currently taking place on the foreseen midterm measures concerning a combination of a technical and a financial element (IMO, 2023f). Promising candidates for this are a GFS and a levy-like market-based measure (IMO, 2023a; 2024a; 2024c). GFS is comparable to the FuelEU scheme and measures the GHG intensity of used energy, while a levy assigns a price to each tonne of CO₂ or GHG emitted (IMO, 2023a). The discussions concern the emission scope (WtW versus TtW) and the exact implementation of a GFS or levy (IMO, 2023b; 2024d). In April 2025, while this study was under review, IMO reached an agreement on its so-called Net-Zero Framework (NZF). Its provisions, relevant to this work, are briefly presented in Section 4.2.

1.3. Motivation

The CII is heavily criticized by the industry (Ecochlor, 2023; Lloyds List, 2023a) due to flaws in its calculation approach (Ghaforian Masodzadeh et al., 2022; Lloyd's List, 2023b). This mainly concerns the effects of empty legs carrying only ballast water (Wang et al., 2021) and the discrepancies in deadweight tonnage (DWT) compared to actual cargo onboard (Ghaforian Masodzadeh et al., 2022; Kim et al., 2023). Additionally, older ships not covered by the Energy Efficiency Design Index (EEDI) standards have an advantage in

² Like green hydrogen and ammonia (Climate Analytics, 2023).

³ LNG or 'zero emission' fuels not derived from renewable energy (Climate Analytics, 2023).

compliance due to their usually oversized engines (Schroer et al., 2022).

Furthermore, the CII incentivizes the extensive application of Engine Power Limitation (EPL), leading to increased sailing times. E. g., Schroer et al. (2022) highlight that a ship's sailing time can increase by over 400 h a year, clearly affecting its usability and employment possibilities. It is often criticized that the CII, as a horizontal regulation, covers ships built to serve different trades and incentivizes slow steaming even on ships transporting perishable goods or running on just-in-time contracts.

This study extends the current research landscape by presenting compliance pathways for operators in a tightened regulatory environment from a practical perspective using real-life sample data from a fleet of 16 containerships. The study will be concerned with how this fleet can be made ready for the future by choosing the cost-optimal compliance pathway from a mixture of technical options and alternative fuels. Besides showing what is needed to comply, the study provides insights into the impact of the currently enforced regulations and derives recommendations for future policy adjustments. Thus, the study aims to address the following research questions:

RQ1: What are the effects of the current regulations on a containership operator, and what is needed for compliance?

RQ2: How should IMO design its midterm measures to substitute for the CII regulation while achieving its GHG reduction targets?

Although the effectiveness of various compliance options has been addressed in several studies in the past (Faber et al., 2021; Ricardo, 2022; Schroer et al., 2022), no attempt has been made in the direction of RQ2. Although the recently agreed NZF deprives the relevant discussion of any practical value, the model developed for the corresponding analysis can still be useful once adjusted to reflect the NZF arrangements.

2. Methodology

To answer the research questions, the study uses a dynamic linear optimization model based on DSC data (the Data Collection System of IMO) for the aforementioned 16 ships, which have been made available by the case company. The optimization model is set up to impose current and potential regulations on the ships, which can comply through technical, operational, or alternative fuel options.

This study extends the work by Schroer et al. (2022), which analyzed the compliance options of six ships with regard to EEXI and CII. The sample is now increased to 16 ships, alternative fuels are introduced as compliance options, and a linear optimization model is developed to examine the compliance with EU ETS, FuelEU, GFS, and a levy, in addition to EEXI and CII.

The modeling first applies the necessary EPL level, ensuring all ships comply with the EEXI regulation. Then, a check is conducted on whether one or more technical and operational compliance options (see Section 2.3) are cost-efficient for a specific ship. The purpose is to install the cost-beneficial compliance options over a ship's lifetime, assuming that a shipowner would install these options regardless of regulatory requirements. From this basis, the fleet's behavior is then optimized to comply with the regulations by choosing the minimal-cost path for using alternative fuels.

2.1. Fleet overview

The study uses 2018 to 2021 DCS data for a fleet of 16 sample ships, selected by the project company. Nine ships fall under EU regulations, as their itinerary includes EU waters. Table 1 presents descriptive data for the anonymized ships, where an average ship lifetime of 25 years is assumed. As can be seen, the remaining lifetime of the fleet spans from 4 to 17 years, with an average age of 16 years. The age of the ships will naturally impact the choice of compliance options.

2.2. Alternative fuels

The alternative fuels considered by the model are all green or blue⁴ renewable fuels. They are biofuels (FAME) and e-methanol from 2024 onwards, while e-hydrogen and e-ammonia are assumed to be available from 2030 onwards (DNV and Ricardo, 2023; IRENA, 2021; MMMCZCS, 2022b). LNG and the grey options of methanol, ammonia, and hydrogen are excluded. All examined fuels satisfy the requirements of IMO's interim guidance on the use of biofuels. Thus, the CII TtW emission factors can be calculated based on their WtW emissions⁵ (IMO, 2023c). The relevant TtW and WtW emission factors and Lower Calorific Values (LCV) are presented in Table 2. The values align with EU or IMO regulations and current literature (EC, 2018; EC, 2023c; IMO, 2023c; IMO, 2023e; Ricardo, 2022). Moreover, issues regarding fuel availability are not addressed; unlimited availability is assumed.

Retrofitting costs and revenue losses due to increased tank size for the alternative fuels are furthermore considered. The retrofitting costs are assumed to represent a portion of the newbuild investment cost of a ship and are set to 16 % for methanol (IMO, 2023d; MMMCZCS, 2021; MMMCZCS 2022a), 24 % for ammonia (IMO, 2023d; MMMCZCS, 2021), and 30 % for hydrogen (EMSA, 2023). The increases in tank size are given by MAN (2022), while new-build investment estimations are primarily derived from Murray (2016).

⁴ Using carbon capture and storage technologies to reduce carbon emissions.

⁵ Estimated through life cycle assessments that take the fuel production pathways into consideration.

Table 1

Overview of sample fleet with descriptive data.

Vessel name	Year of build	Remaining lifetime (years)	EU-fleet	Nominal TEU capacity	EEDI/EEI
A	2003	4	No	2,524	19.0
B	2014	15	Yes	10,500	9.3
C	2006	7	Yes	17,294	11.4
D	2006	7	Yes	17,294	11.6
E	2005	6	No	10,484	11.3
F	2005	6	Yes	10,484	11.3
G	2016	17	Yes	2,500	12.0
H	2011	12	No	4,496	9.7
I	2010	11	Yes	13,102	11.4
J	2004	5	Yes	8,450	14.7
K	2005	6	No	8,450	14.7
L	2008	9	Yes	5,560	16.7
M	2004	5	No	5,560	16.6
N	2005	6	No	5,560	14.3
O	2010	11	Yes	7,090	12.9
P	2011	12	No	7,090	12.9

Table 2

Overview of emission factors.

Fuel	LCV [MJ/g]	CII TtW [gCO ₂ /gFuel]	EU ETS TtW [gCO _{2eq} /gFuel]	FuelEU WtW [gCO _{2eq} /MJ]
Fuel Oil	0.0405	3.114	3.169	91.74
MDO	0.0427	3.206	3.261	90.77 ^(*)
Bio-Diesel	0.0372	0.863	0.918	23.20 ^(†)
e-Methanol	0.0199	0.269	0.324	13.50 ^(‡)
e-Ammonia	0.0186	0.000	0.000	15.00 ^(‡)
e-Hydrogen	0.1200	0.000	0.000	15.00 ^(‡)

Sources: (*) IMO (2023e); (†) Ricardo (2022) p. 57 and IMO (2023c) assigning WtW emissions for fuels saving 65% of GHG emissions and in line with EC (2018) p. 67 which fulfills Article 29; (‡) All e-fuels from Ricardo (2022) p.57 as average values between 2030 and 2050.

2.3. Compliance options

The six technical and operational compliance options considered include EPL, turbocharger cut-out (TCCO), waste heat recovery systems (WHRS), virtual arrival (VA), auxiliary engine economizer (AEE), and variable frequency drives (VFD). Their specific reduction potentials are based on Bouman et al. (2017). For further details on the compliance options, see Schroer et al. (2022), who discuss the application of these options regarding CII and EEXI regulations.

2.4. Assumptions

The following assumptions are made in modeling:

- CII compliance is achieved if a ship reaches the midpoint of Label C as of the regulation (IMO, 2021). Thus, compliance in terms of Label D for a maximum of three years or towards the lower bound of Label C could be possible and lead to a lessened implementation burden, albeit only temporarily.
- The drop-in amount of biofuel is set at a maximum of 30 % (MMMCZCS, 2023). In line with the results of recent tests from major shipping companies on biofuel use, the possibility of 100 % biofuel drop-in is also examined (Barsøe, 2024; Maersk, 2023).
- The amount of pilot fuel needed for methanol is 20 %, for ammonia 8 %, and for hydrogen 5 % (Barsøe, 2024; MMMCZCS, 2022b). Furthermore, biofuel can be used as pilot fuel.
- Each ship can only retrofit once, but there is no restriction to a ship's age regarding the timing of the retrofit.
- Due to the enforcement of onshore power usage in the FuelEU regulation, it is assumed that, while berthed at EU ports, 20 % of the auxiliary engine's energy will be delivered onshore and, therefore, account for zero emissions (EC, 2023c).
- All assumed costs are discounted to December 2023 values, and if necessary, prices are adjusted for inflation (IMF, 2024). Furthermore, currency conversion from USD to EUR is based on the official ECB exchange rate on February 8, 2024 (1USD = 0.93€) (ECB, 2024).
- The modeled fuel prices, expressed in €/tonne, are presented in Appendix 3. Using the LCV values of Table 2, Table 3 below transforms the prices of selected years in €/GJ.
- Forecasts for levy and ETS developments are based on current data from the European Energy Exchange (EEX) and ECB (2023), S&P Global (2022), ESMA (2022), and Enerdata (2023). Table 5 displays the used ETS prices (medium- and high-price schemes). In

Table 3
Fuel prices.

	HFO (€/GJ)	MDO (€/GJ)	Biofuel (€/GJ)	Methanol (€/GJ)	Ammonia (€/GJ)	Hydrogen (€/GJ)
2023	12.73	15.69	34.06	57.46	49.46	23.21
2030	12.45	15.35	29.95	43.39	35.87	19.89
2040	13.28	16.37	26.63	36.19	30.51	15.39
2050	13.97	17.23	24.72	30.18	24.91	10.89

contrast, the low-price scheme is used in the ‘Baseline’ and ‘CII-GFS-levy’ scenarios introduced in [Section 2.6](#), as it is assumed to be the most realistic development ([Enerdata, 2023](#); [S&P Global, 2022](#)).

- Both levy and EU ETS fees will be paid on TtW emissions, including all GHG gases. This aligns with EU ETS regulations and is assumed to be valid for a global levy. Because only e-fuels are considered in the study, critics of a TtW-based levy incentivizing grey alternative fuels are non-applicable ([EC, 2023a](#); [EC, 2023b](#); [IMO, 2023a](#)).

2.5. The model

The approach followed in this study is schematically depicted in [Fig. 1](#). The usual data analysis and preparation was followed by static calculations mainly concerning the necessary EPL levels to comply with the EEXI regulation. These calculations, performed in Python Jupyter Notebooks, served as inputs to a two-stage, cost-minimizing, mixed-integer linear programming (MILP) optimization model developed in Julia. The model was designed to evaluate optimal cost compliance across different regulatory scenarios.

As shown in [Fig. 1](#), the dynamic nature of the optimization process stems from splitting it into two runs, the first feeding its results to the second, albeit manually. In the first run, the model installs all cost-beneficial compliance options (excluding alternative fuels) without enforcing any regulations. In the second run, which takes the results of the first run into account, additional constraints are applied to reflect different regulatory scenarios and the use of alternative fuels. The main rationale for this splitting was the need to isolate the effects of the regulations (second run) from the installation of technical and operational compliance options that exhibit financial benefits irrespective of any regulation (first run).

Due to its length, the model is presented below only in textual form (after applying EPL to ensure EEXI compliance for each ship). A full description of its mathematical formulation, however, is presented in [Appendix 2](#), which also defines the variables, inputs, outputs, and interdependencies between the two optimization modules.

The objective of the optimization model used for the first run is to minimize the lifetime cost for each ship through available technical and operational compliance options. Thus, the objective function sums all relevant cost components discounted to 2023 values. These components include the cost of fuel and diesel oil consumed by the main engine(s), auxiliary engine(s), and boiler(s),

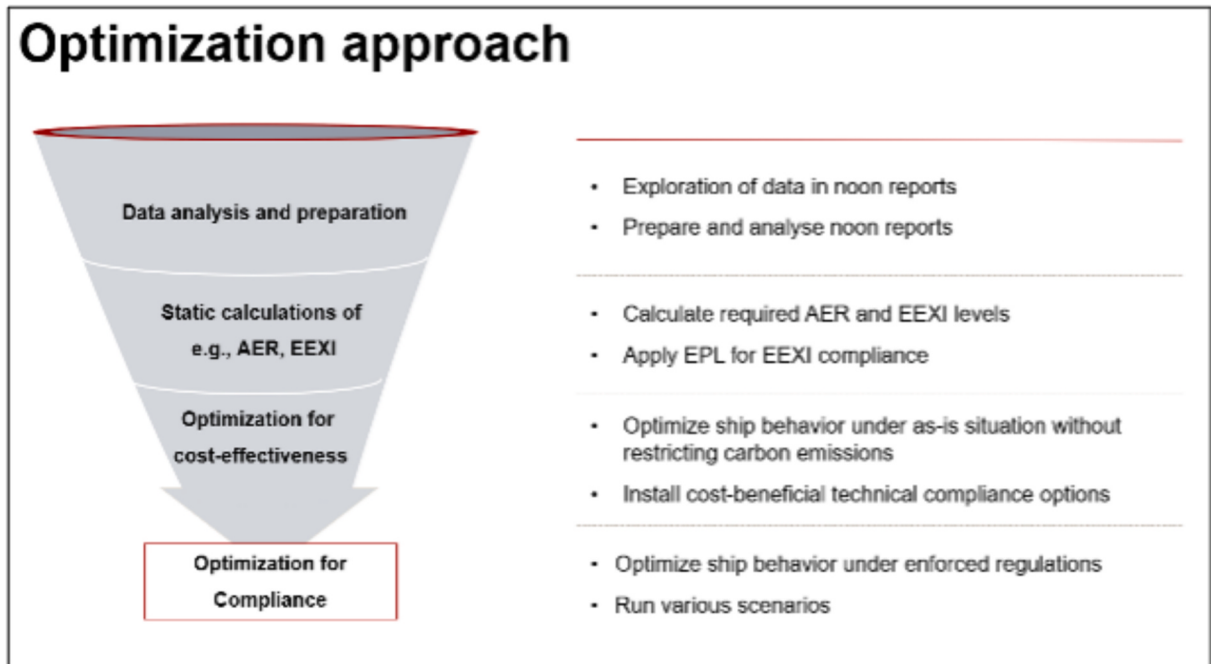


Fig. 1. Graphical depiction of the optimization approach followed.

increased by the capital (CAPEX) and operational/maintenance (OPEX) cost of the compliance options installed. All other costs are excluded from the objective function as unaffected by the installation of the compliance options. Note that all fuel consumptions considered concern operation prior to any optimization with regard to alternative fuels.

A number of constraints are applied in this first run to ensure that:

- The energy level of the fuels consumed by the main engine(s) after the installation of the compliance options is kept at the value they had before the installation, after accounting for the potential fuel consumption reductions due to the compliance options themselves (for every ship, every year in the period examined, and all potential compliance options)
- There is no substitution between fuel oil and diesel oil (for every ship, every year, every fuel type used, and all potential compliance options)
- The fuel consumption in the auxiliary engine(s) is set to the reduced value from potentially applied compliance options (for every ship, every year, every fuel type used, and all potential compliance options)
- There are no changes in the consumption of boiler(s) (for every ship, every year, and every fuel type used)
- The AER is calculated in accordance with the CII regulation. The reefer correction factor, which reduces over the years, is also taken into account in accordance with the same regulation (for every ship, every year, and all fuel types used)
- VFD systems for the turbogenerator condenser pumps can only be used together with a WHRS (for every ship, and every year)
- Only one EPL level can be applied at a time (for every ship, and every year)
- Any compliance option can only be installed once (for every ship and every compliance option)
- All decision variables are of the appropriate type and within the pre-set lower and upper bounds (for every ship, every year, and every compliance option).

The first model run lays the foundation for exploring four scenarios in a second model run. Here, the fuel mix and the compliance options under the CII, FuelEU, GFS, and EU ETS regulations are optimized by taking the results of the first model run as input. [Section 2.6](#) describes these scenarios and the constraints applied for the optimization procedure. The objective function continues to minimize the lifetime costs for each ship, now including costs related to the use of alternative fuels and/or penalties in case of their insufficient use.

2.6. Scenarios

The following scenarios are examined using the optimization model:

Baseline: This scenario reflects the current regulatory framework (CII, FuelEU, EU ETS) adjusted to impose compliance. In practice, this means that the non-compliance penalty is set so high that each ship must comply with the CII and FuelEU regulations yearly. This derives insights into the necessary actions for full compliance.

Again, the objective function is to minimize the sums of all relevant cost components discounted to 2023 values. The fuel costs are now split into the main engine consumption (fuel oil, diesel oil, methanol, biofuel, ammonia, and hydrogen), the auxiliary engine consumption (fuel oil and diesel oil), and the boiler consumption (fuel oil and diesel oil). Further costs considered are: a) the retrofitting costs for methanol, ammonia, and hydrogen dual-fuel engines; b) the secondary costs (forgone revenues) due to the increased size of methanol, ammonia, and hydrogen fuel tanks; c) the cost for non-compliance with FuelEU, the cost for non-compliance with CII, and the cost for EU ETS (price per emitted ton CO_{2eq}), d) the CAPEX for the installation of compliance options and the OPEX for compliance options, and finally e) the installation costs for EPL.

The following constraints applied to the second model run ensure that:

- The energy amount of the fuels consumed by the main engine(s) after optimization is kept at the value it had before optimization, after considering the compliance options installed in the first run (for every ship, every year in the period examined, all fuels and all potential compliance options)
- There is no substitution between fuel oil and diesel oil consumed by the main engine(s) (for every ship, every year, all fuels and all potential compliance options)
- The consumption of the auxiliary engines is adjusted to the compliance options installed in the first run (for every ship, every year, all fuels, and all potential compliance options)
- There are no changes in the consumption of boiler(s) for the ship's lifetime (for every ship, every year, and every fuel type used)
- The AER value is calculated in accordance with the CII regulation. It also considers the reefer correction factor, which is reduced over the years according to the same regulation (for every ship, every year, and all fuels used)
- Cold ironing is modeled to replace 20 % of the AE consumption from 2030 onwards. No emissions enter the AER calculation for cold ironing (in line with FuelEU)
- The AER value cannot exceed the AER limit of the regulation (set to the midpoint of Label C) (for every ship and year)
- Retrofitting to only one alternative fuel is possible per ship (for every ship)
- Biofuel is not being used together with other alternative fuels unless used as pilot fuel (for every ship and year)
- The consumption of biofuel and other alternative fuels aligns with the maximum drop-in or pilot-fuel requirements (for every ship and year)
- Hydrogen and ammonia can only be chosen from 2030 onwards (for every ship)

- The total emissions of the ship pool (all 16 sample ships) do not exceed the emissions targeted by the FuelEU directive (for every year after 2025)
- All decision variables are of the appropriate type and within the pre-set lower and upper bounds (for every ship and every year as appropriate).

CII pooling: Mimics FuelEU's pooling mechanism (EC, 2023c) for the CII regulation to provide flexibility for compliance. As shown by Faber et al. (2021), this could help shipowners and operators comply at a lower cost.

The scenario builds on the baseline scenario, to which the following constraints have been added, ensuring that:

- The value for the pooled AER is the weighted sum of the individual AER values of the pooled ships, using the transport work (= DWT * Distance sailed) of each ship as weight (for every year).
- The regulatory limit for the pooled AER is the weighted sum of the individual AER limits of the pooled ships, using the transport work (= DWT * Distance sailed) of each ship as weight (for every year).
- The pooled AER can be, at most, the pooled AER limit (for every year).

CII-GFS-levy: Both previous scenarios are applied on the EU fleet of the sample (this is the regulatory scope of FuelEU and EU ETS). On the contrary, the CII-GFS-levy scenario is developed to investigate the effects of a global GHG Fuel Standard and a levy, as these were being discussed at the IMO by the time of drafting (Spring 2024) (IMO, 2024a; IMO, 2024c). Here, compliance with the regulation is not enforced, but a penalty similar to the one proposed by FuelEU is applied. The GHG reduction factors of FuelEU (see Table 4) are used for this purpose, as no such factors have been specified for global use by a submission to IMO by the time of analysis (EC, 2023c). A levy on CO_{2eq}[TtW] is implemented with characteristics and prices similar to those of the EU ETS system (EC, 2023a; EC, 2023b). Even though the set-up of a levy and an ETS are different, they both incentivize behavioral change and penalize GHG emissions by assigning a price per unit of emissions. In this regard, this assumption appears appropriate (IMF, 2022).

In line with the FuelEU regulation, a banking arrangement is allowed for the global GFS scheme, meaning that compliance surpluses of the current year can be used for meeting the compliance requirements of the next year. This arrangement is extended to a pool of ships, where the compliance balance of the pool is defined as the sum of the individual compliance balances of the participating ships (for every year).

GFS-levy-No_CII: In view of the CII weaknesses discussed in the introduction, this scenario aims to understand the structure of a global GFS-levy combination that can achieve the same GHG emissions reduction as CII, FuelEU, and GFS together. In other words, the scenario is used for defining the parameters of a GFS and a levy required to eliminate the need for the CII. Thus, a GFS is implemented in line with IMO's indicative checkpoints and overall strategic goals (see Table 4) (IMO, 2023f). The penalty parameters are similar to those in the CII-GFS-levy scenario. There are no penalties on CII, as this regulation is not considered. Instead, the levy must be set high enough to impose GHG reductions similar to those of the regulation-enforced case. Different price levels are tested for the levy. No other adjustments to the optimization model are necessary.

3. Results

As previously stated, the study aims to identify the compliance requirements imposed by the regulations and to provide recommendations for further policy design. To evaluate the different scenarios, the financial implications for shipowners are analyzed along with the expected reductions in GHG emissions. These costs and emissions are compared to a reference level, ensuring that parameter changes within the scenarios are assessed against the same reference point to derive meaningful insights. The feasibility of scenarios and their implications are discussed in Section 4. For the sake of brevity, the results of only a small number of ships are presented in the following subsections. They were selected because they exhibit either a typical behavior or an unexpected finding worth commenting upon. The results of the remaining ships do not provide any additional insights.

3.1. Baseline scenario and CII pooling

According to the baseline scenario, the enforced compliance with FuelEU and CII leads to three (of a total of nine) EU ships retrofitting to hydrogen in 2030, four switching to methanol, and two continuing to use fuel oil. To comply, all ships use biofuel in the early years. For ships transitioning to hydrogen, biofuel uptake serves as a compliance option until 2030, alongside the implementation of low EPL levels. This is illustrated in Fig. 2, which shows the fuel uptake of three sample ships, and Fig. 3, which shows how CII compliance is achieved.

Generally, hydrogen is chosen if a ship transitions to an alternative fuel, as this offers the lowest lifetime cost for most sample ships. According to the data sources, hydrogen is, on average, 30–50 % cheaper than methanol and 33–43 % cheaper than ammonia over the remaining lifetime of the sample fleet. Since hydrogen will only be available from 2030 onwards, methanol will be chosen if an alternative fuel is required for compliance within the 2020 s. In cases where biofuel can entirely substitute fuel oil (100 % drop-in), this is preferred over methanol. Biofuel leads to CII and FuelEU compliance within this decade while at the same time being more cost-effective due to lower energy costs and no retrofitting investments.

It is worth noting that Ship C in Fig. 2 shows a practically unrealistic methanol usage in 2029–2031. The strictly enforced CII regulation forces even aged ships to switch to alternative fuel late in their lifetime. In real life, shipowners are unlikely to retrofit their vessels for such short periods; instead, they would opt for early scrapping or using the three-year D-Label option of the CII regulation.

Table 4

Overview of GHG intensity and reduction factors for FuelEU and the GFS-levy-No_CII scenario.

Year		2023	2025	2030	2035	2040	2045	2050
FuelEU	Reduction factor	0 %	2 %	6 %	14.5 %	31 %	62 %	80 %
	GHG intensity [gCO _{2eq} /MJ]	91.16	89.34	83.98	71.80	49.54	18.83	3.77
GFS-levy-No_CII scenario	Reduction factor	0 %	3 %	20 %	45 %	70 %	85 %	100 %
	GHG intensity [gCO _{2eq} /MJ]	91.16	88.43	72.93	50.14	27.35	13.67	0.00

Implementing a pooling mechanism for CII results in a 10 % reduction in costs because fewer ships transition to alternative fuels; see Fig. 2. However, emissions are projected to increase by 20–150 % between 2030 and 2035 compared to the baseline. This is not because the pooling arrangement is non-compliant. On the contrary, the enforced compliance of the baseline scenario generates much less emissions than those required by the IMO strategy. This discrepancy arises from optimizing vessel retrofitting for hydrogen usage and maximizing hydrogen consumption due to its lower cost per unit of energy than all other fuels. With pooling as an option, fewer ships must transition to alternative fuels, allowing one ship's over-compliance to compensate for others. As a result, the compliance balance of FuelEU is still positive but over 50 % reduced compared to the baseline; see Fig. 4. The main difference is that only one ship utilizes methanol in the CII pooling scenario in the years leading up to 2030. From 2030 onwards, the FuelEU compliance balance for the pool is lower in the CII pooling scenario than the baseline, as fewer ships (two instead of four) switch to hydrogen.

Furthermore, CII pooling changes the installation of technical compliance options. Some ships install more technical compliance options, mainly lower EPL levels, while others install less, as the benefits can be shared across the fleet. Fig. 3 highlights this behavior for ship G, where the AER level is reduced from 2026 to 2029 with EPL before the ship switches to hydrogen in 2030. Thus, ship G contributes significantly to the CII pooling compliance, as it is the cheapest ship to retrofit and apply low levels of EPL.

As illustrated in Fig. 3, ship C alone does not comply with the CII requirements after 2026. However, the fleet is still compliant with the regulation. Using biofuel as a drop-in fuel does not significantly impact cost or emission outcomes. This is particularly true in the initial years, where cost savings resulting from reduced emissions and, consequently, lower ETS costs are offset by the higher expense of biofuel compared to fuel oil.

3.2. Application of a GFS and a levy in addition to CII

This scenario aims to gain insights into the IMO discussions by the time of drafting (Spring 2024). As these discussions on mid-term measures were still ongoing, the GFS is assumed to have characteristics comparable to those of the FuelEU regulation. Furthermore, the levy is modeled with the same carbon price as the EU ETS in the preceding scenarios. However, the sample fleet is extended and no longer restricted to ships operating within the EU scope. As compliance with the regulations is not enforced, a significant difference in fuel uptake among the ships can be observed; see Fig. 5.

Logically, this scenario results in cost savings for shipowners (11.5 %). However, emissions are up to 60 % higher in 2035 compared to the baseline, representing excess emissions not aligned with IMO's emission reduction goals. Fig. 6 illustrates the GHG emission trajectories for this scenario. 81.25 % of the ships would not comply with the CII regulation in at least one year, while GFS compliance is achieved through banking (transferring emission credits/debits from one year to the other for the same ship) and pooling mechanisms. Thus, the enforced penalties are not sufficiently effective in forcing shipowners to reduce emissions; instead, they opt to pay non-compliance penalties. This finding is consistent with recent research from T&E (2022). Implementing a banking mechanism appears to have only minor effects, as the total cost and the GHG emission trajectory stay almost the same; see Fig. 6. Thus, the pooling mechanism is superior to the banking mechanism regarding compliance costs. Pooling is also superior in reducing GHG emissions compared to banking (−2%).

3.3. Is a GFS-levy combination able to substitute for CII?

To replace CII with a GFS-levy combination, the levy must significantly exceed current forecasts of the EU ETS. As outlined in Section 2.6, the applied GFS should establish stricter GHG intensity reduction requirements to meet the indicative checkpoints of the IMO strategy (20 % in 2030 and 70 % in 2040) (IMO, 2023f). To evaluate the effectiveness of various GFS-levy combinations, a reference was established where GFS and CII are enforced to create an emission reduction target line. Furthermore, high, medium, and low-levy schemes were developed and compared against this reference. The different levy schemes are presented in Table 5, and the CO_{2eq}[TtW] emission trajectories of the schemes are illustrated in Fig. 7.

The low-price scenario (yellow) falls short of achieving the required emission reductions illustrated by the compliance force (red). However, the high-price scenario (blue) surpasses them. Lifetime emissions for the low-price scenario sum to 9 Mt CO_{2eq}[TtW] emissions compared to 8.2 Mt of the reference. The variation in the outcomes of the low, medium, and high-price scenarios lies in the

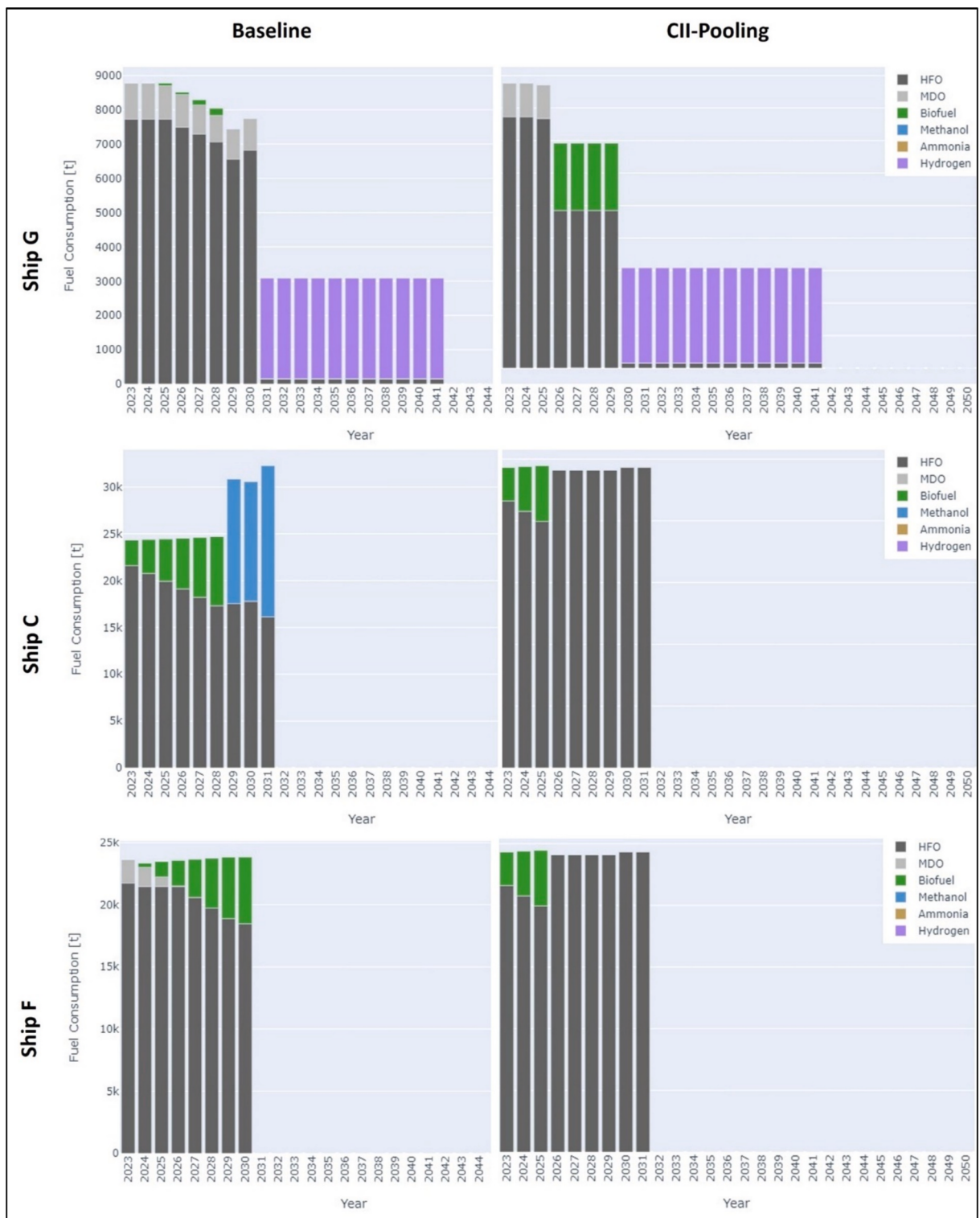


Fig. 2. Fuel consumption of sample ships in the baseline and CII pooling scenarios. (The operating profile, thus energy requirements of the ships remain constant throughout their remaining useful life, unless affected by the installation of compliance options – mainly EPL – in the early years).

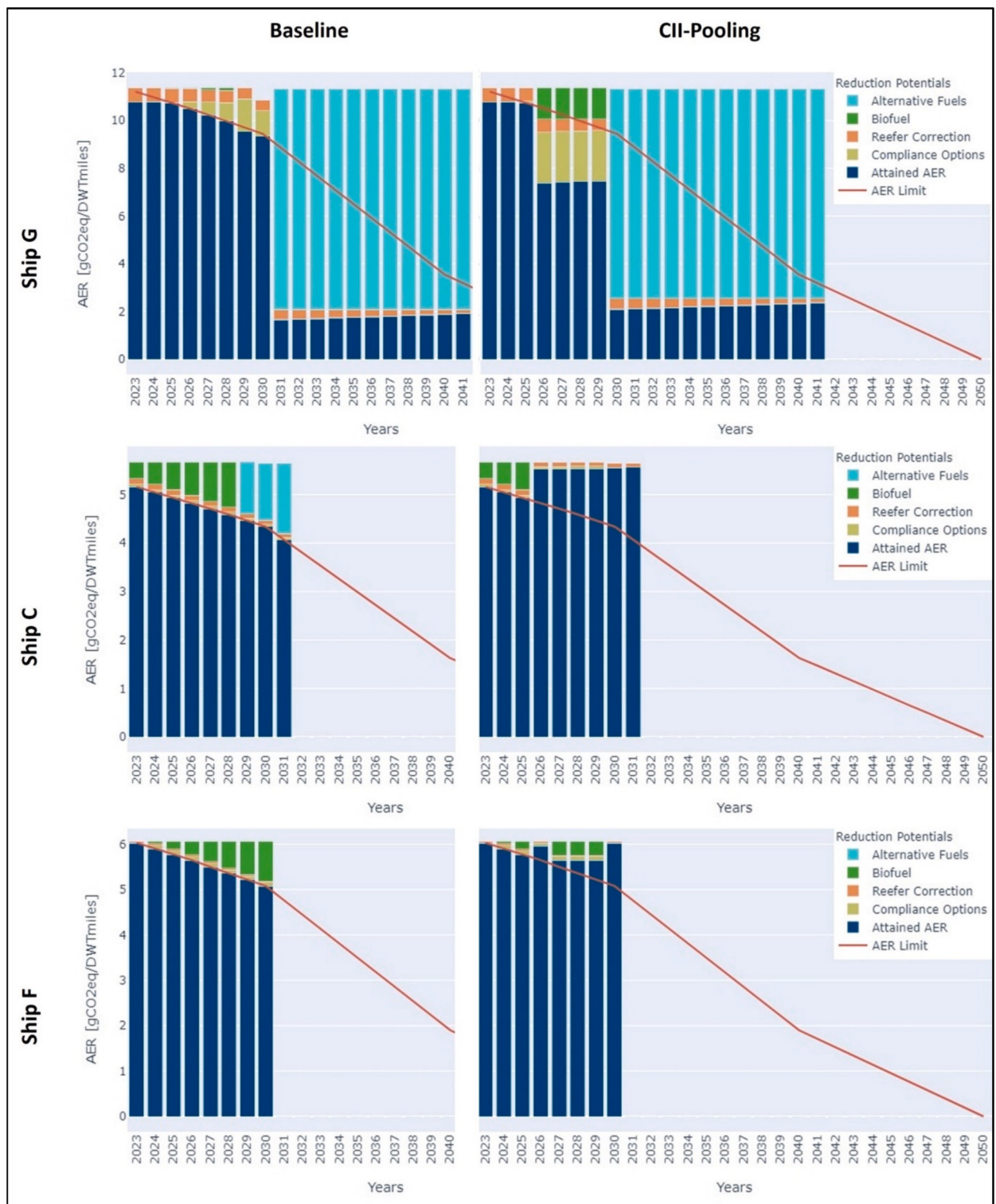


Fig. 3. CII compliance for selected sample ships in the baseline and CII pooling scenarios. Each graph showcases the individual development of the ships' AER over time. (The baseline scenario forces compliance on an individual ship level, whereas CII-pooling forces compliance on a fleet level).

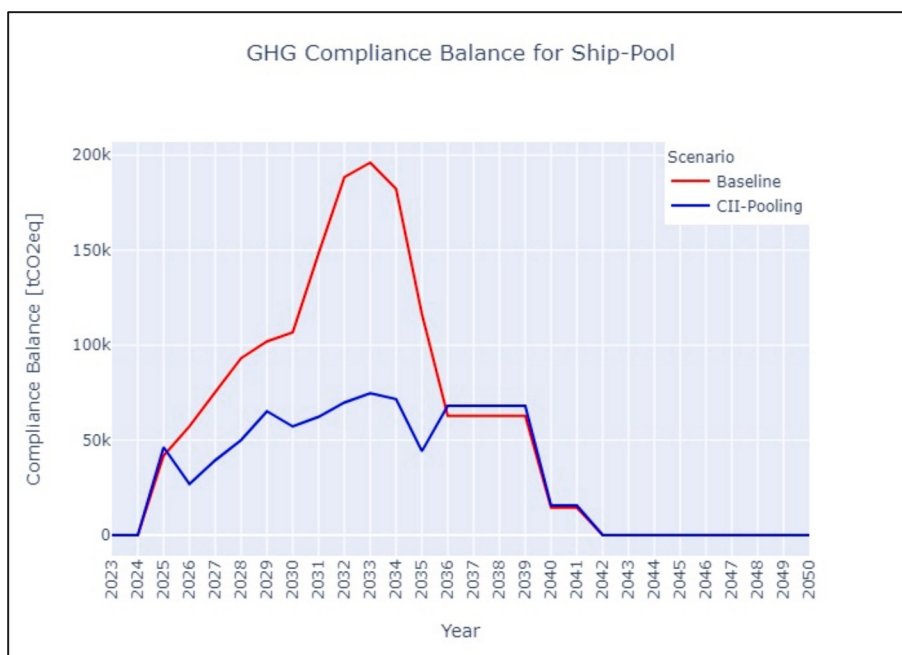


Fig. 4. Comparison of the EU-fleet pool compliance balances for the baseline and the CII-pooling scenarios. (Compliance balances are calculated in absolute values of mass – tonnes – by subtracting the product of the maximum allowed carbon intensity of energy with the actual energy used, from the actual carbon emissions of each ship in the pool, and summing over all participating ships).

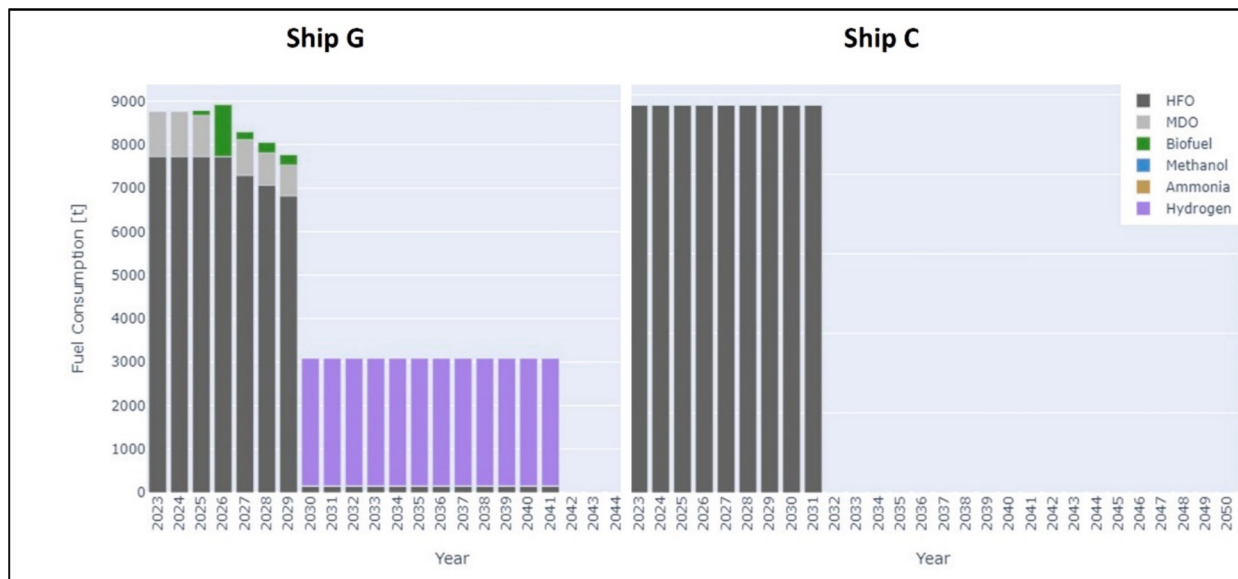


Fig. 5. Fuel consumption of Ship G and Ship C in the Scenario with a GFS based on FuelEU reduction values. (Compliance is not enforced; ships have the option to pay penalties instead).

uptake of alternative fuel. Fig. 8 illustrates the fuel consumption of sample ships G and C. The general behavior of ship G stays the same, with a slight variation in biofuel use from 2023 to 2029. The GFS pooling behavior and a changed fuel uptake of other ships can explain this.

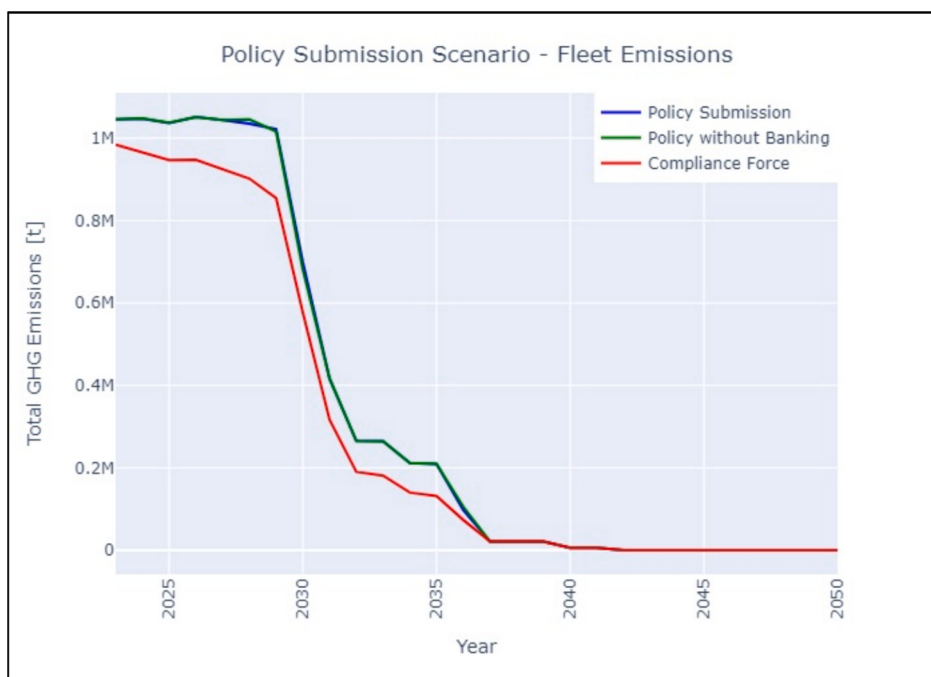


Fig. 6. Total GHG lifetime emission for a GFS based on FuelEU targets and a levy based on EU ETS prices. (The least-cost fuel mix resulting from the model for each ship and year is transformed into TtW carbon emissions through the relevant emission factors, and summed over all 16 ships. The decreasing curves are due to the progressively increasing use of compliance options and alternative fuels, and the exit of ships from the project fleet when they reach the corresponding age limit).

Table 5

Levy schemes in a GFS-levy-No_CII policy combination.

Year	Low price (€ per ton CO _{2eq} [TtW])	Medium price (€ per ton CO _{2eq} [TtW])	High price (€ per ton CO _{2eq} [TtW])
2023	85	85	214
2025	98	98	247
2029	130	250	328
2030	140	250	328
2035	140	200	403
2040	140	200	619
2045	140	200	1.026
2050	140	200	1.466

In contrast, ship C's fuel uptake changes significantly between the schemes. While forced to switch to ammonia in the high-price scenario,⁶ the medium and low-price scenarios result only in biofuel and fuel oil consumption. This effect makes the influence of the levy visible.

The medium-price scenario fails to meet the emission reduction targets until 2029 (+6%) before outperforming the baseline from 2030 onwards (refer to Fig. 7), resulting in fewer lifetime emissions (−2.9 %). Emissions will be reduced from 1.1 Mt CO_{2eq}[TtW] per year in 2023 to 6,000 t in 2040. The medium-price scenario proves to be 10.5 % more cost-effective than the high-price scenario; however, it is approximately 6 % costlier than the reference due to the deviation in emissions. Higher levy payments can explain this. Generally, the GFS-levy combination emits more GHGs until 2030. After that, it outperforms the reference case, as most ships switch to alternative fuel. However, there is no incentive to use many technical compliance options in the early years, contrary to the CII policy. Thus, all scenarios emit more emissions until 2030, after which the emissions decrease and eventually arrive at 2.9 % fewer lifetime emissions in the medium-price scenario. This is due to the strengthened requirement of the GFS in 2030 and a significant increase in levy towards the end of the decade.

Low-price levy schemes did not incentivize a sufficient number of ships to switch to alternative fuels, and, therefore, the emission

⁶ Due to the short lifetime of the vessel, ammonia's higher than hydrogen fuel prices are not sufficient to offset its advantage in terms of investment costs.

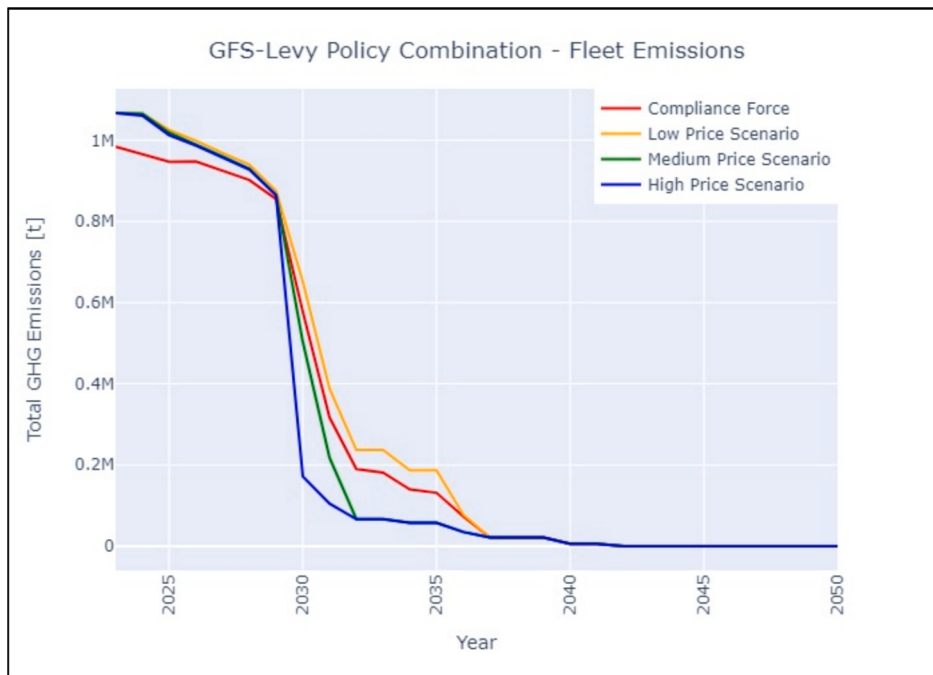


Fig. 7. Total GHG lifetime emission for the GFS-levy-No_CII scenario (Curves are produced as explained in Fig. 6).

targets were not met. Thus, the levy must create a strong incentive in 2029 and 2030 to force ships to transition to alternative fuels. Afterwards, the levy could decline and stay constant during the 2030 s and 2040 s. This finding aligns with forecasts introduced by ECB (2023), Enerdata (2023), and S&P Global (2022).

However, even the high-price scheme, with levy prices above 200 €/tonCO₂eq[TtW] in 2023 and 240 €/tonCO₂eq[TtW] in 2025, is insufficient to meet the baseline's emission targets in those early years, as the cost for technical compliance options or biofuel is still higher. This must be considered when assessing the rather ambitious and strict baseline implementation with highly enforced CII reduction values restricting compliance to the midpoint of Label C.

The individual CII requirements force ships to use technical compliance options, particularly low EPL levels, early this decade. Furthermore, CII forces more ships to transition to alternative fuels due to the absence of flexibility provided by a pooling mechanism. The GFS-levy-No_CII policy combination shares the gained compliance balance across the fleet. This reinforces earlier findings discussed in Section 3.1 on the advantage of a pooling mechanism and fleet compliance. Again, the effect of banking is insignificant, accounting for less than 2 % of cost and emission differences. This reinforces earlier findings, indicating that the pooling mechanism serves as the primary flexibility instrument in this sample.

3.4. Other findings

Based on the analysis performed, CII appears to be the regulation imposing the strictest requirements, driving up costs and producing surplus compliance balances for GFS or FuelEU; see Fig. 4. The strengthened requirements of CII urge ships to utilize more alternative fuel than if only GFS or FuelEU were enforced. This implies that ships can comply with GFS or FuelEU while remaining non-compliant with CII. In addition, the compliance price for CII can exceed the actual value of a ship, being as high as 40 M€ for ship B. Given that the CII regulation only foresees "corrective actions" (IMO, 2021) in the Ship Energy Efficiency Management Plan (SEEMP) without specified penalties, non-compliance, especially for older ships, is plausible.

Furthermore, the emission factors for alternative fuels significantly influence compliance with CII, FuelEU, or GFS. Assuming an extended vessel lifetime might result in ships failing to comply with CII despite fully utilizing hydrogen consumption. The reason is that IMO's interim guideline leads to non-zero TtW emissions for biofuel, eliminating it as a pilot fuel for full CII compliance after 2040. The model would, then, choose the cheaper heavy fuel oil as pilot fuel since compliance with CII is impossible anyway. Fig. 9 shows these effects in 2045 and 2046 for ship G. Thus, compliance with CII in line with IMO's strategy is only possible if TtW emissions for e-fuels, especially biofuel as a drop-in fuel, are set to zero. Alternatively, CII should be based on real WtW emissions.

Another interesting finding concerns the increased share of biofuel, which yields cost savings of up to 8.5 % for the sample fleet, as fewer ships need retrofitting to methanol. Ship C in the pooling arrangement of Fig. 3 is an example. However, due to a higher emission factor, this would increase emissions by 2.2 % compared to other alternative fuels, such as methanol. Fig. 10 shows the different fuel choices of ship L when biofuel can make up to 100 % of the fuel consumption.

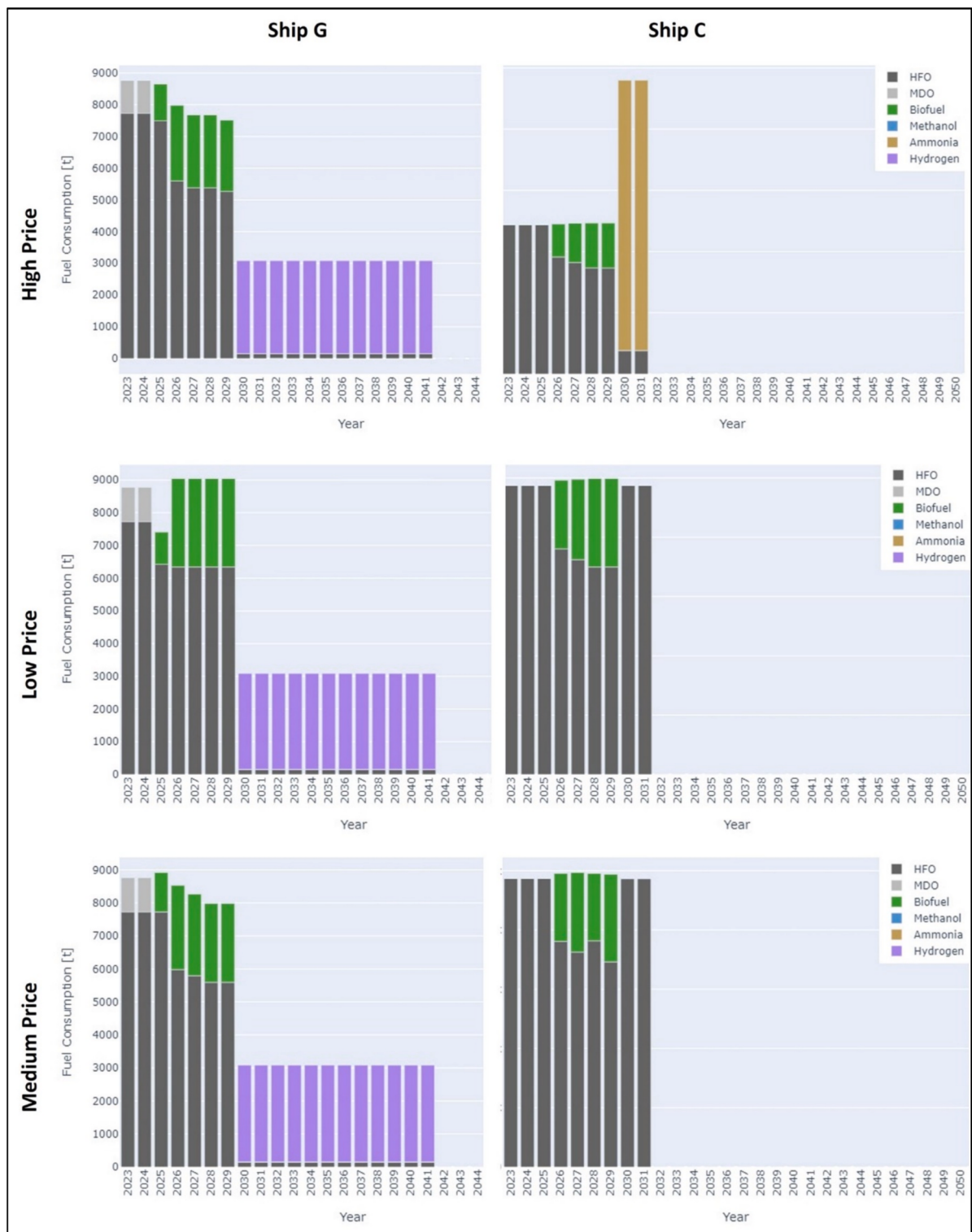


Fig. 8. Fuel consumption for ships G and C in the GFS-Levy-No_CII scenario for different price schemes.

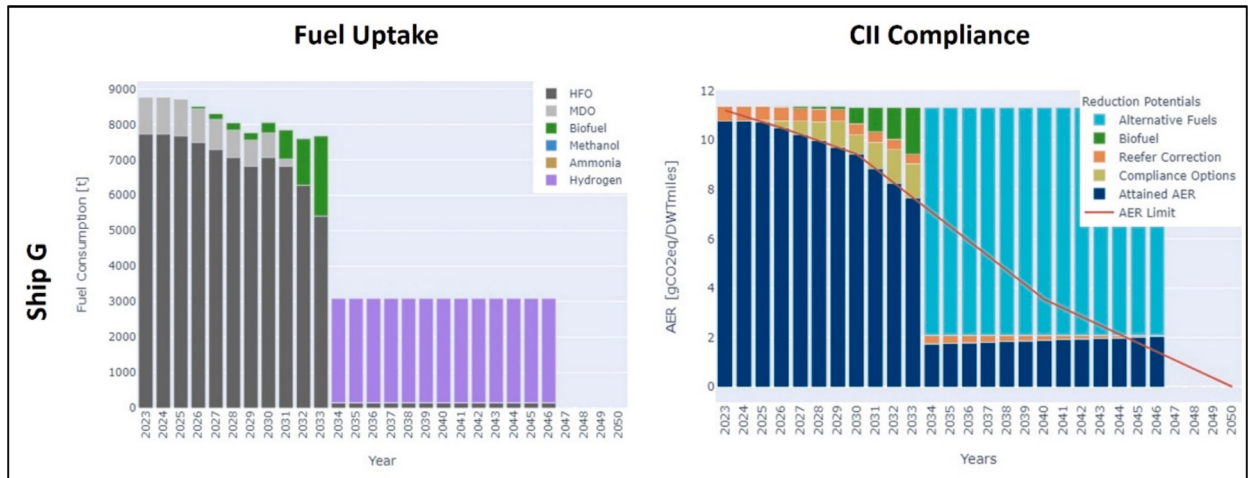


Fig. 9. Fuel consumption and CII compliance for ship G with a prolonged lifetime modeled.

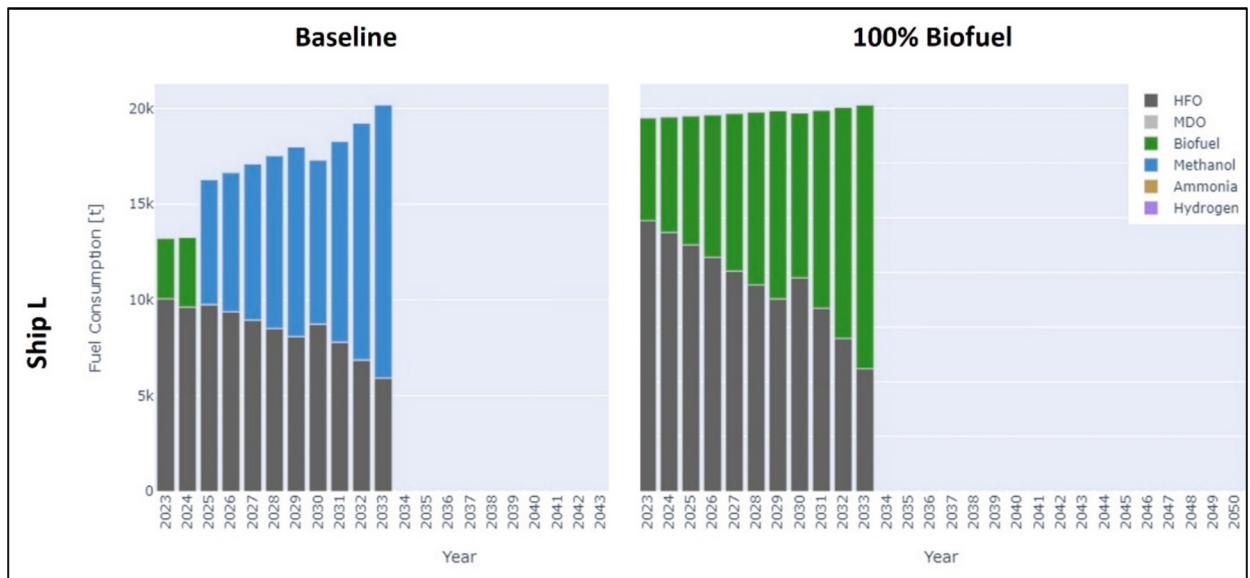


Fig. 10. Fuel consumption of ship L in the baseline scenario and a scenario allowing for 100% biofuel uptake.

4. Discussion and limitations

This section discusses the research questions outlined in [Section 1.3](#) based on the results presented above.

4.1. Impact of regulations and need for compliance

The analysis of the baseline, CII pooling, and CII-GFS-levy scenarios reveal shipowners' significant challenges when transitioning away from fossil fuels. The current CII regulation imposes substantial investments in vessel efficiency, while the FuelEU regulation incentivizes the adoption of alternative fuels. However, the results highlight the unrealistic implications of achieving full compliance on the ship level, forcing ships to transition to alternative fuel late in their life. This would, in practice, lead shipowners to scrap most of their ships earlier than the assumed lifetime of 25 years, as it is financially more advantageous to scrap a ship than to undergo investments for retrofitting. This will certainly be mitigated by introducing a pooling mechanism for CII compliance, as proven by [Faber et al. \(2021\)](#). However, since CII compliance is modeled in this study with the midpoint of Label C, a shipowner would first utilize the three-year Label D option before scrapping a ship. These findings have already been discussed by [Schroer et al. \(2022\)](#), who applied technical compliance options to a part of the sample fleet for CII compliance.

Nevertheless, the results echo concerns raised in existing literature regarding the inability of FuelEU to meet the goals of the Paris Agreement, primarily due to low penalty costs (Barsøe, 2024; T&E, 2022). Although the study did not consider grey alternative fuels, the results support concerns about the insufficient incentive to invest in green alternative fuels. This lack of incentive threatens a successful transition to environmentally sustainable alternatives, as discussed in Kleijn et al. (2022). These findings are also valid for the current GFS submissions to IMO, and to address the challenges, policymakers are urged to strengthen proposed GFS regulations. Options for addressing these challenges are a) implementing stricter GHG intensity reduction factors and b) imposing impactful penalties incentivizing shipowners to opt for alternative fuels over penalty payments. This would create an apparent demand for green alternative fuels, prompting respective energy producers to invest in the necessary supply infrastructure.

Regarding the EU ETS and respective levy structures, the findings align with current research, suggesting that current carbon prices are insufficient to initiate a behavioral change among operators and owners (Chen et al., 2023; IMF, 2022). Instead, variations in fuel and bunker prices have a significantly greater influence on decision-making. Thus, carbon prices must drastically increase to incentivize and effectively facilitate the green transition.

4.2. Substitution or advancement of CII

To address the identified weaknesses of the CII in Section 1.3, a GFS-levy-No_CII policy combination was developed to achieve identical emission reductions while offering shipowners and operators greater flexibility for emission reduction strategies.

Transport & Environment (T&E) has previously proposed adjusting the CII framework to achieve emission reductions effectively (IMO, 2024b). T&E advocated for an energy efficiency index (in MJ per transport work) to align incentives for green alternative fuels (IMO, 2024b). In contrast, the present study chose a technologically open approach to emission reduction. By combining a GFS with an impactful levy, shipowners can select the most cost-effective compliance measures at both the fleet or individual ship levels, whether through technical or operational measures or transitioning to alternative fuels. However, it must be noted that such a policy combination is only impactful if GFS and levy complement each other.

There is a certain sensitivity between the levy price and the GFS penalties. Depending on how these two parameters are chosen, different outcomes are incentivized. A high GFS penalty enforces the uptake of alternative fuel. At the same time, a higher levy could also lead to installing more fuel efficiency measures and technical and operational compliance options. Thus, the composition of the policy combination must be carefully considered. This is an issue that requires further research.

Furthermore, the approach broadens the focus to include all GHG gases and emphasizes a WtW consideration over TtW. This is aligned with the call from various stakeholders for IMO to revise the emissions scope of CII and its legislation (Faber et al., 2021; IMO, 2024b; IMO 2024d).

Another advantage is incorporating flexibility mechanisms such as pooling and banking, which reduce the need for stringent EPL levels on an individual ship level. Within the sample fleet, this led to fewer ships using EPL compared to the CII case. In contrast, fleet compliance was ensured by allocating the most cost-effective compliance measures among vessels. In this respect, Kou et al. (2025) find that a pooling arrangement can further enhance balancing emissions reduction and profitability through dual-speed policies (some ships accelerate and some decelerate). Thus, it is recommended that the IMO either replaces the CII or reconsiders introducing a pooling mechanism, streamlining and facilitating investments in new, more efficient vessels and supporting the adoption of ships capable of running on alternative fuels.

Regarding investments into a vessel's efficiency or the retrofit to alternative fuels, the industry's "split incentive" (Concawe, 2021) between shipowners and charterers must be mentioned. Due to the industry's structure, a shipowner is commonly responsible for Capex investments into a vessel, such as retrofitting or installation of compliance options, while the charterer typically covers operational costs, like fuel costs. If the party responsible for investments does not benefit from them, doubts may arise about the viability of those investments or whether investments are made at all (Concawe, 2021). Consequently, the adoption of energy efficiency measures or fuel retrofitting can be affected by this complication.

High levies reaching at least 250 €/tonCO_{2eq}[TtW] during the 2020 s are necessary to substitute for CII, which, despite the advantages, raises the question of whether this policy would get broad support across the IMO members. Furthermore, this policy recommendation struggles to achieve identical emission reductions until 2030 as those of a strict CII, potentially delaying crucial advancements in energy efficiency measures or adopting alternative fuels. This could further complicate the introduction of such a policy combination even though it seems superior to policies with a technological lock-in. However, this could be counteracted by utilizing the interdependency of levy prices and GFS penalties discussed above. On the other hand, the CII regulation, as applied today, is much softer than the strict CII assumed in the baseline scenario.

On 11 April 2025 (MEPC 83) and while the initial submission of this study was under review, IMO reached agreement⁷ on its mid-term measures, known as the IMO Net-Zero Framework (NZF) (IMO, 2025a). In the form of a set of regulations for the shipping industry to reach net-zero GHG emissions by or around 2050, it comprises of a combination of a technical and economic element (IMO, 2025b). The technical element consists of a Global Fuel Standard (GFS) that sets an increasingly strict well-to-wake GHG Fuel Intensity (GFI), similar in nature to the FuelEU regulation. Ships with a GFI above the targeted value must purchase Remedial Units (RUs), while those with a lower-than-target value can generate Surplus Units (SUs).

⁷ As this agreement was reached through the very rare voting procedure among IMO member states, the adoption of the agreed measures can only take place in the extraordinary MEPC meeting, scheduled for Oct. 2025, and with a majority among parties to MARPOL Annex VI of two thirds, representing at least 50% of global gross tonnage.

However, unlike FuelEU, the IMO's GFS introduces two compliance tiers. Tier 1, the so-called 'Direct compliance GFI', corresponds to the stricter ambitions of the revised IMO strategy, while the milder ones are reflected in Tier 2, the 'Base GFI.' This two-tier scheme forms the basis for the economic element of the NZF. Attained GFI values below Tier 1 generate SUs that can be used to balance deficits of ships with GFI values above Tier 2. Values between Tier 1 and Tier 2 generate 'Tier-1 deficits' that can be balanced only with the purchase (from a central IMO Net-Zero Fund) of RUs at a relatively low price (currently 100 USD/tCO₂eq[WtW]). Values above Tier 2 generate, on top of 'Tier-1 deficits' for the entire difference between the two tiers, 'Tier-2 deficits' that can be balanced through either the purchase of SUs from other ships, or the purchase of RUs from the IMO Net-Zero Fund, albeit at a higher price (currently 380 USD/tCO₂eq[WtW]). Proceeds of the IMO Net-Zero Fund will be used to: (i) reward the use of 'zero and near zero' (ZNZ) fuels and technologies (defined as those emitting below 19 gCO₂eq/MJ until 2034 and below 14 gCO₂eq/MJ onwards) at a unit price that remains to be set, and (ii) ensure a just and equitable transition by addressing, among others, disproportionately negative impacts to member states, especially Small Island Developing States (SIDS) and Least Developed Countries (LDC).

In view of these developments and pending the adoption of the agreed NZF, the discussion on possible substitution of CII by a GFS-levy combination, as well as the corresponding research question RQ2, are of historical significance only. Nevertheless, the model described in Section 2 provides a solid foundation for modeling the IMO's NZF and can be used to update the findings on research question RQ1, after the necessary modifications are performed mainly on its economic element (including the WtW scope of GFI, the two types of deficits involving different RU prices, and the reward for ZNZ fuels among others). Another need for adjustment, resulting from MEPC 83, concerns the CII reduction factors for the period 2027–2030, which are now determined at 13.625 % (2027), 16.25 % (2028), 18.875 % (2029), and 21.5 % (2030) relative to 2019, in place of the assumed values of 13 %, 16 %, 18 %, and 20 % in the model, respectively (IMO, 2025c). All these adjustments, however, can only take place during the next round of model development. Nevertheless, it needs to be noted that the findings of the study concerning CII (need to alter emission scope to WtW, introduction of a pooling arrangement, and the need to revise the biofuel TtW emission factors, remain valid.

4.3. Limitations and critical reflection

The present study exhibits limitations other than those derived from the recent regulatory developments (NZF) mentioned above. Its case-study nature undoubtedly results in limited generalization of the results achieved. However, the study provides valuable insights, and refrains from contradicting existing literature. Instead, the results align well with recent studies by T&E (2022; 2023), IMO (2023d; 2024b), DNV and Ricardo (2023), and Ricardo (2022) on the challenges of the uptake and availability of alternative fuels, as well as the technical feasibility of meeting the required emission targets. Notably, the availability of alternative fuels emerges as, and is known to be, a significant constraint (Faber et al., 2023; IMO, 2024b), a factor not explicitly addressed in this study. Particularly, the feasibility of transitioning a substantial part of the fleet to alternative fuels, here roughly 33–45 % to hydrogen, raises concerns, given projected production capacities (EMSA, 2023; MI, 2023). According to the results of this study, upscaling the demanded fuel to the global container ship fleet means that the voyage-based consumption of over 60 Mt HFO_{eq} would result in a yearly demand of 6.7–9.1 Mt of hydrogen or 40.3–54.9 Mt of methanol (IMO, 2020).

Moreover, the sensitivity of the results to the assumptions made, especially the influence of bunker, fuel oil, and alternative fuel prices, cannot be overstated. The preference for hydrogen in the model contrasts with alternative views favoring ammonia (T&E, 2023) or methanol (MI, 2023) as more cost-effective and viable options for container shipping. In the specific case of hydrogen, higher bunkering times have been left out of this study, which, in reality, would impose further costs on retrofitting to hydrogen. Generally, alternative fuel choice heavily depends on fuel price developments and forecasts and the Capex investments necessary for a retrofit.

Along with the input data discussed, limitations due to the sample size and the available compliance options influence the outcomes. The six compliance options considered represent only a part of the efficiency measures possible in practice. Options such as route optimization and utilization efficiency measures have been left out. Regarding the sample fleet, size and age influence the ship's behavior, with older vessels facing relatively higher retrofitting costs and shorter amortization periods. While retrofitting ships older than 10 years is known to be economically impractical (MMMCCZCS, 2022b), deploying new vessels completely running on alternative fuels, as exemplified by Maersk (2023), presents a more viable strategy.

A further limitation of the study stems from the range of alternative fuels examined. Although the project company does not consider fossil fuels such as LNG, other containership operators, including the global leader, rely on LNG among other solutions. The expansion of the fuel coverage can, thus, increase the practical value of the model developed here.

Lastly, the scenarios do not consider evolving trade volumes and, therefore, no increased fuel demand. However, the results are comparable to a low trade increase coupled with installing energy efficiency measures (e.g., IMO GHG4, SSP4_RCP6) as presented in IMO's 4th GHG study (IMO, 2020).

Regarding model viability, the results are consistent with existing research concerning fleet behavior. The extensive usage of EPL as an effective measure to reduce emissions is especially highlighted in the literature (Faber et al., 2023). Furthermore, the presented cost increase for a green scenario is similar to Faber et al. (2023) and T&E (2022; 2023). The assumption that cost-effective compliance

options will be installed despite regulatory influence is comprehensible, but can be affected by the mentioned ‘split incentive’ between investing and benefiting parties. Nevertheless, this study should be seen from a methodological point of view rather than as specific guidance for individual vessel compliance, as the results depend on various factors. Accordingly, the results must be seen within the context of the assumptions.

In summary, the presented study contributes valuable insights from a practical perspective, focusing on the needs of the shipping industry without considering broader economic dynamics. The model presented here forms the foundation for assisting the decision-making of shipowners in preparing for a greener future. Once updated to adjust to the regulatory reform of NZF, the model can also provide insights into setting pending parameters such as the level of reward for ZNZ fuels and technologies.

5. Conclusion

The study addressed two research questions regarding current emission policies affecting the shipping industry. A sample fleet of 16 container ships and the respective IMO DCS data for 2018–2021 were leveraged to assess the impact of these regulations through a dynamic linear optimization model. The diversity within the sample fleet appears extensive enough to derive general conclusions about the current container world fleet. However, the average age of the vessels significantly influences their behavior. Nevertheless, the results outline valuable insights into the challenges for the (container) shipping industry.

The first research question concerning the necessary actions to comply with FuelEU, EU ETS, CII, and a potential GFS regulation revealed that more than 50 % of the existing fleet must transition to alternative fuel to comply with the CII regulation. However, this can be reduced to 30 % if allowing for a flexibility mechanism in the form of pooling. This flexibility, which FuelEU offers, can significantly ease the shipowner’s approach to compliance while providing a more cost-effective way, saving over 10 % compared to individual compliance. Regarding FuelEU and the newly discussed GFS submissions to the IMO, the results are cohesive with existing literature on the shortfalls of these regulations to a) provide sound incentives to comply and b) enforce a pathway to meet the Paris Agreement requirements. Based on the results, the enforced penalties seem too low, which would lead to non-compliance for a majority of the fleet. However, existing pooling mechanisms provide shipowners with the flexibility to achieve compliance. This puts shipping companies under pressure to effectively utilize the flexibility mechanisms.

Addressing the second research question, the study examined the opportunity of substituting the rather criticized CII with a GFS-levy policy combination, offering more flexibility to ship operators and owners. The results highlight the general feasibility of such a policy combination, even though levy levels far beyond 200 €/tonCO_{2eq}[TtW] would be necessary during the 2020 s, in line with past research results (Trosvik and Brynolf, 2024). Whether such a policy combination would be attractive for a majority of the IMO members remains open, as different views from various stakeholders influence the decision-making process. Further, the discrepancy between the investment financier and beneficiary for efficiency and retrofitting measures on a vessel could negatively affect a fast transition to green alternative fuels. However, pending its adoption, the recently agreed NZF has eliminated all practical meaning from this discussion, as no levy is foreseen, while the economic element of the framework is built around a two-tier GFI. Nevertheless, once updated to adjust to the NZF, the model developed by this study can still provide insights concerning features of the framework that remain open. Furthermore, the study’s findings concerning CII-related issues that need improvement remain valid.

As this study provides insights into the shipping industry’s transition, additional research on compliance options and alternative fuels is necessary. In particular, extending the optimization approach presented to cover additional marine fuels, including LNG, and a larger sample fleet using the latest IMO DSC data could yield valuable insights into recent industry developments.

CRedit authorship contribution statement

Nils Lehmann: Investigation, Writing – original draft, Methodology, Visualization, Formal analysis. **George Panagakos:** Validation, Conceptualization, Supervision, Investigation, Writing – review & editing, Methodology. **Michael Bruhn Barfod:** Writing – review & editing, Conceptualization, Funding acquisition, Supervision, Validation, Methodology.

Declaration of Competing Interest

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

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Appendix 1. Abbreviations

AE	Auxiliary engine
AEE	Auxiliary engine economizer
AER	Annual efficiency ratio
BO	Boiler
CI	Cold ironing (applies from 2030 onwards)
CII	Carbon intensity indicator
CO	Compliance option
CO ₂	Carbon dioxide
DCS	Data collection system
DO	Diesel oil
DWT	Deadweight tonnage
EEDI	Energy efficiency design index
EEOI	Energy efficiency operational indicator
EEXI	Energy efficiency existing ship index
EPL	Engine power limitation
ETS	Emission trading system
EU	European Union
FO	Fuel oil
GFS	GHG fuel standard
GHG	Greenhouse gas
GT	Gross tonnage
HFO	Heavy fuel oil
ICE	Internal combustion engine
IMO	International Maritime Organization
ISWG	Intersessional Working Group
LCV	Lower calorific value
LDC	Least Developed Country
MARPOL	International Convention for the Prevention of Pollution from Ships (IMO)
MCR	Maximum continuous rating
MDO	Marine diesel oil
ME	Main engine
MEPC	Marine Environment Protection Committee
MRV	Measurement, reporting, and verification
NO _x	Nitrogen oxides
NZF	Net-Zero Framework (IMO)
PM	Particulate matter
SEEMP	Ship Energy Efficiency Management Plan
SIDS	Small Island Developing State
SO _x	Sulfur oxides
TCCO	Turbocharger cut-out
TtW	Tank-to-wake
VA	Virtual arrival
VFD	Variable frequency drives
VLSFO	Very low sulfur fuel oil
WHRS	Waste heat recovery system
WtT	Well-to-tank
WtW	Well-to-wake

Appendix 2. The optimization model

A2.1 Model assumptions

- Maximum drop-in amount of biofuel is set at 30 % (except for the scenario investigating the effect of no such limit)
- The maximum amount of methanol in the main engine is set at 80 %
- The maximum amount of ammonia in the main engine is set at 92 %
- The maximum amount of hydrogen in the main engine is set at 95 %
- Dual fuel engines can run either on the chosen alternative fuel or FO on a voyage by-voyage basis
- A vessel can only be retrofitted once
- Ammonia and hydrogen are only available from 2030 onwards
- Cold Ironing replaces 20 % of AE consumption from 2030 onwards
- All scenarios are run on the medium price range of the fuels
- The discount rate is 5 %

A2.2 Input data

Vessel-related data.

- Capacity and total distance sailed in a calendar year
- Ship lifetime counting 25 years from the construction year
- Fuel consumption values of FO and DO in ME, AE and boiler (after application of EPL for EEXI)
- AER limit (midpoint of C) for all years 2023 to 2050
- Value of the reefer correction factor
- Fixed and variable cost values for each technical compliance option and EPL level (after application of EPL for EEXI)
- Reduction potentials in % of fuel consumption for each technical compliance option and EPL level (after application of EPL for EEXI)
- Retrofitting costs for all alternative fuels
- Secondary cost for an increased fuel tank for all alternative fuels

Other data.

- FuelEU/GFS GHG intensity reference value
- Reduction percentages for the FuelEU/GFS reference value
- Reduction values of CII (AER Limit)
- Reduction percentage for the reefer correction factor
- Fuel price projections for all fuels from 2023 to 2050
- ETS and levy price projections from 2023 to 2050
- LCV values for all fuel types
- TtW, WtT, and WtW emission factors for all fuel types for different regulations
- Maximum alternative fuel uptake in main engine
- Discount rate

A2.3 Variable definition

Indices

C	Number of compliance options
F	Number of fossil fuels
S	Number of ships
Y	Number of years from 2023 to 2050

Variables

AER _{s,y}	AER calculated based on the applied fuel mix
AERDiffAfter _{s,y}	Difference between required AER and current AER after optimization
AERDiffBefore _{s,y}	Difference between required AER and current AER of fuels before applying fuel change or compliance options
AERLimit _{s,y}	AER requirement
AERLimitPool _y	AER requirement in the case of CII pooling
AERPool _y	Aggregated AER calculated in the model based on the applied fuel mix for the CII pool
AltFuelChosen _{s,y}	Binary; indicates if any of methanol, ammonia or hydrogen has been chosen
AltFuelExist _{s,y}	Binary; indicates in which years these fuels exist (thus secondary tank cost needs to be paid)
AltFuelRedPot _{s,y}	Reduction potential in AER value from alternative fuel change
AmmoChosen _s	Binary; indicates if ammonia has been chosen
AmmoFixedCost	Retrofitting cost for ammonia
BioChosen _s	Binary; indicates if biofuel has been chosen
BioExist _{s,y}	Binary; indicates in which years biofuel is used
BioRedPot _{s,y}	Reduction potential in AER value from biofuel change
Cap _s	Capacity of the vessel
CarbonCost _{s,y}	Total cost of ETS or levy scheme of a ship in a year
CO2Total _{s,y}	Total CO2 emissions of a ship in a year
ColdIroning	Factor to reduce AE consumption in CI case
CompBalBank _y	Total FuelEU/GFS compliance balance bank
CompBalInd _{s,y}	Addition or consumption of a vessel from the pool bank for FuelEU/GFS respectively
CompBalPool _y	Compliance balance of the pool for FuelEU/GFS
CompChosen _{s,c,y}	Binary; indicates if a technical compliance option has been chosen
CompExist _{s,c,y}	Binary; indicates if a technical compliance option exists in a year
CompExistOld _{s,c,y}	Binary; indicates if a technical compliance option exists in the first iteration of the model
CompFixedCost _{s,c}	Installation cost for technical compliance options
CompMaintOpeCost _{s,c,y}	Operating cost for technical CO for ME
CompRedPotME _{s,y}	Reduction potential of technical CO for ME
CompRedPotAE _{s,y}	Reduction potential of technical CO for AE
ConversionFacTtW-CII	TtW emission factor for FO and DO under CII regulation
ConversionFacAmmo	TtW emission factor for ammonia
ConversionFacHydr	TtW emission factor for hydrogen

(continued on next page)

(continued)

Indices	
ConversionFacBioTtW-CII	TtW emission factor for biofuel under CII regulation
ConversionFacMethTtW-CII	TtW emission factor for methanol under CII regulation
ConversionFacTtW-GHG	TtW emission factor for FO and DO incl. all GHG gases
ConversionFacBioTtW-GHG	TtW emission factor for biofuel incl. all GHG gases
ConversionFacMethTtW-GHG	TtW emission factor for methanol incl. all GHG gases
CORedPot _{s,y}	Reduction potential in AER value
CorrectionElectric _y	Fuel amount for reefer correction
Dist _s	Distance sailed by the vessel in the year
EPLChosen _{s,y}	Binary; indicates if EPL has been chosen
EPLChosenOld _{s,y}	Binary; indicates if EPL has been chosen in the first iteration of the model
EPLExist _{s,y}	Binary; indicates if EPL exists in a year
FuelConsAfterME _{s,f,y}	Fuel consumption for FO and DO in main engines as reported in the data after first model run
FuelConsAfterAE _{s,f,y}	Fuel consumption for FO and DO in auxiliary engines as reported in the data after first model run
FuelConsAfterBo _{s,f,y}	Fuel consumption for FO and DO in boilers as reported in the data after first model run
FuelConsBeforeME _{s,f,y}	Fuel consumption of ME as reported in DCS
FuelConsBeforeAE _{s,f,y}	Fuel consumption of AE as reported in DCS
FuelConsBeforeBo _{s,f,y}	Fuel consumption of boilers as reported in DSC
FuelConsAmmo _{s,y}	Fuel consumption for ammonia
FuelConsBio _{s,y}	Fuel consumption for biofuels
FuelConsHydr _{s,y}	Fuel consumption for hydrogen
FuelConsMeth _{s,y}	Fuel consumption for methanol
FuelPriceFO/DO _y	Fuel prices for FO and DO
FuelPriceAmmo _y	Fuel price for ammonia
FuelPriceHydr _y	Fuel price for hydrogen
FuelPriceMeth _y	Fuel price for methanol
FuelTankCostAmmo	Secondary cost for increased fuel tank size ammonia
FuelTankCostHydr	Secondary cost for increased fuel tank size hydrogen
FuelTankCostMeth	Secondary cost for increased fuel tank size methanol
GHGActual _{s,y}	Actual, attained GHG intensity of a ship in a year
GHGIntFossil _{WtW}	GHG intensity/WtW emission factors for FO and DO
GHGIntAmmo _{WtW}	GHG intensity/WtW emission factor for ammonia
GHGIntBio _{WtW}	GHG intensity/WtW emission factor for biofuels
GHGIntHydr _{WtW}	GHG intensity/ WtW emission factor for hydrogen
GHGIntMeth _{WtW}	GHG intensity/WtW emission factor for methanol
GHGtarget _{s,y}	Target GHG intensity as of the regulation
HydrChosen _s	Binary; indicates if hydrogen has been chosen
HydrFixedCost	Retrofitting cost for hydrogen
LCV	LCV value for FO and DO
LCV _{Ammo}	LCV value for ammonia
LCV _{Bio}	LCV value for biofuel
LCV _{Hydr}	LCV value for hydrogen
LCV _{Meth}	LCV value for methanol
LifeTime _s	Binary; indicates the ship's lifetime
M	Sufficiently high number
max _{Ammo}	Percentage; set maximum amount of ammonia in ME
max _{Bio}	Percentage; set maximum amount of biofuel in ME
max _{Hydr}	Percentage; set maximum amount of hydrogen in ME
max _{Meth}	Percentage; set maximum amount of methanol in ME
MethChosen _s	Binary; indicates if methanol has been chosen
MethFixedCost	Retrofitting cost for methanol
N	Binary; indicates if FuelEU or GFS compliance balance is negative
PoolShip	Vector of binaries that indicates which ships belong to a pool
r	discount rate
R	Binary; indicates non-compliance with CII regulation
ReeferRedPot _{s,y}	Reduction potential in AER value from reefer reduction factor
RefValue	FuelEU/GFS reference value
RefValueRed _y	FuelEU/GFS reference value reduction percentage
TotalEnergy _{s,y}	Total energy of a ship in a year
YearElectric _y	Number of years after initial reefer correction

A2.4 Model run I – selection of cost-beneficial compliance options

Objective function:

Minimize:

$$\begin{aligned}
& \sum_{s=1}^S \sum_{y=1}^Y \text{FuelPriceFO}_y * \text{FuelConsAfterME}_{s,1,y} * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelPriceFO}_y * \text{FuelConsAfterAE}_{s,1,y} * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelPriceFO}_y * \text{FuelConsAfterBo}_{s,1,y} * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelPriceDO}_y * \text{FuelConsAfterME}_{s,2,y} * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelPriceDO}_y * \text{FuelConsAfterAE}_{s,2,y} * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelPriceDO}_y * \text{FuelConsAfterBo}_{s,2,y} * \frac{1}{(1+r)^{y-1}} \\
& + \sum_{s=1}^S \sum_{y=1}^Y \sum_{c=1}^C \text{CompFixedCost}_{s,c} * \text{CompChosen}_{s,c,y} * \frac{1}{(1+r)^{y-1}} \\
& + \text{CompMaintOpeCost}_{s,c} * \text{CompExist}_{s,c,y} * \text{LifeTime}_{s,y} * \frac{1}{(1+r)^{y-1}}
\end{aligned}$$

The objective of the model is to minimize cost. The cost is split into eight categories:

1. Fuel cost for main engine consumption of fuel oil (before optimization)
2. Fuel cost for auxiliary engine consumption of fuel oil (before optimization)
3. Fuel cost for boiler consumption of fuel oil (before optimization)
4. Fuel cost for main engine consumption of diesel oil (before optimization)
5. Fuel cost for auxiliary engine consumption of diesel oil (before optimization)
6. Fuel cost for boiler consumption of diesel oil (before optimization)
7. CAPEX for installation of compliance options
8. OPEX for compliance options

subject to:

The following constraint ensures that the energy level of the fuels in the main engine after the optimization is kept at the same value it had before the optimization:

$$\begin{aligned}
& \sum_{f=1}^F \text{FuelConsAfterME}_{s,f,y} * \text{LCV}_f \\
& \geq \sum_{f=1}^F \text{FuelConsBeforeME}_{s,f} \\
& * \frac{\left(100 - \left(\sum_{c=1}^C \text{CompRedPotME}_{s,c} * \text{CompExist}_{s,c,y}\right)\right)}{100} \\
& * \text{LCV}_f * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y
\end{aligned}$$

The following constraint ensures that there is no change between FO and DO and vice versa:

$$\begin{aligned}
& \text{FuelConsAfterME}_{s,f,y} * \text{LCV}_f \\
& \geq \text{FuelConsBeforeME}_{s,f} \\
& * \frac{\left(100 - \left(\sum_{c=1}^C \text{CompRedPotME}_{s,c} * \text{CompExist}_{s,c,y}\right)\right)}{100} \\
& * \text{LCV}_f * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y, f \in F
\end{aligned}$$

The constraint below sets the fuel consumption in the auxiliary engine(s) to the reduced value from potentially applied compliance options:

$$\begin{aligned}
& \text{FuelConsAfterAE}_{s,f,y} \\
& \geq \text{FuelConsBeforeAE}_{s,f} \\
& * \left(\frac{100 - \left(\sum_{c=1}^C \text{CompRedPotAE}_{s,c} * \text{CompExist}_{s,c,y} \right)}{100} \right) \\
& * \text{LCV}_f * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y, f \in F
\end{aligned}$$

There are no changes for the consumption of the boiler(s):

$$\begin{aligned}
& \text{FuelConsAfterBO}_{s,f,y} \\
& \geq \text{FuelConsBeforeBO}_{s,f} * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y, f \in F
\end{aligned}$$

The following constraint calculates the value for the AER in accordance with the regulation. It also takes the reefer correction factor into account, which reduces over the years in accordance with the regulation:

$$\begin{aligned}
& \text{AER}_{s,y} = \\
& \left(\sum_{f=1}^F \left(\text{FuelConsAfterME}_{s,f,y} + \text{FuelConsAfterAE}_{s,f,y} + \text{FuelConsAfterBO}_{s,f,y} \right) \right. \\
& \quad * \text{ConversionFacTtWCII}_f \\
& \quad \left. - \left(\left((0.75 - 0.03 * \text{YearsElectric}_y) * \text{CorrectionReefer}_s \right) * \text{ConversionFacTtWCII}_{\text{HFO}} \right) \right) \\
& \quad * \frac{1}{\text{Cap}_s * \text{Dist}_s} * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y
\end{aligned}$$

This constraint ensures that TGCP (compliance option 14) can only be used together with a WHRS (compliance option 10):

$$\text{CompExist}_{s,10,y} \geq \text{CompExist}_{s,14,y} \quad \forall s \in S, y \in Y$$

The following constraint ensures that only one EPL level can be applied at a time (EPL are the compliance options 1 to 8):

$$\sum_{c=1}^8 \text{CompExist}_{s,c,y} \leq 1 \quad \forall s \in S, y \in Y$$

The following constraint sets EPLChosen to 1 in case there is any EPL existing in any year:

$$\sum_{c=1}^8 \sum_{y=1}^Y \text{CompExist}_{s,c,y} \leq \text{EPLChosen}_s * M \quad \forall s \in S$$

The following constraints ensure that CompExist is set to 1 from the year where a compliance option has first been chosen (for all non-EPL compliance options that are numbered 9 to 14):

$$\begin{aligned}
& \text{CompChosen}_{s,c,1} = \text{CompExist}_{s,c,1} * \text{LifeTime}_{s,1} \quad \forall s \in S \in [9, 14] \\
& \text{CompExist}_{s,c,y} - \text{CompChosen}_{s,c,y} = \sum_{y=1}^{Y-1} \text{CompChosen}_{s,c,y} * \text{LifeTime}_{s,y} \\
& \quad \forall s \in S \in [9, 14], y \in Y
\end{aligned}$$

The constraint below ensures that any compliance option can only be installed once:

$$\sum_{y=1}^Y \text{CompChosen}_{s,c,y} \leq 1 \quad \forall s \in S, c \in C$$

The following constraints set the decision variable types, as well as lower and upper bounds, where applicable:

$\text{FuelConsAfterME}_{s,f,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsAfterAE}_{s,f,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsAfterBO}_{s,f,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{CompChosen}_{s,c,y} \in \{0,1\}$	$\forall s \in S, c \in C, y \in Y$
$\text{EPLChosen}_s \in \{0,1\}$	$\forall s \in S$
$\text{CompExist}_{s,c,y} \in \{0,1\}$	$\forall s \in S, c \in C, y \in Y$
$\text{AER}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$N_{s,y} \in \{0,1\}$	$\forall s \in S, y \in Y$

The following outcomes from this model run are used as input values to the second run introduced in Section A2.5:

- CompExist variable from 1st run is set as CompExistOld variable for 2nd run
- EPLChosen variable from 1st run is set as EPLChosenOld variable for 2nd run
- FuelConsAfterME variable from 1st run is set as FuelConsBeforeME variable for 2nd run
- FuelConsAfterAE variable from 1st run is set as FuelConsBeforeAE variable for 2nd run
- EPLChosen variable from 1st run is set as EPLChosenOld variable for 2nd run

This results in the FuelConsBefore variables becoming 3-dimensional instead of 2-dimensional now, as the year y is added. Moreover, the following modifications are performed before the 2nd run:

- CompExist variable for the EPL values is set to 1 for all EPL levels higher than the level chosen from the 1st model run
- CompRedPotME gets reduced by the reduction potential applied in 1st run (for non-EPL, these are set to 0; for EPL these are reduced by the reduction potential of the applied EPL level)
- Variable cost estimation of EPL application gets reduced by the cost of the applied EPL level

This again results in the CompRedPotME as well as the CompMaintOpeCost becoming 3-dimensional instead of 2-dimensional with the year y as the additional dimension.

Furthermore, it is ensured that there is no reduction potential from compliance options that have been installed in the first run (and therefore already reduced the fuel consumption after the first run, which is here being used as the fuel consumption before the 2nd run).

A2.5 Model run II – Selection of fuel mix to comply with regulations (baseline scenario)

Objective function:

Minimize:

$$\begin{aligned}
 & \sum_{s=1}^S \sum_{y=1}^Y \text{FuelPriceFO}_y * \text{FuelConsAfterME}_{s,1,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceFO}_y * \text{FuelConsAfterAE}_{s,1,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceFO}_y * \text{FuelConsAfterBo}_{s,1,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceDO}_y * \text{FuelConsAfterME}_{s,2,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceDO}_y * \text{FuelConsAfterAE}_{s,2,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceDO}_y * \text{FuelConsAfterBo}_{s,2,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceMeth}_y * \text{FuelConsMeth}_{s,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceBio}_y * \text{FuelConsBio}_{s,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceAmmo}_y * \text{FuelConsAmmo}_{s,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{FuelPriceHydr}_y * \text{FuelConsHydr}_{s,y} * \frac{1}{(1+r)^{y-1}} \\
 & + \text{MethFixedCost}_s * \text{AltFuelChosen}_{s,y} * \text{MethChosen}_s * \frac{1}{(1+r)^{y-1}}
 \end{aligned}$$

$$\begin{aligned}
& + \text{AmmoFixedCost}_s * \text{AltFuelChosen}_{s,y} * \text{AmmoChosen}_s * \frac{1}{(1+r)^{y-1}} \\
& + \text{HydrFixedCost}_s * \text{AltFuelChosen}_{s,y} * \text{HydrChosen}_s * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelTankCostMeth}_s * \text{AltFuelExist}_{s,y} * \text{MethChosen}_s * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelTankCostAmmo}_s * \text{AltFuelExist}_{s,y} * \text{AmmoChosen}_s * \frac{1}{(1+r)^{y-1}} \\
& + \text{FuelTankCostHydr}_s * \text{AltFuelExist}_{s,y} * \text{HydrChosen}_s * \frac{1}{(1+r)^{y-1}} \\
& + M * R_y * \frac{1}{(1+r)^{y-1}} \\
& + M * N_{s,y} * \frac{1}{(1+r)^{y-1}} \\
& + \sum_{s=1}^S \sum_{y=1}^Y \text{CarbonCost}_{s,y} * \frac{1}{(1+r)^{y-1}} \\
& + \sum_{s=1}^S \sum_{y=1}^Y \sum_{c=1}^C \text{CompFixedCost}_{s,c} * \text{CompChosen}_{s,c,y} * \frac{1}{(1+r)^{y-1}} \\
& + \text{CompMaintOpeCost}_{s,c} * \text{CompExist}_{s,c,y} * \text{LifeTime}_{s,y} * \frac{1}{(1+r)^{y-1}} \\
& + \sum_{s=1}^S \text{EPLChosen}_s * \text{CompFixedCost}_{s,1} * (1 - \text{EPLChosenOld}_s) * \frac{1}{(1+r)^{y-1}}
\end{aligned}$$

The objective of the model is to minimize cost. The cost is split into 22 categories:

Fuel cost for main engine consumption of fuel oil (after optimization)
 Fuel cost for auxiliary engine consumption of fuel oil (after optimization)
 Fuel cost for boiler consumption of fuel oil (after optimization)
 Fuel cost for main engine consumption of diesel oil (after optimization)
 Fuel cost for auxiliary engine consumption of diesel oil (after optimization)
 Fuel cost for boiler consumption of diesel oil (after optimization)
 Fuel cost for methanol consumption in main engine (after optimization)
 Fuel cost for biofuel consumption in main engine (after optimization)
 Fuel cost for ammonia consumption in main engine (after optimization)
 Fuel cost for hydrogen consumption in main engine (after optimization)
 Retrofitting cost for methanol engine
 Retrofitting cost for ammonia engine
 Retrofitting cost for hydrogen engine
 Secondary cost for increased tank size for methanol fuel tank
 Secondary cost for increased tank size for ammonia fuel tank
 Secondary cost for increased tank size for hydrogen fuel tank
 Cost for non-compliance with FuelEU regulation
 Cost for non-compliance with CII regulation
 Cost for EU ETS (price per emitted tonne CO_{2eq})
 CAPEX for installation of compliance options
 OPEX for compliance options
 Installation cost of EPL with regard to the first run

Subject to:

Energy conservation

The following constraint ensures that the fuel before and after the optimization maintains the required energy level while also taking the ship's lifetime into account:

$$\begin{aligned}
& \sum_{f=1}^F \text{FuelConsAfterME}_{s,f,y} * \text{LCV}_f \\
& + \text{FuelConsMeth}_{s,y} * \text{LCV}_{\text{Meth}} \\
& + \text{FuelConsAmmo}_{s,y} * \text{LCV}_{\text{Ammo}} \\
& + \text{FuelConsHydr}_{s,y} * \text{LCV}_{\text{Hydr}} \\
& + \text{FuelConsBio}_{s,y} * \text{LCV}_{\text{Bio}} * \text{BioExist}_{s,y} \\
& \geq \sum_{f=1}^F \text{FuelConsBeforeME}_{s,f} \\
& * \left(100 - \left(\sum_{c=1}^C \text{CompRedPotME}_{s,c} * \text{CompExist}_{s,c,y} * 1 - \text{CompExistOld}_{s,c,y} \right) \right) / 100 \\
& * \text{LCV}_f * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y
\end{aligned}$$

The constraint below ensures that there is no fuel change happening from DO to FO and vice versa so that they can only be replaced by alternative fuels but not by one another:

$$\begin{aligned}
& \text{FuelConsAfterME}_{s,f,y} * \text{LCV}_f \\
& + \text{FuelConsMeth}_{s,y} * \text{LCV}_{\text{Meth}} \\
& + \text{FuelConsAmmo}_{s,y} * \text{LCV}_{\text{Ammo}} \\
& + \text{FuelConsHydr}_{s,y} * \text{LCV}_{\text{Hydr}} \\
& + \text{FuelConsBio}_{s,y} * \text{LCV}_{\text{Bio}} * \text{BioExist}_{s,y} \\
& \geq \text{FuelConsBeforeME}_{s,f} \\
& * \left(100 - \left(\sum_{c=1}^C \text{CompRedPotME}_{s,c} * \text{CompExist}_{s,c,y} * 1 - \text{CompExistOld}_{s,c,y} \right) \right) / 100 \\
& * \text{LCV}_f * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y, f \in F
\end{aligned}$$

Also, the consumption of the auxiliary engines is adjusted according to the compliance options installed in the first run:

$$\begin{aligned}
& \text{FuelConsAfterAE}_{s,f,y} \\
& \geq \text{FuelConsBeforeAE}_{s,f} \\
& * \left(100 - \left(\sum_{c=1}^C \text{CompRedPotAE}_{s,c} * \text{CompExist}_{s,c,y} * 1 - \text{CompExistOld}_{s,c,y} \right) \right) / 100 \\
& * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y, f \in F
\end{aligned}$$

There is no fuel change for the boiler(s). Only the ship's lifetime needs to be considered:

$$\text{FuelConsAfterBo}_{s,f,y} \geq \text{FuelConsBeforeBo}_{s,f} * \text{LifeTime}_{s,y} \quad \forall s \in S, y \in Y, f \in F$$

AER

The following constraint calculates the value for the AER in accordance with the regulation. It also takes the reefer correction factor into account, which reduces over the years. The second constraint introduces cold ironing from 2030 onwards, which is modeled to replace 20 % of the AE consumption and is accounted as 0 emissions (for FuelEU and assumed for CII):

$$\begin{aligned}
& \text{AER}_{s,y} \\
& = \left(\sum_{f=1}^F \left(\text{FuelConsAfterME}_{s,f,y} + \text{FuelConsAfterAE}_{s,f,y} + \text{FuelConsAfterBo}_{s,f,y} \right) \right) \\
& * \text{ConversionFacTtWCII}_f \\
& + \text{FuelConsMeth}_{s,y} * \text{ConversionFacMethTtWCII}
\end{aligned}$$

$$\begin{aligned}
& + FuelConsBio_{s,y} * ConversionFacBioTtWCII \\
& + FuelConsAmmo_{s,y} * ConversionFacAmmoTtWCII \\
& + FuelConsHydr_{s,y} * ConversionFacHydrTtWCII \\
& - (((0.75 - 0.03 * YearsElectric_f) * CorrectionReefer_s) * ConversionFacTtWCII_{HFO}) \\
& * \frac{1}{Cap_s * Dist_s} * LifeTime_{s,y} \forall s \in S, y \in [1,7] \\
& AER_{s,y} \\
& = \left(\sum_{f=1}^F \left(FuelConsAfterME_{s,f,y} + FuelConsAfterAE_{s,f,y} * ColdIroning \right) \right. \\
& \quad + FuelConsAfterBo_{s,f,y} \left. \right) * ConversionFacTtWCII_f \\
& \quad + FuelConsMeth_{s,y} * ConversionFacMethTtWCII \\
& \quad + FuelConsBio_{s,y} * ConversionFacBioTtWCII \\
& \quad + FuelConsAmmo_{s,y} * ConversionFacAmmo \\
& \quad + FuelConsHydr_{s,y} * ConversionFacHydr \\
& \quad - (((0.75 - 0.03 * YearsElectric_f) * CorrectionReefer_s) * ConversionFacTtWCII_{HFO}) \\
& * \frac{1}{Cap_s * Dist_s} * LifeTime_{s,y} \forall s \in S, y \in [8,Y]
\end{aligned}$$

The constraint below requires the AER to be at most the AER limit (which in the data is set to the midpoint of category C) or otherwise sets N to 1:

$$AER_{s,y} \leq AERLimit_{s,y} + M * N_{s,y} \forall s \in S, y \in Y.$$

Alternative Fuels

The following constraint ensures that only one retrofitting to an alternative fuel is possible per vessel:

$$MethChosen_s + AmmoChosen_s + HydrChosen_s \leq 1 \forall s \in S.$$

The constraints below ensure that the binary variable for an alternative fuel chosen is set to 1 if there is any consumption of the chosen fuel in any year:

$$\begin{array}{ll}
FuelConsAfterBio_{s,y} \leq BioChosen_s * M & \forall s \in S, y \in Y \\
FuelConsAfterMeth_{s,y} \leq MethChosen_s * M & \forall s \in S, y \in Y \\
FuelConsAfterAmmo_{s,y} \leq AmmoChosen_s * M & \forall s \in S, y \in Y \\
FuelConsAfterHydr_{s,y} \leq HydrChosen_s * M & \forall s \in S, y \in Y
\end{array}$$

The following constraint ensures that the BioExist variable is only set to 1 when there is biofuel consumption:

$$BioExist_{s,y} \leq FuelConsBio_{s,y} \forall s \in S, y \in Y$$

This constraint ensures that biofuel is not being used together with other alternative fuels:

$$FuelConsBio_{s,y} \leq M * (1 - AltFuelExist_{s,y}) \forall s \in S, y \in Y$$

The following constraints ensure that the fuel consumption of biofuel and the other alternative fuels are in line with the maximum drop-in or pilot-fuel requirements:

$$FuelConsBio_{s,y} \leq maxBio * \sum_{f=1}^F FuelConsAfterME_{s,f,y} + FuelConsBio_{s,y} \forall s \in S, y \in Y.$$

$$FuelConsMeth_{s,y} \leq maxMeth * \left(\sum_{f=1}^F FuelConsAfterME_{s,f,y} + FuelConsMeth_{s,y} \right) * AltFuelExist_{s,y} \forall s \in S, y \in Y.$$

$$FuelConsAmmo_{s,y} \leq maxAmmo * \left(\sum_{f=1}^F FuelConsAfterME_{s,f,y} + FuelConsAmmo_{s,y} \right) * AltFuelExist_{s,y} \forall s \in S, y \in Y.$$

$$FuelConsHydr_{s,y} \leq maxHydr * \left(\sum_{f=1}^F FuelConsAfterME_{s,f,y} + FuelConsHydr_{s,y} \right) * AltFuelExist_{s,y} \forall s \in S, y \in Y.$$

The next two constraints ensure that hydrogen and ammonia can only be chosen from 2030 onwards:

$$\begin{aligned} \text{FuelConsAmmo}_{s,y} &= 0 & \forall s \in S, y \in [1,7] \\ \text{FuelConsHydr}_{s,y} &= 0 & \forall s \in S, y \in [1,7] \end{aligned}$$

These constraints ensure that AltFuelChosen is set to 1 in the year when alternative fuel consumption appears first:

$$\begin{aligned} &\text{FuelConsMeth}_{s,Z} + \text{FuelConsAmmo}_{s,Z} + \text{FuelConsHydr}_{s,Z} \\ &\leq \sum_{y=1}^Z \text{AltFuelChosen}_{s,y} * M \quad \forall s \in S, Z \in Y \end{aligned}$$

The constraints below ensure that AltFuelExist is set to 1 from the first year the alternative fuel is chosen and onwards:

$$\begin{aligned} &\text{AltFuelChosen}_{s,1} = \text{AltFuelExist}_{s,1} * \text{LifeTime}_{s,1} \quad \forall s \in S \\ &\text{AltFuelExist}_{s,y} - \text{AltFuelChosen}_{s,y} = \sum_{y=1}^{Y-1} \text{AltFuelChosen}_{s,y} * \text{LifeTime}_{s,y} \\ &\quad \forall s \in S, y \in Y \end{aligned}$$

Compliance options

The following constraint ensures that TGCP (compliance option 14) can only be used together with a WHRS (compliance option 10):

$$\text{CompExist}_{s,10,y} \geq \text{CompExist}_{s,14,y} \quad \forall s \in S, y \in Y$$

This constraint ensures that only one EPL level can be applied at a time (EPL are the compliance options 1 to 8):

$$\sum_{c=1}^8 \text{CompExist}_{s,c,y} \leq 1 \quad \forall s \in S, y \in Y$$

The constraint below sets EPLChosen to 1 in case there is any EPL existing in any year:

$$\sum_{c=1}^8 \sum_{y=1}^Y \text{CompExist}_{s,c,y} \leq \text{EPLChosen}_s * M \quad \forall s \in S$$

These constraints ensure that the CompExist binary variable is set to 1 from the year where a compliance option has first been chosen (for all non-EPL compliance options that are numbered 9 to 14):

$$\begin{aligned} &\text{CompChosen}_{s,c,1} = \text{CompExist}_{s,c,1} * \text{LifeTime}_{s,1} \quad \forall s \in S, c \in [9, 14] \\ &\text{CompExist}_{s,c,y} - \text{CompChosen}_{s,c,y} = \sum_{y=1}^{Y-1} \text{CompChosen}_{s,c,y} * \text{LifeTime}_{s,y} \\ &\quad \forall s \in S, c \in [9, 14], y \in Y \end{aligned}$$

The following constraint ensures that a compliance option can only be installed once:

$$\sum_{y=1}^Y \text{CompChosen}_{s,c,y} \leq 1 \quad \forall s \in S, c \in C$$

FuelEU and GFS compliance

The following constraint calculates the total energy produced by a ship in a year. This is important for calculating the compliance balance for FuelEU or GFS:

$$\begin{aligned} &\text{TotalEnergy}_{s,y} \\ &= \sum_{f=1}^F \left(\text{FuelConsAfterME}_{s,f,y} + \text{FuelConsAfterAE}_{s,f,y} + \text{FuelConsAfterBo}_{s,f,y} \right) \\ &\quad * \text{LCV}_f \\ &\quad + \text{FuelConsBio}_{s,y} * \text{LCV}_{\text{Bio}} \\ &\quad + \text{FuelConsMeth}_{s,y} * \text{LCV}_{\text{Meth}} \\ &\quad + \text{FuelConsAmmo}_{s,y} * \text{LCV}_{\text{Ammo}} \\ &\quad + \text{FuelConsHydr}_{s,y} * \text{LCV}_{\text{Hydr}} \quad \forall s \in S, y \in Y \end{aligned}$$

The next two constraints calculate the GHG target as well as the GHG actual value in order to calculate the compliance balance:

$$\text{GHGtarget}_{s,y} = \text{RefValue}_s * \text{RefValueRed}_y * \text{TotalEnergy}_{s,y} \quad \forall s \in S, y \in Y$$

As cold ironing is modeled to replace 20 % of the AE consumption from 2030 onwards and this is accounted as 0 emissions, a separate constraint applies for these later years involving the ColdIroning variable:

$$\begin{aligned}
& GHGactual_{s,y} \\
&= \sum_{f=1}^F \left(FuelConsAfterME_{s,f,y} + FuelConsAfterAE_{s,f,y} + FuelConsAfterBo_{s,f,y} \right) \\
& * LCV_f * GHGIntFossilWtW_f \\
&+ FuelConsBio_{s,y} * LCV_{Bio} * GHGIntBioWtW \\
&+ FuelConsMeth_{s,y} * LCV_{Meth} * GHGIntMethWtW \\
&+ FuelConsAmmo_{s,y} * LCV_{Ammo} * GHGIntAmmoWtW \\
&+ FuelConsHydr_{s,y} * LCV_{Hydr} * GHGIntHydrWtW \quad \forall s \in S, y \in [1, 7]
\end{aligned}$$

$$\begin{aligned}
& GHGactual_{s,y} \\
&= \sum_{f=1}^F \left(FuelConsAfterME_{s,f,y} + FuelConsAfterAE_{s,f,y} * ColdIroning \right. \\
&+ FuelConsAfterBo_{s,f,y} \left. \right) * LCV_f * GHGIntFossilWtW_f \\
&+ FuelConsBio_{s,y} * LCV_{Bio} * GHGIntBioWtW \\
&+ FuelConsMeth_{s,y} * LCV_{Meth} * GHGIntMethWtW \\
&+ FuelConsAmmo_{s,y} * LCV_{Ammo} * GHGIntAmmoWtW \\
&+ FuelConsHydr_{s,y} * LCV_{Hydr} * GHGIntHydrWtW \quad \forall s \in S, y \in [8, Y]
\end{aligned}$$

The constraint below calculates the compliance balance for FuelEU or GFS for each ship in a year. The regulation starts in 2025 (i.e., $y = 3$):

$$CompBalInd_{s,y} = GHGactual_{s,y} - GHGtarget_{s,y} \quad \forall s \in S, y \in [3, Y]$$

The following constraint enforces the pool compliance:

$$CompBalPool_y = \sum_{s=1}^S CompBalInd_{s,y} * PoolShip_s \quad \forall s \in S, y \in [3, Y]$$

$$CompBalPool_y * (1 - R_y) \geq 0 \quad \forall y \in [3, Y]$$

ETS Cost

The first constraint calculates the ETS/Levy cost as a carbon cost per year per ship. The CountFactor is a percentage as of the EU ETS regulation and is 40 % in 2024 and 70 % in 2025. In this period only CO₂ is accounted for, which is why the TtW conversion factor for CII is used:

$$\begin{aligned}
& CarbonCost_{s,y} = CountFactor_y * CarbonPrice_y \\
& * \left[\sum_{f=1}^F \left(FuelConsAfterME_{s,f,y} + FuelConsAfterAE_{s,f,y} + FuelConsAfterBo_{s,f,y} \right) \right. \\
& \quad * ConversionFacTtWCII \\
& \quad + FuelConsBio_{s,y} * ConversionFacBioTtWCII \\
& \quad + FuelConsMeth_{s,y} * ConversionFacMethTtWCII \\
& \quad + FuelConsAmmo_{s,y} * ConversionFacAmmo \\
& \quad \left. + FuelConsHydr_{s,y} * ConversionFacHydr \right] \quad \forall s \in S, y \in [2, 3]
\end{aligned}$$

Because from 2026 onwards the regulation extends coverage to include all GHG gases, the constraint below uses the GHG TtW conversion factor for these years. Furthermore, the CountFactor is left out because from 2026 onwards 100 % of emissions are covered by the regulation:

$$\begin{aligned}
& CarbonCost_{s,y} = CarbonPrice_y \\
& * \left[\sum_{f=1}^F \left(FuelConsAfterME_{s,f,y} + FuelConsAfterAE_{s,f,y} + FuelConsAfterBo_{s,f,y} \right) \right. \\
& \quad * ConversionFacTtWGHG \\
& \quad + FuelConsBio_{s,y} * ConversionFacBioTtWGHG \\
& \quad + FuelConsMeth_{s,y} * ConversionFacMethTtWGHG \\
& \quad + FuelConsAmmo_{s,y} * ConversionFacAmmo \\
& \quad \left. + FuelConsHydr_{s,y} * ConversionFacHydr \right] \quad \forall s \in S, y \in [4, Y]
\end{aligned}$$

AER Reduction calculations

The following constraints are not necessary for the optimization approach but help to understand the AER reduction potentials and are used to evaluate the feasibility of the results. They are listed below:

Calculation of difference of attained AER and required AER before and after optimization:

$$\begin{aligned}
& AERDiffBefore_{s,y} \\
& = \left(\left(\sum_{f=1}^F \left(FuelConsAfterME_{s,f,y} + FuelConsAfterAE_{s,f,y} + FuelConsAfterBo_{s,f,y} \right) * ConversionFacTtWCII_f * \frac{1}{Cap_s * Dist_s} \right) \right. \\
& \quad \left. - AERLimit_{s,y} \right) * LifeTime_{s,y} \quad \forall s \in S, y \in Y \\
& AERDiffAfter_{s,y} = AER_{s,y} - AERLimit_{s,y} \quad \forall s \in S, y \in Y
\end{aligned}$$

Set N to 1 in case of non-compliance:

$$AERDiffAfter_{s,y} \leq M * N_{s,y} \quad \forall s \in S, y \in Y$$

Compliance option reduction potential:

$$\begin{aligned}
& CORedPot_{s,y} \\
& = \left(\left(\left(\sum_{f=1}^F FuelConsBeME_{s,f,y} * ConversionFacTtWCII_f \right) \right. \right. \\
& \quad * \left(\sum_{c=1}^C CompRedPotME_{s,c,y} * CompExist_{s,c,y} \right) * 100 \left. \right) \\
& \quad + \left(\left(\sum_{f=1}^F FuelConsBeAE_{s,f,y} * ConversionFacTtWCII_f \right) \right. \\
& \quad \left. * \left(\sum_{c=1}^C CompRedPotAE_{s,c,y} * CompExist_{s,c,y} \right) * 100 \right)
\end{aligned}$$

$$* \frac{1}{Cap_s * Dist_s} * LifeTime_{s,y} \quad \forall s \in S, y \in Y$$

Reefer reduction potential:

$$ReeferRedPot_{s,y}$$

$$= \left(\left(\left(0.75 - 0.03 * YearsElectric_y \right) * CorrectionElectric_s \right) * ConversionFacTtWCII_{HFO} \right) * \frac{1}{Cap_s * Dist_s} * LifeTime_{s,y} \quad \forall s \in S, y \in Y$$

Alternative fuels reduction potential

$$AltFuelRedPot_{s,y}$$

$$\begin{aligned}
& = \left(\left(\left(\left(\sum_{f=1}^F \left(FuelConsBeME_{s,f,y} + FuelConsBeAE_{s,f,y} + FuelConsBeBo_{s,f,y} \right) \right) \right. \right. \right. \\
& \quad \left. \left. * ConversionFacTtWCII_f \right) \right)
\end{aligned}$$

$$\begin{aligned}
& - \left(\left(\sum_{f=1}^F \left(\text{FuelConsAfterME}_{s,f,y} + \text{FuelConsAfterAE}_{s,f,y} + \text{FuelConsAfterBo}_{s,f,y} \right) \right. \right. \\
& \quad \left. \left. * \text{ConversionFacTtWCII}_f \right) + \text{FuelConsMeth}_{s,y} * \text{ConversionFacMethTtWCII}_f + \text{FuelConsAmmo}_{s,y} * \text{ConversionFacAmmoTtWCII}_f \right. \\
& \quad \left. + \text{FuelConsHydr}_{s,y} * \text{ConversionFacHydrTtWCII}_f \right) * \frac{1}{\text{Cap}_s * \text{Dist}_s} - \text{CORedPot}_{s,y} \Big) * \text{AltFuelExist}_{s,y} \quad \forall s \in S, y \in Y
\end{aligned}$$

Biofuel reduction potential:

$$\begin{aligned}
\text{BioRedPot}_{s,y} = & \left(\left(\left(\left(\sum_{f=1}^F \left(\text{FuelConsBeME}_{s,f,y} + \text{FuelConsBeAE}_{s,f,y} + \text{FuelConsBeBo}_{s,f,y} \right) * \text{ConversionFacTtWCII}_f \right) \right. \right. \right. \\
& - \left(\left(\sum_{f=1}^F \left(\text{FuelConsAfterME}_{s,f,y} + \text{FuelConsAfterAE}_{s,f,y} + \text{FuelConsAfterBo}_{s,f,y} \right) * \text{ConversionFacTtWCII}_f \right) \right. \\
& \left. \left. + \text{FuelConsBio}_{s,y} * \text{ConversionFacBioTtWCII}_f \right) \right) * \frac{1}{\text{Cap}_s * \text{Dist}_s} - \text{CORedPot}_{s,y} \Big) * \text{BioExist}_{s,y} \quad \forall s \in S, y \in Y
\end{aligned}$$

Variable definition

The following constraints set the decision variable types together with their lower and upper bounds, where applicable:

$\text{FuelConsAfterME}_{s,f,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsAfterAE}_{s,f,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsAfterBo}_{s,f,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsMeth}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsBio}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsAmmo}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{FuelConsHydr}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{MethChosen}_s \in \{0,1\}$	$\forall s \in S$
$\text{BioChosen}_s \in \{0,1\}$	$\forall s \in S$
$\text{BioExist}_{s,y} \in \{0,1\}$	$\forall s \in S, y \in Y$
$\text{AmmoChosen}_s \in \{0,1\}$	$\forall s \in S$
$\text{HydrChosen}_s \in \{0,1\}$	$\forall s \in S$
$\text{CompChosen}_{s,c,y} \in \{0,1\}$	$\forall s \in S, c \in C, y \in Y$
$\text{CompExist}_{s,c,y} \in \{0,1\}$	$\forall s \in S, c \in C, y \in Y$
$\text{AER}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{EPLChosen}_s \in \{0,1\}$	$\forall s \in S$
$N_{s,y} \in \{0,1\}$	$\forall s \in S, y \in Y$
$\text{AERDiffBefore}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{AERDiffAfter}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{CompBalPool}_y \in \mathbb{Q}$	$\forall y \in Y$
$\text{CompBalBank}_y \in \mathbb{Q}$	$\forall y \in Y$
$\text{CompBalInd}_{s,y} \in \mathbb{Q}$	$\forall s \in S, y \in Y$
$R_y \in \{0,1\}$	$\forall y \in Y$
$\text{AltFuelChosen}_{s,y} \in \{0,1\}$	$\forall s \in S, y \in Y$
$\text{AltFuelExist}_{s,y} \in \{0,1\}$	$\forall s \in S, y \in Y$
$\text{CarbonCost}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{TotalEnergy}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{GHGactual}_{s,y} \geq 0$	$\forall s \in S, y \in Y$
$\text{GHGtarget}_{s,y} \geq 0$	$\forall s \in S, y \in Y$

A2.6 Scenario 1 – CII Pooling

For this scenario, CII pooling is enabled and therefore the following constraints are added:

The following constraint sets the value for the pooled AER as the weighted sum of the individual AER values of the ships participating in the pool, using the product of ship capacity and distance traveled as weights:

$$\text{AERPool}_y = \frac{\sum_{s=1}^S \text{AER}_{s,y} * \text{PoolShip}_s * \text{DWT}_s * \text{Distance}_{s,y}}{\sum_{s=1}^S \text{PoolShip}_s * \text{DWT}_s * \text{Distance}_{s,y}}$$

$\forall y \in Y$

The following constraint sets the value for the pooled AER limits as the weighted sum of the individual AER limits, also weighted by the product of ship capacity and distance travelled:

$$AERLimitPool_y = \frac{\sum_{s=1}^S AERLimit_{s,y} * PoolShip_s * DWT_s * Distance_{s,y}}{\sum_{s=1}^S PoolShip_s * DWT_s * Distance_{s,y}} \quad \forall y \in Y$$

The following constraint requires the pooled AER to be at most the pooled AER limit or otherwise sets the non-compliance binary variable to one:

$$AERPool_y \leq AERLimitPool_y + M * N_y \quad \forall y \in Y$$

The following variables are defined in addition to the baseline model:

$$\begin{aligned} AERPool_y &\in Q & \forall s \in S, y \in Y \\ AERLimitPool_y &\in Q & \forall s \in S, y \in Y \end{aligned}$$

A2.7 Scenario 2 – GFS as of ISWG 16/2/7

This scenario enforces a global fuel standard (GFS) as of the current submissions ISWG 16/2/7 and 16/2/10. All constraints from the main model need to be considered and there is no CII pooling. The data input changes from 9 to now 16 ships.

In the objective function, the penalty for non-compliance of GFS ($R = 1$) is set to a similar value as the regulation proposes. Here it is 1.5 m€ after manual calculations for penalty in the example fleet. There is no force to comply. Also, the penalty for not complying with CII ($N = 1$) is set to 1€ and therefore removes the CII requirements. In the regulation banking is allowed, therefore the following constraints are added:

This constraint sets the bank at the value of the over-compliance from the previous year:

$$CompBalBank_y = CompBalPool_{y-1} \quad \forall y \in [4, Y]$$

First, the compliance balance of the pool is set to be the sum of the individual compliance balances in year 3, before it gets readjusted, taking the bank into account:

$$\begin{aligned} CompBalPool_y &= \sum_{s=1}^S \left(CompBalInd_{s,y} * PoolShip_s * LifeTime_{s,y} \right) & \forall s \in S, y \in [3] \\ CompBalPool_y &= \sum_{s=1}^S \left(CompBalInd_{s,y} * PoolShip_s * LifeTime_{s,y} \right) & + CompBalBank_y \quad \forall s \in S, y \in [4, Y] \end{aligned}$$

The following variables are defined in addition to the baseline model:

$$CompBalBank_y \geq 0 \quad \forall s \in S, y \in Y$$

A2.8 Scenario 3 – GFS and levy

In this scenario, a GFS together with a levy replace the EU ETS, FuelEU, and CII regulations. The goal is to find a combination of GFS GHG values with a corresponding levy to achieve the same GHG reductions. The GFS is adjusted starting from the baseline of 91.16 g/CO_{2eg} in 2023, to 0 in 2050 to be in line with the IMO 2023 Strategy. The reduction factors can be seen in the main text (Table 4). Different price levels are tested for a levy. No adjustments to the code are necessary.

Appendix 3. Fuel prices

The fuel prices and forecasts are based on current pricing and literature. Sources include: [MMMCZCS \(2021\)](#); [MMMCZCS \(2022b\)](#); [Nami et al. \(2021\)](#); [Hendriksen et al. \(2021\)](#); [Franz et al. \(2021\)](#); [Murray \(2016\)](#); [MAN SE \(2022\)](#); [IMF \(2024\)](#); [ECB \(2023\)](#).

The following table provides the prices that enter the model (in €/tonne):

Year	FO	DO	Biofuel	e-Methanol	e-Ammonia	e-Hydrogen
2023	515.41	670.04	1,266.98	1,143.53	919.95	2,784.67
2024	521.02	677.32	1,262.28	1,098.51	878.70	2,727.84
2025	487.40	633.62	1,163.56	1,055.28	839.29	2,671.01
2026	493.00	640.91	1,159.46	1,013.76	801.65	2,614.18
2027	493.00	640.91	1,141.98	973.88	765.70	2,557.35
2028	498.61	648.19	1,137.28	935.58	731.37	2,500.52
2029	498.61	648.19	1,119.60	898.79	698.57	2,443.69
2030	504.21	655.47	1,114.30	863.46	667.24	2,386.86
2031	509.81	662.75	1,105.97	847.93	656.52	2,332.87
2032	515.41	670.04	1,097.19	832.68	645.98	2,278.88
2033	515.41	670.04	1,076.25	817.70	635.60	2,224.89
2034	521.02	677.32	1,066.78	803.00	625.39	2,170.91
2035	526.62	684.60	1,056.86	788.56	615.35	2,116.92
2036	526.62	684.60	1,035.46	774.38	605.46	2,062.93
2037	532.22	691.89	1,024.86	760.45	595.74	2,008.94
2038	532.22	691.89	1,003.24	746.78	586.17	1,954.95
2039	537.82	699.17	1,002.14	733.35	576.75	1,900.96
2040	537.82	699.17	990.49	720.16	567.49	1,846.98
2041	543.43	706.45	989.03	707.21	556.09	1,792.99
2042	543.43	706.45	977.26	694.50	544.93	1,739.00
2043	549.03	713.74	975.44	682.01	533.98	1,685.01
2044	549.03	713.74	963.54	669.74	523.26	1,631.02
2045	554.63	721.02	961.36	657.70	512.75	1,577.03
2046	554.63	721.02	949.34	645.88	502.46	1,523.04
2047	560.23	728.30	946.79	634.27	492.37	1,469.06
2048	560.23	728.30	934.65	622.86	482.48	1,415.07
2049	565.83	735.58	931.74	611.66	472.79	1,361.08
2050	565.83	735.58	919.48	600.67	463.30	1,307.09

The prices of [Table 3](#) in the text (expressed in €/GJ) are derived from the above ones after division by the LCV values of [Table 2](#) in the text and the necessary unit adjustments.

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