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Optimizing Compliance Pathways for a Containership Fleet under the IMO Net-Zero Framework: A Case Study on the Far East–Europe Service

by

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The world today is full of uncertainty, but it is precisely within such uncertainty that new opportunities arise. I hope to apply the knowledge and skills I have gained at MEL to contribute, in my own way, to the future of global shipping.

Abstract

This thesis investigates cost-effective compliance pathways for an existing 13-vessel containership fleet on the Far East–Europe route under FuelEU Maritime (2025–2027) and the IMO Net-Zero Framework (2028–2040). A scenario-based techno-economic model is combined with regulatory analysis to evaluate five strategies, including biofuel blending, methanol adoption, and retrofitting options.

The findings show that the IMO Net-Zero Framework is structurally more stringent and globally harmonized than regional schemes such as the EU ETS and FuelEU Maritime, creating a stronger long-term driver for fuel substitution and fleet adaptation despite unresolved design features. Among compliance options, biodiesel and LNG represent the most cost-effective pathways for existing vessels, while methanol remains economically unattractive under current assumptions but could become viable if green methanol prices converge with fossil methanol. Optimal strategies involve dynamic blending of biodiesel and bioLNG supported by pooling mechanisms, whereas capital-intensive retrofits for HFO vessels are not cost-effective in the near term.

The study also highlights systemic risks. Limited biofuel availability and cross-sectoral competition may create a two-tier market disadvantaging smaller operators, while decarbonization is projected to more than double fuel costs by 2040 against limited willingness to pay from shippers. These dynamics underline the need for regulatory clarity, transparent platform, and credible compensation mechanisms to incentivize low-carbon fuel use. In particular, the IMO Net-Zero Fund, though not yet fully defined, will be crucial to ensure fair cost distribution and equitable access to green fuels. By integrating fleet-level modelling with policy analysis, this thesis contributes practical insights for shipowners in planning compliance strategies and for policymakers in designing effective and inclusive decarbonization frameworks.

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List of abbreviations

BioLNG	Liquefied Biomethane
CB	Compliance Balance
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CH_4	Methane
DF	Dual-fuel
ECA	Emission Control Area
EEA	European Economic Area
EU ETS	European Union Emissions Trading System
EUR/tCO_2e	Euro per tonne of CO2
FAME	Fatty Acid Methyl Esters
FCR	Fuel Consumption Rate
gCO_2e/MJ	grams of CO_2 equivalent per megajoule
GHG	Greenhouse Gas
GWP100	Global Warming Potential over 100 years
GFI	Greenhouse Gas Fuel Intensity
HFO	Heavy Fuel Oil
IFO380	Intermediate Fuel Oil 380
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MEPC 83	Marine Environment Protection Committee
MGO	Marine Gas Oil
MJ	Megajoule
MRV	Monitoring, Reporting and Verification
NH_3	Ammonia

N_2O	Nitrous Oxide
RU	Remedial Unit
SAFs	Sustainable Aviation Fuels
SIDS	Small Island Developing States
SU	Surplus Unit
TTW	Tank-to-Wake
USD/tCO_2e	US dollars per tonne of CO_2 equivalent
WTW	Well-to-Wake
WTT	Well-to-Tank
ZNZ	Zero or Near-Zero

Chapter 1 Introduction

1.1 Background

Seaborne trade accounts for approximately 88% of total global trade (Clarksons, 2025), yet the shipping sector has long depended on fossil fuels. This reliance has resulted in significant greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). From a Well-to-Wake (WTW) perspective, which encompasses emissions from fuel extraction, production, transportation, and onboard combustion, the global shipping fleet emitted an estimated 1,051 million tonnes of GHG emission (CO_2 equivalent) in 2024, representing about 2% of total global GHG emissions (Clarksons, 2025). This underscores the shipping sector's substantial contribution to climate change and the urgent need for effective decarbonization strategies.

Although shipping is the most CO_2-efficient mode of freight transport, emitting only 12 gCO_2/tonne-km for large deep-sea containerships compared with 18 for rail and 121 for trucks (Nelissen et al., 2022), its absolute emissions are rising rapidly. Since 1990, the shipping sector's GHG emissions have grown by 34% (European Parliament, 2022), driven by expanding trade volumes and increased vessel ton-mile demand (Solakivi, et al., 2022; UNCTAD, 2024). Moreover, over the past five years, emissions have risen by an average of 2.54% annually due to the global vessel ton-mile demand increase for geopolitics and chokepoint reasons, outpacing the long-term trend (Clarksons, 2025). Without effective action, shipping GHG emissions could reach 130% of 2008 levels by 2050, threatening the Paris Agreement targets (European Commission, 2025). This underscores the urgent need for effective decarbonization measures.

Thus, to mitigate shipping's climate impact, the International Maritime Organization (IMO) adopted its Initial GHG Strategy in 2018, targeting a 50% reduction in annual GHG emissions by 2050 from 2008 levels and full decarbonization in the longer term (IMO, 2023). Moreover, the 2023 Revised Strategy introduced fuel uptake targets and timeline benchmarks, yet its ambition remains debated. Zhang, et al. (2024) argue that the 5–10% zero-emission fuel target for 2030 is far below the 15–26% needed for alignment, while near-complete adoption with 85–95% will be required by 2050. Additionally, existing instruments such as the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII) link emissions to transport performance but lack enforcement strength. For example, low CII ratings only trigger corrective plans without immediate penalties, while rewards for high-rated ships remain voluntary (IMO, 2025; Carvalho & Comer, 2024). Without stronger measures, the IMO risks falling short of the deep emission cuts required.

In contrast, the European Union (EU) has taken a firmer stance by extending its Emissions Trading System (EU ETS) to shipping and introducing FuelEU Maritime. Both are binding, market-based mechanisms that create financial incentives for shipowners to cut CO_2 emissions (DNV, 2025; ClassNK, 2024). Yet the EU framework applies only within the European Economic Area (EEA), raising concerns over higher compliance costs for EU-focused operators and potential competitive distortions for global carriers.

In response, the IMO has proposed its first global GHG pricing system—the IMO Net-Zero Framework—expected to be adopted in 2025 and enter into force in 2028 (IMO, 2025). Similar to FuelEU Maritime, it applies a well-to-wake metric of GHG emissions per unit of energy to encourage the uptake of low-carbon fuels. However, its interaction with existing EU measures remains uncertain. Vessels voyaging within Europe could face overlapping obligations and potentially incur double compliance costs. Also, although a unified global framework would possibly reduce competitive distortions and channel revenues into decarbonization, it would still raise shipping costs worldwide, raising questions about political feasibility and the consequences if adoption fails. Such uncertainty risks delaying shipowner investment decisions and slowing the pace of maritime decarbonization.

Moreover, as the IMO Net-Zero Framework tightens GHG intensity requirements, shipowners face growing challenges in finding cost-effective compliance pathways, particularly for existing vessels that cannot be replaced quickly. Fuel choice is central, which could directly determine a vessel's emissions profile and represents the largest share of operating expenditure (OPEX). Additionally, compliance pooling mechanisms, which allow overperformance in one vessel to offset underperformance in another (Lloyd's Register, 2024), make these decisions even more strategic. However, alternative fuels such as LNG, methanol, ammonia, and biodiesels each involve trade-offs in cost, availability, and lifecycle emissions, with no universally applicable solution. Consequently, the dominant pathway remains uncertain, leaving shipowners exposed to considerable risks in long-term investment decisions.

For shipowners, early and well-informed action, especially when leveraging pooling mechanisms, can enable long-term fleet planning, reduce regulatory and market risks, and create first-mover advantages that translate into both compliance cost savings and potential surplus revenue streams. As UNCTAD (2023) stresses that vessels optimized for scalable fuels with supporting infrastructure are more likely to secure competitive advantage during the transition, yet questions remain about long-term availability and price stability of the chosen fuel.

For regulators and governments, the challenge lies in designing a framework that incentivizes decarbonization while accounting for higher shipping costs, limited early-stage fuel availability, and the need to ensure a just and equitable transition that balances the interests of developing countries and smaller shipowners. A further concern is how revenues can be transparently and fairly reinvested into decarbonization, so that the benefits can extend across the entire industry rather than concentrating in a few regions.

Accordingly, this thesis focuses on fuel choice as the central determinant for shipowners to balance compliance costs, fuel expenses, and emissions performance under tightening regulations. At the same time, it acknowledges that uncertainty surrounding the upcoming IMO Net-Zero Framework raises critical issues of political feasibility, rising costs, limited green fuel availability, and the need to ensure a just transition. Thus, how different stakeholders respond to these challenges will be decisive. Together, these two dimensions form the foundation for the research question addressed in the following section.

1.2 Research Question

Building on these challenges, this thesis mainly turns to the forthcoming IMO Net-Zero Framework, which represents a critical milestone as the first global regulation to combine mandatory GHG intensity limits with a pricing mechanism for international shipping. In anticipation of its adoption and entry into force, shipowners must not only assess fuel-related compliance strategies in terms of cost-effectiveness and operational feasibility but also confront the risks and uncertainties associated with regulatory design and market response.

Notably, container shipping is a particularly relevant focus, accounting for about 60% of seaborne trade by value and roughly 30% of sectoral CO_2 emissions (Song, 2021; Yu et al., 2025). Within this segment, the Asia–Europe route is especially significant, representing around 20% of global container trade (Rodrigue, 2024), characterized by high fuel consumption, and expected to be heavily affected by GHG regulations.

To ground this analysis, the study adopts a representative liner service between Shanghai and Rotterdam as a case example, illustrating both the scale of long-haul container trade and its high exposure to emerging GHG regulations under the IMO Net-Zero Framework. Based on this case, the thesis simulates how a representative fleet could be adjusted and evaluates the associated cost, operational, and compliance implications. On this basis, the research addresses the following central question:

How can a representative containership fleet be optimized to comply with the upcoming IMO Net-Zero Framework in a cost-effective manner?

To further explore this main question, the following sub-questions have been formulated:

1. *How does the IMO Net-Zero Framework differ from the EU ETS and FuelEU Maritime in terms of scope, enforcement, and compliance mechanisms?*
2. *What are the advantages and disadvantages of the main alternative fuel options for containerships, and which are more suitable for deployment in the existing fleet under current regulatory frameworks?*
3. *Which fuel strategies can a containership fleet adopt to comply with the IMO Net-Zero Framework, and how cost-effective are these options in balancing regulatory compliance with financial performance?*
4. *What are the main risks and uncertainties under the IMO Net-Zero Framework and how can shipowners and policymakers develop adaptive strategies to manage them?*

As the IMO Net-Zero Framework is still in its early stages and remains underexplored in the literature, this thesis provides timely and practical insights into how shipowners can respond effectively by modelling and comparing multiple fuel-based compliance scenarios. The findings contribute to the academic literature by bridging a gap in fleet-level modelling of compliance strategies under emerging global regulations, while also offering practical guidance for shipowners in identifying cost-effective pathways and informing regulators in designing effective and equitable decarbonization policies.

1.3 Research Design and Methodology

To address the research questions, this thesis adopts a two-stage research design that integrates qualitative regulatory analysis with quantitative fleet-level modelling. The first stage conducts a critical review of the three main regulatory frameworks, including the EU ETS, FuelEU Maritime, and the IMO Net-Zero Framework, focusing on their scope, enforcement mechanisms, and compliance implications for the shipowners. This is complemented by an assessment of alternative fuel options, including biodiesel, LNG, methanol, and ammonia, with respect to their technical feasibility, lifecycle emissions performance, and economic competitiveness. Together, this stage establishes the regulatory and technological context that frames subsequent modelling.

The second stage applies a techno-economic modelling approach to a representative fleet operating on the Asia–Europe route (Shanghai–Rotterdam). Using data from Clarksons Shipping Intelligence, DNV, and other industry sources, the model simulates multiple compliance pathways from 2025 to 2040 under both FuelEU Maritime (2025–2027) and the IMO Net-Zero Framework (2028–2040). Each scenario incorporates distinct strategies such as biofuel blending, LNG and methanol retrofitting, and do-nothing options. Fleet performance is mainly assessed across two dimensions:

1. Environmental compliance: annual WTW GHG intensity relative to regulatory thresholds.
2. Economic outcomes: total fuel expenditure, compliance costs, and retrofit investments.

The scenarios are compared to identify the most cost-effective compliance pathways. In addition, sensitivity analyses are conducted on fuel prices and compliance unit prices to test the robustness of the results under uncertainty. This dual focus not only quantifies cost and emissions trade-offs but also highlights the risks posed by price volatility and regulatory ambiguity.

Through this mixed-methods design, the study bridges qualitative policy review and quantitative fleet modelling, generating practical insights for shipowners on compliance strategies while informing policymakers of the design challenges in creating effective and equitable decarbonization frameworks.

1.4 Thesis Structure

The remainder of this thesis is organized as follows. Chapter 2 reviews the relevant literature, focusing on existing maritime GHG regulations, particularly the EU ETS, FuelEU Maritime, and the IMO Net-Zero Framework, and on the advantages and limitations of alternative fuel options for containerships. Chapter 3 outlines the research methodology, including the assumptions, data sources, and scenario-based modelling approach applied to a representative Asia–Europe fleet. Chapter 4 presents the results of the simulations, comparing alternative compliance strategies in terms of cost, emissions performance, and operational feasibility, and includes sensitivity analyses to capture regulatory and price uncertainties. Chapter 5 discusses the key findings, with particular attention to fuel availability, high shipping costs, and the broader risks and uncertainties under the IMO Net-Zero Framework. Finally, Chapter 6 concludes by summarizing the main contributions, outlining policy and industry implications, and highlighting limitations and suggestions for future research.

Chapter 2 Literature Review

This chapter provides a critical review of the literature that underpins the subsequent analysis. It first examines market-based instruments for regulating maritime emissions, evaluating their relative advantages and limitations to assess which mechanisms are most likely to shape the future regulatory framework including EU ETS, FuelEU Maritime and IMO Net-Zero Framework. Second, it synthesizes research on different alternative fuels, comparing their technical feasibility, lifecycle emissions performance, and economic competitiveness to identify the most viable compliance options for deep-sea container shipping. Finally, the chapter highlights the main research gaps, thereby motivating the modelling approach adopted in this thesis.

2.1 Policy & Regulation

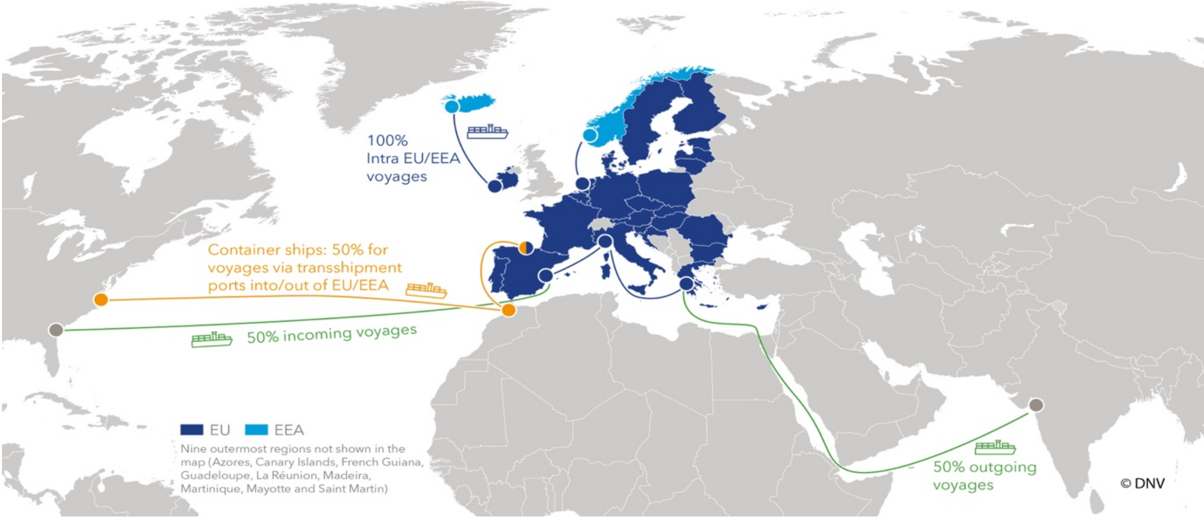
This section addresses Sub-question 1: "*How does the IMO Net-Zero Framework differ from the EU ETS and FuelEU Maritime in terms of scope, enforcement, and impact?*" It first introduces each regulation individually and then compares them to highlight their key differences.

2.1.1 EU ETS

The European Union has emerged as a frontrunner in maritime decarbonization by being the first jurisdiction to implement two distinct market-based instruments: the EU Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation (European Commission, 2025). At first glance, their coexistence may appear to result in double regulation. However, the two measures are designed to address different dimensions of the problem. The EU ETS functions as a carbon-pricing mechanism that internalizes the cost of onboard emissions, whereas FuelEU Maritime imposes a GHG intensity standard that gradually enforces the use of low-carbon fuels (DNV, 2025; European Commission, 2025). In this respect, the schemes are largely complementary, with the ETS influencing cost structures and FuelEU Maritime directly shaping fuel choices.

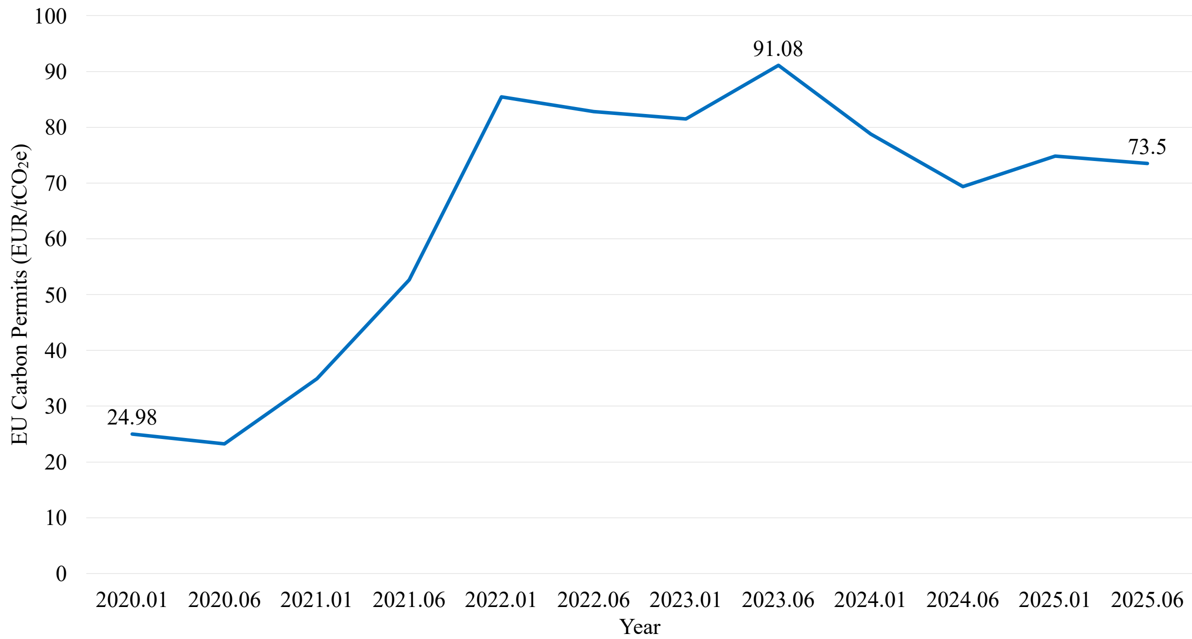
Since January 2024, the EU ETS has been extended to cover CO_2 emissions from ships above 5,000 gross tonnages calling at EU ports, irrespective of flag state (European Commission, 2025). Moreover, shipping companies are now required to surrender allowances for 100% of emissions from intra-EU voyages and 50% of emissions on extra-EU voyages, as shown in Figure 1 (European Commission, 2025). Moreover, 40% of emissions are included in the ETS scope in 2024, rising to 70% in 2025 and reaching 100% in 2026 (DNV, 2025). Particularly, it will apply a 4.3% (2024 - 2027) and 4.4% (after 2028) annual cut to the overall allowances, thereby gradually lowering the emissions cap each year (European Commission, 2025). However, these will largely affect the price of EU Allowances, which has already shown significant volatility. Notably, the price of the EUA in 2021 rose nearly fourfold compared to 2020, as shown in Figure 2 (Trading Economics, 2025). This surge was largely driven by the post-pandemic economic rebound, which increased energy demand and fossil fuel consumption, thereby raising the value of emissions allowances (Manzagol & Nakolan, 2022). Predictably, EUA prices are likely to increase further as the cap tightens and allowance supply shrinks.

Figure 1. EU ETS based on percentage of emissions on voyages



Source: DNV (2025)

Figure 2. EU Allowance Price



Source: Trading Economics (2025)

This dynamic creates an incentive structure in which shipowners must weigh the relative costs of abatement measures, including right fuel choices and improving energy efficiency, against purchasing allowances (Hansson, et al., 2022). Nevertheless, it has the upper limits of the EUA price as if the operators do not have enough allowances for their emissions, they can pay EUR 100 penalty for each tonne of excess emissions (European Commission, 2025). However, Flodén et al. (2024) argue that while EUA prices are expected to increase as the cap tightens, current and near-term price levels remain far below the abatement costs of zero-carbon fuels such as biofuels, ammonia, or hydrogen. For instance, significant fuel substitution only becomes cost-effective above EUR 150–200 per tonne of CO_2, yet current ETS prices have fluctuated below that threshold. Hansson, et al. (2022) have also found that ships will not use the biofuel until the costs for ETS above 100 per ton of CO_2 and will be most likely to improve vessels' energy efficiency as they have lower costs when the carbon abatement costs are low. Consequently, while the ETS raises costs of using fossil fuels, it is unlikely on its own to induce deep fuel transitions without higher ETS price incentives or complementary policies such as FuelEU Maritime or targeted subsidies (Hansson, et al., 2022).

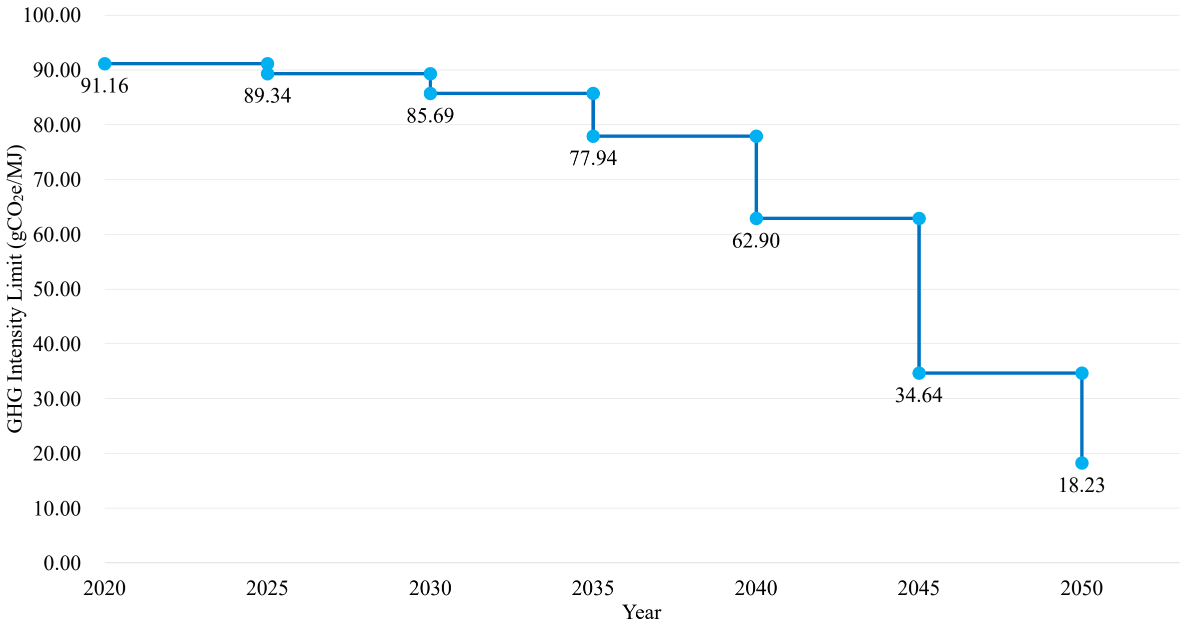
Furthermore, from 2026, methane (CH_4) and nitrous oxide (N_2O) will also be included in the maritime ETS scope, strengthening its climate coverage (Flodén et al., 2024). Yet, the ETS remains restricted to Tank-to-Wake (TTW) emissions (onboard fuel combustion), overlooking upstream fuel-cycle impacts (Well-to-Tank (WTT)). However, this limitation is particularly problematic for adopting alternative fuels. For example, while fossil methanol and biomass-based methanol emit nearly identical CO_2 at combustion, the latter is nearly carbon-neutral on a WTW basis because the carbon released was previously absorbed during biomass growth (Brynolf et al., 2014). Moreover, Flodén, et al. (2024) estimate that WTT emissions contribute about 15% of marine fuel WTW emissions, and in some cases, WTW intensities can be nearly double TTW values (Trosvik & Brynolf, 2024). Thus, the ETS provides only a partial signal compared to policies explicitly designed on a lifecycle basis. As Lloyd's Register (2024) notes that while the EU ETS mainly incentivizes energy efficiency, FuelEU Maritime focuses on promoting clean fuel uptake, thereby providing a stronger driver for decarbonization.

2.1.2 FuelEU Maritime

In contrast, the FuelEU Maritime Regulation, effective from January 2025, adopts a GHG intensity standard approach from a WTW perspective. It establishes annual maximum limits for the lifecycle GHG intensity of energy consumed by ships within the same scope as the ETS (DNV, 2025). Starting with a 2% reduction from a 2020 baseline (91.16 gCO_2e/MJ) in 2025, the target rises progressively to 6% in 2030 and 80% by 2050 (European Commission, 2023), shown in Figure 3. Unlike the EU ETS, FuelEU Maritime explicitly covers CO_2, CH_4, and N_2O on a WTW basis, with intensities calculated from the total emissions per unit of energy consumed (Nelissen et al., 2022). Specifically, this is done by converting fuel use into energy with default calorific values, applying fuel-specific upstream and combustion emission factors, and aggregating CO_2, CH_4, and N_2O into CO_2-equivalents using 100-year time horizon global warming potential (GWP100) values before dividing by total energy consumed (Nelissen et al., 2022).

Moreover, non-compliance triggers penalties equivalent to EUR 2,400 per tonne of VLSFO-equivalent in excess emissions (DNV, 2025). As illustrated in Figure 3, the regulatory pressure will more intensify after 2030, when the GHG intensity limits decline steeply, thereby strongly incentivizing the adoption of low-carbon fuels. Besides, FuelEU Maritime introduces a reward factor, under which the use of renewable fuels is counted double in the GHG intensity calculation, thereby rewarding early adopters of low-carbon fuels (BetterSea, 2024). This has important implications for fleet investment decisions as given that vessels typically operate for 25 years (Stopford, 2009), choices made at the newbuilding stage, particularly regarding fuel compatibility and long-term fuel availability, will determine compliance costs over the vessel's lifetime (DNV, 2023). By penalizing high-intensity fuels and rewarding cleaner options, the regulation seeks to address the "chicken-and-egg" dilemma of alternative fuel markets, creating demand signals that can stimulate investment in production capacity and gradually narrow price differentials (Hughes, 2021).

Figure 3. FuelEU Maritime GHG Intensity Limit



Source: DNV (2025)

Furthermore, FuelEU Maritime introduces a pooling mechanism that allows companies to combine the compliance performance of multiple vessels, such that the over-compliance of one ship can offset the under-compliance of another, provided the pool's net balance remains positive (Wartsila, 2024). This mechanism is intended to create compliance flexibility during the initial years of the regulation, when low-carbon fuel supply remains constrained (European Commission, 2021). Importantly, pooling reduces the immediate investment burden by enabling companies to phase in costly upgrades across their fleet. Instead of retrofitting or converting every vessel simultaneously, an operator can invest in a single alternative fuel vessel and spread the compliance benefit across the pooled fleet (Wartsila, 2024). For example, if one vessel operates at 120% of the required performance and another at 80%, the combined pool achieves full compliance (Bureau Veritas, 2023).

The financial logic of pooling further enhances its attractiveness. By avoiding heavy non-compliance penalties, companies can redirect savings into successive rounds of investment, creating a self-reinforcing cycle. Initial investment in one compliant vessel generates compliance surplus, which reduces penalties and frees capital to finance a second alternative fuel-ready vessel or energy-saving retrofits on existing ships (Wartsila, 2024). Furthermore, over time, this process can accelerate fleet decarbonization while smoothing cash flows. Besides, pooling is not restricted to a single owner. Instead, vessels from different operators may also form a pool if they share the same verifier. Thereby, this enables monetization of surplus performance and reduces overall compliance risk, offering particular benefits for smaller operators (Wartsila, 2024).

Nevertheless, pooling is a useful but imperfect mechanism. It adds administrative burden and operates under strict constraints (one pool per ship, no borrowing, single verifier) (Lloyd's Register, 2025). Overreliance diminishes vessel-level incentives and cannot mask structural non-compliance and its value narrows as intensity limits tighten, often favoring large companies that can assemble compliant fleets, while smaller operators may struggle to access suitable partners (Roche & Hansen, 2025). Thus, pooling should be seen as a transitional cost-smoothing tool, not a substitute for fuel switching.

Furthermore, the FuelEU Maritime also presents several drawbacks. First, although the regulation is "technology-neutral," in practice it is expected to favor drop-in biofuels for the large number of existing vessels (ClassNK, 2024; BetterSea, 2025). Yet the sustainable supply of biofuels is highly constrained. Under the Renewable Energy Directive (RED II/III), crop-based biofuels are excluded (European Commission, 2021), limiting the eligible feedstock base. However, advanced and waste-based biofuels, envisioned as the main pillar of the EU fuel mandate, are projected to fall short of long-term demand across transport sectors, with shipping competing directly with aviation, which faces binding obligations under ReFuelEU Aviation (Transport & Environment, 2024; Lloyd's Register, 2024). This scarcity, coupled with strong incentives, heightens the risk of fraudulent claims and underscores the need for transparent certification systems (Transport & Environment, 2024). As a result, FuelEU Maritime may lock near-term compliance into reliance on scarce biofuels while deferring investment in scalable e-fuels such as green methanol, ammonia, and hydrogen (Hughes, 2021; DNV, 2023). Moreover, larger carriers are likely to pre-secure limited volumes, creating competitive distortions that disadvantage smaller operators (Hughes, 2021).

Second, as both FuelEU Maritime and the EU ETS are regional measures, they carry the risk of carbon leakage, which means vessel may strategically change their operations to avoid the rules (European Commission, 2025). Operators may reroute via non-EEA transshipment hubs to reduce exposure to EU carbon costs, potentially increasing overall emissions against the regulation's intention (Kotzampasakis, 2025). For instance, even at an allowance price of only EUR 25 per tonne, container carriers could divert calls from EU hubs such as Piraeus and Algeciras to non-EU ports like Izmir or Tanger Med (Lagouvardou & Psaraftis, 2022). As carbon prices rise, the incentive to avoid EU ports will strengthen, and exemptions are unlikely to eliminate such behaviors (Faria, 2024). Moreover, speed reductions on EU routes could be offset by higher speeds elsewhere, limiting net global emission reductions (Park, et al., 2024).

Finally, the regional scope of FuelEU Maritime raises concerns that similar frameworks could be adopted by other major economies, including China (Lurkin, 2025), in the absence of a global regime. This would force carriers to comply with divergent standards, leading to overlapping reporting requirements and escalating costs. By contrast, the forthcoming IMO Net-Zero Framework seeks to establish a globally harmonized WTW intensity limitation with pricing and pooling mechanisms to align economic incentives globally (Bureau Veritas, 2025). Such a system could mitigate competitive distortions and create a level playing field across the industry (Allem, 2025). Nevertheless, once the IMO Net-Zero Framework enters into force, questions will arise as to whether the EU regime should be harmonized, retained, or phased out. Without careful alignment, the coexistence of regional and global measures risks imposing double compliance costs, disproportionately affecting European trade and smaller operators (Pringle, 2025). The next section therefore examines the IMO Net-Zero Framework, focusing on its design features, economic implications, and potential to address the shortcomings of the EU regime.

2.1.3 IMO Net-Zero Framework

The IMO took a decisive step toward to its 2023 GHG Strategy by approving the draft IMO Net-Zero Framework during the 83rd session of the Marine Environment Protection Committee (MEPC 83) in April 2025. This framework marks the world's first legally binding climate regime to apply a combination of mandatory marine fuel standards and GHG emission pricing across the maritime industry sector from a global perspective (IMO, 2025). Set to be formally adopted in October 2025 and enforced from 2028, the regulations will apply to ocean-going vessels above 5,000 gross tonnages (GT), which account for 85% of international shipping's CO_2 emissions (IMO, 2025).

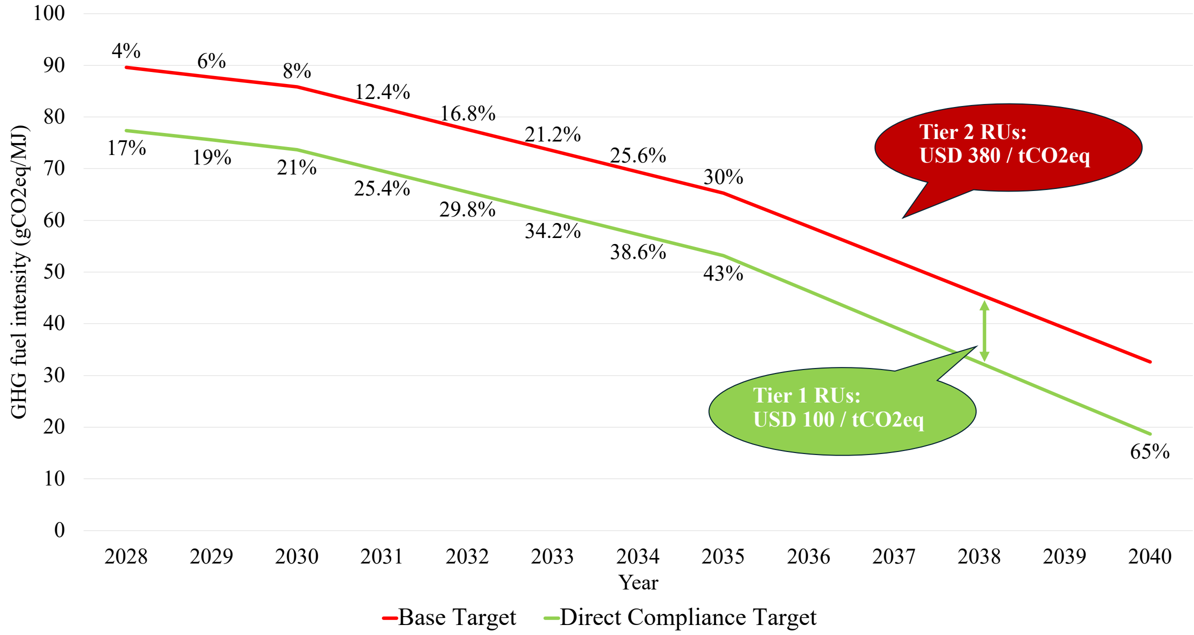
Specifically, the IMO Net-Zero Framework consists of two main pillars. The first pillar is the introduction of a global fuel standard that mandates progressive reductions in ships' annual GHG fuel intensity (GFI), calculated on a WTW basis. Under this requirement, the annual attained GFI, expressed in grams of CO_2 equivalent per megajoule (gCO_2e/MJ) of all fuels consumed within a calendar year, must fall below the corresponding target annual GFI (ABS, 2025).

Specifically, the regulation establishes two performance targets: the Base Target and a more ambitious Direct Compliance Target, with a roadmap extending to 2040 (IMO, 2025). Under the Base Target, ships are required to reduce their attained GFI by 30% by 2035 relative to a 2008 baseline of 93.3 gCO_2e/MJ (IMO, 2025). Moreover, it also sets the direct compliance target with a 65% reduction in 2040 compared to 2008 (IMO, 2025). The annual reduction trajectory from 2028 to 2040 is illustrated in Figure 4.

Based on the first pillar, the second pillar introduces a global pricing mechanism for compliance. Ships exceeding target annual GFI must acquire remedial units (RUs), while those surpassing the direct compliance target can earn surplus units (SUs). These surplus units can be banked for future use or transferred to other vessels facing a compliance deficit within two years (DNV, 2025). If a ship meets the base target (red line) but fails to reach the direct compliance target (green line), shown in Figure 4, the owner must purchase Tier 1 RUs from the IMO Net-Zero Fund at a rate of USD 100 per tonne of CO_2e to bridge the compliance gap (IMO, 2025).

However, in cases where the base target itself is not achieved, the vessel owner must first acquire Tier 2 RUs, priced at USD 380 per tonne of CO_2e, or obtain SUs from other compliant vessels, before being eligible to purchase Tier 1 RUs to meet the full compliance requirement.

Figure 4. IMO Net-Zero Framework GFI Base and Direct Compliance Target (2028-2035)



Source: (IMO, 2025)

These transactions will be managed through the newly established IMO Net-Zero Fund, designed not only to reward low-emission ships but also to support innovation, infrastructure development, and just transitions in vulnerable developing states (IMO, 2025). Moreover, if the vessel uses zero or near-zero (ZNZ) GHG fuels may receive rewards, but the final methodology and the amount of the reward has not been defined (IMO, 2025).

Based on the forecast in 2030 from Shuang (2025), for most existing vessels, the most cost-effective compliance strategy in the near term is to meet the Base Target and offset the gap to the Direct Compliance Target by purchasing Tier 1 RUs. However, falling between the Base and Direct targets often leads to the highest compliance costs where the marginal costs of green fuel higher than Tier 1 RUs. In contrast, a small number of frontrunners may significantly outperform the Direct Target by using large shares of ZNZ fuels, benefiting from Surplus Unit transfers and ZNZ rewards, thereby lowering net compliance costs. However, it depends on the green fuel prices, availabilities, and the amount of ZNZ rewards (Shuang, 2025). Nevertheless, the specific values and methodology for calculating fuel GHG emissions, especially for ZNZ fuels, will only be defined in 2027, creating a blind spot for shipowners who must make long-term investments while facing the wide cost gap between conventional and ZNZ fuels (Schneiter, 2025).

Furthermore, while the IMO Net-Zero Framework represents a significant step towards global decarbonization, it faces several shortcomings. As Luman (2025) points out, the IMO Net-Zero

Framework prices only emissions above the intensity targets through a two-tier charge, rather than covering all emissions with a uniform carbon price signal determined by the market as under the EU ETS. As a result, this partial coverage weakens the price and climate signal. Moreover, ambition and timing are also cautious, with entry delayed until 2028 and near-term checkpoints less stringent than earlier IMO commitments, risking limited abatement this decade and fall behind the Paris agreement of efforts to limit the increase to 1.5°C (Transport & Environment, 2025; Luman, 2025). Moreover, its fuel-neutral design may in practice favor cheaper drop-in biofuels and LNG compatible with existing fleets, even where lifecycle benefits are modest once methane slip and indirect land-use change are accounted for, underscoring the need for stricter LCA rules (Ünalan & Baldino, 2025).

Besides, as mentioned previously, key design elements remain unsettled, including the future level of charges in the two-tier system beyond 2030, revenue redistribution rules, certification procedures, unit trading, and the governance of the Net-Zero Fund, thereby creating uncertainty over compliance costs and financing flows (Luman, 2025). Finally, its interaction with regional measures such as FuelEU and the EU ETS is unresolved, raising the risk of duplicative compliance and competitiveness distortions (Transport & Environment, 2025; Luman, 2025).

Therefore, while the IMO Net-Zero Framework lays an important foundation, it must be strengthened through clearer price signals, more ambitious interim targets, robust lifecycle accounting rules, and transparent governance arrangements to ensure it drives deep decarbonization and avoids regulatory fragmentation.

Yet, because the IMO Net-Zero Framework has only recently been adopted, the academic literature on its practical implications remains limited. In particular, there is little research that rigorously tests which fuels may prove optimal under different price trajectories, or how compliance costs will interact with vessel investment strategies (Zhang, 2025; Lloyd's Register, 2025). Likewise, the broader impacts on the maritime sector and on future fuel supply chains have not yet been systematically observed. These gaps highlight the need for further analysis to assess how the framework will influence fleet behaviors and fuel market dynamics in practice.

2.1.4 Comparison of the IMO Net-Zero Framework with the EU ETS and FuelEU Maritime

Table 1 shows the comparison of each regulation and answers the Sub-question 1. These main differences will largely affect the maritime industry. First is the scope of the regulation, as mentioned EU ETS and FuelEU Maritime only implemented in the EU area instead IMO is global one. This divergence in geographical coverage has significant implications. Regional schemes as EU ETS and FuelEU, could provide faster implementation and stronger short-term decarbonization incentives within the EU, thereby creating a demand-pull effect for alternative fuels and energy efficiency technologies (Faber, et al., 2022; Flodén et al., 2024). However, their limited scope raises concerns about carbon leakage, competitive distortions, and potential rerouting strategies to avoid compliance, which will affect the regional economics and even bring up the global emission level (Kotzampasakis, 2023; Wu, et al., 2024). In contrast, global measures under the IMO can offer a level playing field across all routes and reduce the risk of trade diversion (Psaraftis, et al., 2021). Yet, the global approach has been slower to materialize, reflecting the challenge of reaching consensus among member states with divergent economic interests (Rojon, et al., 2021). Ultimately, while regional initiatives can act as important frontrunners that accelerate innovation and put pressure on the IMO, only a global framework can ensure uniform standards, prevent regulatory fragmentation, and provide the certainty required for long-term investment in maritime decarbonization. Therefore, the IMO's global regime should be regarded as the central pillar of shipping's climate governance in the future.

Table 1. Comparison of the EU ETS, FuelEU Maritime and IMO Net-Zero Framework

Regulation	EU ETS	FuelEU	IMO Net-Zero Framework
Geographical scope	Regional (EU/EEA ports; 100% intra-EU, 50% extra-EU voyages)	Regional (EU/EEA ports; 100% intra-EU, 50% extra-EU voyages)	Global
Vessel scope	All ships of 5,000 gross tonnage (GT) and above for transporting passengers or commercial cargo		
Start Date	2024	2025	2028
Ambition	62% cut by 2030 (vs 2005, all ETS sectors)	2% cut in 2025 and 80% cut by 2050 (vs 2020)	30% (Base) cut by 2035 and 65% (Direct) cut by 2040 (vs 2008 baseline)
GHG Metric	WTT	WTW	WTW
Compliance System	Cap-and-trade system with an annually declining emissions cap; operators must surrender allowances equal to verified emissions	Annual WTW GHG intensity limits for energy use, progressively tightening; compliance assessed per vessel, with pooling option across fleets	Dual WTW GHG intensity targets (Base and Direct Compliance) with pooling option; exceeding units must purchase Remedial Units, while over-performers generate tradable Surplus Units
Penalty	Compliance price determined by EUA market price; failure to surrender incurs a	Fixed penalty of EUR 2,400 per tonne VLSFO-equivalent for excess GHG intensity	Two-tier system: Tier 1 Remedial Units priced at USD100/tCO_2e and Tier 2 at USD380/tCO_2e;

	EUR100 per tonne of CO_2e statutory penalty		Surplus Units can only offset deficits for Tier 2
Incentive Signal	Primarily raises the cost of fossil fuel use, encouraging energy efficiency and operational measures when EUA prices remain below green fuel abatement costs	Directly incentivizes uptake of low and zero carbon fuels by imposing progressive WTW intensity limits and penalizing high-intensity fuels	Aims to stimulate global deployment of green fuels through intensity standards combined with tradable over-compliance credits, while funding innovation and transition support via the Net-Zero Fund
Strengths	Market-wide carbon pricing; cross-sector efficiency	Accelerating and rewarding uptake of low- and zero-carbon fuels; penalizes fossil fuels with high intensity	Global scope reduces carbon leakage and competitive distortions; stronger abatement potential; revenues redistributed for R&D, infrastructure, and developing countries
Weaknesses	TTW-only; EU-only; EUA prices may stay too low for green fuel switching	Regional scope; reliance on limited biofuel supply; fixed penalty may weaken incentive under low fuel price scenarios	Lack of full carbon pricing; unresolved governance and certification rules; early targets less ambitious; compliance details still evolving
Impact on shipowners	Moderate: mainly efficiency and operational adjustments; compliance cost volatility due to EUA market, not affect vessel do not operating in EU area	Stronger: requires gradual fuel transition, fleet-level pooling helps short-term flexibility but creates long-term pressure, not affect vessel do not operating in EU area	Strongest: higher cumulative compliance costs, especially pre-2045; creates stronger economic case for early fuel-switching and long-term investment

Second, the scope of emissions coverage differs substantially between the EU ETS and the FuelEU Maritime or the IMO Net-Zero Framework. The EU ETS applies only to TTW emissions, overlooking upstream production and supply-chain impacts. This narrow focus neglects a significant share of lifecycle emissions and does not directly incentivize the use of low-carbon fuels, since combustion emissions from fossil and bio-based fuels of the same type are largely identical. As a result, the EU ETS primarily encourages improvements in energy efficiency and operational measures rather than fuel substitution. In contrast, both FuelEU Maritime and the IMO Net-Zero Framework adopt a WTW perspective, assessing the greenhouse gas intensity of fuels across their full lifecycle. This design provides a stronger demand signal for the uptake of green fuels, though it also raises short-term concerns over the limited availability of sustainable alternatives, particularly biofuels. Nevertheless, in the long run, such an approach is expected to accelerate investment, scale up production, and ultimately reduce the cost of alternative fuels, thereby supporting a more durable decarbonization pathway.

Third, the enforcement mechanisms differ considerably across the EU ETS, FuelEU Maritime, and the IMO Net-Zero Framework. The EU ETS relies on a robust monitoring, reporting, and verification (MRV) system, under which ship operators must surrender allowances equivalent to their verified CO_2 emissions. Compliance costs are determined by the market price of EU Allowances, which creates a strong but volatile price signal that may generate uncertainty for shipowners. In cases of non-compliance, a statutory penalty of EUR 100 per tonne of CO_2 applies in addition to the obligation to surrender missing allowances in subsequent years (Flodén et al., 2024). In contrast, the FuelEU Maritime enforces compliance by assessing the annual well-to-wake GHG intensity of the energy used by each vessel, with the option of pooling compliance across fleets. Exceeding the prescribed limits results in a fixed penalty of EUR 2,400 per tonne of VLSFO-equivalent above the threshold. This provides cost predictability for operators, though the fixed nature of the penalty may weaken incentives if fossil fuel or carbon prices fall significantly (DNV, 2025). The IMO Net-Zero Framework adopts yet another approach, introducing a two-tier compliance system in which ships are charged for emissions above their intensity targets, with flexibility provided through pooling and the use of two-tier Remedial Units. Revenues are used for the IMO Net-Zero Fund to support infrastructure, R&D, and transition assistance in developing countries. However, its effectiveness remains uncertain due to the absence of a comprehensive global trading system, clear price trend, incomplete compliance mechanisms, and unresolved details regarding certification and governance (Luman, 2025).

Fourth, the influence on shipowners will also be different among the regulations. Apparently, both FuelEU Maritime and the IMO Net-Zero Framework will exert stronger impacts on shipowners than the EU ETS, but in different ways.

Moreover, a Lloyd's Register (2025) modelling study compared the potential financial and abatement outcomes for a hypothetical vessel consuming 10,000 tonnes of VLSFO and 1,000 tonnes of ULSFO annually between 2025 and 2050. The results show that the ship consistently fails to meet the targets under both regimes, thereby incurring penalties. In the "worst-case" scenario, where maximum penalties are applied, the IMO Net-Zero Framework generates higher annual compliance costs up to 2045, while FuelEU imposes greater penalties thereafter, though the cumulative costs remain higher under the IMO Net-Zero Framework. This illustrates that the IMO system is more punishing in the near- to medium-term, whereas FuelEU could become comparatively more costly after mid-century.

However, the analysis also shows that when the vessel adopts low-carbon fuels sufficient to meet both targets, the GHG abatement achieved is consistently greater under the IMO, both annually and cumulatively. This highlights an important distinction that the IMO Net-Zero Framework is structurally more stringent, both in terms of abatement potential and cumulative penalties, while FuelEU is less demanding in its early trajectory but tightens later. For shipowners, this implies that under the IMO Net-Zero Framework there is a stronger economic case for early investment in fuel-switching and fleet adaptation, whereas FuelEU offers greater compliance flexibility in the short term, especially through pooling mechanisms, but still generate significant costs in the long run.

More broadly, this raises questions about regulatory coexistence. FuelEU recital 69 explicitly notes that the regulation could be withdrawn if a global measure of equivalent environmental effectiveness were adopted (Pringle, 2025). Given that the IMO Net-Zero Framework not only produces higher cumulative abatement but also imposes a more globally harmonized framework, shipowners must prepare for the possibility that FuelEU could eventually be phased out or integrated into the IMO system. Until then, operators voyaging into Europe will possibly face the dual burden of both regimes, amplify compliance risks and reinforce the importance of fuel choice. Thus, the next section evaluates the main alternative fuel options for containerships and motivates which fuels enter the scenario design in Chapter 3.

2.2 Alternative Fuels

Building on the regulatory context, shifting to alternative fuels is no longer an optional operational choice but a regulatory pathway to compliance under these regulations, especially for the IMO Net-Zero Framework, which will dominate the trend of the future maritime industry. Yet, decarbonization through alternative fuels remains an evolving landscape, with no single option having emerged as a definitive solution.

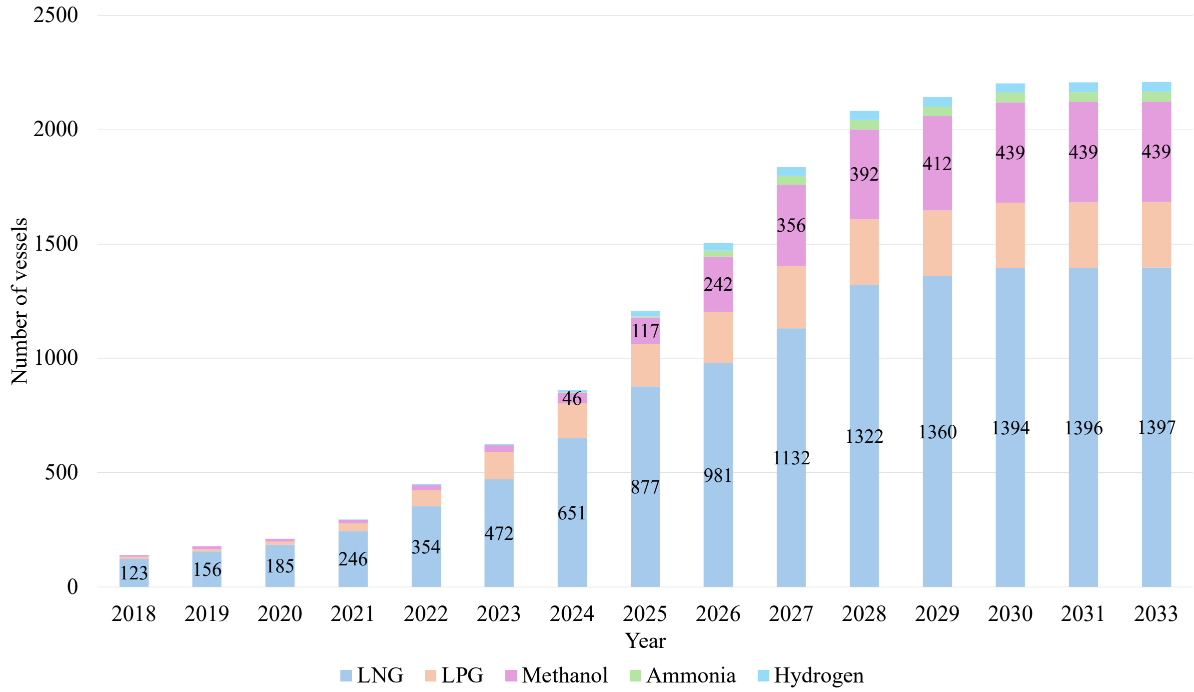
This section addresses Sub-question 2: "*What are the advantages and disadvantages of the main alternative fuel options for containerships, and which are more suitable for deployment in the existing fleet under current regulatory frameworks?*" It proceeds in three steps. First, it outlines adoption trends in the containership segment, both in operation and on orderbook, to identify the main alternative fuels currently in use. Second, it evaluates each fuel in terms of characteristics, operational feasibility, and economic and environmental advantages and limitations. Finally, it synthesizes these insights to compare the options, highlighting which fuels are more practical for existing containerships and selecting those carried forward into the scenario analysis.

2.2.1 Trends on alternative fuels in shipping

Although recent fleet orders show accelerating adoption trends that are reshaping the industry, but still with uncertainty on which alternative fuel to be used in the future. According to the latest DNV

Alternative Fuels Insight (2025), alternative fuels currently still represent a minimal share, less than 1% (approximately 0.94%), of the global maritime fleet, yet their adoption rate is rapidly increasing. Among alternative fuels, liquefied natural gas (LNG) dominates the existing operational fleet, accounting for about 0.7%, with significantly smaller shares attributed to liquefied petroleum gas (LPG) (0.15%), methanol (0.07%), hydrogen, and ammonia. Notably, this distribution shifts notably based on current vessel orders, where alternative fuel vessels represent 16% of the global orderbook. Moreover, LNG continues to lead with a 9% share, closely followed by methanol at 5%, while LPG, ammonia, and hydrogen share the remaining portion. In total, vessels currently in service or on order now over 2,100 units, including approximately 1,370 LNG-fueled vessels, 435 methanol-fueled vessels, 290 LPG-fueled vessels, and several powered by hydrogen or ammonia (DNV, 2025), as shown in Figure 5.

Figure 5. Growth of alternative fuel uptake by number of vessels



Source: DNV (2025)

Additionally, containerships lead in alternative fuel adoption, notably LNG (560 vessels) and methanol (240 vessels), as they are highly energy-intensive and central to meeting EU and IMO decarbonization targets. Thus, large liner companies such as Maersk and MSC possess the capital to invest in dual-fuel newbuilds, unlike bulk, tanker, or small-vessel operators (Prussi et al., 2021), as their fixed, long-haul routes with calls at major hubs (e.g., Singapore, Rotterdam, Shanghai) align with the limited availability of LNG and methanol infrastructure, making them more accessible to alternative fuels (Wang & Wright, 2021; Chen, et al., 2023). In addition, container ships can more easily accommodate the larger tank volumes required for fuels such as methanol and ammonia without significant cargo loss, which is a challenge for smaller or irregularly operating vessels (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022).

Despite the clear regulatory momentum, uncertainty remains as to which alternative fuel will ultimately dominate the containership sector, since major carriers are pursuing divergent strategies. Maersk, widely recognized as a frontrunner in maritime decarbonization, has prioritized biodiesel, green methanol (e-methanol or bio-methanol), and bio-LNG as its primary pathways (Maersk, 2024). The company currently operates 14 dual-fuel methanol vessels, with a further 25 scheduled for delivery by 2027, and an additional 50–60 dual-fuel vessels, including LNG-fueled ships, expected thereafter. Upon completion of these newbuilds and retrofits, dual-fuel vessels will account for approximately one quarter of Maersk's total fleet (Maersk, 2025). Moreover, biodiesels are already deployed within its existing fleet to provide low-carbon transport services for customers (Maersk, 2025).

In contrast, MSC has adopted a somewhat different approach. Its fleet expansion strategy over the next five years centers on LNG and ammonia dual-fuel vessels, many of which are equipped with air-lubrication systems to reduce fuel consumption and associated emissions (MSC, 2025; MARIN, 2025). Looking further ahead, MSC places greater emphasis on retrofitting and constructing vessels with dual-fuel capability and integrating onboard carbon-capture technologies. While biofuels are recognized as transitional options for large ocean-going vessels, MSC also highlights the role of green hydrogen, batteries, and fuel cells for smaller ships and short-sea operations (MSC, 2025).

Both companies are simultaneously building strategic partnerships with fuel suppliers and technology developers to secure future supplies of green fuels and accelerate deployment of novel technologies (Maersk, 2025; MSC, 2025). These different strategies further illustrate that each alternative fuel carries unique advantages and constraints, thereby shaping divergent corporate pathways. Consequently, a detailed examination of potential solutions and strategies identified in existing literature is essential and will be explored in the subsequent sections.

Notably, as shown in Figure 5, there are mainly five alternative fuel choices. However, this paper specifically focuses on fuel alternatives suited to long-range containership operations, thereby excluding LPG and hydrogen from the analysis due to practical constraints. While LPG has advantages in gas carriers that can repurpose cargo tanks for bunkering, its applicability to retrofitted or newly built containerships is limited (WLPGA, 2021). Containerships would require costly storage systems and modifications, rendering LPG comparatively uneconomic relative to LNG, methanol, or ammonia (Balcombe, et al., 2019). Also, hydrogen remains largely infeasible for long-haul deep-sea shipping under current technologies considering its low volumetric energy density, high storage and insulation costs, and the need for extensive safety systems confine its effective use to short-sea or inland operations rather than ocean-going vessels (DNV GL, 2019). Consequently, the analysis will focus on biodiesel, LNG, methanol, and ammonia, as these fuels have demonstrated the potential technical feasibility and supply for long-range containerships.

2.2.2 Biodiesel

Biodiesel has emerged as one of the most practical compliance options for the existing containership fleet under the FuelEU Maritime Regulation and the IMO Net-Zero Framework, primarily because it is a drop-in fuel that can be used with minimal modifications to ship engines and infrastructure (Balcombe et al., 2019; MAN Energy Solution, 2023; Kosmajac, 2024). In practice, fatty acid methyl ester (FAME) is currently the most widely available form of biodiesel and is often blended with conventional fossil fuel, with typical blends of 24% in Singapore and 30% in Rotterdam, the two largest biofuel bunkering hubs worldwide (DNV, 2025; Ship & Bunker, 2025). Sales volumes in these ports increased from roughly 0.3 million tonnes in 2021 to over 1.6 million tonnes in 2024, driven largely by regulatory compliance incentives under FuelEU Maritime (Argus, 2025). High-profile demonstrations have reinforced its operational feasibility, such as Maersk has voyaged a vessel from Rotterdam to Shanghai using a 20% biofuel blend that saved 1,500 tonnes of CO_2 in 2019 (Maritime Executive, 2019) and the AIDA cruise ship trials of B100 biodiesel in Rotterdam in 2024, expected to reduce GHG emissions by 85% compared with fossil fuels (Snyder, 2024). These examples suggest that biodiesel can already deliver measurable reductions in GHG emissions without major technical barriers.

The life-cycle emissions of biodiesel, however, vary significantly depending on the feedstock and production pathway. Balcombe et al. (2019) reported a range from 22 to more than 110 gCO_2e/MJ for FAME, illustrating that sustainable feedstocks such as used cooking oil and animal fats perform substantially better than crop-based oils. CE Delft's analysis of the FuelEU Maritime Annex II factors highlights that waste-derived FAME can reach 16.2 gCO_2e/MJ, a reduction of over 80% relative to VLSFO (Nelissen et al., 2022). At such levels, biodiesel enables ships to remain below regulatory intensity thresholds and avoid penalties, or potentially even generate compliance credits under the IMO framework. Furthermore, biodiesel generally has negligible Sulphur content and tends to reduce particulate matter emissions relative to marine gas oil, making it attractive for compliance not only with GHG standards but also with regulations in Emission Control Areas (ECAs) (Wei et al., 2018).

From an economic perspective, biodiesel appears more expensive compared with VLSFO, but when regulatory penalties are factored in, waste-based biodiesel can prove its cost-effectiveness. Rystad Energy (2025) estimates that blending biodiesel at 30% to 50% can already mitigate short-term compliance risks, while full substitution with 100% sustainable biofuel offers the greatest long-term savings by maximizing GHG abatement and reducing exposure to penalties. This explains why biofuels are increasingly deployed as a transitional strategy by major carriers, particularly for existing ships where costly retrofits for alternative fuels are less viable.

Nevertheless, several constraints limit the long-term scalability of biodiesel in shipping. Technically, biodiesel suffers from issues such as oxidative degradation, microbial growth, and poor cold-flow properties, which increase the risk of clogged filters and corrosion if not carefully managed (DNV, 2020; McCormick & Moriarty, 2023). While these risks can be controlled through good housekeeping practices, they add operational complexity (Selvam, et al., 2025). More importantly, global supply constraints represent a structural barrier as projections suggest that even if shipping demand were to rise sharply leading to more investment in production, total biodiesel capacity will remain capped by the availability of sustainable feedstocks, which are also in high demand from aviation and road transport (IEA, 2023; Transport & Environment, 2024). This suggests that while biodiesel offers an immediately deployable and regulation-compliant solution, it is unlikely to serve as the dominant long-term decarbonization pathway for deep-sea shipping.

In summary, biodiesel provides the shipping industry with a technically feasible, regulation aligned, and operationally proven means of reducing emissions in the near term, particularly for the existing fleet. However, its feedstock constraints mean that it should be regarded as a transitional option, especially for existing vessels, that helps bridge the gap until scalable zero-carbon fuels such as green methanol can be deployed at industrial scale.

2.2.3 Liquefied Natural Gas (LNG)

LNG is considered as one of the most mature and widely available alternative marine fuels, offering a lower-emission pathway under current regulatory regimes, particularly when combined with bioLNG or renewable e-LNG, which are expected to deliver among the lowest abatement costs (Visser & Beddoe, 2025). Technically, LNG is primarily methane cooled to –162°C to reduce its volume for efficient storage and transportation (Chevron, 2025). This requires dedicated cryogenic storage tanks and onboard vaporization systems, rather than just liquefaction facilities, making LNG handling considerably more complex and costly (Yao et al., 2022). Furthermore, LNG's volumetric energy density is significantly lower than conventional marine fuels, implying that LNG vessels require 2 to 3 times more tank volume to achieve equivalent range (DNV, 2023). Despite this drawback, LNG retains a higher energy content per unit volume than oil-based fuels, which can improve fuel efficiency on a per-tonne basis (Lloyd's Register, 2025).

Currently LNG holds a dominant position in the alternative maritime fuel transition, with 70% of the operational alternative fuel fleet runs on LNG, and 58% of new alternative fuel ship orders are LNG dual fuel vessels (DNV, 2025). Moreover, LNG bunker infrastructure has expanded rapidly with nearly 200 ports and 60 LNG bunkering vessels now in operation worldwide (SEA-LNG, 2025). Additionally, Lloyd's Register (2025) also notes increasing retrofit activity, as conversions can yield immediate reductions to comply with short-term regulatory thresholds.

From an emission reduction perspective, LNG offers significant and immediate benefits, which is nearly Sulphur-free and produces lower NOx and particulate matter, facilitating compliance with ECA limits (Le Fevre, 2018). Moreover, on a TTW basis, fossil LNG can reduce onboard CO_2 emissions by 18% to 26% compared to fuel oil (Schuller et al., 2021; Miyake, 2024), while a case study of a HFO 8500TEU container vessels converted to LNG dual fuel report reductions in CO_2, NO_x, PM, and SO_x of 25.7%, 76.3%, 92.9% and 98.6%, respectively (Wu & Lin, 2021). However, under the WTW perspective adopted by FuelEU and the IMO Net-Zero Framework, reductions are smaller, typically 10% to 17% versus HFO, due to upstream liquefaction emissions and methane slip (Miyake, 2024; Visser & Beddoe, 2025). Therefore, WTW emissions must be considered minimized to show the full GHG emissions benefits of LNG (Visser & Beddoe, 2025).

Particularly, methane slip remains a central technical concern for LNG vessels. Incomplete combustion allows unburned methane (25 times higher global warming potential than for CO_2 over a 100-year time perspective) to escape, undermining GHG savings (Selma et al., 2014; Amir et al., 2019). Nevertheless, recent studies show that methane slip varies considerably across engine technologies, with newer designs achieving much lower levels than earlier systems (Sachgau, 2025). Moreover, continued advances, including generational upgrades and abatement solutions, are expected to drive methane emissions closer to zero (Visser & Beddoe, 2025). This is particularly relevant as the IMO Net-zero Framework explicitly includes methane in WTW GHG intensity calculations (Nelissen et al., 2022).

Notably, beyond fossil LNG, bioLNG and e-LNG are frequently discussed as long-term pathways. However, e-LNG is produced using CO_2 and e-hydrogen is not mature currently, which is still in the concept level as electrolysis facilities need to be industrialized at scale (Lloyd's Register, 2025). BioLNG, typically produced via anaerobic digestion of agricultural and municipal waste (SEA-LNG, 2025), can achieve WTW GHG intensities as low as 15 gCO_2e/MJ, which is 79% and 83% below fossil LNG and VLSFO, respectively (Nelissen et al., 2022). Visser & Beddoe (2025) further show that blending 1% bio-LNG is sufficient for FuelEU 2035 compliance, with 28% and 78% blends required for 2040 and 2045, respectively. Yet, the bioLNG availability remains highly constrained as Rystad Energy (2025) projects that over 90% of bioLNG supply is already committed to power and road transport, leaving less than 10% for shipping. Furthermore, the price of bioLNG also poses challenges as its bunkering costs are nearly 2.5 times higher than fossil LNG (S&P Global, 2025).

Remarkably, policy incentives and pooling mechanisms can partly close this gap. Rystad Energy (2025) notes that subsidies could make bioLNG cost competitive with biodiesel, while Visser & Beddoe (2025) argue that overcompliance by one bioLNG vessel in the fleet can offset the penalties of 19 VLSFO vessels under FuelEU Maritime's pooling mechanism. Supporting this, Q2 2025 sales of bioLNG in the Port of Rotterdam hit a record high, attributed to shipowners purchasing bioLNG to generate overcompliance credits (Al-Khalisy et al., 2025).

In summary, LNG's strengths are its technical maturity, global infrastructure, immediate TTW emission reductions, and compliance with ECA limits, while its weaknesses are high capital costs, larger tanker space, methane slip, and bio-LNG limited availability and high price. For shipowners, LNG represents a near-term compliance pathway, but its long-term decarbonization potential hinges on methane management, expanded biomethane and e-LNG supply, and regulatory support.

2.2.4 Methanol

Orderbook data and recent reviews indicate that methanol, especially green methanol (biomethanol and e-methanol), is emerging as a leading alternative for deep-sea shipping, with rapidly growing uptake in the container segment (Svanberg et al., 2018; Zincir & Deniz, 2021; DNV, 2025). Chemically, methanol is the simplest alcohol (CH_3OH), a liquid at ambient conditions (boiling point ≈ 65 °C) already produced at large industrial scale for the chemical sector (DNV, 2023). Its handling at ambient temperature and pressure and compatibility with conventional shipyard practices reduces integration complexity relative to cryogenic fuels. Moreover, DNV (2023) estimates that incremental capital expenditure (CAPEX) for methanol fuel systems (tanks, piping, methanol-capable engines) is nearly one-third of LNG systems because no cryogenic or high-pressure storage is required. However, a key drawback is its low energy density. Methanol's lower calorific value (LCV) (20 MJ/kg) is roughly half that of marine oil (40 to 42 MJ/kg). Thus, its fuel tank capacities have a size approximately 2.3 to 2.6 times and 1.3 times larger than oil tanks and LNG tanks, respectively, for the same energy content (DNV, 2023).

Notably, the adoption of methanol fueled vessels is advancing quickly in liner shipping. Maersk has ordered 25 large methanol-capable container vessels and reports 14 already in operation, complemented by a rolling retrofit program (Anner, 2025; Ship & Bunker, 2025). COSCO has also placed dual-fuel methanol orders (Bahtić, 2024). Furthermore, Maersk's large-scale retrofit further demonstrates methanol's feasibility. After a 15 m hull extension to accommodate methanol tanks and installation of a dual-fuel engine, the vessel not only completed conversion in 88 days but also gained about 690 TEU in nominal capacity (Rasmussen, 2024; Krüger, 2025). These cases illustrate the industry's growing confidence in methanol as an emerging marine fuel. From a ship-integration perspective, methanol engines are already commercially available, and retrofitting existing vessels to methanol is relatively straightforward compared to ammonia, which remains at an earlier stage of technological maturity and piloting (Boyland, 2025).

Similar to biodiesel and LNG, lifecycle performance depends entirely on the production pathway. Fossil methanol from natural gas is typically 100 to 110 gCO_2e/MJ, while coal-based methanol can reach about 300 gCO_2e/MJ (Svanberg et al., 2018; Methanol Institute, 2022). On this basis, conventional methanol does not decarbonize shipping and even exceed the WTW intensity of fuel oil. By contrast, biomethanol (from wastes/residues or lignocellulosic feedstocks) and e-methanol (from renewable H2 and captured CO_2) can achieve 10 to 40 gCO_2e/MJ, with some pathways approaching near-zero or net-negative if biogenic CO_2 and renewable electricity are used (Methanol Institute, 2022). Using FuelEU Annex II factors, biomethanol from farmed wood is estimated at about 18.7 gCO_2e/MJ, which is 82% lower than fossil methanol (102.9 gCO_2e/MJ) (Nelissen et al., 2022). These values align methanol, when produced sustainably, with the WTW intensity standards under FuelEU Maritime and the IMO Net-Zero Framework, making it a strong candidate for penalty avoidance and over-compliance credit

generation. However, e-methanol remains at a testing stage, while both electrolysis and air capture technologies still need to be industrialized at scale (Lloyd's Register, 2025).
Furthermore, methanol combustion eliminates Sulphur and substantially reduces PM. Also, NO_x is generally lower owing to cooler flames, although absolute reductions depend on engine calibration and after-treatment (Ammar, 2019). However, methanol's toxicity and low flashpoint introduce distinctive safety challenges as flames can be hard to see, and exposure risks require strict controls (DNV, 2022). Accordingly, safe design relies on double-walled piping, leakage detection, segregation and ventilation, and crew training under low-flashpoint fuel codes (Andersson & Salazar, 2015; Ellis & Tanneberger, 2015; DNV, 2022). Also, material compatibility is another practical consideration as methanol can attack aluminum, zinc and certain polymers, and its low lubricity necessitates suitable materials, coatings, and additive management in fuel and lube systems (Verhelst et al., 2019; DNV, 2022). These requirements are manageable but add engineering complexity and OPEX (Verhelst, et al., 2019).
From an economic perspective, the CAPEX of methanol engines and storage systems is comparatively modest relative to LNG, yet current OPEX remains higher due to low energy density, the elevated price of green methanol and limited supply. Nonetheless, green methanol presents a scalable pathway, as it can be synthesized from diverse routes, including biomass, renewable hydrogen, and captured CO_2 (GENA Solutions, 2025). However, multiple techno-economic studies indicate that renewable methanol is unlikely to achieve cost parity with HFO before the 2040s without substantial policy support (Helgason et al., 2020; Wang & Wright, 2021). Conversely, GENA Solutions (2025) recently estimates that although current green methanol's costs are high, production is projected to expand rapidly, from 2 million tons in 2025 to more than 50 million tons by 2030, with cost parity with fossil methanol potentially achievable by the mid-2030s (Carlsson, 2025). Furthermore, under WTW-based regulations, biomethanol and e-methanol can achieve significant compliance value through both penalty avoidance and potential overcompliance credits, narrowing the cost gap materially (Dierickx, 2024).
In summary, methanol's ambient-temperature handling, retrofit feasibility, and alignment with WTW regulatory requirements (green methanol) position it as a compelling option for containership decarbonization. Its drawbacks such as low energy density, safety and toxicity concerns, and the current high cost and limited availability of green methanol, are significant, yet could be increasingly addressed through technical solutions and regulatory support. Crucially, the scalability of green methanol, underpinned by multiple production pathways and expected rapid capacity expansion, enhances its mid- and long-term potential. Overall, methanol is unlikely to emerge as a solution for the short term, but it remains as one of the most readily deployable fuels for meeting IMO Net-Zero Framework while preserving flexibility for deeper decarbonization as supply scales.

2.2.5 Ammonia

Ammonia has attracted significant attention as a potential zero-carbon marine fuel, owing to its carbon-free molecular structure and the possibility of achieving substantial reductions in GHG emissions when produced from biomass or renewable sources (Lloyd's Register, 2021; Laursen et al., 2022). At ambient conditions ammonia is a colorless gas, but it can be liquefied relatively easily either under moderate pressure or by cooling to –33 °C, making its storage and handling simpler than LNG or hydrogen (DNV, 2022). However, its energy density is broadly comparable to methanol, though considerably lower than fuel oil and LNG, which imposes larger tanker space and may occupy more cargo space (Ash & Scarbrough, 2019; Lloyd's Register, 2021). Kim et al. (2020) estimated that ammonia tanks could be about three times larger than conventional fuel oil tanks for equivalent energy content, with an associated weight penalty of 1.5 times.

At present, ammonia propulsion remains in the laboratory stage, with only three vessels engaged in pilot operations and engine manufacturers such as MAN, Wartsila and WinGD expecting commercial-scale deliveries only from 2026 onwards (DNV, 2025; Fortescue, 2025; Willmington, 2025). Nevertheless, there has shown a trend with deploying ammonia ships, as evidenced by 42 ammonia-fueled vessels currently on order (DNV, 2025) and the completion of initial bunkering demonstrations in Singapore, Rotterdam and Dalian (MPA, 2024; Port of Rotterdam, 2025; Ship & Bunker, 2025).

From a regulatory perspective, ammonia's WTW performance is highly dependent on production pathways as green ammonia from renewable hydrogen and captured nitrogen can deliver up to a 90% WTW GHG reduction relative to fuel oil, whereas grey or brown variants can be even one third more carbon-intensive than HFO (Wartsila, 2025; Thurman, 2025). Blue ammonia, produced with carbon capture, offers an intermediate pathway with the potential to align with IMO 2030 intensity targets (Zincir, 2022). Empirical modelling by Zincir (2022) on short-sea shipping confirms this differentiation. His study found that brown ammonia derived from coal or oil increases CO2 emissions compared to fossil fuels, while 95% blue ammonia use enables a 42.8% reduction, sufficient to meet IMO 2030 targets. Green ammonia produced from renewable wind power achieved a 79.2% reduction, consistent with IMO 2050 ambitions, while higher ammonia shares also yielded greater reductions in NOx, SOx, and PM. However, Zincir (2022) emphasizes that green ammonia is not currently a viable alternative due to prohibitively high costs. As such, blue ammonia is best positioned as a mid-term transition fuel, with a shift to green ammonia feasible only once costs decline and regulatory stringency increases.

Despite its long-term potential, ammonia adoption faces several major challenges. First, availability is constrained. Around 80% of global ammonia production is already committed to the fertilizer industry, and if 30% of shipping were to switch to ammonia, global ammonia supply would need to almost double (S&P Global, 2025; Thurman, 2025). Moreover, meeting projected bunker demand, rising from 2.3 million tons in 2030 to 62 million by 2040 and 245 million tons by 2050, would require a massive scale-up in production capacity, with individual plants taking four to six years to build (Ship & Bunker, 2024; Thurman, 2025). This expansion trajectory remains far behind the rapid growth expected for methanol (GENA Solutions, 2025). Therefore, the gap between the demand and supply of the ammonia, especially green ammonia, may not be filled quickly even when the ammonia fueled ships come to the commercial period, which may burden the development of the ammonia in the maritime industry.

Second, costs remain prohibitive. Ammonia prices are currently around twice those of fuel oil, reflecting both limited supply and the premium for low-carbon production (S&P Global, 2025). Techno-economic modelling suggests that total ownership costs for ammonia fueled vessels could be 3.5–5.2 times those of HFO baselines at present prices, though this premium might be halved if bunker prices fall to USD 400 per tonne (Kim et al., 2020).

Third, safety and integration present serious operational barriers. Ammonia is highly toxic and corrosive, demanding extensive crew training, double-walled fuel systems, more frequent maintenance, and robust safety protocols (Thurman, 2025). Combustion also carries the risk of unburned NH_3 slip and N_2O emissions, both potent climate forcers, necessitating costly catalyst after-treatment (Zincir, 2022).

In summary, ammonia offers one of the most compelling long-term decarbonization pathways, being carbon-free at the point of use and fully compatible with WTW GHG intensity regulation if sourced renewably. However, high costs, feedstock competition, toxicity, infrastructure shortages, and the immaturity of shipboard technologies currently limit its role to demonstration projects and early adoption. For the medium term, blue ammonia may act as a transitional fuel, while green ammonia could emerge as a viable large-scale option once production scales up and regulatory pressures strengthen (Zincir, 2022; DNV, 2022; Thurman, 2025).

2.2.6 Summary

In summary, the literature demonstrates that no single alternative fuel offers a complete solution for maritime decarbonization. Rather, each fuel is likely to play a role at different stages of the transition, depending on its technical characteristics, scalability, and regulatory alignment. Table 2 summarizes the key features of each fuel, which answers the Sub-question 2: *What are the advantages and disadvantages of the main alternative fuel options for containerships?*

Table 2. Alternative Fuel Comparison

Fuel	Biodiesel	LNG	Methanol	Ammonia
Technical Feasibility	Drop-in fuel; minimal modifications; already used in operations	Requires liquefaction facilities and cryogenic storage; methane slip concerns; commercially mature; dominates the alternative fuel market	Liquid at ambient temperature; easier storage/retrofit than LNG; low energy density (larger tanks); safety concern for toxicity and low flashpoint; already used in operations	Requires liquefaction facilities and cryogenic storage; low energy density (larger tanks); corrosive and toxic concerns; still in pilot stage

WTW GHG Reduction Potential	60–85% depending on feedstock (waste oils best, crop-based low)	10–20% (fossil LNG, WTW); 70–80% (bio-/e-LNG)	80–90% (bio-/e-methanol); fossil methanol worse than HFO	40% (blue ammonia); up to 90% (green ammonia); fossil ammonia worse than HFO
Cost	Higher than HFO but partly offset by overcompliance rewards	High CAPEX for tanks and engines; fossil LNG affordable; bio-/e-LNG costly	CAPEX lower than LNG; OPEX high due to more consumption of the fuel and expensive limited green methanol	CAPEX higher than methanol; OPEX very high due to limited supply and more consumption of the fuel
Availability & Scalability	B24–B30 blending available at major ports; large-scale or high-blend expansion constrained by limited sustainable feedstock	Fossil LNG widely available at major ports; bio-/e-LNG scarce and compete with other sectors	Fossil methanol widely produced; bio-/e-methanol scalable via multiple routes; rapid supply growth expected by 2030s	Very limited availability and 80% of supply used in fertilizer; plant build 4–6 years; supply expansion potentially by 2040
Readiness Level	High: immediately deployable for existing fleet	High: commercially mature	Medium–High: growing uptake, scalable mid/long term	Low: pilot/demonstration stage; long-term potential

Particularly, biodiesel stands out as the most immediate, drop-in compliance option, but its long-term role is constrained by limited sustainable feedstocks. Besides, LNG is commercially mature and supported by an extensive global infrastructure network, yet its climate benefits are undermined by methane slip and the constrained availability of bioLNG, which faces the same biomass limitations as biodiesel. However, methanol emerges as one of the most promising mid to long term pathways due to its retrofit feasibility, alignment with well-to-wake regulation, and diverse and scalable production routes. Nevertheless, high costs and limited availability of green methanol remain pressing challenges. Ammonia is widely recognized as a carbon-free option with significant long-term potential, but current barriers related to technology maturity, safety, cost, and supply readiness confine it to a post-2040 role. Thus, building on these insights, it also addresses another part of the Sub-question 2: *Which alternative fuels are more suitable for deployment in the existing fleet under current regulatory frameworks?* The literature review demonstrates that biodiesel, LNG, and methanol represent the most relevant compliance options for the existing vessels, given their technical feasibility, regulatory alignment, and availability. By contrast, ammonia, while strategically important as a carbon-free solution in the longer term, is not yet technically mature or economically viable for large-scale adoption in the near term. Instead, ammonia is more likely to be a choice for newbuilds. Lin (2022) further notes that building ammonia conversion-ready vessels offers a better option, as they can be retrofitted once ammonia becomes widely available, reducing future retrofitting costs.

Accordingly, this paper narrows its analytical focus to biodiesel, LNG, and methanol as the primary alternatives for evaluating fleet compliance strategies during 2025 to 2040. Importantly, despite extensive literature on alternative fuels choices especially under FuelEU Maritime and EU ETS, there remains a critical research gap regarding how compliance strategies for the existing fleet can be optimized under the newly adopted IMO Net-Zero Framework. In particular, little attention has been given to how pooling mechanisms and differentiated compliance costs may shape fuel and investment choices across existing fleets. To address this gap, the following sections develop a quantitative model to evaluate cost-effective compliance strategies for deep-sea containerships under the IMO Net-Zero Framework, considering biodiesel, LNG, and methanol.

Chapter 3 Methodology

This study examines a representative fleet of 13 containerships operating on the Far East–North Europe route. A Maersk fleet on the AE1 service from Shanghai to Rotterdam is selected as the analytical unit, given its weekly frequency and its position on one of the world's busiest and most strategically significant trade lanes. The objective is to evaluate cost-effective compliance pathways under the forthcoming IMO Net-Zero Framework (2028–2040) by optimizing fleet composition and fuel strategy, while also accounting for FuelEU Maritime (2025–2027) prior to the IMO Net-Zero Framework entry into force in 2028.

Furthermore, the pooling mechanism is applied, treating the 13 vessels as a single operational pool to minimize total compliance costs by reducing the use of high-priced biofuels wherever possible and selling surplus units when the whole fleet's performance exceeds regulatory requirements. This fleet-level optimization approach, rather than a vessel-by-vessel analysis, aims to minimize overall compliance costs and assess the effectiveness of pooling, while enabling collective decisions on retrofitting and biofuel adoption. Within the pool, the fleet consists of 3 LNG dual-fuel vessels and 10 conventional heavy fuel oil (HFO) vessels. The HFO vessels are further divided into two subgroups: 6 older ships with higher fuel consumption and 4 newer ships with more efficient engines. Thus, the fleet can be categorized into three groups based on engine type.

The methodology employs scenario-based techno-economic modelling to identify the most cost-efficient transition pathway over a 15-year horizon (2025–2040). Key decision variables include:

1. The number of vessels using biofuels and the blending ratios over time in response to tightening regulations and potential surplus units as overcompliance rewards.
2. The timing of fuel-switching decisions.
3. The number of conventional vessels to be retrofitted with LNG or methanol propulsion systems.

The model incorporates regulatory constraints from FuelEU Maritime (2025–2027) and the IMO Net-Zero Framework (2028–2040). The following sections detail the assumptions, data inputs, and scenario settings.

3.1 Assumption

To ensure the feasibility and comparability of the optimization model, the following simplifying assumptions are made:

1. Within each group of the vessel, no significant differences are assumed in fuel consumption rates or other technical specifications. Each vessel has an assumed lifespan of 25 years, with the current average age being approximately 10 years (Clarksons, 2025), resulting in a 15-year modelling horizon.
2. The total number of vessels in the fleet remain constant as 13 vessels, which is assumed to maintain weekly service between major ports in Asia and Northern Europe.

3. Although recent geopolitical disruptions have temporarily prompted rerouting via the Cape of Good Hope (UNCTAD, 2024), this study assumes a return to the traditional Suez Canal route, reflecting the recent trend of large container vessels resuming transit (Suez Canal Authority, 2025). The Suez route is considered more representative for long-term analysis, as it shortens the round voyage by approximately 7,000 nautical miles while maintaining the same port rotation. Moreover, port calls and total route distance are assumed constant across all scenarios for the 15-year horizon.
4. Fuel prices are assumed geographically uniform, with no regional price differentials.
5. FuelEU Maritime and the IMO Net-Zero Framework are assumed to operate sequentially rather than simultaneously. Specifically, compliance costs under FuelEU Maritime are applied from 2025 to 2027, after which the IMO Net-Zero Framework takes effect from 2028. This assumption reflects the potential convergence of the two regimes, given FuelEU Maritime's self-termination clause (Recital 69 and Article 30), which favors a global approach under the IMO due to its broader scope (Pringle, 2025).
6. For the Base Compliance Target (Tier 2), IMO currently are not specified for 2036–2039. A linear interpolation is applied between the 2035 target and the 2040 target (65% reduction from the 2008 baseline) (IMO,2025), assuming equal annual reductions over this period. For the Direct GFI reduction (Tier 1), no 2040 target is provided. This study assumes an 80% reduction by 2040, in line with the "2023 IMO Strategy on Reduction of GHG Emissions from Ships" (IMO, 2023). Annual reduction rates for 2036–2039 for Tier 1 are derived using the same interpolation method. Regulations are assumed unchanged between 2025 and 2035 with IMO settings.
7. Surplus units (SUs) from over-compliance with the Direct Compliance Target (Tier 1) are first reallocated within the fleet to cover deficits against the Base Compliance Target (Tier 2). If the fleet meets its Tier 2 obligations after internal balancing, remaining surplus units are sold in the same year. Although IMO surplus units can be banked for up to two compliance years, early-period banking is assumed inefficient, as vessels exceeding the Tier 1 target in one year are generally expected to meet Tier 2 obligations the following year (Dibdin et al., 2025). Immediate sale is therefore assumed to be the preferred strategy.
8. Methanol consumption is estimated based on the energy demand of an equivalent LNG-fueled vessel. This is supported by the fact that both LNG and methanol dual-fuel engines operate on the Diesel cycle and exhibit similar thermal efficiency under comparable operational profiles (MAN Energy Solutions, 2021). Assuming identical energy demand, the required methanol volume is calculated by dividing total energy input by the lower calorific value (LCV) of methanol.
9. Due to limited data on exact retrofitting costs, particularly opportunity costs such as downtime or revenue loss, this study assumes such costs are incorporated into the retrofitting estimates

referring to Zhao et al. (2025). Moreover, given that the fleet examined is 10 years old, major maintenance is expected, and recent fuel oil engine's conversions to methanol have taken around 88 days, consistent with typical drydock periods (Anner, 2025). This assumption enables the analysis to focus on long-term strategic implications rather than short-term operational disruptions.

10. When operating on LNG or methanol, 5% of HFO is assumed as pilot fuel to mitigate risks such as knocking and misfiring (Akman, 2023).

3.2 Scenario Setting

This study evaluates five compliance strategies through scenario-based modelling, as outlined below.

Scenario 1: Benchmark

This reference scenario establishes a baseline for both economic and environmental performance over the 15-year horizon. All 13 vessels retain their current configurations, 3 LNG dual-fuel vessels and 10 conventional HFO vessels, without modifications or fuel switches. The model calculates cumulative GHG emissions, assessing compliance costs against both the Base and Direct compliance targets. Any non-compliance is fully offset by penalties from FuelEU Maritime and purchasing Tier 1 and Tier 2 Remedial Units (RUs) from IMO. This scenario quantifies the long-term economic burden of a "do-nothing" strategy and serves as the benchmark for evaluating the cost-effectiveness of alternative decarbonization pathways. It also defines an upper boundary for the acceptable solution: if an alternative scenario's total cost exceeds this baseline, paying for RUs would be economically preferable.

Scenario 2: Biofuel Blending Strategy

Scenario 2 explores achieving compliance solely through fuel switching, without technical modifications to the fleet. All vessels retain their current configurations, but conventional fuels can be partially or fully replaced with sustainable alternatives, biodiesel blends for HFO vessels and bio-LNG for LNG vessels.

The optimization determines cost-minimizing blend ratios to meet annual compliance targets in each year, with the option of strategic overcompliance to generate SUs for internal reallocation or sale through the pooling mechanism. This scenario evaluates whether fuel substitution alone is more economical than purchasing RUs or investing in retrofits and quantifies the resulting total costs over the 15-year period.

Scenario 3 and 4: Replacement Strategy

Scenarios 3 and 4 evaluate the impact of replacing the fleet's oldest, highest-emitting HFO vessel with a newly built methanol dual fuel (DF) vessel, reflecting Maersk's early adoption of methanol propulsion on high-emission, long-haul routes such as Far East–North Europe, where regulatory and financial benefits are significant. Also, early deployment of a green-fueled vessel on this route is advantageous under stricter EU regulations in the initial years.

For modelling and comparing the cost in the same level purposes, the CAPEX of the new vessel is excluded, assuming redeployment from elsewhere in Maersk's global fleet. Scenario 3 assesses the pooling effect of the replacement when the methanol vessel operates at varying green methanol blend ratios while other vessels continue using fossil fuels. Scenario 4 extends the analysis by optimizing biofuel blending across the entire fleet, considering the methanol vessel's OPEX, life-cycle emissions, and its influence on biofuel needs for the remaining ships. In both cases, any residual compliance gap is met through RUs purchases, and the results quantify the methanol vessel's contribution to improving overall fleet GFI and reducing compliance costs.

Scenario 5: Retrofit Strategy

Scenario 5 evaluates retrofitting existing 10 HFO vessels to either LNG dual-fuel or methanol dual-fuel propulsion. The model simultaneously optimizes the time of retrofits, the number of retrofits, the choice of the fuel and the required biofuel blending rates to achieve Direct Compliance Target at the lowest total cost. In addition to compliance optimization, the scenario estimates the payback period for each retrofit option over the 15-year horizon to assess financial viability.

Table 3 summarizes each scenario's compliance strategy. The comparative analysis of these scenarios provides insight into the trade-offs between fuel adjustments, technical upgrades, and market-based compliance mechanisms, enabling identification of cost-effective pathways for fleet decarbonization.

Table 3. Scenario for compliance strategy modelling

Scenario	Strategy	Fleet Configuration	Compliance Approach	Purpose
1	Do-nothing baseline	10 HFO vessels + 3 LNG DF (no change) (total 13 vessels)	All non-compliance offset with FuelEU penalties and Tier 1 & 2 RUs.	Establishes economic & environmental baseline; defines upper cost boundary.
2	Fuel switching only	Existing fleet retained (no retrofits) (total 13 vessels)	HFO partly/fully supplied by biodiesel; LNG supplied with bioLNG; optimization of blend ratios.	Tests if fuel substitution alone is cheaper than paying penalties, RUs or retrofits.
3	Methanol vessel replacement	Replace 1 HFO vessel with 1 methanol DF (total 13 vessels)	Methanol DF operated with varying green methanol blends; rest continue fossil fuels.	Evaluates methanol vessel's isolated contribution to GFI improvement and total fleet cost reduction.
4	Methanol vessel	Same as Scenario 3 (total 13 vessels)	Adds optimization of biodiesel/bio-LNG blends across entire	Assesses combined impact of methanol deployment and fleet-

	+ biofuel blending		fleet alongside methanol vessel operation.	wide blending on emissions, and total cost reduction.
5	Fleet retrofits	Retrofit HFO vessels to LNG DF or methanol DF (total 13 vessels)	Model optimizes time/number/type of retrofits + blending rates.	Examines trade-offs between retrofit options, payback period, and total cost and emission reduction.

3.3 Data

This section outlines the input data used in the modelling framework, covering route characteristics, vessel specifications, fuel properties, emission factors, fuel prices, and cost parameters. Data are drawn from the Clarksons Shipping Intelligence Network (SIN), peer-reviewed literature, industry reports, and regulatory documents issued by the IMO and the European Commission. Unless stated otherwise, all cost figures are presented in constant 2025 USD.

3.3.1 Route Information

The route of the Maersk AE1 service is based on Maersk's official schedule from the website (2025). As illustrated in Figure 6, and according to route modelling conducted using Netpas Distance (2025), the AE1 loop connects major ports in Far East Asia and Northern Europe via a round-voyage structure with weekly frequency. The service departs from Shanghai and calls at Yantian, Tanjung Pelepas, Singapore, Tangier, London Gateway, Rotterdam, and Hamburg, before returning to Shanghai (Maersk, 2025).

Figure 6. Route Information (Maersk, 2025; Netpas Distance, 2025)

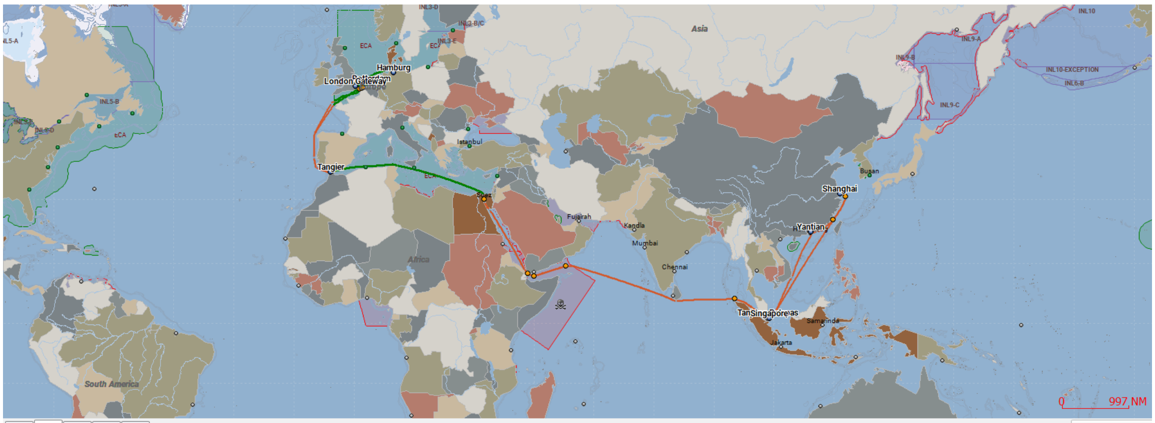


Table1 Table2 Table3 Table4 Table5 — Simple Estimation

SUEZ PANAMA KIEL — To NVM — To Estimator — 21,955 (5,349) NM — 70.37 Days — Speed : 13.0 kt's — W.F : 0 %

No	Port Name or Coordinates	Distance TTL	ECA	W.F	Speed	Sea	Port	Port Charge	Arrival	Departure
1	Shanghai (CN) [+08:00]						0.00	0.00		
2	Yantian (CN) [+08:00]	840	0	0%	13.00	2.69	0.00	0.00		
3	Tanjung Pelepas (MY) [+08:00]	1,471	0	0%	13.00	4.72	0.00	0.00		
4	Rotterdam (NL) [+01:00]	8,405	2,348	0%	13.00	26.94	0.00	0.00		
5	Hamburg (DE) [+01:00]	308	308	0%	13.00	0.99	0.00	0.00		
6	London Gateway (GB) [+00:00]	401	401	0%	13.00	1.29	0.00	0.00		
7	Tangier (MA) [+00:00]	1,316	364	0%	13.00	4.22	0.00	0.00		
8	Singapore (SG) [+08:00]	7,019	1,928	0%	13.00	22.50	0.00	0.00		
9	Shanghai (CN) [+08:00]	2,195	0	0%	13.00	7.03	0.00	0.00		
10										
	Total	21,955	5,349	NM		70.37	0.00	0.00		

Source: Maersk (2025); Netpas Distance (2025)

For modelling purposes, the fleet is assumed to operate via the Suez Canal, representing the standard routing under normal geopolitical conditions. The total round-trip distance is approximately 21,955 nautical miles, of which 5,349 nautical miles fall within Emission Control Areas (ECAs), as shown in the table accompanying the route map. Under current IMO regulations, vessels operating in ECAs must either use fuel with a Sulphur content not exceeding 0.10% or adopt exhaust gas cleaning systems (EGCS) that achieve equivalent SOx reductions (DNV, 2023). In this study, all 10 HFO vessels are fitted with scrubbers (Clarksons, 2025), eliminating the need to switch to Marine Gas Oil (MGO) for ECA compliance. LNG and methanol, being inherently low in Sulphur, also meet ECA limits without fuel switching. Consequently, ECA-related fuel switching is excluded from the model for all fuel configurations considered.

Based on Maersk's published schedule (Maersk, 2025), the average port time at each call is approximately two days. With weekly service and a deployment of 13 ships, the total round-trip duration for each vessel is estimated at 91 days (13 weeks). Subtracting 16 days of port time for eight port calls (8 × 2 days), each vessel spends roughly 75 days at sea per cycle. Covering a total round-voyage distance of 21,955 nautical miles, this corresponds to an average sailing speed of about 12 knots, which aligns with the recommended fuel-efficient speed for large containerships (Powell, 2025). Allowing for routine maintenance and buffer periods, each vessel is estimated to complete approximately four full round trips per year under this operational profile.

Furthermore, for the first three years of FuelEU Maritime implementation in this study, only 100% of GHG emissions within the EU area and 50% of emissions on voyages to or from the EU are counted towards compliance. Applying this adjustment, the effective distance subject to FuelEU Maritime requirements is estimated at 8,879 nautical miles.

3.3.2 Fleet Information

The modelled fleet comprises 13 containerships deployed on the Maersk AE1 service, treated as a pooled operational unit in line with the pooling assumption outlined in Section 3.1. Of these, 3 vessels are equipped with LNG dual-fuel engines, while the remaining 10 operate on HFO with scrubbers installed (Clarksons, 2025).

Moreover, the 10 conventional HFO vessels fall into two main types. The first, built around 2014, has a capacity of approximately 18,270 TEU. The second, built in 2018, offers a larger capacity of 20,568 TEU and is considered more fuel-efficient due to a newer main engine design and optimized auxiliary generators (Clarksons, 2025).

For modelling purposes, this study applies the annual average fuel consumption per nautical mile (kg/nm) reported in the EU MRV GHG Emission Report (EMSA, 2025). As methanol-fueled vessels have only recently entered commercial service, empirical fuel consumption data are limited. Therefore, methanol vessel consumption is estimated from the annual energy demand of the equivalent LNG dual-fuel vessel.

Based on engine type and vessel characteristics, the fleet is categorized into four representative groups:

- Group 1 (G_1): 2014-built HFO vessels
- Group 2 (G_2): 2018-built HFO vessels
- Group 3 (G_3): 2020-built LNG/Methanol dual-fuel vessels

Within each group, technical specifications are represented by average values to ensure consistency in the modelling framework. Table 4 summarizes the key specifications of Groups 1-3, including fuel type and consumption rates.

Table 4. Summary of Vessel Specifications by Group

Vessel Type	Group 1 (HFO Old)	Group 2 (HFO New)	Group 3 (LNG/Methanol)
Number of the Vessels	6	4	3
Built Year [a]	2014	2018	2020
Total Capacity (TEU) [a]	18,270	20,568	21,940
Fuel Type [a]	HFO	HFO	Dual-Fuel
Main Engine Type [a]	8S80ME-C9.2 (59,360mkW @ 73rpm)	7G80ME-C9.5 (62,000mkW @ 70.50rpm)	11G95ME-C10.5 (75,570mkW @ 80rpm)
Fuel Consumption (kg/n mile) [b]	325	310	270
EEXI ($gCO_2/t{\cdot}nm$) [b]	6.78	6.75	5.27
Scrubber [a]	Installed	Installed	-
Rudder Bulb [a]	Installed	Installed	Installed
Ballast Water Treatment System (BWTS) [a]	Installed	Installed	Installed

Source: [a] Clarksons (2025); [b] EMSA (2025)

3.3.3 Retrofitting Information

Table 5 summarizes the estimated costs of retrofitting HFO vessels to LNG or methanol dual-fuel propulsion. These costs include both material expenses, such as engine components, fuel tanks, and pipelines, opportunity costs and labor charges incurred at the shipyard (Lagemann et al., 2022; Lin, 2022; Zhao et al., 2025). LNG retrofits are substantially more expensive due to the requirement for cryogenic storage tanks, complex fuel gas supply systems, and extensive engine and safety modifications (Zincir, 2022). By contrast, methanol can be stored at ambient temperature, requiring simpler tank arrangements and less intrusive engine modifications, making it a comparatively more cost-effective retrofit option (Lagemann et al., 2022).

Table 5. Retrofitting Costs

From \ To	LNG Dual Fuel Vessel	Methanol Dual Fuel Vessel
HFO Vessel	35,000,000	24,000,000

Source: Lagemann et al. (2022); Lin (2022); Zhao et al. (2025)

3.3.4 Emission Factor

This analysis adopts a WTW approach to quantify greenhouse gas (GHG) emissions, encompassing CO_2, CH_4, and N_2O. However, the IMO's life-cycle assessment (LCA) framework for marine fuels is still under development, and comprehensive WTW emission factors, particularly for biofuels, have not yet been finalized (Miyake, 2024). In contrast, the FuelEU Maritime Regulation, already in force, provides default WTW emission factors for fossil fuels and biofuels in Annex II (European Union, 2023).

Accordingly, this study uses FuelEU Maritime default emission factors as the reference values for GHG intensity. Given the substantial variability in biofuel GHG intensity, driven by differences in feedstock and production pathways, especially in the WTT phase, and the absence of feedstock-specific traceability, this study adopts the WTW emission factors from Nelissen et al. (2022). Those values are calculated based on Annex II of the proposed FuelEU Maritime Regulation and the Renewable Energy Directive (RED II) as shown in Table 6.

Table 6. Emission Factor for each fuel

Fuel Composition (c)	HFO (c_1)	Biodiesel 100% (FAME) (c_2)	Fossil-LNG (c_3)	Bio-LNG 100% (c_4)	Fossil-Methanol (c_5)	Biomethanol 100% (c_6)
LCV (MJ/g)	0.0405	0.0372	0.0491	0.0491	0.0199	0.0199
EF_{WTT} (gCO_2e/MJ)	88.57	14.9	72.4	14.0	31.3	10.4
EF_{TTW} (gCO_2e/MJ)	3.17	2.5	2.78	1.7	71.57	2.5
EF_{WTW} (gCO_2e/MJ)	91.74	16.2	75.18	15.7	102.87	12.9

Source: Nelissen, et al. (2022)

The WTW emission factor (EF_{WTW}) is divided into two components: EF_{WTT} is the upstream GHG emission factor from fuel extraction, processing, refining, and distribution and EF_{TTW} is the direct GHG emission factor from onboard fuel combustion. The total EF_{WTW} is obtained by summing EF_{WTT} and EF_{TTW}, expressed in gCO_2e/MJ. Additionally, the lower calorific value (LCV), representing the energy content of fuels (Singh et al., 2021), is also provided in Table 3 alongside the corresponding fuel.

3.3.5 Fuel Choice

This study evaluates a range of marine fuels and their bio-based alternatives to assess compliance strategies under regulatory constraints. Vessels in Group 1 and Group 2 use HFO as their baseline fuel, with biodiesel considered as a drop-in substitute modelled at blending ratios of 30% (reflecting current use in Rotterdam), 50%, 75%, and 100% (DNV, 2025). Group 3 LNG dual-fuel vessels operate on fossil LNG, with bioLNG treated as a drop-in replacement at the same blend levels. Methanol is introduced for the replacement in Scenarios 3 and 4 and for retrofitted vessels in Scenario 5, with biomethanol modelled at corresponding blend ratios.

For both LNG and methanol dual-fuel vessels, 5% HFO is assumed as pilot fuel to prevent operational issues such as knocking and misfiring when running on alternative fuels (Akman, 2023). Table 7 summarizes all fuel types considered in this study.

Table 7. Fuel types and index used in the model

Index f	Fuel Type	Fuel Composition
1	High Fuel Oil	100% HFO
2	BioDiesel-B30	30% Biodiesel blended with HFO
3	BioDiesel-B50	50% Biodiesel blended with HFO
4	BioDiesel-B75	75% Biodiesel blended with HFO
5	BioDiesel-B100	100% Biodiesel
6	Fossil LNG	95% Fossil LNG with 5% HFO
7	BioLNG-B30	30% BioLNG blended with fossil LNG and 5% HFO (Pilot Fuel)
8	BioLNG-B50	50% BioLNG blended with fossil LNG and 5% HFO (Pilot Fuel)
9	BioLNG-B75	75% BioLNG blended with fossil LNG and 5% HFO (Pilot Fuel)
10	BioLNG-B95	95% BioLNG blended with fossil LNG and 5% HFO (Pilot Fuel)
11	Fossil Methanol	Conventional fossil fuel with 5% HFO (Pilot Fuel)
12	Biomethanol-B30	30% Biomethanol blended with fossil methanol and 5% HFO (Pilot Fuel)
13	Biomethanol-B50	50% Biomethanol blended with fossil methanol and 5% HFO (Pilot Fuel)
14	Biomethanol-B75	75% Biomethanol blended with fossil methanol and 5% HFO (Pilot Fuel)
15	Biomethanol-B95	95% Biomethanol blended with fossil methanol and 5% HFO (Pilot Fuel)

3.3.6 Fuel Consumption

Annual fuel consumption (tonnes) for each vessel group is calculated based on the fuel consumption rate (FCR, kg/nm) and the annual sailing distance (nm), reported either as total consumption under the IMO Net-Zero Framework (Total) or as the consumption within the scope of FuelEU Maritime (EU):

$$F_{Gi}^{HFO} = \frac{FCR_{Gi} \times Dist_j}{1000}, i = \{1,2\}, j = \{Total, EU\} \tag{1}$$

$$F_{G3}^{F-LNG} = \frac{FCR_{G3} \times P^{F-LNG} \times Dist_j}{1000}, j = \{Total, EU\} \tag{2}$$

$$F_{G3}^{P-HFO} = \frac{FCR_{G3} \times P^{P-HFO} \times Dist_j}{1000}, j = \{Total, EU\} \tag{3}$$

Where F_{Gi}^{HFO} is the annual HFO consumption (tonnes) of a Group 1 or Group 2 vessel and FCR_{Gi} is the corresponding fuel consumption rate (kg/nm) of the vessel. Moreover, F_{G3}^{F-LNG} and F_{G3}^{P-HFO} is the annual fossil LNG and pilot fuel consumption (tonnes) of a Group 3 vessel based on the proportion (%) of the fossil LNG (P^{F-LNG}) and pilot fuel (P^{P-HFO}), respectively. $Dist_j$ is the total annual sailing distance (nm) or the total annual sailing distance within the scope of FuelEU Maritime (nm).

Furthermore, based on the annual fuel consumption and LCV, the total annual energy content can be estimated as follows, where E represents the annual energy content (MJ) with different groups of vessels:

$$E_{total}^{HFO-Gi} = F_{Gi}^{HFO} \times 10^6 \times LCV^{HFO}, i = \{1,2\} \tag{4}$$

$$E_{total}^{LNG-G3} = F_{G3}^{F-LNG} \times 10^6 \times LCV^{F-LNG} + F_{G3}^{P-HFO} \times 10^6 \times LCV^{HFO} \tag{5}$$

Following the principle of equivalent energy demand for the same engine type and route (Tan et al., 2020), annual consumption for blended biodiesels (tonnes) is calculated as Wu et al. (2022):

$$F_{Gi}^{f-BioD} = \frac{E_{total}^{HFO-Gi} \times P^{j-BioD}}{LCV_{BD} \times 10^6}, f = \{2,3,4,5\}, i = \{1,2\}, j = \{30\%, 50\%, 75\%, 100\%\} \tag{7}$$

$$F_{Gi}^{f-HFO} = \frac{E_{total}^{HFO-Gi} \times (1 - P^{j-BioD})}{LCV^{HFO} \times 10^6}, f = \{2,3,4,5\}, i = \{1,2\} \tag{8}$$

Where F_{Gi}^{f-BioD} represents the annual biodiesel consumption (tonnes) of fuel type f used by a Group 1 or Group 2 vessel and P^{j-BioD} denotes the corresponding proportion of biodiesel used in the fuel blend (%). Moreover, F_{Gi}^{f-HFO} is the remaining annual HFO consumption (tonnes) of fuel type f used by a Group 1 or Group 2.

Similarly, the annual consumption of bioLNG and biomethanol (tonnes) is calculated as follows:

$$F_{G3}^{Pilot} = \frac{E_{total}^{LNG-G3} \times P^{P-HFO}}{LCV^{HFO} \times 10^6} \tag{9}$$

$$F_{G3}^{f-BioL/M} = \frac{E_{total}^{HFO-Gi} \times P^{j-BioL/M}}{LCV^{BioL/M} \times 10^6}, f = \{7-10, 11-15\}, j = \{30\%, 50\%, 75\%, 95\%\} \tag{10}$$

$$F_{G3}^{f-FL/M} = \frac{E_{total}^{HFO-Gi} \times (1 - P^{j-BioL/M} - P^{P-HFO})}{LCV^{FL/M} \times 10^6}, f = \{7-10, 11-15\} \tag{11}$$

Where F_{Gi}^{Pilot} indicates the annual pilot fuel consumption of a dual-fuel vessel (Group 3) (tonnes) and P^{P-HFO} is the proportion of pilot fuel (%). $F_{Gi}^{f-BioL/M}$ represents the annual bioLNG or biomethanol consumption (tonnes) of type f used by a Group 3 vessel and $P^{j-BioL/M}$ denotes the proportion of biofuels used (%). Furthermore, $F_{Gi}^{f-FL/M}$ is the the annual fossil LNG or methanol consumption (tonnes) in the fuel blend.

All results for the annual consumption of each fuel type are presented in Appendix A.

Moreover, the total fuel cost (USD) is calculated using the fuel prices summarized in Table 8, which are assumed constant from 2025 to 2040. These values are based on S&P Global's (2025) monthly average bunker prices in Rotterdam for June 2025. Other fuel price trajectories are examined separately in the sensitivity analysis and discussion part.

Table 8. Fuel Price (2025-2040)

Fuel Type	HFO	100% Biodiesel	Fossil-LNG	100% BioLNG	Fossil-Methanol	100% Biomethanol
Price (USD/ton)	410	1,100	720	1,650	330	985

Source: S&P Global (2025)

3.3.7 GHG Emission and Intensity

Thus, the annual GHG emission are calculated from the total annual energy content and the corresponding WTW emission factor (gCO_2e/MJ) as shown in Equation (12) and (13):

$$GHG_f = E_{total}^{HFO-Gi} \times P^{j-BioD} \times EF_{WTW-fBioD} + E_{total}^{HFO-Gi} \times (1 - P^{j-BioD}) \times EF_{WTW-HFO},$$
$$f = \{1-5\}, i = \{1,2\}, j = \{30\%, 50\%, 75\%, 100\%\} \quad (12)$$

Where GHG_f denotes the annual greenhouse gas emissions (gCO_2e) of fuel type f; $EF_{WTW-fBioD}$ refers to the WTW emission factor (gCO_2e/MJ) of the corresponding biodiesel used in the blend and $EF_{WTW-HFO}$ is the WTW emission factor (gCO_2e/MJ) of the HFO.

$$GHG_f = E_{total}^{LNG-G3} \times P^{j-BioL/M} \times EF_{WTW-fBioL/M} + E_{total}^{LNG-G3} \times P^{P-HFO} \times EF_{WTW-HFO}$$
$$+ E_{total}^{LNG-G3} \times (1 - P^{j-BioL/M} - P^{P-HFO}) \times EF_{WTW-fFL/M}$$
$$f = \{6-15\}, j = \{30\%, 50\%, 75\%, 95\%\} \quad (13)$$

Where $EF_{WTW-fBioL/M}$ refers to the WTW emission factor (gCO_2e/MJ) of the corresponding type of bioLNG and biomethanol used in the blend; and $EF_{WTW-fFL/M}$ refers to the WTW emission factor (gCO_2e/MJ) of the corresponding fossil LNG and methanol used in the blend.

Furthermore, the attained GHG fuel intensity for each combination of fuel can be estimated as follows, as referenced in Zhang (2025):

$$GFI_{attained-f} = \frac{GHG_f}{E_{total}^{HFO-Gi}}, f = \{1-5\}, i = \{1,2\} \; or \; GFI_{attained-f} = \frac{GHG_f}{E_{total}^{LNG-G3}}, f = \{6-15\} \quad (14)$$

Where $GFI_{attained-f}$ represents the attained GHG fuel intensity of the vessel (gCO_2e/MJ) with using different type of fuels f.

3.3.8 FuelEU Maritime Compliance Cost

From 2025 to 2027, the FuelEU Maritime regulation is incorporated into the model to estimate compliance costs arising from the decarbonization of maritime fuel consumption. The regulation sets annual GHG fuel intensity limits (gCO_2e/MJ) for energy used onboard vessels calling at EU ports.

The compliance cost is calculated based on the actual GHG fuel intensity of the fuel used during voyages within, or to/from EU ports (denoted as $GFI_{attained-f}$) compared to the regulatory limit ($GFI_{EU-target}$). Any emission excess over the target is penalized at a rate of USD 640 per tonne CO_2e (BetterSea, 2025). Moreover, under the pooling mechanism, surplus compliance credits generated by vessels below the target can be sold to other ships (Pringle, 2025). The price of surplus units ($P_t^{Surplus}$) is set at USD 200 per tonne CO_2e according to OceanScore (2025).

The compliance balance (CB) indicates whether a vessel incurs a FuelEU Maritime penalty or generates surplus units. It is calculated by comparing the vessel's attained GFI with the annual regulatory threshold. The compliance balance is defined as:

$$CB_f = GFI_{attained-f} - GFI_{EU-target} \tag{14}$$

Where CB_f denotes the compliance balance (gCO_2e/MJ) of each fuel type of the vessel (f). A positive value indicates non-compliance and incurs a penalty, while a negative value reflects overperformance, generating surplus units that can be redistributed within the fleet or sold via a pooling mechanism. Furthermore, the total annual FuelEU Maritime compliance cost for the fleet is estimated using the following equation:

$$C_t^{FuelEU} = \begin{cases} \sum_{i=1}^{n=13} \frac{CB_f \times E_{f,EU} \times N_{f,i}}{10^6} \times P_t^{FuelEU}, if \sum_{i=1}^{n=13} \frac{CB_f \times E_{f,EU} \times N_{f,i}}{10^6} \geq 0 \\ \sum_{i=1}^{n=13} \frac{CB_f \times E_{f,EU} \times N_{f,i}}{10^6} \times P_t^{Surplus}, if \sum_{i=1}^{n=13} \frac{CB_f \times E_{f,EU} \times N_{f,i}}{10^6} < 0 \end{cases} \tag{15}$$

Where C_t^{FuelEU} is the total cost or rewards from selling the surplus units (SUs) (USD). $E_{f,EU}$ denotes the total annual energy consumption (MJ) of vessels using fuel type f under the FuelEU Maritime scope. $N_{f,i}$ indicates the number of vessels of type f operating. If the weighted fleet-level compliance balance is positive, indicating overall non-compliance, it is multiplied by the penalty rate P_t^{FuelEU} (USD/tonne CO_2e) in year t. Conversely, if the balance is negative, reflecting a net surplus from overcompliance, it is monetized using $P_t^{Surplus}$(USD/tonne CO_2e).

3.3.9 IMO Net-Zero Framework Compliance Cost

From 2028 onwards, the model assumes that the IMO Net-Zero Framework replaces the FuelEU Maritime regulation. The compliance calculation follows a similar principle, comparing each vessel's attained GFI against the required GFI, with the cost (or credit) determined by the deviation from the target multiplied by annual energy consumption. However, unlike FuelEU Maritime, the IMO Net-Zero framework adopts a dual-target structure: a Direct Compliance Target and a Base Compliance Target. Based on these, a vessel's annual compliance status falls into three categories:

1. Attained GFI is lower than the Direct Compliance Target

If a vessel's $GFI_{attained-f}$ is below the Direct Compliance Target (GFI_{IMO-D}), it generates SUs. As assumed the SUs will be sell to other vessels vessel at the same year. The SUs is calculated following Zhang (2025). Moreover, the price of SUs is set at USD 312 per tonne of CO_2e (P_t^{SUs}) estimated by Ship & Bunker (2025). The amount of SUs (tonnes) is calculated following (Zhang, 2025):

$$SUs_f = \begin{cases} \frac{\left(GFI_{IMO-D} - GFI_{attained-f}\right) \times E_f}{1 \times 10^6}, if\ GFI_{attained-f} \leq GFI_{IMO-D} \\ 0, otherwise \end{cases} \quad (16)$$

2. Attained GFI lies between the Base Compliance Target and the Direct Compliance Target

If a vessel's $GFI_{attained-f}$ below the Base Compliance Target (GFI_{IMO-B}) but fails to meet the Direct Compliance Target (GFI_{IMO-D}), it incurs a Tier 1 non-compliance gap. This gap must be offset by purchasing Tier 1 Remedial Units (Tier 1 RUs) from the IMO Net-Zero Fund, currently priced at USD 100 per tonne of CO_2e ($P_t^{IMOTier1}$). The amount of Tier 1 RUs is calculated following (Zhang, 2025):

$$RUs_{Tier\ 1-f} = \begin{cases} 0, if\ GFI_{attained-f} \leq GFI_{IMO-D} \\ \frac{(GFI_{attained-f} - GFI_{IMO-D}) \times E_f}{1 \times 10^6}, if\ GFI_{IMO-D} < GFI_{attained-f} \leq GFI_{IMO-B} \\ \frac{(GFI_{IMO-D} - GFI_{IMO-B}) \times E_f}{1 \times 10^6}, if\ GFI_{attained-f} > GFI_{IMO-B} \end{cases} \quad (17)$$

3. Attained GFI exceeds the Base Compliance Target

If a vessel fails to meet the Base Compliance Target, it incurs both Tier 1 and Tier 2 non-compliance gaps. The Tier 1 gap must be balanced using Tier 1 RUs under the same conditions as above. The Tier 2 gap, however, can be addressed through purchasing Tier 2 RUs from the IMO Net-Zero Fund at a price of USD 380 per tonne of CO_2e ($P_t^{IMOTier2}$). The amount of Tier 2 RUs is calculated following (Zhang, 2025), as shown in Equation 18:

$$RUs_{Tier\ 2-f} = \begin{cases} 0, if\ GFI_{attained-f} \leq GFI_{IMO-B} \\ \frac{(GFI_{attained-f} - GFI_{IMO-B}) \times E_f}{1 \times 10^6}, if\ GFI_{attained-f} > GFI_{IMO-B} \end{cases} \quad (18)$$

All results for GHG Annual Emission Gaps and Surpluses of Different Fuels under FuelEU Maritime and IMO Net-Zero Framework are presented in Appendix B.

Thus, the total compliance cost (C_t^{IMO}) for the IMO Net-Zero Framework is calculated as shown in Equation 19.

$$C_t^{IMO} = \begin{cases} \left(RUs_{Tier\ 2-f} \times N_{f,i} - SUs_f \times N_{f,i}\right) \times P_t^{IMOTier2} + RUs_{Tier\ 1-f} \times N_{f,i} \times P_t^{IMOTier1}, \\ if\ RUs_{Tier\ 2-f} \times N_{f,i} - SUs_f \times N_{f,i} > 0 \\ \left(RUs_{Tier\ 2-f} \times N_{f,i} - SUs_f \times N_{f,i}\right) \times P_t^{SUs} + RUs_{Tier\ 1-f} \times N_{f,i} \times P_t^{IMOTier1}, \\ if\ RUs_{Tier\ 2-f} \times N_{f,i} - SUs_f \times N_{f,i} < 0 \end{cases} \quad (19)$$

3.4 Model Setting

The objective of this model is to minimize the total cost of operating the 13-vessel fleet over a 15-year period (2025–2040), considering compliance with both the FuelEU Maritime (2025–2027) and the IMO Net-Zero Framework (2028–2040). The optimization evaluates different compliance strategies, including the adoption of alternative fuels and changes to fleet composition through retrofitting. The total cost consists of three main components: regulatory compliance costs (FuelEU and IMO), fuel costs, and retrofitting costs (Scenario 5). The objective function is:

$$minTC = \sum_{t=2025}^{2027} \left(C_t^{FuelEU} + C_t^{Fuel}\right) + \sum_{t=2028}^{2040} \left(C_t^{IMO} + C_t^{Fuel}\right) + \sum_{r\in\{LNG,Methanol\}} P_{Retrofit}^{r} \times R^r ,$$
$$0 \leq R^{LNG} + R^{Methanol} \leq 10 \tag{20}$$

Where $minTC$ denotes the minimized total cost over the 15 years. C_t^{FuelEU}, $C_t^{IMO}$and C_t^{Fuel} represent the annual compliance costs under FuelEU Maritime, the IMO Net-Zero Framework, and the fuel expenditure in year t respectively. $P_{Retrofit}^{r}$ denotes the unit cost of retrofitting a HFO vessel to LNG or methanol dual-fuel vessel, as shown in Table 5, and R^r represents the number of vessels retrofitted under retrofit option r during the transition period.

Moreover, there are two decision variables in the model:

1. $N_{f,i,t}$: Number of vessels in group i operating on fuel type f in year t, reflecting adjustments to tightening regulations and the potential generation of surplus units through over-compliance.
2. R^r: Number of HFO vessels retrofitted under option r (LNG or methanol), applicable only in Scenario 5.

These variables are optimized jointly, subject to constraints on fleet size and vessel allocation, fuel-blending proportions, and the irreversibility of retrofit decisions. $N_{f,i,t}$ determines annual fuel consumption, corresponding fuel expenses, emissions, and corresponding compliance costs, while R^r directly influences feasible retrofitting solution and corresponding retrofit costs.

Specifically, this model is subject to the following constraints:

1. Fleet Size and Vessel Allocation Constraint

   The total fleet size remains fixed at 13 vessels, modeled as an integer constraint. In Scenarios 1 and 2, the number of vessels assigned to each group remains unchanged throughout the modeling horizon. In Scenarios 3 and 4, only one vessel from Group 1 is replaced by a methanol dual-fuel vessel. In Scenario 5, the number of HFO vessels retrofitted from Group 1 and Group 2 to alternative fuel vessels (Group 3) cannot exceed the original number of vessels in their respective groups.
2. Fuel Blending Proportion Constraint

   For each vessel group in each year, the total share of each of fuels used must sum to 100% on an energy-equivalent basis.
3. Irreversibility of Retrofit Decisions (Scenario 5 only)

Once a vessel is retrofitted from Group 1 or Group 2 to Group 3 (LNG/Methanol dual-fuel vessels), it cannot be reverted to its original configuration. This constraint is modeled through a binary state variable that preserves the vessel's retrofit status across all subsequent years.

This chapter outlined the scenario-based techno-economic optimization framework, integrating operational parameters, regulatory requirements, and cost components to evaluate compliance pathways for the fleet. It defined the key decision variables, constraints, and assumptions underpinning the modeling process. The subsequent chapter presents the simulation results and discusses their regulatory and strategic implications.

Chapter 4 Result

This chapter answers Sub-question 3: "*Which fuel strategies can a containership fleet adopt to comply with the IMO Net-Zero Framework, and how cost-effective are these options in balancing regulatory compliance with financial performance?*"

It is structured in five steps. First, it provides a comparative overview of all scenarios' results, highlighting their economic and environmental performance. Second, it assesses the underlying drivers of these outcomes, focusing on the GHG fuel intensity, annual emissions, and corresponding compliance costs of different fuel and engine combinations. Third, it discusses related fuel consumption and associated expenditures, which is the main part of the OPEX. Fourth, it identifies the compliance strategies emerging from each scenario and explains the rationale behind them. Finally, a sensitivity analysis assesses how variations in compliance prices and fuel prices influence the outcomes, to evaluate the robustness of the fuel strategies.

4.1 Scenario Analysis and Comparison

This section compares five compliance strategies for the 13-vessel fleet under the FuelEU Maritime regulation (2025–2027) and the IMO Net-Zero Framework (2028–2040):

- Scenario 1 (Benchmark): No vessel or fuel changes; all shortfalls met through Remedial Units (RUs) purchases.
- Scenario 2 (Biofuel): Complete biofuel substitution without technical modifications.
- Scenario 3 (Methanol Replace): Replacement of one Group 1 (older) HFO vessel with one methanol dual-fuel ship, while remaining vessels still using fossil fuels.
- Scenario 4 (Methanol + Biofuel): Same vessel replacement as in Scenario 3, with additional biofuel blending for other ships.
- Scenario 5 (Retrofit): Retrofitting of HFO vessels to LNG or methanol vessels with biofuel blending.

As summarized in Table 9, under constant fuel and compliance prices, Scenario 1 yields the highest total cost at USD 4.56 billion and highest CO_2e emissions over 15 years, serving as the baseline.

Scenario 2 reduces total cost by 12% to USD 4.02 billion (lowest), primarily because its CO_2e emissions are about 50% lower than the benchmark. This lower emission generates substantial surplus units, recorded as negative compliance costs (–USD 1.31 billion), which offset the higher fuel expenditure (USD 5.33 billion). This result demonstrates that large-scale biofuel adoption, despite elevated fuel costs, can yield net financial benefits through market mechanisms.

Scenario 3 records the highest total cost at USD 4.74 billion, about 4% above the benchmark (USD 4.69 billion). Although CO_2e emissions are reduced by 6% relative to Scenario 1, and compliance costs are therefore lower, this benefit is outweighed by substantially higher fuel expenditure (USD 2.89 billion).

This indicates that adopting methanol as a single-fuel replacement is economically unfeasible as the modest GHG reduction cannot offset the additional fuel costs.

Table 9. Summary of total costs and CO_2e emission for different scenarios (2025–2040)

Scenario	Scenario 1 Benchmark	Scenario 2 Biofuel	Scenario 3 Methanol	Scenario 4 Methanol + Biofuel	Scenario 5 Retrofit
Total Cost (USD billion)	4.56	4.02	4.74	4.25	4.02
Cost Change (%)	-	-12%	+4%	-7%	-12%
Compliance Cost (USD billion)	1.92	-1.31	1.85	-1.07	-1.31
Fuel Cost (USD billion)	2.64	5.33	2.89	5.32	5.33
Retrofit Cost (USD billion)	-	-	-	-	0
CO_2e Emission (thousand ton)	20,865	10,524	19,461	11,363	10,524
Emission Change (%)	-	-50%	-6%	-46%	-50%

Remarkably, Scenario 4 combines the methanol vessel replacement with strategic biofuel blending for the remaining vessels, reducing the total cost to USD 4.25 billion and generating a negative compliance cost (–USD 1.07 billion) with similar CO_2e emission as Scenario 2, despite higher fuel expenditure (USD 5.32 billion). However, compared with Scenario 2 (using biodiesel and bioLNG), the inclusion of methanol increases the fleet's attained GFI in pooling terms, thereby partially offsetting the compliance benefits gained from biofuel adoption in other vessels.

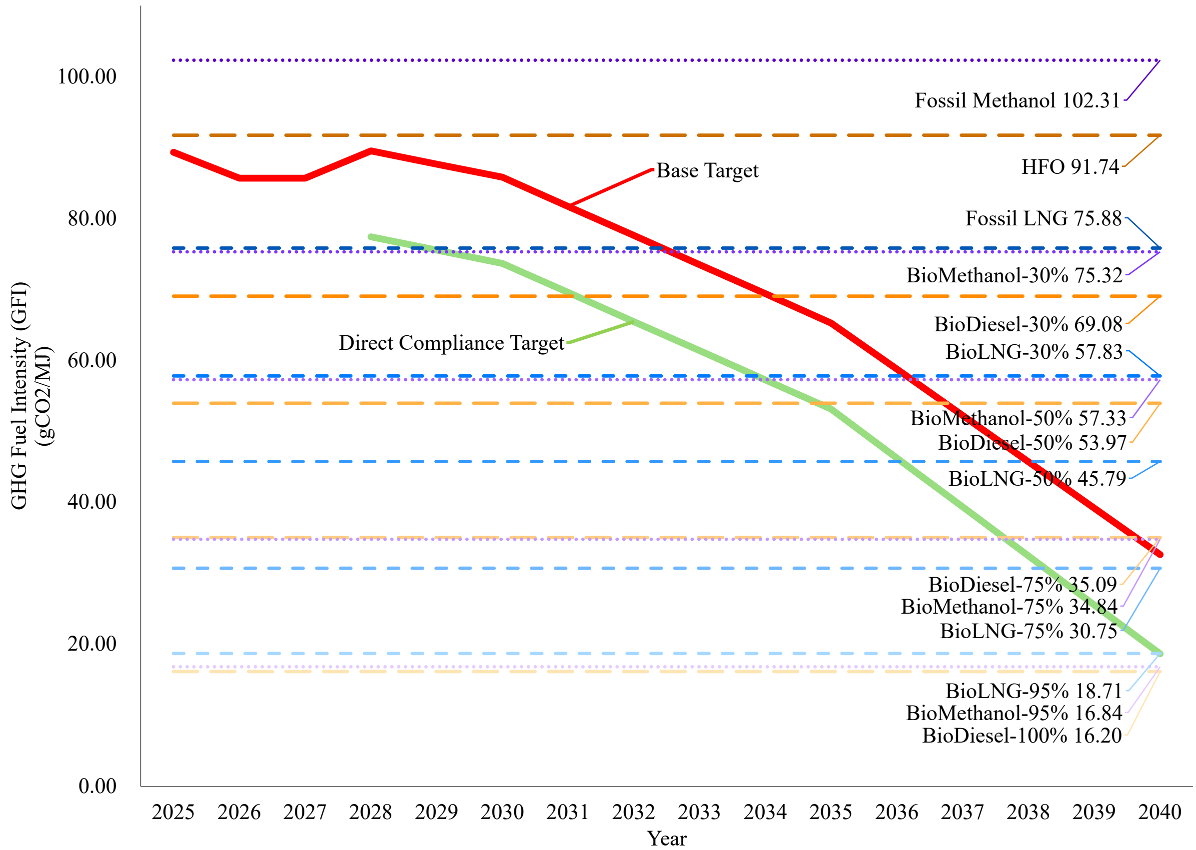
Therefore, it is straightforward to see that although Scenario 5 permits retrofitting, the optimization selects no conversions to either methanol or LNG. The resulting outcome mirrors Scenario 2 (USD 4.02 billion), indicating that biodiesel, on which Scenario 2 is primarily based, may offers a more cost-effective compliance pathway than technical conversions under the current price assumptions. Therefore, for the subsequent analysis, Scenario 5 is presented jointly with Scenario 2.

Overall, these results underscore that, under the present assumptions, even high-priced biofuels can deliver lower total costs when overcompliance enables surplus unit trading, thereby promoting decarbonization. However, since fuel choice fundamentally affects both costs and emissions, a detailed assessment of each fuel's economic and environmental performance is required to uncover the underlying drivers and provide a basis for informed decisions.

4.2 GFI and GHG Emission

Figure 7 illustrates the attained GFI (gCO_2e/MJ) for each fuel type, benchmarked against the Base and Direct Compliance targets of FuelEU Maritime (2025–2027) and the IMO Net-Zero Framework (2028–2040). The results reveal a pronounced performance gap between fossil and bio-based fuels. For 100% fossil fuels, both fossil methanol and HFO exceed the base compliance target throughout the period. HFO's overshoot rises sharply from 18.5% in 2025 to nearly 400% above the direct target by 2040, while fossil methanol (102.31 gCO_2/MJ) immediately exceeds the base limit by 13 gCO_2/MJ even in 2025. Consequently, vessels using these fuels must therefore either bear full penalty or remedial unit costs or shift to biofuel blends when economically preferable.

Figure 7. Each type of fuel's GFI



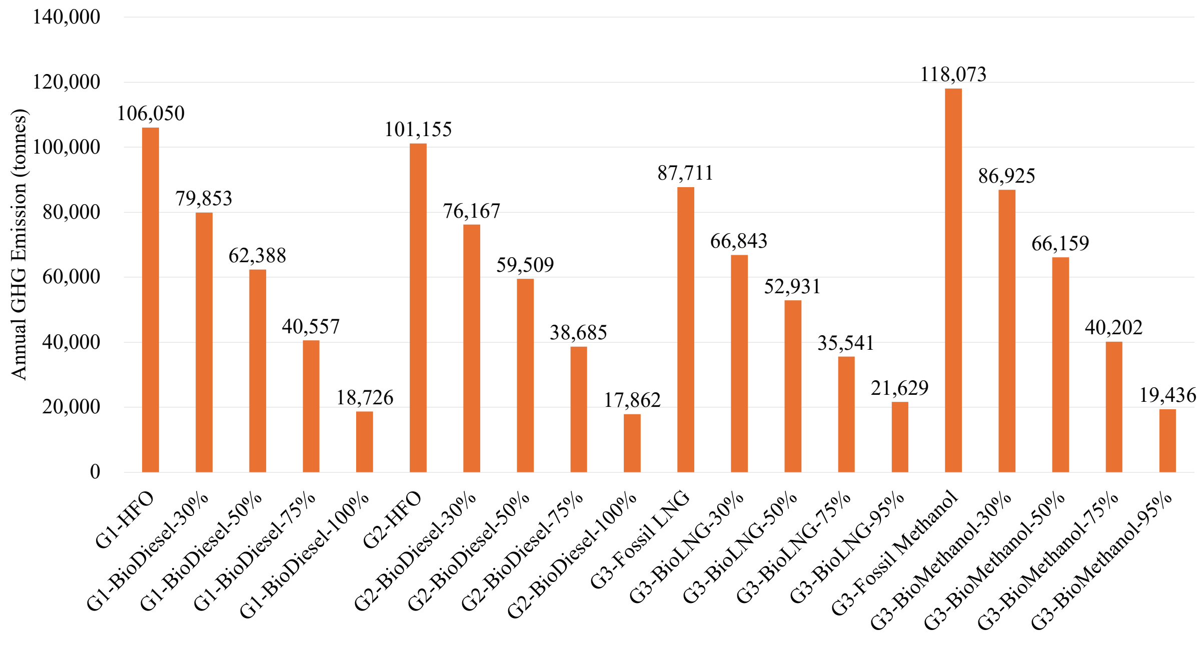
In contrast, fossil LNG shows a clear initial advantage, complying with both base targets until 2032 and even meeting the direct target in the first IMO year (2028). This could allow LNG dual-fuel vessels to postpone the transition to higher-cost bioLNG. High-blend biofuels, 95% bioLNG or biomethanol, or 100% biodiesel, meet both base and direct targets consistently from 2025 to 2040. Biodiesel performs best overall, as bioLNG and biomethanol still require a 5% HFO pilot fuel. This may explain the reason why the Scenario 2 can achieve the lowest total cost across all scenarios as it has the best GHG emission performance, which leads to producing higher SUs.

Furthermore, all 75% blends also meet base targets and can generate surplus units until 2037, but tightening targets (with the base and direct gap widening from 12% to 14%) eventually push them above direct compliance. However, all blends below 50% biofuel fail to meet base compliance by 2037 and direct targets by 2036, limiting their role to transitional adoption.

Thus, this comparison demonstrates LNG's early-stage practicality, given its compliance potential even in fossil form. Moreover, among all bioLNG options, except the 95% blend, bioLNG deliver the best overall performance. However, methanol becomes more competitive only at blends exceeding 30% biomethanol, with lower shares performing poorly. Still, biodiesel remains consistently advantageous, particularly at 100%, though its high price requires weighing whether the compliance benefits from surplus units can offset the additional fuel costs, or if using cheaper HFO and purchasing remedial units would be more cost-effective.

Furthermore, based on the GFI results, Figure 8 presents the estimated annual GHG emissions for different vessel groups and fuel types. While both Group 1 (G1) and Group 2 (G2) operate on HFO, the Group 2 vessel achieves lower emissions due to its higher fuel efficiency. For example, baseline emissions from G1-HFO reach 106,050 tons annually, compared with 101,155 tons from G2-HFO, an approximate 4.6% reduction, highlighting the role of vessel fuel consumption efficiency in emission mitigation.

Figure 8. Annual GHG emission of different vessels groups and fuels



Notably, across all fuel types, GHG emissions decline non-linearly as biofuel shares increase. Raising the blending ratio by 25% can accelerate emission reductions from roughly 20% to over 40%, indicating that higher blends may yield a more favorable balance between compliance and cost, particularly in early regulatory years, when more surplus unit sales can further enhance cost-effectiveness.

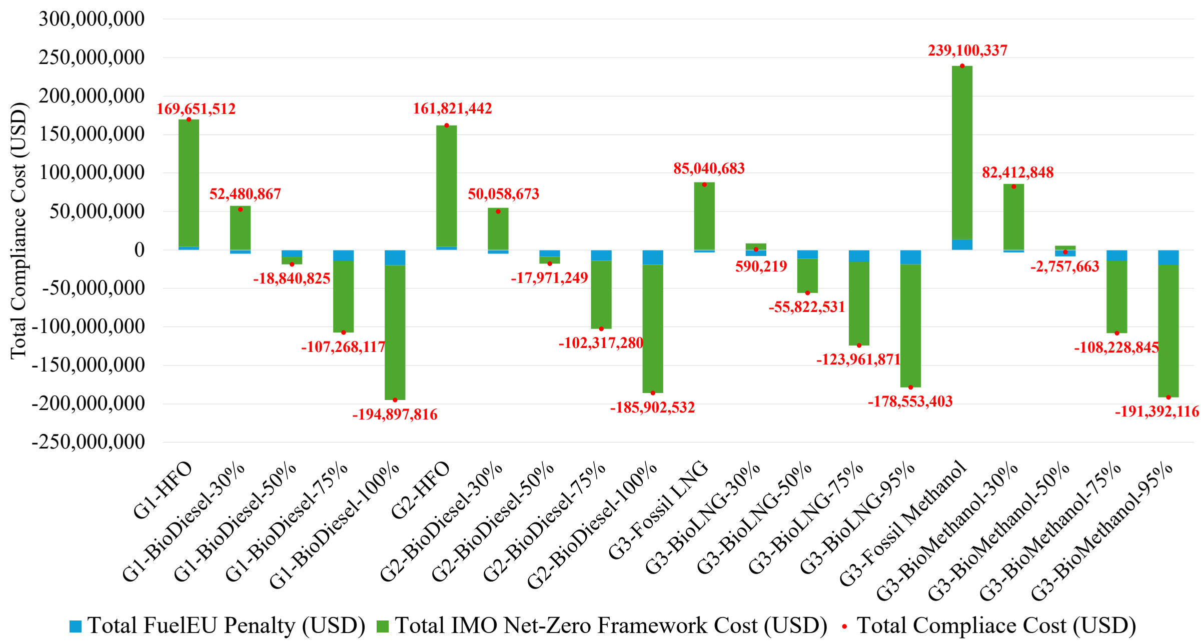
For both HFO vessel groups, 100% biodiesel could reduce annual emissions by over 82%, to around 18,000 tons, representing the lowest emissions among all fuels. This underscores biodiesel's significant mitigation and adoption potential, particularly given its drop-in compatibility, which avoids additional technical modifications and costs.

However, the fossil LNG vessel records 87,711 tons annually, substantially lower than HFO and methanol vessels, but still above any other biofuel configurations. Transitioning to 95% bioLNG cuts emissions to 21,629 tons (a 75% reduction), although this remains less effective than 100% biodiesel. Across blends of 30% to 75%, LNG consistently outperforms biodiesel and biomethanol at equivalent blend ratios, positioning it as an intermediate solution, more environmentally favorable than HFO or partially blended methanol, yet less effective than 100% biodiesel or biomethanol.

Furthermore, methanol vessels record the highest emissions among all fuel categories when using fossil methanol (118,073 tons), even surpassing HFO. This is primarily due to fossil methanol's substantially higher WTT emissions. In contrast, switching to 95% biomethanol cuts annual emissions to 19,436 tons with an 83% reduction, highlighting the fuel's strong dependency on renewable feedstock content and the pivotal role of feedstock origin in lifecycle GHG performance.

Subsequently, the annual GHG emissions for each vessel and fuel configuration were monetized under the FuelEU Maritime and IMO Net-Zero Framework compliance schemes. Figure 9 presents the cumulative compliance cost for each vessel–fuel configuration over 2025–2040. Red-labeled values denote the total net compliance cost, combining Fuel EU penalties, IMO remedial unit cost and surplus unit revenues.

Figure 9. Total Compliance Cost for different vessels and fuels (2025-2040)



The results reveal an obvious divergence in economic performance across fuel types once emission costs are considered. Importantly, compliance costs for G1-HFO, G2-HFO, and fossil methanol are more than double those for fossil LNG (USD 85 million), showing fossil LNG's relative advantage in compliance costs over other fossil fuels. Hence, in situations of limited biofuel availability, fossil LNG may represent a more viable transitional pathway for compliance.

Moreover, fossil methanol ranks worst at USD 239 million, consistent with its position as the highest-GHG-intensity fuel. G1-HFO and G2-HFO follow at USD 169.7 million and USD 161.8 million, respectively. Especially, Group 2's improved efficiency achieves a 5% reduction compared to Group 1 in total emission-related costs, underscoring both economic and environmental value of improving fuel efficiency.

In contrast, 100% biodiesel and 95% biomethanol deliver the most favorable outcomes, each achieving full compliance and generating net gains of roughly USD 190 million through surplus unit sales under the pooling mechanism. However, the compliance cost varies with the proportion of biofuel used. Although blends of 75% biodiesel and biomethanol also offer strong cost advantages, compliance benefits diminish sharply at 50% or 30% biofuel shares, compared to bioLNG.

Nevertheless, bioLNG stands out for its flexibility. While 95% BioLNG (USD 179 million net gain) does not outperform 100% biodiesel or biomethanol in absolute compliance cost savings, it remains economically attractive. Importantly, at blending ratios of 30–75%, bioLNG achieves substantially lower compliance costs than equivalent methanol or biodiesel blends and exhibits more stable performance, reinforcing LNG's role as an intermediate yet adaptable compliance option.

This may suggest that for LNG vessels, it may not be optimal to increase bio-LNG blending aggressively at beginning to generate surplus units, as fossil LNG already delivers relatively low GHG emissions with lower compliance costs and the incremental emission reductions from higher blends are modest. The limited surplus revenues may not compensate for the higher fuel costs, implying that a more suitable strategy is to scale up blending gradually as regulatory stringency increases.

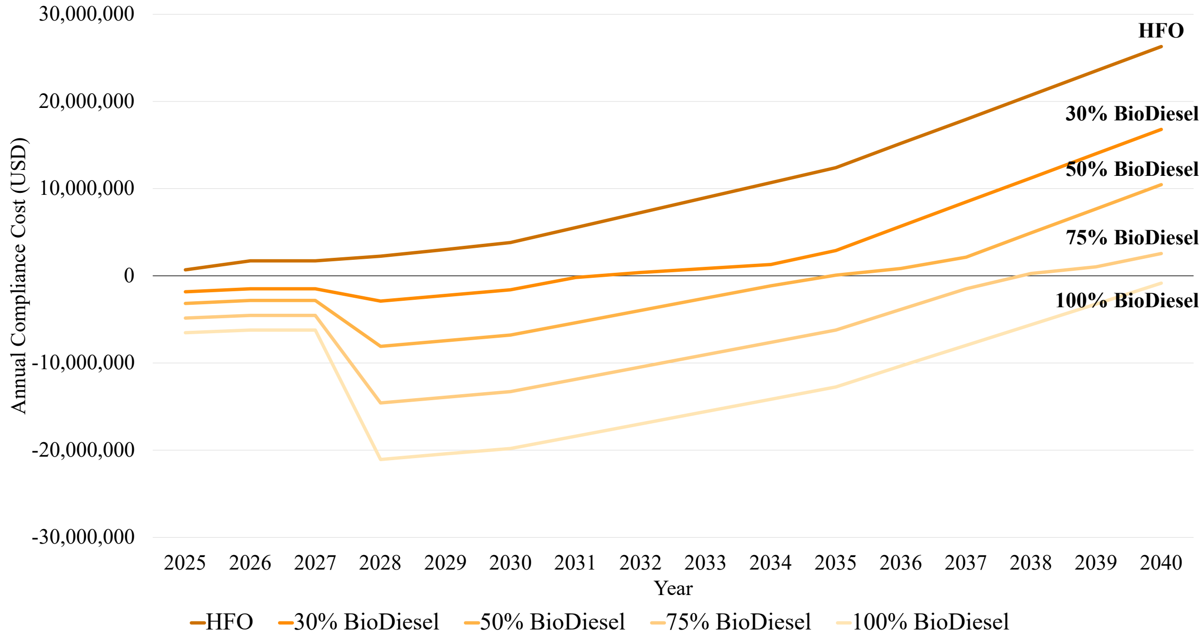
Additionally, to evaluate the annual evolution of compliance costs and determine the optimal biofuel blending ratio, it is necessary to consider the progressively tightening regulatory requirements from 2025 to 2040. This is especially critical for biodiesel and biomethanol, as their compliance costs are highly responsive to changes in blend proportion. Figure 10 illustrates this dynamic for a Group 2 vessel operating on HFO with varying proportions of biodiesel. The results show a clear interplay between tightening regulations and each fuel's corresponding compliance costs.

In the early years, particularly after the introduction of the IMO Net-Zero Framework in 2028, high biofuel shares (75% and 100%) deliver substantial overcompliance benefits. For example, 100% biodiesel generates more than USD 21 million in surplus unit revenues in 2028 alone, effectively transforming environmental overperformance into financial gains. These benefits can help offset the higher cost of biofuels relative to fossil fuels.

However, as regulatory stringency increases, the marginal benefit of overcompliance steadily declines. By 2040, only the 100% biodiesel vessel maintains a negative compliance cost (–USD 0.85 million), while all lower-ratio blends shift into positive compliance costs. For instance, the 75% biodiesel vessel transitions from a benefit of –USD 14.6 million in 2028 to a cost of USD 2.56 million by 2040, as the narrowing gap between attained and required GFI reduces the available surplus units.

Nevertheless, compliance costs for high GFI fuels with lower blending ratios are substantially higher. At lower biodiesel blending ratios, vessels capture limited compliance benefits at first, after which compliance costs rise at an accelerating pace in response to tightening regulatory limits. Meanwhile, HFO's compliance costs rise sharply throughout the period, from USD 0.69 million in 2025 to over USD 26.3 million in 2040, driven entirely by stricter regulations.

Figure 10. Annual Compliance Costs for single Group 2 vessel with different proportion of biodiesels



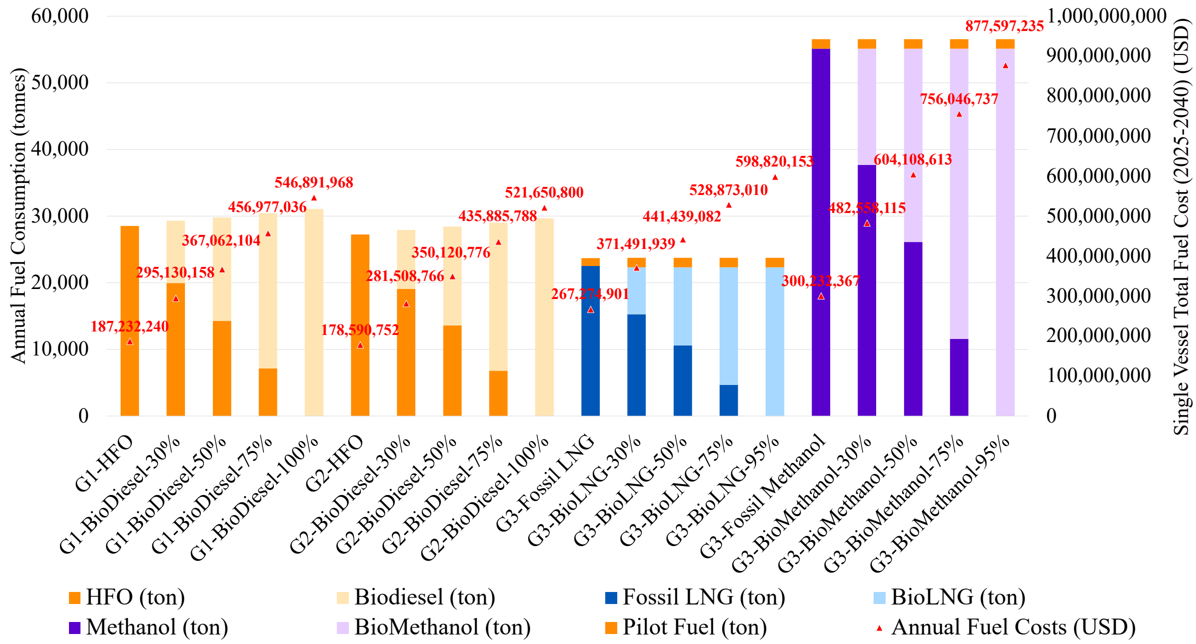
Therefore, while the diminishing benefits of surplus units may discourage high biofuel blending ratios in later years, lower blending ratios would expose shipowners to increasing remedial unit costs as regulations tighten. Ultimately, this dynamic pushes shipowners toward gradually adopting higher biofuel proportions.

Overall, the results indicate that the economically optimal compliance pathway evolves over time, beginning with higher biofuel adoption to capture surplus unit revenues and subsequently shifting to the lowest-cost configuration that still meets compliance limits once those incentives diminish. Nevertheless, the proportion of biofuel adoption is contingent on whether the revenues from over-compliance or the savings from avoided penalties are sufficient to offset the costs of high GFI fuels. Furthermore, as the IMO Net-Zero Framework has not yet been finalized, regulatory design will play a decisive role in shaping the timing of fuel transitions and could significantly alter the optimal fuel choice.

4.3 Fuel Consumption

Fuel cost is a fundamental component of a vessel's total OPEX, particularly given that biofuels are significantly more expensive than fossil fuels for shipowners. Figure 11 presents the annual fuel consumption (tonnes) and the corresponding total fuel cost over 15 years (USD) for a single vessel using different fuel types and blending ratios, based on the assumption of constant fuel prices. The results clearly indicate that LNG-based fuels require the lowest amount of fuel, owing to LNG's high lower calorific value (LCV). In contrast, methanol and biomethanol require the highest volumes of fuel, due to their significantly lower energy density.

Figure 11. Annual fuel consumption and Single vessel total fuel costs (2025-2040)



Importantly, although methanol and biomethanol are the cheapest options per tonne, both for fossil and bio-based fuels, their total fuel cost over time is the highest. This is a direct result of the high volume required to meet the same energy demand. For example, the 95% biomethanol configuration, despite its lower unit price compared to bioLNG and biodiesel, leads to the highest total fuel expenditure of USD 878 million over 15 years, driven by an annual fuel consumption of over 55,000 tons. This is more than twice the consumption of BioLNG-95% (22,239 tons), which costs USD 599 million over the same period with a higher price. However, despite its low consumption volume, LNG remains the most expensive fuel per tonne. As a result, even though LNG requires less fuel, its total cost still exceeds that of HFO and biodiesel. Therefore, when comparing different fuels, it is essential to consider total cost per voyage or VLSFO-equivalent energy-adjusted prices to ensure an accurate comparison on a consistent energy basis.

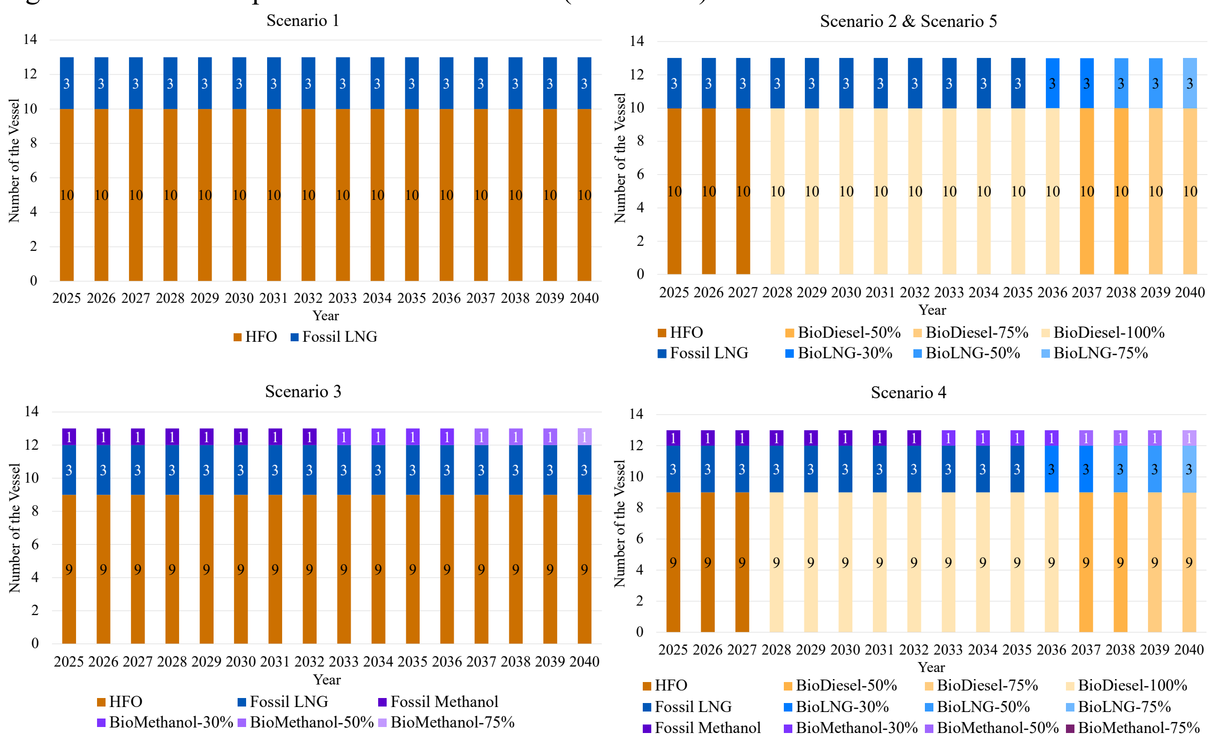
Biodiesel, which is slightly more expensive than methanol on a per-tonne basis, benefits from higher LCV, resulting in lower fuel consumption. This leads to moderate total fuel costs, as using 100% of biodiesel costs around USD 530 million over 15 years, significantly less than 100% bioLNG and biomethanol configurations. Notably, the impact of engine efficiency is also evident. When using 100% biodiesel, the Group 2 vessel (with a more efficient engine) incurs a total fuel cost of USD 435.9 million, saving over USD 20 million compared to the less efficient Group 1 vessel.

Additionally, biodiesel presents operational advantages. Since it is a drop-in fuel, it does not require any technical modifications to existing vessels, thereby avoiding retrofit costs. Combined with the potential for earning surplus units through overcompliance, biodiesel emerges as a promising solution for existing fleets aiming to meet regulatory targets while avoiding costly upgrades. Conversely, methanol's high fuel costs, being the most expensive among equivalent biofuel blends, further undermine its feasibility. Combined with its comparatively poor GHG intensity performance, this explains why Scenario 3 records the highest total cost and why no vessels are retrofitted to methanol propulsion in Scenario 5.

4.4 Fleet Optimization

The optimized fleet composition outcomes for each scenario, shown in Figure 12, reflect the model's balancing of fuel costs and GHG compliance costs under the FuelEU Maritime and IMO Net-Zero Framework from 2025 to 2040. Firstly, Scenario 1, representing a baseline static strategy with 10 HFO-fueled vessels and 3 LNG-fueled vessels maintained throughout the entire period with a total cost of USD 4.56 billion. Therefore, any other scenario has a higher cost above this will not be recommended.

Figure 12. Fleet Composition for each scenario (2025-2040)



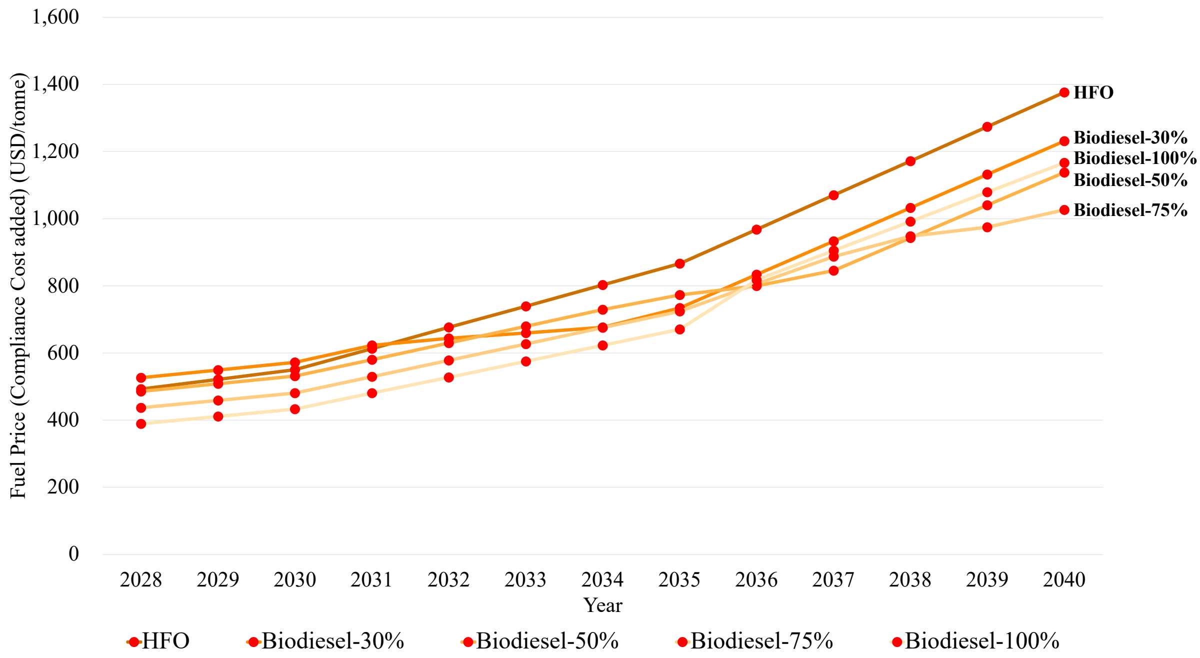
Note: Scenario 5 represents retrofitting, but the optimization selects no conversions, resulting in the same result as Scenario 2

Scenario 2 incorporates flexibility only in transitioning to biodiesel and bioLNG, yet it achieves the lowest total cost among the five scenarios, amounting to USD 4.02 billion over the 2025 to 2040 period. In the initial years, when the FuelEU Maritime is in effect, the fleet operates primarily on HFO and fossil LNG, reflecting the relatively modest gap between actual emissions and the compliance threshold. At this stage, the economic incentive to shift toward higher-priced biofuels remains limited, as the value of penalties and overcompliance, measured by the revenue from selling surplus units, are not sufficient to justify the additional fuel expenditure.

However, a significant shift occurs from 2028 onward, when the IMO Net-Zero Framework comes into force. At this point, the entire HFO fleet transitions immediately to 100% biodiesel, confirming the findings from previous sections: early adoption of high-biofuel blends can generate substantial financial gains through surplus unit trading. This result is consistent with Transport & Environment (2025), which found that ships could opt to bunker sufficient biofuels to generate a large number of surplus units, which could then be sold to offset the emissions of vessels that would otherwise face penalties. Additionally, it also follows Argus estimates that B100 seen attractive shipping fuel option under the IMO Net-Zero Framework (Teo, 2025).

Moreover, this behavior aligns with the cost dynamics illustrated in Figure 13, which presents the adjusted fuel prices after incorporating compliance costs and revenues from surplus units. This figure clearly demonstrates when and why the model selects particular blending ratios over time.

Figure 13. HFO and Biodiesel prices incorporated with the compliance cost



In 2028, the effective price of 100% biodiesel, after accounting for overcompliance rewards through the pooling mechanism, falls to USD 389 per tonne which is even lower than unadjusted HFO. This implies that surplus unit revenue is not only sufficient to cover the cost difference, but it also makes 100% biodiesel the most economically attractive option. Similarly, 50% and 75% biodiesel blends are also cheaper than HFO with compliance costs included, with the latter reaching up to USD 493 per tonne.

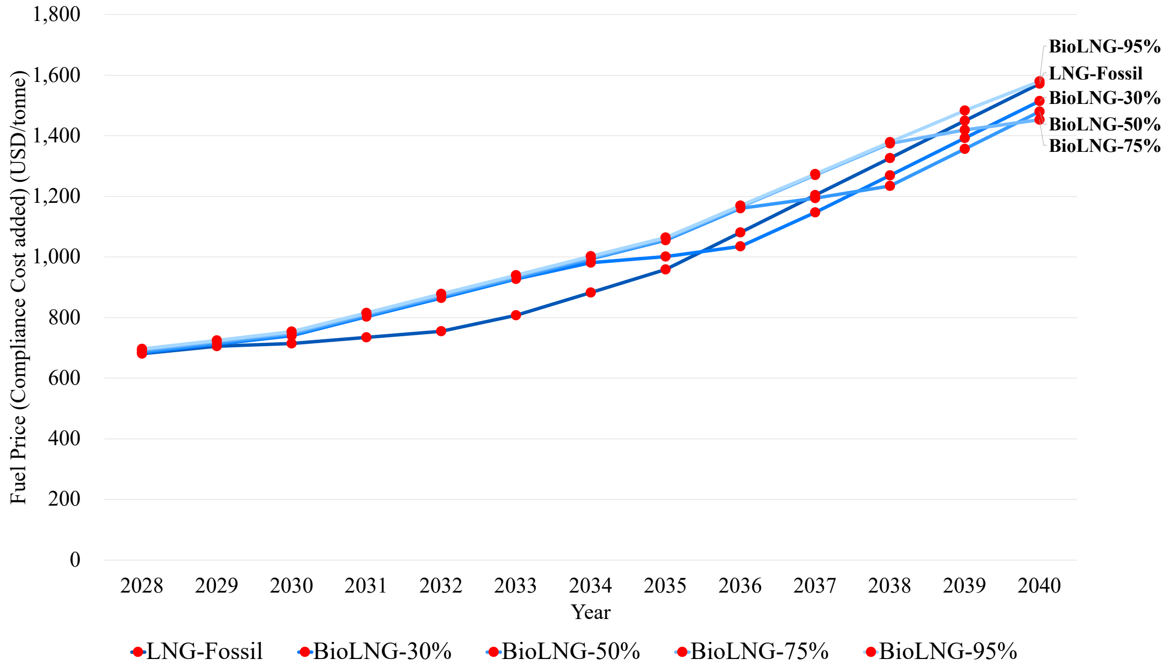
Interestingly, in 2037 and 2038 the model shifts from 100% to 50% biodiesel, indicating that under tightened emission targets and diminishing marginal rewards for overcompliance, the high cost of 100% biodiesel can no longer be fully offset. In this context, accepting partial non-compliance and paying a moderate penalty becomes the more cost-effective strategy. After 2039, the model reverts to a 75%

biodiesel blend as further tightening of compliance thresholds makes it cheaper to adopt a slightly higher biofuel share than to bear the escalating penalty costs.

Notably, by 2040, when compliance costs are incorporated into fuel prices, even the lowest cost option exceeds USD 1,000 per tonne, approximately 2.5 times the current market price. Such an increase would have a profound impact on vessel operating costs in the absence of additional compensation mechanisms. This escalation could significantly affect the maritime industry, undermine the cost advantage of seaborne freight which is considered as the most economical mode of transportation for a long term. In turn, the increasing cost of freights will pressure on global commodity prices.

Moreover, for LNG dual-fuel vessels within the fleet, the model indicates a more gradual transition toward bioLNG, with blending beginning only in 2036 at 30%, increasing to 50% in 2038, and reaching 75% by 2040. This gradual trajectory contrasts with the earlier, immediate adoption of high biodiesel blends by HFO vessels. As shown in Figure 14, which presents the adjusted LNG and bioLNG prices after incorporating both compliance costs and surplus rewards, fossil LNG remains the most cost-effective option until 2035, only being surpassed by 30% bioLNG from that point onward. This result is consistent with Argus's estimate (Jenkins, 2025).

Figure 14. LNG and BioLNG prices incorporated with the compliance cost

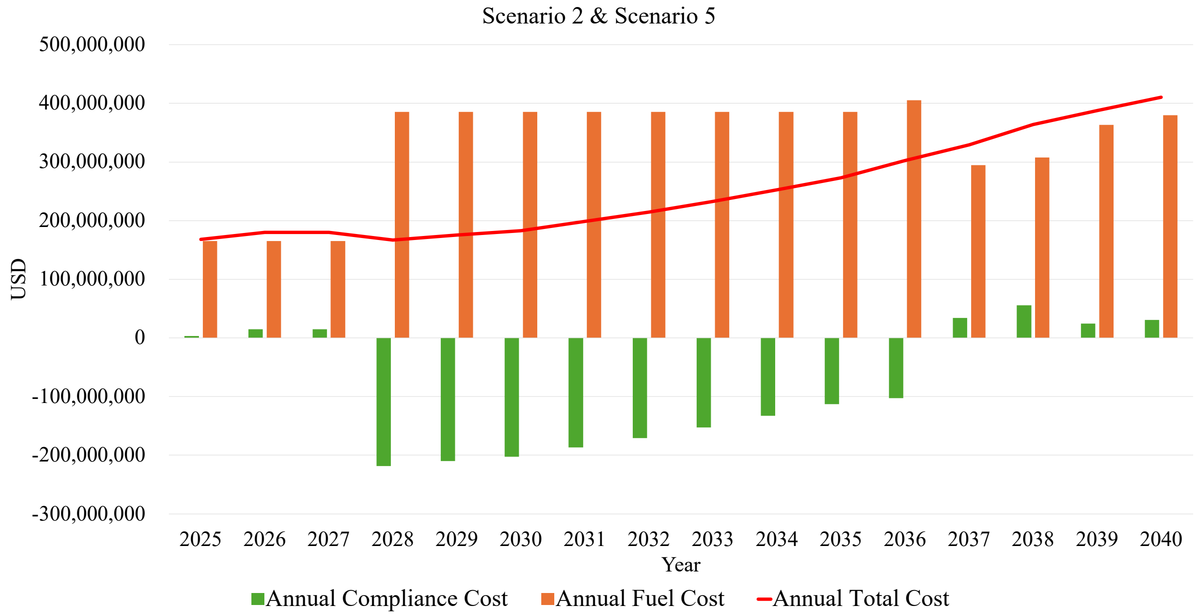


This differing pattern of fuel adoption between biodiesel and bioLNG can be explained by two primary factors. First, fossil LNG has a significantly lower GHG intensity compared to HFO, enabling it to earn surplus units under the FuelEU Maritime regulation and meet the IMO Base Target until approximately 2033 without incurring the expensive Tier 2 penalties. Although it still falls short of the Direct Compliance target, the Tier 1 penalty rate is substantially lower than the price of adopting bioLNG, allowing fossil LNG to remain cost-competitive for a longer period.

Second, bioLNG is considerably more expensive than biodiesel on a per-tonne basis. As a result, the current reward mechanisms under the IMO Net-Zero Framework are not sufficient to fully compensate for the high cost of bioLNG during the earlier regulatory years. This leads to a low marginal benefit of overcompliance when using bioLNG, reducing the economic incentive for early adoption. Consequently, the model postpones its uptake until after 2035, when regulatory thresholds become significantly stricter, and the cost of non-compliance escalates sharply. From this point, the increasing penalty exposure justifies a rapid increase in bioLNG blending, rising from 30% to 75% within a five-year span.

Furthermore, Scenario 2 presents a well-structured and cost-effective compliance pathway for the representative fleet that exploits the advantages of biodiesel and bioLNG. Figure 15 illustrates the annual compliance and fuel costs to clarify the overall cost structure. In the early years, high biodiesel blends are strategically deployed to maximize surplus generation under favorable reward conditions, effectively converting environmental overperformance into economic gain to compensate the high price of biofuels. As regulatory thresholds tighten and the marginal benefit of surplus trading declines, the strategy transitions toward bioLNG adoption and lower biodiesel shares, focusing on penalty avoidance at minimal cost. This staged approach underscores the importance of fuel-specific timing, regulatory foresight, and dynamic blending optimization in fuel strategy, balancing fuel prices, emission intensity, compliance stringency, and marginal economic returns across the entire horizon. However, the annual total cost shows an increasing trend, which may create higher barriers by raising future freight costs for customers.

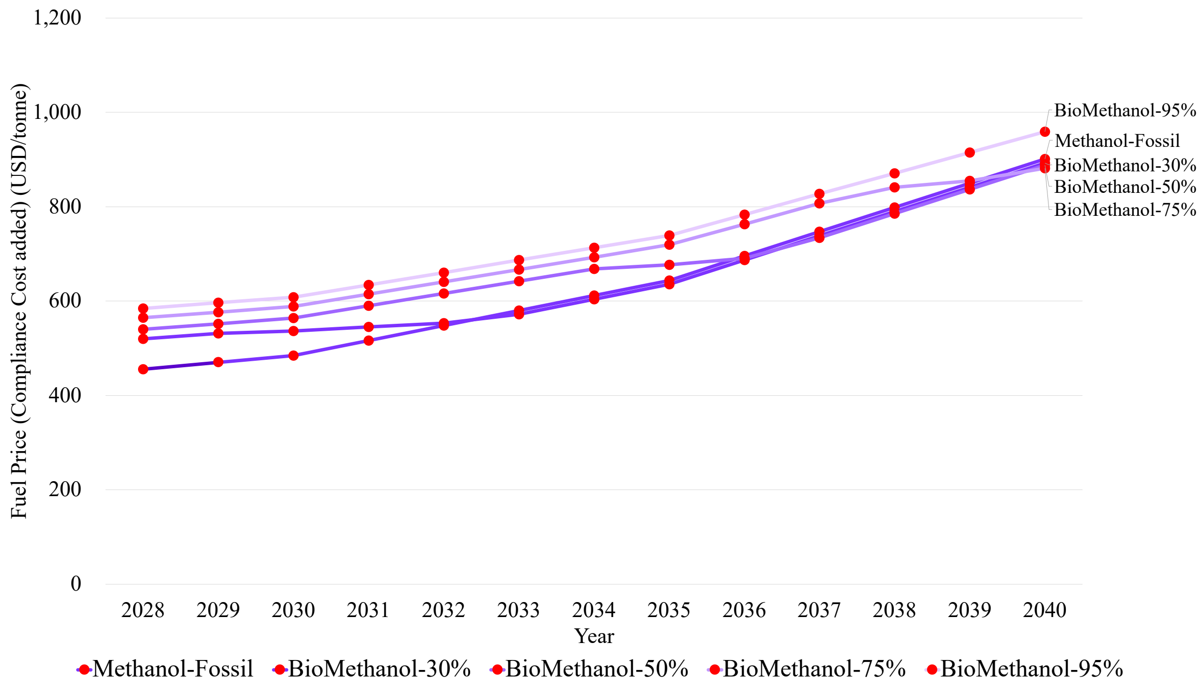
Figure 15. Annual Compliance, Fuel, and Total Costs under Scenario 2 (Scenario 5) (2025–2040)



Note: Scenario 5 represents retrofitting, but the optimization selects no conversions, resulting in the same result as Scenario 2

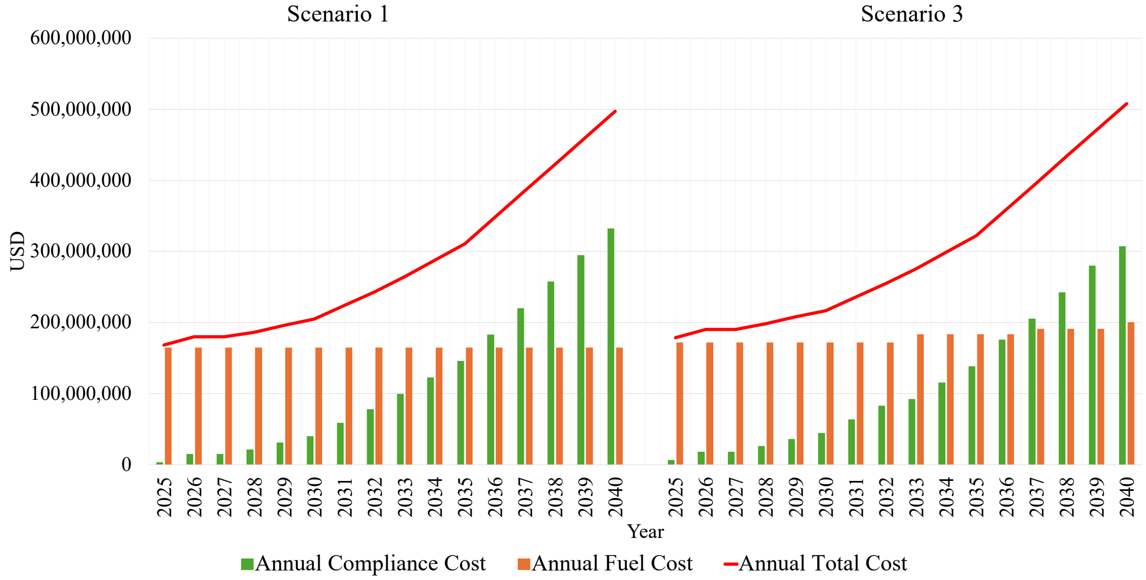
Scenario 3 introduces a single methanol-fueled vessel into the fleet, replacing one Group 1 HFO vessel, while the remaining ships continue operating on HFO and fossil LNG. Over the 15-year horizon, this scenario is deemed infeasible, generating the highest total cost of USD 4.74 billion, which exceeds the benchmark (Scenario 1). The model's blending schedule for this single methanol vessel mirrors the late-stage adoption observed for bioLNG, but begins earlier, reflecting methanol's weaker GHG intensity performance relative to LNG. Specifically, the methanol vessel adopts 30% biomethanol in 2033, rising to 50% in 2037 and 70% by 2040. As shown in Figure 16, even when accounting for the over-compliance benefits from surplus units, 95% biomethanol remains prohibitively expensive under the adjusted methanol price scenario. Moreover, as highlighted earlier, significant GHG intensity reductions from methanol are only more competitive at high blending ratios (95%), while surplus compliance units remain insufficient to offset the elevated fuel costs.

Figure 16. Methanol and Biomethanol prices incorporated with the compliance cost



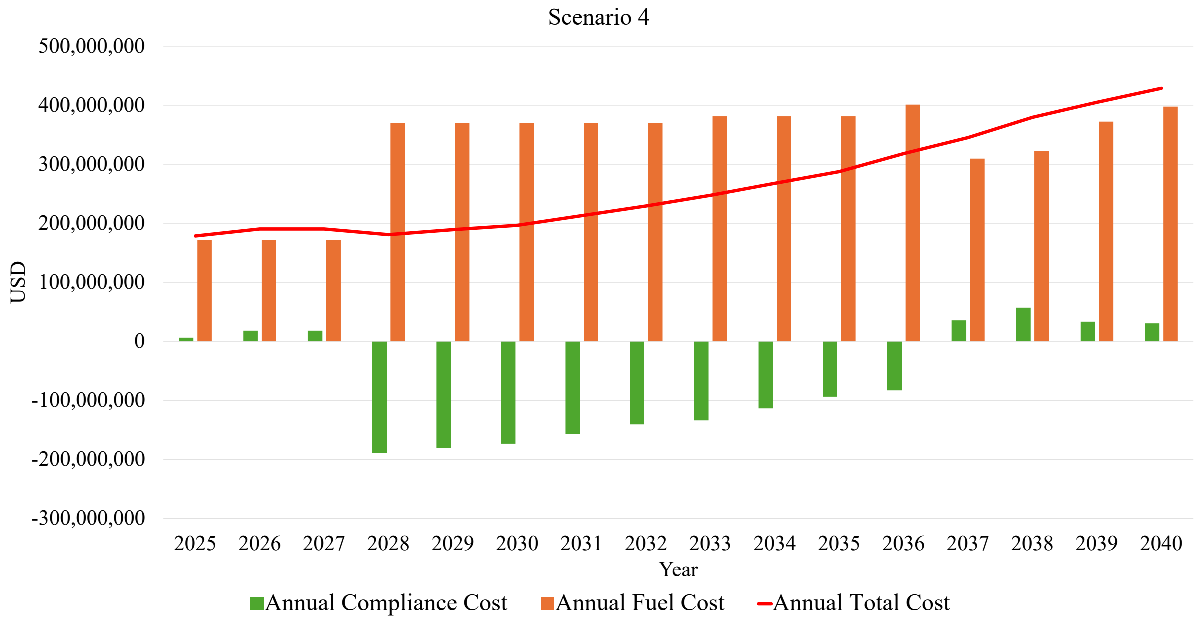
Also, its inherently low energy density necessitates substantially higher consumption volumes relative to other fuels, driving total fuel expenditure considerably upward. Although biomethanol is among the lowest-cost biofuels on a per-tonne basis, this volume effect effectively erodes its nominal price advantage. As shown in Figure 17, while Scenario 3 lowers compliance costs by 6% relative to Scenario 1 in the final seven years, its earlier compliance costs are 25% higher and fuel costs average 10% higher over the full 15 years, resulting in a higher total cost than Scenario 1. In the current fleet configuration, with only one methanol vessel replacement, the compliance benefits from GHG reductions are insufficient to offset the additional fuel costs arising from methanol's higher consumption and the elevated price of biomethanol. Consequently, its overall economic performance falls well short of the more adaptive and cost-efficient biodiesel and bioLNG strategy observed in Scenario 2.

Figure 17. Annual Compliance, Fuel, and Total Costs under Scenario 1 and Scenario 3(2025-2040)



Scenario 4 retains the methanol vessel from Scenario 3 but allows the remaining ships to follow the same biodiesel and bioLNG adoption pathway as in Scenario 2. Similarly, under this structure, high-biofuel blends are used early to capitalize on overcompliance rewards, and bioLNG is phased in later as regulations tighten. While this improves cost efficiency relative to Scenario 3, the total 15-year cost remains USD 4.25 billion, still notably higher than Scenario 2's USD 4.02 billion. Figure 18 shows the annual cost over 15 years. Notably, while the annual fuel cost is similar to Scenario 2, the average annual compliance cost is 2.56% higher. The persistence of the methanol vessel continues to weigh on fleet-wide optimization, as its limited compliance impact and high total fuel consumption prevent the fleet from achieving the same level of economic performance as Scenario 2. It further proves that the use of biodiesel and bioLNG is a better choice for this fleet.

Figure 18. Annual Compliance, Fuel, and Total Costs under Scenario 4 (2025–2040)



Taken together, Scenarios 3 and 4 reinforce the conclusion that methanol, under current price, energy density, and reward assumptions, is an economically inefficient choice when deployed within the fleet. Its cost competitiveness is undermined by the combination of high consumption volumes and the need for high pricing 95% biomethanol to deliver meaningful emissions reductions. However, this finding appears to contradict the current industry trend, as an increasing number of shipping companies are investing in methanol vessels (DNV, 2025). This will be further explored in the discussion part.

Scenario 5 was designed to assess whether retrofitting vessels to methanol or LNG dual-fuel vessels could be economically justified. However, the results from earlier scenarios indicate that methanol offers limited compliance benefits relative to its high fuel consumption and unfavorable GHG intensity, while bioLNG, although cleaner, is less cost-effective than biodiesel especially in the early years when revenues from surplus units are most advantageous. When the additional capital cost of retrofitting is factored in, biodiesel remains the most cost-efficient option in 15 years. Consequently, the optimization model selects no retrofits, and Scenario 5 replicates the fleet composition and fuel adoption pathway of Scenario 2, producing an identical total cost outcome. Moreover, the absence of retrofit activity highlights the model's capacity to reject capital-intensive interventions when operational fuel-switching provides equivalent or superior economic performance.

However, annual total costs show an upward trend across both all scenarios and will ultimately be passed on to customers through higher freight rates. Moreover, as regulations tighten, constant compliance prices provide little incentive for shipowners to adopt higher biofuel blends. Instead, paying Remedial Units becomes cheaper, undermining sustained decarbonization. This highlights the need for additional mechanisms, such as additional compensation mechanisms for green fuels, to ensure continued biofuel adoption and prevent cost pass-through from weakening policy effectiveness.

Nevertheless, the analysis so far assumes constant fuel and compliance prices. In reality, both are subject to considerable uncertainty. To accelerate decarbonization, regulators may raise compliance prices to strengthen incentives for biofuel adoption, while fuel prices could decrease through economies of scale in production or, conversely, increase due to rising demand and constrained supply. These potential fluctuations highlight the need for a sensitivity analysis to evaluate the robustness of the model.

4.5 Sensitivity Analysis

This section conducts sensitivity analysis in two main areas. First, it examines the potential impact of changes in compliance prices under the IMO Net-Zero Framework, recognizing that the post-2030 price trajectory has not yet been determined. The objective is to assess how different price escalation scenarios, particularly higher penalty and surplus unit prices, could influence the adoption of alternative fuels and the resulting composition of the fleet.

Second, the analysis considers variations in fuel prices, given that fuel costs represent the largest component of vessel operating expenditure with high volatility and are therefore expected to have a significant influence on total costs. By testing these two parameters, the sensitivity analysis aims to evaluate the robustness of the optimization results under different market and regulatory conditions.

4.5.1 Price of the Remedial Units and Surplus Units

The compliance price is a critical factor in determining the financial incentive for ship owners to reduce GHG intensity and adopt low-carbon fuels. Since the post-2030 price trajectories under the IMO Net-Zero Framework have not yet been established, this study defines three escalation scenarios to assess their potential impact on fuel adoption. In these scenarios, Tier 2 RUs prices (starting at USD 380/tCO_2e in 2028) increase every three years by 10%, 15%, or 20%, while the corresponding escalation rates for Tier 1 RUs prices (starting at USD 100/tCO_2e) and Surplus Units (SUs, starting at USD 312/tCO_2e) are set at 5%, 7.5%, and 10%, respectively, as shown in the Table 10.

The larger increases for Tier 2 are intended to provide a progressively stronger penalty signal for failing to meet the Base Compliance Target and urge the decarbonization. Also, the scenario with a 15% three-yearly increase in Tier 2 is treated as the baseline case, as it is designed to reach approximately USD 640/tCO_2e by 2040, broadly aligning with the penalty level projected under the FuelEU Maritime, while avoiding abrupt price spikes that could cause excessive market disruption. It is further assumed that the European Union would coordinate with the IMO to ensure that IMO penalties are not set at levels that are too low, potentially allowing the FuelEU Maritime regulation to be suspended for vessels covered by the IMO scheme to avoid double charging.

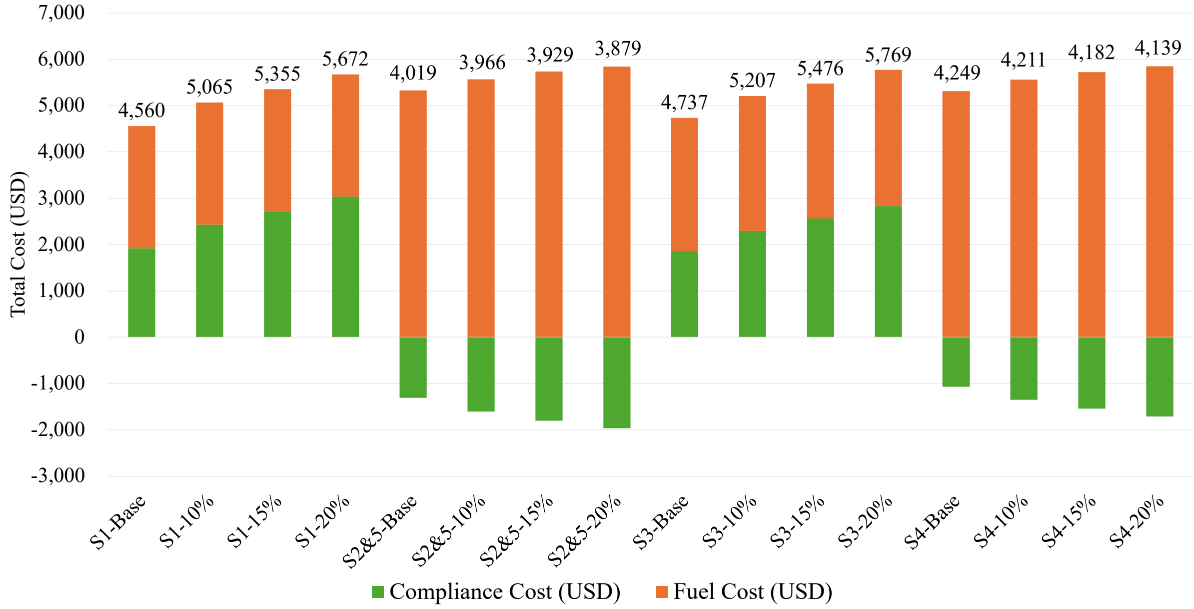
Table 10. Assumed Compliance Price under Sensitivity Analysis

Compliance Price (USD/tCO_2e)	Growth Rates (%)	2028-2030	2031-2033	2034-2036	2037-2039	2040
A: 10% Change						
Tier 1 RUs	5%	100	105	110	116	122
Tier 2 RUs	10%	380	418	460	506	556
SUs	5%	312	328	344	361	379
B: 15% Change						
Tier 1 RUs	7.5%	100	108	116	124	134
Tier 2 RUs	15%	380	437	503	578	665
SUs	7.5%	312	335	361	388	417
C: 20% Change						
Tier 1 RUs	10%	100	110	121	133	146
Tier 2 RUs	20%	380	456	547	657	788
SUs	10%	312	343	378	415	457

Moreover, the use of three-year adjustment intervals reflects the likely periodic review cycles of the IMO framework, providing a gradual but credible strengthening of the compliance price signal to accelerate the adoption of lower-emission fuels. Meanwhile, the more moderate adjustments for Tier 1 and SUs maintain a stable and predictable price gradient, thereby avoiding excessive volatility in the overcompliance market. This approach is consistent with emissions-trading market design principles, where structured, interval-based price escalations offer clear investment signals while giving regulated entities sufficient time to adapt operational strategies and fuel procurement plans.

Figure 19 presents the sensitivity analysis results for each scenario under varying compliance price escalation rates. However, two distinct trends emerge. First, for Scenario 1 and Scenario 3, both predominantly reliant on fossil fuels, the total cost rises steeply as compliance prices increase. In Scenario 1, compliance costs surpass fuel costs once the compliance price rises by more than 15%, indicating that, without any decarbonization measures, compliance payments would constitute the largest component of operating expenditure. This highlights the economic unsustainability of a "do-nothing" approach under tightening regulatory conditions.

Figure 19. Total Cost under Compliance Price Sensitivity Scenarios



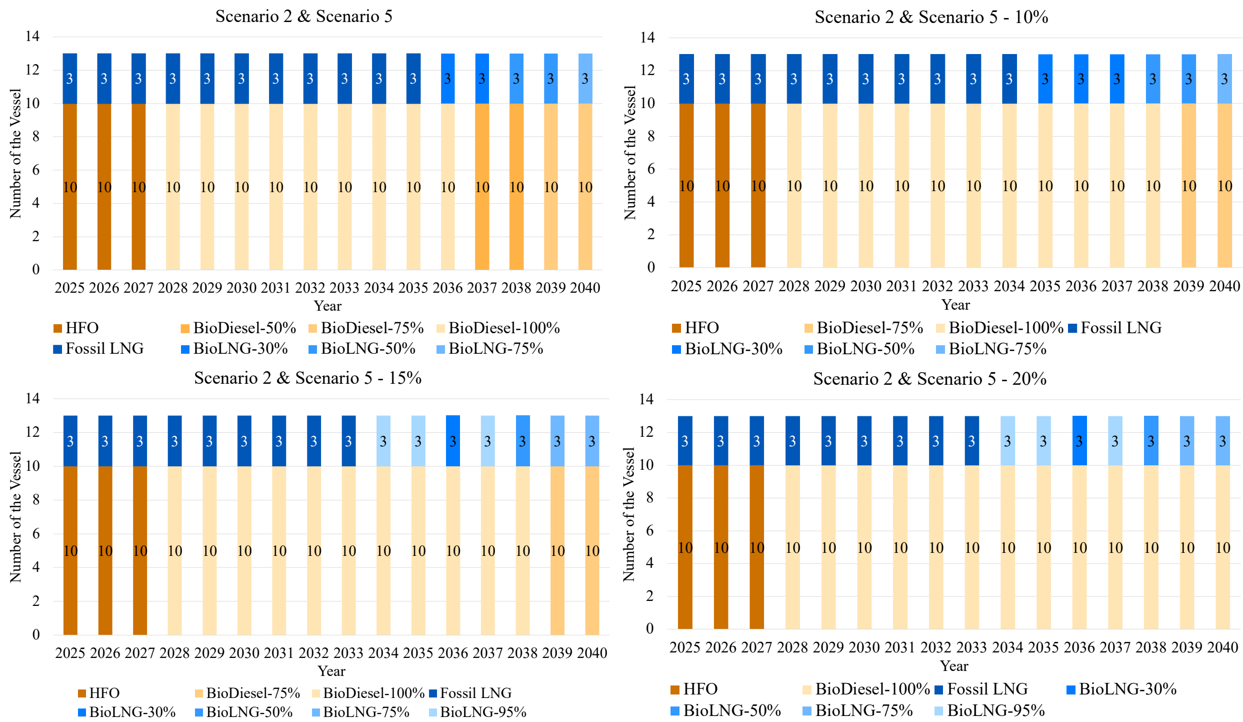
Note: Scenario 5 represents retrofitting, but the optimization selects no conversions, resulting in the same result as Scenario 2

Conversely, Scenarios 2 (5) and 4, characterized by earlier and higher biofuel adoption, exhibit a reduction in total cost as compliance prices increase. This counterintuitive outcome occurs because higher compliance prices amplify the value of overcompliance rewards from surplus unit trading, which more than offsets the additional fuel expenditure associated with biofuel use. Scenario 5, despite being designed to explore potential retrofitting to LNG or methanol, yields identical results to Scenario 2, reflecting the model's finding that retrofitting is still not economically justified even under elevated compliance price conditions. Therefore, HFO vessels using biodiesels remains a more cost-effective compliance strategy than capital-intensive fuel-switch retrofits. Furthermore, it reinforces the critical role of biodiesel for complying the regulations.

Across all compliance price levels, the total costs of Scenario 2 remain consistently lower than those of Scenarios 3 and 4, respectively. This reinforces the earlier conclusion that introducing a methanol vessel into the fleet, whether in isolation (Scenario 3) or in combination with other optimized biofuel strategies (Scenario 4), is economically disadvantageous. Even when compliance prices are high, methanol's relatively poor GHG intensity reduction and higher total fuel consumption undermine its competitiveness, thereby weakening the fleet's overall cost performance.

Moreover, higher compliance prices directly lead to greater adoption of biofuels across the fleet. As the compliance price and corresponding surplus unit selling price increase, Scenarios 2 (5) and 4 experience a reduction in total cost because the elevated reward for overcompliance incentivizes shipowners to maximize the use of low GHG emission fuels. Figure 20 illustrates the fleet composition in Scenario 2 (5) under constant fuel prices and under 10%, 15%, and 20% increases in the Tier 2 RU price, with the corresponding Tier 1 RU and surplus unit prices increasing at half those rates.

Figure 20. Scenario 2 (Scenario 5)'s Fleet Composition under Compliance Price Sensitivity Analysis



Note: Scenario 5 represents retrofitting, but the optimization selects no conversions, resulting in the same result as Scenario 2

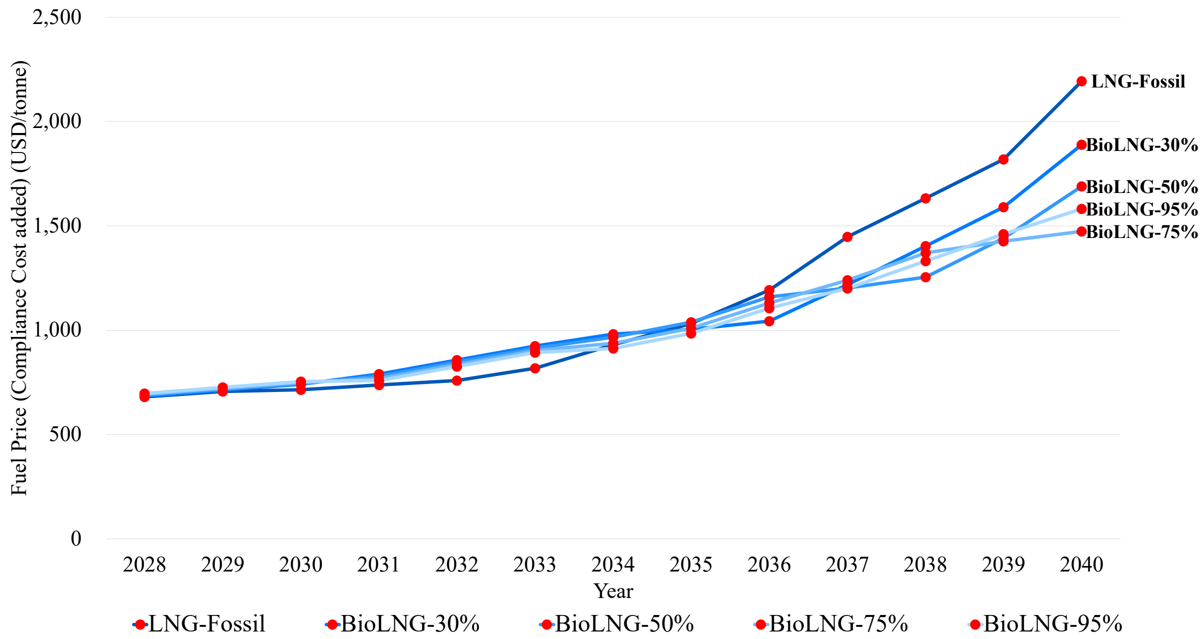
Notably, at higher compliance price levels, the model eliminates the 50% biodiesel blend previously observed after 2036, maintaining 100% biodiesel use until 2040 under a 20% increase scenario, and only switching to 75% biodiesel after 2039 under the 10% and 15% increase scenarios.

For LNG dual-fuel vessels, higher compliance prices also accelerate the transition to high bioLNG blends. Under 15% and 20% Tier 2 RU price increases, the fleet begins using 95% bioLNG immediately after fossil LNG can no longer meet the Base Target, thereby avoiding the sharply higher Tier 2 penalties and make full use of the benefits from using high share of biofuels.

Figure 21 shows LNG price trajectories with compliance costs included under a 15% Tier 2 RU price increase (and corresponding 7.5% Tier 1 RU and surplus unit increase). Interestingly, the model identifies 2034–2035 as the cost-optimal period for 95% bioLNG use, when regulatory thresholds are not yet at their strictest and surplus rewards are sufficient to fully offset the fuel's higher base price, making it temporarily the cheapest option. However, as the regulatory stringency increases further, the marginal reward from overcompliance declines relative to the cost of 95% bioLNG, prompting the model to shift to 50% or 75% blends. This dynamic clearly demonstrates that once fossil LNG fails to meet the Base Compliance Target, its adjusted price escalates rapidly, surpassing all bioLNG blends and rendering its continued use economically infeasible. In such circumstances, compliance price escalation acts as a strong policy lever, effectively pushing shipowners toward higher biofuel adoption and accelerating the fleet's decarbonization trajectory.

Nevertheless, even under elevated compliance prices, fossil LNG remains cost-optimal for nearly a decade until it can no longer achieve the Base Compliance Target. Thus, it may therefore serve as a practical option in contexts of constrained biofuel availability, highlighting its transitional function.

Figure 21. LNG prices incorporated with the compliance cost with 15% compliance price increase



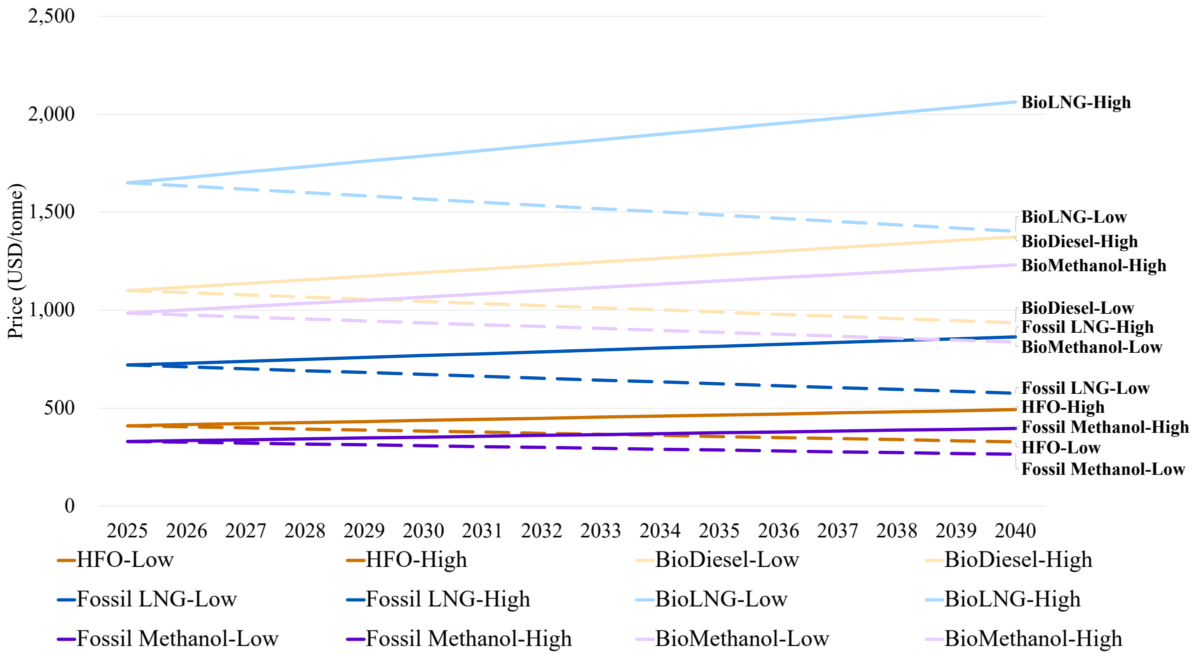
Nevertheless, under a 15% or 20% increase of the compliance price, the result for the LNG vessels remains unchanged. This implies that at such levels, compliance incentives alone would no longer promote the uptake of greener bioLNG, as the compliance reward cannot offset its higher price if bioLNG prices remain constant. Therefore, examining the impact of fuel price dynamics becomes essential.

Overall, the sensitivity analysis confirms that compliance price trajectories are a decisive driver of optimal fuel strategy. Specifically, Higher compliance prices not only accelerate the adoption of biofuels but also extend the period during which high-blend biofuel ratios remain economically optimal. This effect is most pronounced for biodiesel, where elevated rewards sustain 100% blends well beyond the baseline scenario. Crucially, these results reinforce the earlier conclusion that flexible fuel-switching within the existing fleet with biodiesels and bioLNG remains the most robust pathway under a range of policy stringency levels. They also highlight a potential policy implication: if regulators aim to accelerate decarbonization, increasing the compliance price (by extension, the surplus unit value) can create powerful economic incentives for early and sustained adoption of low-carbon fuels, particularly when such mechanisms are aligned with predictable and progressively tightening targets. Nevertheless, when compliance costs rise beyond a certain threshold, the compliance price signal alone may lose its effectiveness if greener fuels continue to be priced at a premium. Moreover, higher compliance prices not only raise fuel costs, potentially leading to higher freight rates for customers, but also intensify demand for biofuels, whose availability is constrained.

4.5.2 Fuel price

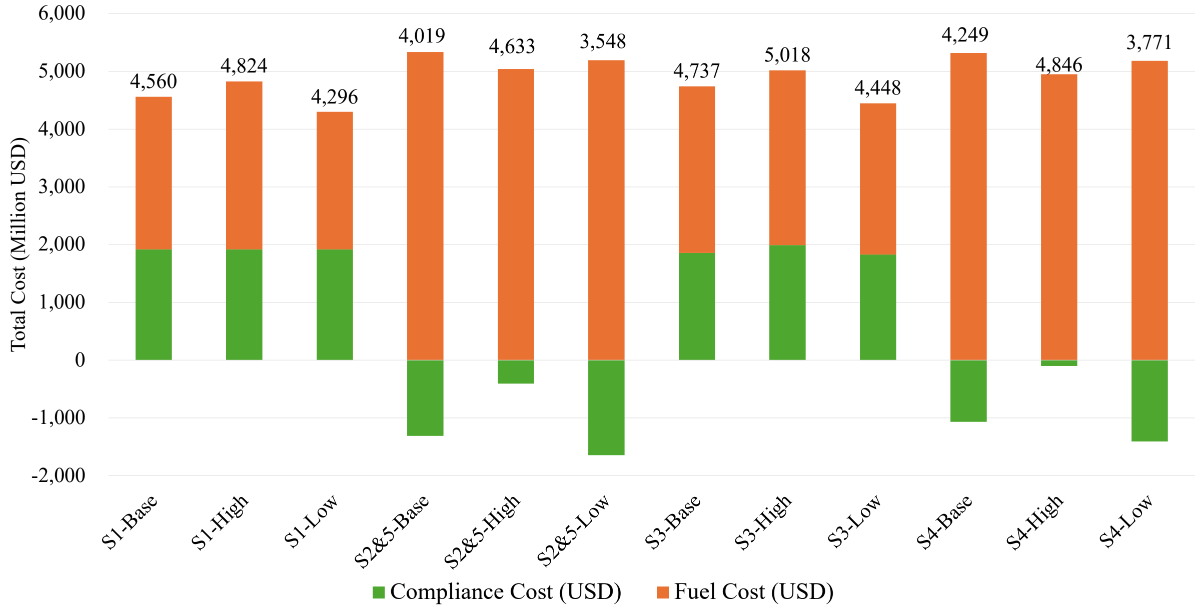
Fuel price is another critical factor that significantly influences shipowners' decision-making. In this sensitivity analysis, the assumptions are derived from multiple sources, including the Annual Energy Outlook 2025 (EIA, 2025), the highest and lowest forecasts from DNV (2025), and the Alternative Fuels Insight by ClassNK (2025). To capture typical non-crisis price volatility and foreseeable market uncertainty, following price ranges are applied over the next 15 years: an increase of 20% for fossil fuels and 25% for biofuels (High case, reflecting higher demand), and a decrease of 20% for fossil fuels and 15% for biofuels (Low case, reflecting large-scale supply expansion), as illustrated in Figure 22.

Figure 22. Assumed Fuel Price Trajectories under Sensitivity Analysis



Fossil fuel prices are assumed to follow a moderate trajectory in line with long-term oil and gas production forecasts, reflecting relatively stable supply and demand expectations. By contrast, biofuel prices incorporate projected cost reductions driven by technology improving and scale-up, while still maintaining a substantial premium over fossil alternatives due to persistent feedstock constraints, particularly given the anticipated surge in biofuel demand across multiple industries over the next 15 years. Figure 23 presents the total cost outcomes for each scenario under varying fuel price assumptions. Evidently, lower fuel prices incentivize the uptake of greener fuels, as reflected in reduced compliance costs, while higher prices have the opposite effect.

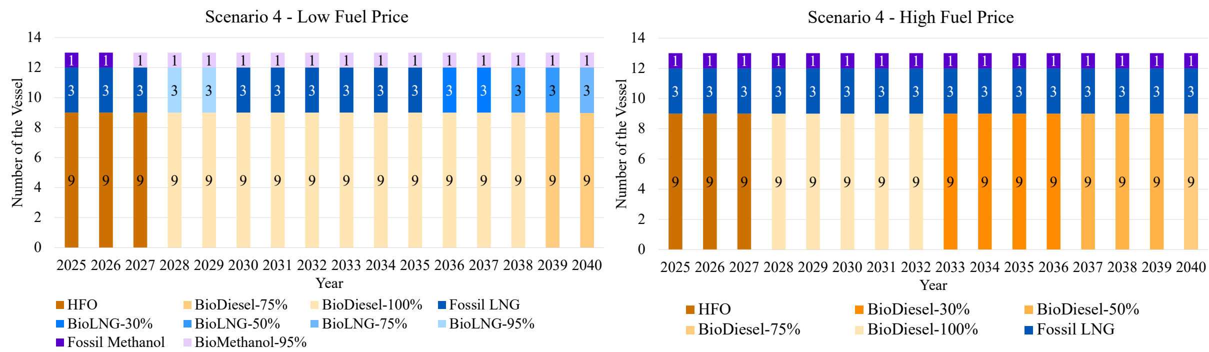
Figure 23. Total Cost under Fuel Price Sensitivity Scenarios



Note: Scenario 5 represents retrofitting, but the optimization selects no conversions, resulting in the same result as Scenario 2

A notable finding is that Scenario 4, which under baseline assumptions achieves a lower total cost than the benchmark, becomes more expensive than the benchmark (S1-High) once fuel prices rise. This outcome highlights the strong sensitivity of biomethanol to price fluctuations. As illustrated in Figure 24, under higher price conditions the methanol vessel remains on fossil methanol throughout the 15-year period, since the modest over-compliance revenues from surplus units cannot justify the significantly higher cost of biomethanol. However, fossil methanol has the worst GHG intensity among all fuels, which drives up compliance costs and ultimately pushes Scenario 4 above the benchmark.

Figure 24. Scenario 4's Fleet Composition under Fuel Price Sensitivity Analysis

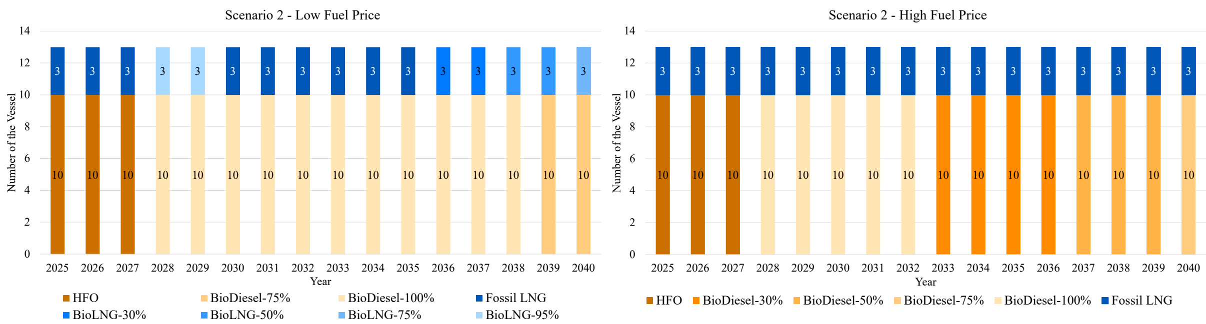


Conversely, when fuel prices fall, the methanol vessel adopts 95% biomethanol from 2027, maintaining this level until 2040. This demonstrates that the viability of biomethanol is highly dependent on fuel prices: once costs decline, a rapid shift toward high biomethanol blending ratios becomes economically attractive, whereas low blending shares remain non-competitive. The results therefore underline the crucial role of methanol price trajectories in determining the methanol's competitiveness as a decarbonization pathway.

However, Scenario 3 still performs worse than the benchmark, even under reduced fuel price assumptions. This shows that although biomethanol becomes more competitive when prices decline, as in Scenario 4, its cost performance remains inferior to biodiesel. Furthermore, even when fuel prices fall, retrofitting from HFO to LNG or methanol (Scenario 5) is still economically unjustified. Overall, biodiesel offers the most resilient compliance pathway for HFO vessels, owing to its relatively lower price, its ability to achieve compliance without capital reinvestment, and its flexibility to generate surplus-unit rewards.

Additionally, in Scenario 2 as shown in Figure 25, changes in fuel strategy emerge under different price settings. With rising fuel prices, LNG vessels continue to operate on fossil LNG because the limited over-compliance benefits cannot justify the additional rising cost of bioLNG, especially given that fossil LNG is able to meet the base compliance target for the majority of the 15-year horizon. In contrast, even with higher biofuel prices, biodiesel continues to be selected for HFO vessels, indicating that surplus unit compensation remains sufficient to incentivize its adoption. Under falling price scenarios, the fleet transitions to 100 % biodiesel until 2039 before shifting to 75 % biodiesel as a more cost-efficient late-period solution. Notably, 95% bioLNG is adopted under falling fuel prices, as the surplus units generated from over-compliance during the initial two years can offset its cost premium, thus incentivizing higher uptake of green fuel.

Figure 25. Scenario 2's Fleet Composition under Fuel Price Sensitivity Analysis



Overall, these results highlight that fuel prices are a decisive determinant of optimal fuel strategy. Due to methanol's high fuel consumption and the substantial differences between fossil methanol and bio-based methanol in both GHG intensity and cost, its competitiveness remains strongly dependent on fuel price developments. Similarly, LNG, though more efficient than methanol, remains disadvantaged relative to biodiesel due to its higher per-tonne costs, which limit the potential benefits from overcompliance. In contrast, biodiesel offers strong compliance outcomes while avoiding exposure to fuel price fluctuations. Its ability to capture surplus rewards without requiring structural fleet modifications makes it a particularly robust compliance option.

4.6 Summary

Based on the results from both the original model and the sensitivity analysis, the answer to the Sub-question 3 is clear that Scenario 2, switching to biodiesel and bioLNG, emerges as the most consistently feasible and robust compliance pathway across all examined conditions for the representative fleet to comply with the IMO Net-Zero Framework. The main logic of fuel choice is to minimize total costs, defined as fuel costs incorporated with its compliance costs linked to GHG emission intensity requirement. As regulatory requirements tighten progressively each year, this choice must be made dynamically, with optimal strategies evolving over time.

Specifically, for the existing HFO vessels in the fleet, the optimal strategy in the early years is to adopt 100% biodiesel. Since HFO has relatively high emissions, 100% biodiesel delivers the strongest GFI performance and the lowest cost among biofuels on a per-tonne basis. The substantial over-compliance generated at this stage produces surplus units sufficient to offset the high biodiesel price. However, as regulatory stringency increases, surplus units diminish and are no longer able to cover the cost premium, making a lower blending share (e.g., 50%) preferable. Toward the later years, as compliance thresholds tighten further, a gradual increase to 75% biodiesel becomes optimal. Nevertheless, as shown in the sensitivity analysis, higher compliance prices and lower fuel price would provide stronger incentives for higher blending ratios, making 100% biodiesel more attractive.

Furthermore, for LNG vessels in the fleet, fossil LNG alone can meet the base compliance requirement for the first nine years, making it more cost-effective to cover the residual shortfall with relatively cheaper Tier 1 RUs than to switch to bioLNG. However, as standards tighten, gradually increasing the share of bioLNG becomes preferable to avoid the higher cost of Tier 2 RUs. Furthermore, lower fuel prices incentivize high bioLNG blending in the initial years, while higher compliance prices stimulate its adoption once fossil LNG fails to meet the Base Compliance Target. These results suggest that surplus units can offset the cost premium of bioLNG at different periods depending on price developments, highlighting the need for fuel choice to adapt dynamically to market conditions.

This chapter also examines the methanol vessel in Scenarios 3 and 4 through sensitivity analysis. Under the assumed conditions, methanol vessels are not economically viable compared with Scenario 2, as they combine relatively poor GHG performance at low biomethanol blends with high total fuel costs due to low energy density. Additionally, the sensitivity analysis further shows that methanol's competitiveness is highly price-sensitive, becoming more attractive when fuel prices decline.

Moreover, the optimization model does not select retrofitting HFO vessels to methanol or LNG dual-fuel vessels under any circumstance, as biodiesel provides a more cost-effective compliance pathway without requiring capital-intensive investments. A summary of the overall scenario assessment is presented in Table 11.

Table 11. Overall assessment of each scenario

Scenario	Overall Assessment
1	Highest total cost and CO_2e emissions; compliance relies entirely on penalties and RU purchases without abatement action; not feasible.
2	Most cost-effective strategy with lowest total cost and emissions; For HFO vessels, start with higher biodiesel blends to generate surplus units, then reduce shares as regulation tightens and gradually increase again when stricter; For LNG vessels, use fossil LNG until base target cannot be met, then gradually increasing the share of bioLNG.
3	Replacement of one HFO vessel with methanol-fueled ship increases total costs due to methanol low energy density with high fuel cost and low CO_2e emission reductions if not high biomethanol blends; not competitive.
4	Combining methanol replacement with biofuel blending reduces compliance cost relative to Scenario 3 but remains more expensive than Scenario 2; methanol fuel cost and environmental benefit burden persists, making it economically unattractive.
5	Retrofitting HFO vessels to dual-fuel engines yields no additional economic benefit compared to Scenario 2; additional CAPEX with limited compliance gains from LNG or methanol; not feasible.

Overall, the analysis underscores that biodiesel offers a resilient and cost-effective compliance pathway. However, the assessment does not account for availability of sustainable biofuels, which may be limited and subject to competition from other industries. Hence, the long-term viability of fuels should be evaluated dynamically to ensure both economic and environmental sustainability.

Moreover, even under the lowest fuel price scenario, the inclusion of compliance costs and biofuel adoption will substantially raise shipping costs, potentially undermining the competitiveness of maritime transport and placing disproportionate burdens on smaller economies, if there is no additional compensation mechanisms. In addition, as the IMO Net-Zero Framework has not yet been finalized, many regulatory details remain uncertain, creating further risks for shipowners' investment decisions. Therefore, it is crucial for policymakers to design effective measures that ensure both decarbonization and a just transition in global shipping.

Chapter 5 Discussion

This discussion section addresses Sub-question 4: "*What are the main risks and uncertainties under the IMO Net-Zero Framework, and how can shipping companies and governmental or international institutions develop adaptive strategies to manage them?*"

Notably, the results and sensitivity analysis indicate that the IMO Net-Zero Framework is likely to accelerate the adoption of biofuels, particularly biodiesel and bioLNG. Even under high fuel price scenarios, these fuels remain more cost-effective than continuing to rely on fossil fuels and paying penalties. However, two critical risks could undermine the effectiveness of the framework: (1) the limited availability of sustainable biofuels, and (2) the potential escalation of shipping costs, which could substantially influence commodity prices and global economic stability, with disproportionate impacts on small and vulnerable countries. These risks also nourish the broader regulatory uncertainty, especially regarding the upcoming IMO vote scheduled for October 2025, which will determine whether the framework is formally approved.

5.1 Availability of biofuels

The first challenge concerns the limited availability of sustainable biofuels, particularly biodiesel. While biodiesel represents an attractive "drop-in" option requiring no retrofits and has shown strong cost-effectiveness in this study, global supply may fall short of shipping's decarbonization demand. However, Rystad Energy (2025) projects that the biodiesel's demand could exceed 140 million tonnes by 2028, whereas production capacity may only reach 120 million tonnes. Moreover, stricter sustainability criteria narrow the usable pool further as FuelEU Maritime excludes food- and feed-based biofuels, while the IMO applies land-use change factors in life-cycle assessments (Mærsk McKinney Møller Center for Zero Carbon Shipping, 2025).

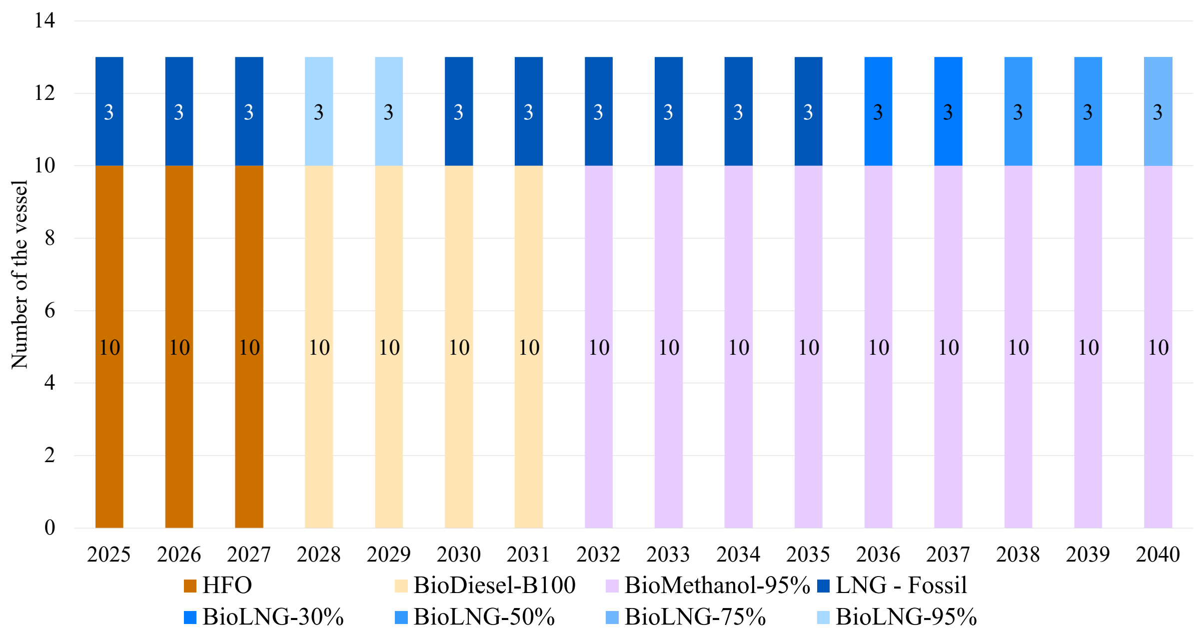
Furthermore, competition from other sectors intensifies this constraint. Road transport, aviation, and power generation are also seeking biodiesels, leaving shipping with a smaller share of supply. For bioLNG, Rystad Energy (2025) estimates that over 90% of production is already committed to electricity and road transport, leaving less than 10% available for maritime use. This indicates that shipowners will face tighter competition and more volatile prices than assumed in this study's scenarios, casting doubt on biodiesel and bioLNG as large-scale long-term solutions.

In contrast, green methanol, especially e-methanol derived from captured CO_2 and green hydrogen, provides a more scalable decarbonization pathway in the future by reducing reliance on scarce biomass feedstocks (Meulen, et al., 2023). While current prices remain high, studies suggest significant cost reduction potential. IRENA and the Methanol Institute (2021) project that renewable methanol (e-methanol) could approach fossil methanol prices considering the scale-up of production and use with policy interventions. Furthermore, according to European Energy, cost parity between green methanol and fossil methanol could be achieved by 2035 (Carlsson, 2025). GENA Solutions (2025) highlights a dramatic scale-up pipeline from 2 million tonnes in 2025 to 51.3 million tonnes by 2030, a 25-fold increase in five years, underscoring its rapid growth potential. Therefore, as green methanol can be produced via multiple pathways, including biomass and electrolysis, its future supply potential is expected to be substantial. In this context, biomethanol can serve as a transitional solution in the short to medium term, while e-methanol is likely to become the dominant long-term option once large-scale renewable production is achieved.

Building on this trend, this study incorporates an additional scenario to test whether a substantial decline in green methanol prices could alter the optimal fuel choice and fleet composition. In this scenario, fuel prices follow the same downward trajectories as in the sensitivity analysis, except for green methanol, which is assumed to decline gradually to USD 330 per tonne by 2035 and remain stable thereafter, following Carlsson (2025). In the early years, green methanol supply is primarily biomethanol, but as electrolysis matures and e-methanol production scales up, the average price of green methanol is expected to decrease, providing a basis to assess its future competitiveness.

Figure 26 presents the fleet composition under the lower biomethanol price scenario. Once green methanol prices approach fossil methanol levels, the fleet composition shifts significantly. By 2032, all ten HFO vessels in Groups 1 and 2 are retrofitted to methanol vessels and subsequently operate on 95% biomethanol through 2040. Notably, methanol becomes the optimal choice even at an estimated 2032 price of USD 527 per tonne, well above the assumed long-term price of USD 330, indicating strong competitiveness before full price parity is achieved. This aligns with the previous finding that methanol's competitiveness is highly price-sensitive: when the cost of low-GFI methanol decreases, methanol vessels quickly emerge as a viable and competitive option.

Figure 26. Fleet composition under the lower biomethanol price scenario



Compared with the low fuel price sensitivity scenario, the economics of retrofitting are markedly improved, with a payback period of approximately 3 years. By 2035, cumulative fuel and compliance cost savings in the first three years amount to around USD 265 million, exceeding the total retrofit investment of USD 240 million. Over the full 15-year horizon, savings surpass USD 526 million. These results demonstrate that, if green methanol, especially e-methanol, were to achieve cost parity with fossil methanol, it would become a highly competitive option for large-scale deployment in container shipping. Nevertheless, biodiesel and LNG remain important transitional fuels in the near term, as their immediate availability enables early emissions reductions and compliance cost savings before methanol reaches maturity.

The sharp decline in green methanol prices makes methanol vessels increasingly preferable, which helps explain why leading carriers such as Maersk and COSCO have made substantial investments in methanol vessels and pursued vertical integration into production, bunkering, and certification (Li, 2023; Dahl, 2024). Moreover, through vertical integration across production, bunkering, and certification, large players not only safeguard fuel availability, but also mitigate market volatility by securing early access to competitively priced green methanol.

However, while these efforts accelerate scale-up and infrastructure readiness, such integration also raises concerns about equity and market concentration. Unlike the current maritime fossil fuel market, where prices are set globally and no single shipping company has direct control, the emerging green methanol market is more fragmented and capital-intensive. If major carriers achieve scale and dominate production capacity for maritime use, they could secure preferential contracts, dominate supply chains, and obtain significant price-setting power. This could allow them to use green methanol at competitive costs internally while charging a premium to smaller carriers, who would otherwise face even higher compliance costs if they failed to adopt low-carbon fuels, especially considering the limit supply of biodiesels and bioLNG.

These dynamic risks the emergence of a "two-tier shipping market," in which early movers enjoy cost-effective access to green fuels while smaller operators face higher costs or limited availability. Accordingly, the International Transport Forum (ITF) (2023) warns that early adopters with purchasing power can shape fuel supply chains in ways that disadvantage latecomers. Similarly, Transport & Environment (2024) notes that the concentration of green fuel contracts by a few large carriers' risks creating an uneven playing field, where small carriers cannot access affordable alternative fuels. Also, BCG (2025) further emphasizes that first movers are likely to lock in economies of scale and preferential supplier contracts, reinforcing competitive asymmetries.

From a policy perspective, this raises the question of how to balance efficiency gains from rapid scale-up with the risks of inequitable access. Potential solutions include joint procurement platforms, transparent certification and price benchmarks, and targeted subsidies for smaller operators especially in developing countries. Without such safeguards, the IMO Net-Zero Framework could unintentionally consolidate market power among a few dominant carriers. Yet, it must also be acknowledged that large-scale investments by leading carriers are essential for accelerating fuel development and infrastructure deployment. Therefore, balancing the benefits of rapid scale-up against the risks of inequitable access to green fuels will be critical challenge for regulators and industry stakeholders.

5.2 High shipping costs

The adoption of green fuels and the enforcement of emission reduction regulations will inevitably raise shipping costs. As shown in this study, even the lowest-cost biodiesel pathway, when combined with compliance obligations, reaches approximately USD 800 per tonne in 2040, nearly double the current HFO price. Given that fuel represents the largest share of operating expenses, these increases are likely to be transferred to shippers through surcharges.

This trend is already visible under the EU ETS. Since its introduction in 2024, major carriers such as Maersk have implemented quarterly-adjusted surcharges (EMS/ESS) to reflect carbon prices (Rajan, 2023). Moreover, passing compliance costs through surcharges is generally easier than charging for efficiency upgrades (Flodén et al., 2024). At the same time, carriers are experimenting with incentive schemes: Maersk's "ECO Delivery" exempts customers from ETS surcharges if they select low-GHG fuels through a mass-balance approach (Maersk, 2025), while Hapag-Lloyd's "Ship Green" offers biofuel packages that proportionally reduce ETS costs (Hapag-Lloyd, 2025). However, these schemes can help the shipping companies transit to green fuels with less emissions, but it also brings up the freight costs.

Nevertheless, customer willingness to pay for the green service remains limited. A BCG (2024) survey found that although more than 80% of shippers report being willing to pay for greener transport, the actual premium they accept averages only around 4%. In contrast, achieving full decarbonization would require a premium of 10% to 15%, and in the short term, premiums of 30% to 40% may be necessary to scale up alternative fuel production. Furthermore, based on our modelling, when fuel costs are combined with regulatory compliance costs, the effective premium can approach near 100% to meet regulatory requirements with the most optimal option. Inevitably, these premiums will be passed on to import prices and ultimately to consumers through higher inflation.

Moreover, as shown by the OECD (2021), a 50% increase in shipping costs within a single quarter raises quarter-on-quarter import price inflation by about 2.5 percentage points, and after one year import price inflation remains roughly 2.0 percentage points higher. Although the pass-through to consumer prices is limited as less than 1% after a year, its effect fades gradually, indicating long adjustment dynamics.

Looking ahead, cost increases under the IMO Net-Zero Framework are unlikely to be one-off shocks. If the framework is formally adopted in October 2025 and implemented from 2028, the global fuel-intensity standard will tighten progressively and be paired with a pricing mechanism, thereby driving up compliance costs as targets become more stringent. Without a rapid scale-up in the supply of alternative fuels to bring down the fuel cost, structurally higher shipping costs and sustained upward pressure on inflation are likely to persist. Moreover, according to the IMF (2022) and OECD (2025), this impact will be more pronounced in countries with high reliance on seaborne trade, particularly small island states and developing economies, which tend to experience larger pass-through effects.

Taken together, these findings suggest that the transition to green shipping will be more likely to result in structurally higher freight costs as standards tighten and alternative fuels remain scarce. Thus, in the absence of compensation mechanisms for green fuel adoption or measures to expand supply and lower fuel prices, the resulting costs could erode trade competitiveness and impose persistent upward pressure on consumer prices.

Furthermore, the political dimension further complicates this picture. The U.S. government has already criticized the IMO Net-Zero Framework as a "global carbon tax" with potentially regressive effects (U.S. Department of State, 2025). Such opposition from the world's largest economy and importer underlines the regulatory uncertainty surrounding the framework's adoption and long-term credibility.

5.3 Regulatory uncertainty

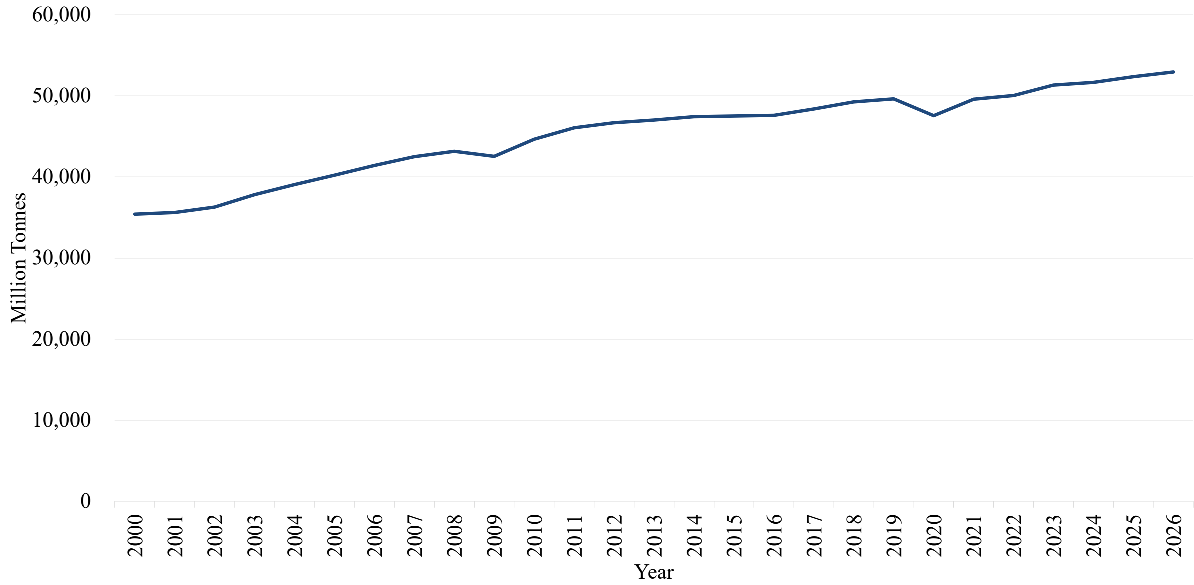
Moreover, the United States has warned that, if the IMO Net-Zero Framework is adopted, it may retaliate through trade measures (U.S. Department of State, 2025). Such opposition poses a significant threat to the framework's long-term credibility, particularly for countries economically dependent on the United States (Bush, 2025). Thus, a third critical uncertainty lies in the regulatory environment.

However, U.S. opposition should also be weighed against a strong coalition of supporters, including the EU, China, and small island developing States (SIDS), all of which have strategic incentives to see the framework succeed. The EU seeks to align global measures with its own regional initiatives such as FuelEU Maritime, while China has positioned itself as a leader in green shipbuilding and fuel production. Pacific island states, highly vulnerable to climate change, have consistently lobbied for ambitious IMO action. This broad base of support reduces the likelihood that U.S. resistance alone will disrupt the framework, though it does add to short-term uncertainty.

Conversely, if the framework is not approved in October 2025, the lack of a global mechanism could hinder the maritime green transition and force the industry to operate within a fragmented system of regional schemes and overlapping requirements. This would escalate compliance uncertainty and heighten risks for both investment and trade competitiveness.

Moreover, the urgency of a global mechanism is underscored by current emission trends. As shown in Figure 27, global shipping GHG emissions remain on an upward trajectory and are projected to rise further in 2026 (Clarksons, 2025). Although the IMO Net-Zero Framework outlines a progressive pathway, its delayed entry has already fallen short of earlier IMO commitments (Luman, 2025), increasing the risk of missing the Paris Agreement's 1.5°C goal. Without strong global incentives, shipowners have little motivation to adopt low-carbon fuels, which in turn depresses investment in production capacity, creating a vicious cycle of underinvestment and delayed decarbonization.

Figure 27. Annual Global GHG Emissions (CO_2e)



Source: Clarksons (2025)

Furthermore, in the absence of a global scheme, regional regulations are likely to increase. FuelEU Maritime already sets binding intensity targets, and similar frameworks are being considered in other major economies, including China (Lurkin, 2025). Such regionalization risks carbon leakage that vessels may detour around regulated areas or adjust speed to minimize compliance costs, ultimately increasing fuel consumption and emissions. Given the central role of EU and Chinese ports in global trade, carriers will have to comply with their standards, creating overlapping reporting systems and escalating costs. Smaller or developing countries, by contrast, often lack the leverage to enforce strict penalties, leaving them unable to reinvest in decarbonization infrastructure.

More critically, this fragmentation risks entrenching inequalities between advanced and developing economies. Revenues from compliance instruments in advanced economies are typically reinvested into port electrification, alternative fuel infrastructure, and subsidies, reinforcing their competitive advantage. However, developing countries would face higher compliance costs without comparable revenues to support transition efforts. UNCTAD (2023) warns that this imbalance undermines the principle of a "just and equitable transition." The result is a two-speed decarbonization process that advanced economies benefit from scale and capital access, while many developing countries remain constrained by high borrowing costs or mounting debt crises, leaving them unable to keep up (Stiell, 2024). Such asymmetries not only slow global progress toward net-zero shipping but also risk destabilizing supply chains and amplifying climate-related disruptions.

Alternatively, the global framework could mitigate these risks by providing incentives and generating revenues for redistribution to accelerate decarbonization and assist developing countries to encounter higher maritime logistics costs (UNCTAD, 2023).

Notably, the IMO Net-Zero Fund, established as part of the framework, is designed to channel resources into research, infrastructure, and just transition support, especially in developing countries (IMO, 2025). Yet its financing model remains uncertain. Transport & Environment (2025) estimates that most contributions will come from Tier 1 RUs, priced at USD 100 per tonne of CO_2e, far below the USD 380 per tonne of CO_2e cost of Tier 2 RUs. This could limit the Fund's revenues and undermine its adequacy beyond 2030. While raising Tier 1 prices would increase revenues, it also raises shipowners' costs, illustrating the trade-off between financial sufficiency and industry burden.

This highlights the need for complementary public financing mechanisms. The World Bank (2023) argues that revenues from carbon markets should be reinvested into maritime decarbonization to bridge cost gaps, support infrastructure, and accelerate the uptake of low- and zero-carbon fuels. It further emphasizes that such revenues must be distributed equitably and transparently, ensuring that all countries, including those without significant shipping industries or ports, can benefit from the energy transition (World Bank, 2023). The ITF (2019) similarly stresses the importance of targeted support to prevent disproportionate impacts on developing economies and smaller operators.

Furthermore, the aviation industry offers a valuable precedent. Governments have introduced measures to reduce the cost gap for sustainable aviation fuels (SAFs), such as ReFuelEU Aviation, the U.S. SAF tax credit, and ICAO's CORSIA scheme (European Commission, 2025; IRS, 2025; ICAO, 2025). The EU, for instance, combines direct financial support with regulatory incentives to stimulate SAF adoption. De-risking mechanisms are provided through Horizon Europe, the Innovation Fund, and InvestEU, alongside state aid for SAF production. To narrow the price differential with fossil fuels, airlines benefit from SAF allowances under the ETS and preferential taxation (European Commission, 2025). In parallel, regulatory instruments such as the EU SAF Clearing House and the Net Zero Industry Act facilitate approval of new fuel pathways and infrastructure, while the EU taxonomy and environmental labelling schemes improve transparency and access to private investment. Together, these measures have fostered a supportive ecosystem that reduces costs, stimulates supply, and builds long-term confidence in SAF markets, which can be a good example for the maritime industry to accelerate the scale-up of green fuels.

However, shipping's green transition is more complex than aviation's. While aviation converges largely on SAFs, maritime decarbonization lacks a one-size-fits-all solution that different vessel types and trade routes may require different fuels. This diversity makes the transition more investment-intensive and highlights the need for diversified funding streams to support experimentation and scale-up across several pathways. At the same time, the aviation experience illustrates the risks of inequitable distribution. Airlines in fiscally stronger regions have already secured early advantages, and a similar dynamic could emerge in shipping if the IMO Fund disproportionately benefits developed economies or China. While such measures would accelerate fuel scale-up, they could also consolidate control over production and infrastructure, leaving smaller economies with limited and costly access to alternative fuels.

These risks highlight the importance of designing the IMO Net-Zero Fund's governance and revenue distribution to promote equitable participation. Ideally, the Fund should operate as a transparent platform for collective investment, avoiding fragmented or duplicative national schemes and reducing the risk of inefficient competition. In this way, the transition can be both accelerated and made more inclusive, ensuring that developing countries and smaller operators are not left behind.

Ultimately, the effectiveness of the IMO Net-Zero Fund will depend not only on the scale of resources mobilized but also on how transparently and fairly they are distributed. While the transition to low-carbon shipping will increase costs, these burdens should not fall disproportionately on consumers, smaller operators, or developing nations. Ensuring fairness requires a coordinated approach that governments and international institutions must provide financial and policy support for infrastructure and innovation, while industry commits to transparent cost-sharing and inclusive fuel access. Only through such collective governance can maritime decarbonization achieve both environmental ambition and global equity.

For this reason, concerns raised by the U.S. and other opponents cannot be dismissed. The distributive outcome will ultimately depend on how the IMO Net-Zero Fund is designed and implemented, which remains uncertain. This leaves open the possibility of either reinforcing existing asymmetries or creating a genuinely equitable transition mechanism. Yet, in a broader context, the establishment of a global framework with revenue redistribution represents a critical step toward aligning shipping with climate goals. While the distributional impacts will only become clear once governance is finalized, the direction of travel is unmistakable that a global mechanism, if effectively implemented, will deliver deeper and more equitable decarbonization than fragmented regional schemes.

5.4 Final consideration

This discussion answers Sub-question 4 and shows that compliance under the IMO Net-Zero Framework is shaped by three interlinked risks: limited fuel availability, rising shipping costs, and regulatory uncertainty.

For shipping companies, although biodiesel and bioLNG remain the most cost-effective near-term options for the existing fleet, their scalability is limited by feedstock competition and cross-sector demand. In contrast, green methanol offers stronger long-term scalability through diverse production pathways, and if its price drops toward fossil methanol, methanol vessels and retrofits could become highly competitive. Accordingly, companies should secure scarce biofuels supplies for existing vessels, adopt dynamic blending schedules to minimize compliance costs, leverage pooling and surplus units to buffer regulatory fluctuations, and time capital-intensive retrofits, such as methanol conversions, around clear regulatory milestones and credible price trajectories. Particularly, for small vessel operators, they may need to collaborate and build their own pool to share compliance surpluses, mitigate exposure to high penalties, and reduce individual cost burdens.

For governments and international institutions, establishing a global framework through collaboration is essential to achieving climate goals and avoiding fragmented regional schemes with overlapping compliance requirements. In the absence of such alignment, decarbonization would be delayed and impose greater costs and uncertainties on maritime stakeholders. However, action is needed to reduce regulatory uncertainty and safeguard equitable access to green fuels. Unresolved elements of the regime, such as future RU pricing, alignment with FuelEU, and the governance and revenue adequacy of the IMO Net-Zero Fund, complicate investment timing and risk creating a two-tier market that disadvantages smaller operators. Policy clarity and coordination are therefore essential, including transparent and predictable compliance pricing, harmonized certification and accounting rules, and equitable governance of the Net-Zero Fund. At the same time, joint procurement platforms, coordinated infrastructure investment, and targeted subsidies for developing countries, can help avoid market concentration while enabling broad participation. Yet, regulators must also recognize that large-scale investments by major carriers are indispensable for scaling fuel supply and infrastructure. Balancing the efficiency gains from rapid scale-up with the risks of inequitable access will thus be a critical challenge for the IMO and other international institutions.

Ultimately, the credibility of the IMO Net-Zero Framework will rest on its ability to balance efficiency with equity. A global mechanism that accelerates fuel scale-up while distributing costs and benefits fairly offers the best prospect of aligning shipping with climate goals. Without such balance, the transition risks consolidating market power and leaving smaller operators and vulnerable economies behind.

Chapter 6 Conclusion

This thesis set out to answer the research question: "**How can a representative containership fleet be optimized to comply with the upcoming IMO Net-Zero Framework in a cost-effective manner?**" To address this, the study examined an existing 13-vessel containership fleet on the Far East–Europe route, applying scenario-based techno-economic modelling combined with a detailed review of regulatory requirements and potential alternative fuel choices. Five compliance strategies were assessed, allowing for a systematic comparison of different alternative fuels, retrofitting options, and regulatory mechanisms. The results provide new insights into optimal compliance strategies under the IMO Net-Zero Framework and yield practical implications for both shipowners and policymakers.

6.1 Key findings

First, the IMO Net-Zero Framework is structurally more stringent and globally harmonized than the EU ETS and FuelEU Maritime. By adopting a well-to-wake perspective and linking fuel GHG intensity with emission pricing, it provides a stronger long-term incentive for fuel substitution and fleet adaptation. Its global scope also reduces the risk of fragmented regional schemes that would otherwise increase compliance uncertainty and distort trade competitiveness.

Second, among the alternative fuels available for existing containerships, biodiesel, LNG, and methanol are the most relevant due to technical feasibility and regulatory alignment. However, fuel strategies must remain dynamic. Fuel price trajectories and progressively tightening GHG intensity requirements are decisive in determining the optimal pathway, with strategies evolving over time rather than remaining static.

Third, the results show that drop-in biodiesel and bioLNG consistently emerge as the most cost-effective compliance pathways. For HFO vessels, 100% biodiesel adoption in the early years generates surplus units that offset high biofuel costs. However, as regulatory stringency rises and surplus units diminish, a lower blend becomes preferable, before gradually increasing again to avoid costly Tier 2 RUs. For LNG vessels, fossil LNG supplemented by Tier 1 RUs remains optimal until it cannot achieve the Base Compliance Target, after which bioLNG becomes more economical than reliance on Tier 2 RUs. However, limited biofuel supply and strong cross-sectoral competition constrain biofuel scalability, suggesting that biodiesel and bioLNG are better viewed as transitional fuels. By contrast, methanol is currently uneconomical due to its low energy density, high fuel consumption, and modest GHG performance at low blends. Yet sensitivity analysis shows that methanol's competitiveness is highly price-dependent: if green methanol, particularly e-methanol, reaches large-scale production and prices converge with fossil methanol, retrofitting and adopting methanol vessels could become a feasible long-term option.

Fourth, unresolved design elements in the IMO Net-Zero Framework and rising costs create significant transition risks. The future trajectory of RU/SU pricing, methodologies for ZNZ fuels, and the governance of the Net-Zero Fund remain unclear, generating regulatory uncertainty that complicates long-term investment. At the same time, green fuel pathways are projected to more than double fuel-related operating expenditure by 2040, with carriers already passing costs to shippers whose willingness to pay remains limited. To mitigate these risks, transparent platform, coordinated infrastructure investment, and fair use of Net-Zero Fund revenues are essential to accelerate fuel scale-up while ensuring an equitable transition for smaller operators and vulnerable economies.

6.2 Limitations

This study has several limitations. First, it models a single representative fleet as a fixed pool, thereby overlooking more flexible pooling structures and fleet renewal strategies that could yield lower compliance costs. Second, fuel consumption and emissions are estimated using average coefficients, which neglect variation in hull condition, load factors, weather, and routing, potentially leading to deviations from real-world performance, as detailed vessel-level operational data were not available. Third, fuel specifications and well-to-wake emission factors are treated as fixed values, even though differences in feedstock, production pathways, and methane slip could substantially alter the relative cost-effectiveness of compliance options, as detailed empirical data on specific fuel and supply chains were not available. Fourth, baseline assumptions of stable fuel and compliance prices understate the risks posed by price volatility, regional price differentials, and sudden regulatory changes, although sensitivity analyses partly mitigate this concern. Fifth, maintenance, depreciation, and other operating expenditures are simplified, reducing the precision of total cost estimates. Finally, the policy environment is modelled sequentially, whereas in practice overlap between the IMO Net-Zero Framework and FuelEU Maritime could reshape compliance incentives, pooling behavior, and investment timing.

6.3 Suggestions

For shipping companies, the findings highlight the value of a dynamic compliance strategy. In the near term, securing limited biofuel supplies, adopting flexible blending schedules, and pooling across suitable vessels can generate surplus units and reduce compliance costs. As surplus availability declines, operators should shift to lower biofuel blends before gradually increasing them again once stricter regulations make direct compliance unavoidable. Capital-intensive conversions, such as methanol retrofits, should be timed carefully against clear regulatory milestones and credible price signals. For smaller operators, collaborative pooling offers an important means to share surplus units, buffer regulatory volatility, and lower compliance costs.

For policymakers, reducing regime uncertainty and enhancing transparency are essential. Clear forward guidance on compliance price trajectories beyond 2030, alignment of certification and accounting rules with FuelEU, and transparent governance of the IMO Net-Zero Fund would reduce investment risks and accelerate deployment of low-carbon fuels. To prevent scarce green fuels from being captured primarily by large players, policies that broaden access, such as joint procurement mechanisms, targeted support for small operators and developing-country fleets, and credible certification and traceability, are needed to ensure a fair and inclusive transition.

For future research, three directions stand out. First, exploring alternative pooling structures could reveal more cost-efficient compliance strategies. Second, incorporating real-world operational data, detailed operating expenditures, and refined fuel specifications would improve the accuracy of cost and emissions estimates. Third, developing models that incorporate dynamic fuel and compliance price forecasts, and analyzing the overlapping implementation of FuelEU, the EU ETS, and the IMO Net-Zero Framework, would better capture real-world risks and provide a more realistic view of policy interactions.

Looking ahead, the adoption of the IMO Net-Zero Framework marks a decisive shift for global shipping, yet unresolved design elements and limited fuel availability leave the industry at a crossroads. As major carriers move ahead with large-scale green fuel investments, questions of equity, cost distribution, and the role of the IMO Net-Zero Fund become increasingly urgent. The insights from this thesis contribute to today's debate on how shipping can balance cost-effectiveness with fairness, and the choices made in the coming years will determine whether decarbonization leads to an inclusive transition or a fragmented, two-tier market.

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Appendices

Appendix A: Annual Fuel Consumption by Vessel Type and Biodiesel Proportion

Appendix A1: Group 1 HFO vessel

Ship Fuel Type	Group 1 (HFO)	Group 1 (BioDiesel-B30)	Group 1 (BioDiesel-B50)	Group 1 (BioDiesel-B70)	Group 1 (BioDiesel-B100)
Fuel Consumption Rate (kg / nm)	325	-	-	-	-
Alternative Fuel 1 (Green) Proportion (%)	-	30%	50%	75%	100%
Alternative Fuel 2 (Grey) Proportion (%)	-	70%	50%	25%	0%
Pilot Fuel Proportion (%)	-	-	-	-	-
Total Proportion (%)	100%				
Annual Main Fuel 1 (Green) Consumption (t)	-	9,322	15,537	23,305	31,073
Annual Main Fuel 2 (Grey) Consumption (t)	28,542	19,979	14,271	7,135	0
Annual Pilot Fuel Consumption (t)	-	-	-	-	-
Annual Energy Content (MJ)	1,155,930,750				

Appendix A2: Group 2 HFO vessel

Ship Fuel Type	Group 2 (HFO)	Group 2 (BioDiesel-B30)	Group 2 (BioDiesel-B50)	Group 2 (BioDiesel-B75)	Group 2 (BioDiesel-B100)
Fuel Consumption Rate (kg / nm)	310	-	-	-	-
Alternative Fuel 1 (Green) Proportion (%)	-	30%	50%	75%	100%
Alternative Fuel 2 (Grey) Proportion (%)	-	70%	50%	25%	0%
Pilot Fuel Proportion (%)	-	-	-	-	-
Total Proportion (%)	100%				
Annual Main Fuel 1 (Green) Consumption (t)	-	8,892	14,820	22,229	29,639
Annual Main Fuel 2 (Grey) Consumption (t)	27,224	19,057	13,612	6,806	0
Annual Pilot Fuel Consumption (t)	-	-	-	-	-
Annual Energy Content (MJ)	1,102,580,100				

Appendix A3: Group 3 LNG dual-fuel vessel

Ship Fuel Type	Group 3 (LNG-Fossil)	Group 3 (BioLNG-30%)	Group 3 (BioLNG-50%)	Group 3 (BioLNG-75%)	Group 3 (BioLNG-95%)
Fuel Consumption Rate (kg/nm)	270	-	-		-
Alternative Fuel 1 (Green) Proportion (%)	-	30%	50%	75%	95%
Alternative Fuel 2 (Grey) Proportion (%)	95%	65%	45%	20%	0%
Pilot Fuel Proportion (%)	5%	5%	5%	5%	5%
Total Proportion (%)	100%				
Annual Main Fuel 1 (Green) Consumption (mt)	-	7,051	11,752	17,628	22,329
Annual Main Fuel 2 (Grey) Consumption (mt)	22,526	15,277	10,577	4,701	-
Annual Pilot Fuel Consumption (mt)	1,186	1,425	1,425	1,425	1,425
Annual Energy Content (MJ)	1,154,033,838				

Appendix A4: Group 3 Methanol dual-fuel vessel

Ship Fuel Type	Group 3 (Methanol - Fossil)	Group 3 (BioMethanol -30%)	Group 3 (BioMethanol -50%)	Group 3 (BioMethanol -75%)	Group 3 (BioMethanol -95%)
Fuel Consumption Rate (kg / nm)	-	-	-	-	-
Alternative Fuel 1 (Green) Proportion (%)	-	30%	50%	75%	95%
Alternative Fuel 2 (Grey) Proportion (%)	95%	65%	45%	20%	0%
Pilot Fuel Proportion (%)	5%	5%	5%	5%	5%
Total Proportion (%)	100%				
Annual Main Fuel 1 (Green) Consumption (mt)	-	17,397	28,996	43,494	55,092
Annual Main Fuel 2 (Grey) Consumption (mt)	55,092	37,695	26,096	11,598	-
Annual Pilot Fuel Consumption (mt)	1,425	1,425	1,425	1,425	1,425
Annual Energy Content (MJ)	1,154,033,838				

Appendix B: Annual GHG Emission Gaps and Surpluses of Different Fuels under FuelEU Maritime and IMO Net-Zero Framework

Appendix B1: GHG Gaps and Surpluses for HFO (gCO_2e/MJ)

Fuel Type	HFO			BioDiesel-B30		
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct
2025	2.40	-	-	0.00	-	20.26
2026	6.05	-	-	0.00	-	16.61
2027	6.05	-	-	0.00	-	16.61
2028	2.18	12.13	0.00	0.00	0.00	8.36
2029	4.04	12.13	0.00	0.00	0.00	6.49
2030	5.91	12.13	0.00	0.00	0.00	4.63
2031	10.01	12.13	0.00	0.00	0.00	0.52
2032	14.12	12.13	0.00	0.00	3.58	0.00
2033	18.22	12.13	0.00	0.00	7.69	0.00
2034	22.33	12.13	0.00	0.00	11.79	0.00
2035	26.43	12.13	0.00	3.77	12.13	0.00
2036	32.96	12.50	0.00	10.30	12.50	0.00
2037	39.49	12.88	0.00	16.83	12.88	0.00
2038	46.02	13.25	0.00	23.36	13.25	0.00
2039	52.55	13.63	0.00	29.89	13.63	0.00
2040	59.09	14.00	0.00	36.43	14.00	0.00
Fuel Type	BioDiesel-B50			BioDiesel-B75		

Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct
2025	0.00	-	35.37	0.00	-	54.25
2026	0.00	-	31.72	0.00	-	50.60
2027	0.00	-	31.72	0.00	-	50.60
2028	0.00	0.00	23.47	0.00	0.00	42.35
2029	0.00	0.00	21.60	0.00	0.00	40.49
2030	0.00	0.00	19.73	0.00	0.00	38.62
2031	0.00	0.00	15.63	0.00	0.00	34.52
2032	0.00	0.00	11.52	0.00	0.00	30.41
2033	0.00	0.00	7.42	0.00	0.00	26.31
2034	0.00	0.00	3.31	0.00	0.00	22.20
2035	0.00	0.79	0.00	0.00	0.00	18.09
2036	0.00	7.69	0.00	0.00	0.00	11.19
2037	1.72	12.88	0.00	0.00	0.00	4.28
2038	8.25	13.25	0.00	0.00	2.62	0.00
2039	14.78	13.63	0.00	0.00	9.53	0.00
2040	21.32	14.00	0.00	2.43	14.00	0.00
Fuel Type	BioDiesel-B100					
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct			
2025	0.00	-	73.14			
2026	0.00	-	69.49			

2027	0.00	-	69.49			
2028	0.00	0.00	61.24			
2029	0.00	0.00	59.37			
2030	0.00	0.00	57.51			
2031	0.00	0.00	53.40			
2032	0.00	0.00	49.30			
2033	0.00	0.00	45.19			
2034	0.00	0.00	41.09			
2035	0.00	0.00	36.98			
2036	0.00	0.00	30.08			
2037	0.00	0.00	23.17			
2038	0.00	0.00	16.27			
2039	0.00	0.00	9.36			
2040	0.00	0.00	2.46			

Appendix B2: GHG Gaps and Surpluses for LNG (gCO_2e/MJ)

Fuel Type	LNG - Fossil			BioLNG-30%		
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct
2025	0.00	-	13.46	0.00	-	31.27
2026	0.00	-	9.81	0.00	-	27.62
2027	0.00	-	9.81	0.00	-	27.62
2028	0.00	0.00	1.56	0.00	0.00	19.37
2029	0.00	0.31	0.00	0.00	0.00	17.51

2030	0.00	2.17	0.00	0.00	0.00	15.64
2031	0.00	6.28	0.00	0.00	0.00	11.54
2032	0.00	10.38	0.00	0.00	0.00	7.43
2033	2.36	12.13	0.00	0.00	0.00	3.33
2034	6.46	12.13	0.00	0.00	0.78	0.00
2035	10.57	12.13	0.00	0.00	4.89	0.00
2036	17.10	12.50	0.00	0.00	11.79	0.00
2037	23.63	12.88	0.00	5.82	12.88	0.00
2038	30.16	13.25	0.00	12.35	13.25	0.00
2039	36.69	13.63	0.00	18.88	13.63	0.00
2040	43.22	14.00	0.00	25.41	14.00	0.00
Fuel Type	BioLNG-50%			BioLNG-75%		
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct
2025	0.00	-	43.15	0.00	-	57.99
2026	0.00	-	39.50	0.00	-	54.34
2027	0.00	-	39.50	0.00	-	54.34
2028	0.00	0.00	31.25	0.00	0.00	46.09
2029	0.00	0.00	29.38	0.00	0.00	44.23
2030	0.00	0.00	27.52	0.00	0.00	42.36
2031	0.00	0.00	23.41	0.00	0.00	38.26
2032	0.00	0.00	19.31	0.00	0.00	34.15
2033	0.00	0.00	15.20	0.00	0.00	30.05

2034	0.00	0.00	11.10	0.00	0.00	25.94
2035	0.00	0.00	6.99	0.00	0.00	21.84
2036	0.00	0.00	0.09	0.00	0.00	14.93
2037	0.00	6.82	0.00	0.00	0.00	8.02
2038	0.47	13.25	0.00	0.00	0.00	1.12
2039	7.00	13.63	0.00	0.00	5.79	0.00
2040	13.54	14.00	0.00	0.00	12.69	0.00
Fuel Type	BioLNG-95%					
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct			
2025	0.00	-	69.87			
2026	0.00	-	66.22			
2027	0.00	-	66.22			
2028	0.00	0.00	57.97			
2029	0.00	0.00	56.10			
2030	0.00	0.00	54.24			
2031	0.00	0.00	50.13			
2032	0.00	0.00	46.03			
2033	0.00	0.00	41.92			
2034	0.00	0.00	37.82			
2035	0.00	0.00	33.71			
2036	0.00	0.00	26.81			
2037	0.00	0.00	19.90			

2038	0.00	0.00	13.00			
2039	0.00	0.00	6.09			
2040	0.00	0.81	0.00			

Appendix B3: GHG Gaps and Surpluses for Methanol (gCO_2e/MJ)

Fuel Type	Methanol - Fossil			BioMethanol-30%		
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct
2025	12.97	-	0.00	0.00	-	14.02
2026	16.62	-	0.00	0.00	-	10.37
2027	16.62	-	0.00	0.00	-	10.37
2028	12.75	12.13	0.00	0.00	0.00	2.12
2029	14.61	12.13	0.00	0.00	0.00	0.25
2030	16.48	12.13	0.00	0.00	1.62	0.00
2031	20.58	12.13	0.00	0.00	5.72	0.00
2032	24.69	12.13	0.00	0.00	9.83	0.00
2033	28.79	12.13	0.00	1.80	12.13	0.00
2034	32.90	12.13	0.00	5.91	12.13	0.00
2035	37.00	12.13	0.00	10.01	12.13	0.00
2036	43.53	12.50	0.00	16.54	12.50	0.00
2037	50.06	12.88	0.00	23.07	12.88	0.00
2038	56.59	13.25	0.00	29.60	13.25	0.00
2039	63.12	13.63	0.00	36.13	13.63	0.00
2040	69.66	14.00	0.00	42.67	14.00	0.00

Fuel Type	BioMethanol-50%			BioMethanol-75%		
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct
2025	0.00	-	32.01	0.00	-	54.50
2026	0.00	-	28.36	0.00	-	50.85
2027	0.00	-	28.36	0.00	-	50.85
2028	0.00	0.00	20.11	0.00	0.00	42.60
2029	0.00	0.00	18.24	0.00	0.00	40.74
2030	0.00	0.00	16.38	0.00	0.00	38.87
2031	0.00	0.00	12.27	0.00	0.00	34.77
2032	0.00	0.00	8.17	0.00	0.00	30.66
2033	0.00	0.00	4.06	0.00	0.00	26.56
2034	0.00	0.04	0.00	0.00	0.00	22.45
2035	0.00	4.15	0.00	0.00	0.00	18.34
2036	0.00	11.05	0.00	0.00	0.00	11.44
2037	5.08	12.88	0.00	0.00	0.00	4.53
2038	11.61	13.25	0.00	0.00	2.37	0.00
2039	18.14	13.63	0.00	0.00	9.28	0.00
2040	24.67	14.00	0.00	2.18	14.00	0.00
Fuel Type	BioMethanol-95%					
Year	Gap between Attached GHG and Base	Gap between Attached GHG and Direct	Surplus GHG from Direct			
2025	0.00	-	72.50			

2026	0.00	-	68.85			
2027	0.00	-	68.85			
2028	0.00	0.00	60.60			
2029	0.00	0.00	58.73			
2030	0.00	0.00	56.86			
2031	0.00	0.00	52.76			
2032	0.00	0.00	48.65			
2033	0.00	0.00	44.55			
2034	0.00	0.00	40.44			
2035	0.00	0.00	36.34			
2036	0.00	0.00	29.44			
2037	0.00	0.00	22.53			
2038	0.00	0.00	15.63			
2039	0.00	0.00	8.72			
2040	0.00	0.00	1.82			

Appendix C: Projected Fuel Prices

Appendix C1: Constant Price Scenario (2025–2040) (USD/tonne)

Year	HFO	BioDiesel	Fossil LNG	BioLNG	Fossil Methanol	Bio Methanol
2025	410	1,100	720	1,650	330	985
2026	410	1,100	720	1,650	330	985
2027	410	1,100	720	1,650	330	985
2028	410	1,100	720	1,650	330	985
2029	410	1,100	720	1,650	330	985
2030	410	1,100	720	1,650	330	985
2031	410	1,100	720	1,650	330	985
2032	410	1,100	720	1,650	330	985
2033	410	1,100	720	1,650	330	985
2034	410	1,100	720	1,650	330	985
2035	410	1,100	720	1,650	330	985
2036	410	1,100	720	1,650	330	985
2037	410	1,100	720	1,650	330	985
2038	410	1,100	720	1,650	330	985
2039	410	1,100	720	1,650	330	985
2040	410	1,100	720	1,650	330	985

Appendix C2: Declining Price Scenario (2025–2040) (USD/tonne)

Year	HFO	BioDiesel	Fossil LNG	BioLNG	Fossil Methanol	Bio Methanol
2025	410	1,100	720	1,650	330	985
2026	405	1,089	710	1,634	326	975
2027	399	1,078	701	1,617	321	965
2028	394	1,067	691	1,601	317	955
2029	388	1,056	682	1,584	312	946
2030	383	1,045	672	1,568	308	936
2031	377	1,034	662	1,551	304	926
2032	372	1,023	653	1,535	299	916
2033	366	1,012	643	1,518	295	906
2034	361	1,001	634	1,502	290	896
2035	355	990	624	1,485	286	887
2036	350	979	614	1,469	282	877
2037	344	968	605	1,452	277	867
2038	339	957	595	1,436	273	857
2039	333	946	586	1,419	268	847
2040	328	935	576	1,403	264	837
Assumed Total Price Reduction by 2040 (%)	-20%	-15%	-20%	-15%	-20%	-15%

Appendix C3: Increasing Price Scenario (2025–2040) (USD/tonne)

Year	HFO	BioDiesel	Fossil LNG	BioLNG	Fossil Methanol	Bio Methanol
2025	410	1,100	720	1,650	330	985
2026	415	1,118	730	1,678	334	1,001
2027	421	1,137	739	1,705	339	1,018
2028	426	1,155	749	1,733	343	1,034
2029	432	1,173	758	1,760	348	1,051
2030	437	1,192	768	1,788	352	1,067
2031	443	1,210	778	1,815	356	1,084
2032	448	1,228	787	1,843	361	1,100
2033	454	1,247	797	1,870	365	1,116
2034	459	1,265	806	1,898	370	1,133
2035	465	1,283	816	1,925	374	1,149
2036	470	1,302	826	1,953	378	1,166
2037	476	1,320	835	1,980	383	1,182
2038	481	1,338	845	2,008	387	1,198
2039	487	1,357	854	2,035	392	1,215
2040	492	1,375	864	2,063	396	1,231
Assumed Total Price Increase by 2040 (%)	20%	25%	20%	25%	20%	25%

Appendix D: Projected IMO Net-Zero Framework Remedial and Surplus Unit Prices

Appendix D1: Constant Price Scenario (2025–2040) (USD/tonne)

Year	RU 1	RU 2	SU Sell Price
2028-2030	100	380	312
2031-2033	100	380	312
2034-2036	100	380	312
2037-2039	100	380	312
2040	100	380	312

Appendix D2: Escalation Scenario – 10% (2025–2040) (USD/tonne)

Year	RU 1	RU 2	SU Sell Price
2028-2030	100	380	312
2031-2033	105	418	328
2034-2036	110	460	344
2037-2039	116	506	361
2040	122	556	379

Note: Tier 2 RUs increase 10% and Tier 1 RUs & SUs increase 5% every 3 years

Appendix D3: Escalation Scenario – 15% (2025–2040) (USD/tonne)

Year	RU 1	RU 2	SU Sell Price
2028-2030	100	380	312
2031-2033	108	437	335
2034-2036	116	503	361
2037-2039	124	578	388
2040	134	665	417

Note: Tier 2 RUs increase 15% and Tier 1 RUs & SUs increase 7.5% every 3 years

Appendix D4: Declining Price Scenario (2025–2040) (USD/ton)

Year	RU 1	RU 2	SU Sell Price
2028-2030	100	380	312
2031-2033	110	456	343
2034-2036	121	547	378
2037-2039	133	657	415
2040	146	788	457

Note: Tier 2 RUs increase 20% and Tier 1 RUs & SUs increase 10% every 3 years