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Report

IMO Net-Zero Framework:

Fuel Cost and Carbon Price Impacts

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Fuel Cost and Carbon Price Impacts

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Solutions for Our Climate (SFOC) is an independent nonprofit organization that works to accelerate global greenhouse gas emissions reduction and energy transition. SFOC leverages research, litigation, community organizing, and strategic communications to deliver practical climate solutions and build movements for change.

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Executive Summary

In April 2025, the International Maritime Organization (IMO) approved mid-term measures to reduce greenhouse gas (GHG) emissions from the shipping sector, marking a major turning point in the path toward net-zero in international shipping. Going beyond energy efficiency-focused regulations, the newly introduced "Net-Zero Framework" emphasizes total emission reductions with new price mechanisms.

This report examines the impact of the Net-Zero Framework on shipping companies' fuel consumption, operational strategies, and cost structures, utilizing a linear programming-based cost optimization model. Incorporating a carbon pricing structure that charges between \$100 and \$380 per tCO_2eq based on GHG Fuel Intensity (GFI), the study compares fuel consumption, fuel costs, and carbon tax burdens across three scenarios: BAU, Base Target, and Direct Compliance Target.

The total cost trajectories diverge significantly depending on the scenario, and the key analytical findings are as follows:

1. Under the **Non-compliance scenario**, high-emitting fossil fuels incur significant carbon price burdens. However, the current pricing levels are insufficient to incentivize a shift to e-fuels.
2. The **Base Target scenario** balances carbon taxes of \$100/tCO_2eq with the costs of fuel transition, representing a path that secures both policy acceptability and the effectiveness of incentives.
3. The **Stricter Target Scenario**, complying with the Direct Compliance target, meets regulatory requirements through early adoption of alternative fuels without carbon tax liability, but imposes the highest short-term costs, indicating the need for complementary institutional measures.

These findings suggest that relying solely on market forces may not be sufficient to achieve decarbonization in international shipping. It is therefore imperative to establish a clear pricing structure and guidelines for Surplus Units (SUs), the IMO-issued credits granted to ships that achieve the Direct Compliance Target. This will ensure adequate compensation for first movers and enhance market predictability.

Moreover, governments must prioritize building infrastructure for the production and supply of ZNZ (Zero and Near-Zero Emission) fuels, reorganizing port-centered supply chains, offering subsidies for fuel cost differences, implementing tax incentives, and integrating green financing. Using the Base Target scenario as a realistic starting point and gradually guiding the sector toward the Stricter Target represents a rational strategy that aligns industry acceptability, policy effectiveness, and actual GHG reductions.

The IMO mid-term measures are not merely regulatory—they serve as the first policy milestone toward achieving net-zero in international shipping by 2050. Current policy choices will shape the pace and cost of future transitions, and South Korea must take a proactive role in designing and implementing them.

1. Introduction

The global shipping industry is undergoing a paradigm shift. In April 2025, the International Maritime Organization (IMO) approved a set of mid-term GHG reduction measures at the 83rd session of the Marine Environment Protection Committee (MEPC 83). Known as the "IMO Net-Zero Framework," these measures are more than just a new regulatory tool—they signal a fundamental shift in the regulatory landscape, moving the focus from "energy efficiency" to "absolute emissions reductions" and "carbon pricing." In this new era, improving efficiency alone will no longer be enough for the shipping sector to meet its responsibilities.

[Table 1] provides a summary of major maritime decarbonization regulations, detailing the target GHGs, accounting methodologies, application levels, and monitoring mechanisms associated with each regulation.

[Table 1] Major International Maritime Decarbonization Regulations

Regulation	Authority	Target GHG	Accounting Methodology	Application Level	Monitoring Mechanism
EEDI	IMO	CO_2	Tank to Wake	Individual ship	Energy Efficiency Design Index
EEXI	IMO	CO_2	Tank to Wake	Individual ship	Energy Efficiency Design Index
CII	IMO	CO_2	Tank to Wake	Individual ship	Energy Efficiency Operational Indicator
EU-ETS	EU	CO_2	Tank to Wake	Individual ship	GHG Emissions
FuelEU Maritime	EU	CO_2, N_2O, CH_4	Well to Wake	Fleet	GHG Intensity
GHG Fuel Standard	IMO	CO_2, N_2O, CH_4	Well to Wake	Fleet	GHG Intensity

A central element of these new measures is the tiered pricing mechanism, which assesses the GHG intensity of fuels—known as GHG fuel intensity (GFI)—and imposes a carbon price on emissions that exceed the set thresholds. Ships emitting above GFI thresholds can achieve compliance by purchasing remedial units (RUs) based on a two-tier pricing system: Tier 1 units are priced at US$100 per tonne of CO_2eq, while Tier 2 units are more burdensome at US$380 per tonne of CO_2eq. Alternatively, Tier 2 undercompliant ships can comply by purchasing surplus units (SUs). With these new measures, reducing GHG emissions is no longer simply a matter of choice; it now directly impacts the company's bottom line. Global shipping companies that use fuels failing to meet reduction targets will face a dual burden, as they must pay for both the fuel and the associated emission credits.

The study aims to quantitatively evaluate the impact of the mid-term measures approved at IMO MEPC 83, focusing in particular on the carbon reduction pathway and carbon pricing scheme, and their effects on fuel transition and transport costs. The study presents three scenarios with different compliance levels—Non-Compliance (Business as Usual, BAU), Base Target Compliance (base target), and Stricter Target Compliance (direct compliance target)—and forecasts the impact of fuel switching costs and carbon pricing on the overall operational costs for the shipping industry. Ultimately, this study aims to assess whether these mid-term measures can effectively guide the industry toward meaningful pathways for emissions reduction. It also seeks to address practical questions such as how much policy intervention is needed beyond market-driven actions and what kind of strategic balance shipping companies should aim for in response.

2. Methodology & Scenarios

Methodology

Decarbonization in the global shipping sector has become a financial imperative that demands a pragmatic, cost-based approach, which must be supported by quantitative analysis and strategic decision-making. This study applies a linear programming (LP) optimization model—following the approach used in MEPC 83/7/22[1]—to identify the most cost-effective fuel mix under two primary constraints: onboard GHG emissions and fuel switching costs.

Decarbonizing the shipping sector poses a significant challenge, mainly due to the conflict between economic interests and environmental purposes. Shipping companies must minimize operational costs while meeting emissions reduction targets under frameworks like the Paris Agreement, a challenging balancing act. Linear programming provides a powerful tool for quantitatively evaluating the varying impacts of fuel transitions, depending on the timing and pace of implementation, and therefore helps identify the most cost-effective pathways. This approach is particularly beneficial for evaluating next-generation e-fuels, which involve high upfront costs when viewed from a life cycle analysis (LCA) perspective, as viable options for meeting the IMO targets. Moreover, as fuel choices in shipping are primarily driven by variables with linear characteristics—such as fuel price, energy intensity, and carbon intensity (measured on a well-to-wake basis)—linear programming can help simplify the modeling of complex decisions as well as ensure computational efficiency in the process.

Centering on the mid-term measures approved at MEPC 83, this study focuses on fuel cost (OPEX) rather than shipbuilding cost (CAPEX) to assess decarbonization pathways quantitatively. The mid-term measures are designed to reduce emissions across the whole lifespan of a given marine fuel (well-to-wake). Under this framework, conventional fossil fuels such as HSFO, LSFO, and LNG are expected to face significant cost burdens due to their high emission factors. In contrast, e-fuels produced from renewable

1 IMO MEPC 83 "Cost-effective pathways to reach net zero by 2050 for the international shipping sector: fuel transition outlook and policy implications"

energy and RFNBOs (Renewable Fuels of Non-Biological Origin)-based biofuels are likely to become more competitive owing to policy incentives, with zero-emission fuels receiving additional benefits.[2]

This study centers its analysis on fuel costs, considering the central role they play in the cost structure and decision-making processes within the shipping industry. Fuel cost is the largest operational expense for shipping companies. At the same time, fuel costs are directly and immediately impacted by global fuel price fluctuations and policy measures, such as carbon pricing, making it a critical factor shaping operations strategies. In contrast, shipbuilding costs are long-term, fixed capital investments that require decades to recover, making short-term investment decisions challenging. This distinction is particularly relevant under the mid-term measures, which set a base target of 65% for 2040 but leave specific targets beyond 2035 undefined, adding uncertainty to long-term planning. In practice, shipping companies adjust their operations strategies based on annual fuel costs, while decisions related to shipbuilding or retrofitting are guided by long-term capital planning. Taking these factors into account, this study focuses on fuel costs as it examines transition pathways under the mid-term measures within the 2035 implementation period.

Data

This study draws on fuel consumption data from 2019 to 2021, as reported in the IMO's Global Integrated Shipping Information System (GISIS). This dataset covers ships of 5,000 gross tonnage (GT) and above—those required to fulfill obligations under Regulation 22A of MARPOL Annex VI—which represents approximately 93% of reported global tonnage. Specifically, the analysis covers fuel consumption by 15,387 ships with a gross tonnage (GT) of 5,000 tonnes or above in 2021, which together consume an estimated 210 million tonnes annually. Cost projections for both fossil fuels and alternative fuels are based on recent market prices as of 2025, along with a scenario analysis published by a research institute in 2024.[3] The well-to-wake GHG fuel intensity values for each fuel type are sourced from the FuelEU Maritime database (2023).[4]

2 IMO MEPC 83 "Report of the nineteenth meeting of the Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 19)and the Working Group on Reduction of GHG Emissions from Ships"
3 Methanol Institute 2024 "Economic value of methanol for shipping under fuelEU maritime and EU ETS"
4 European Commission 2023 "FuelEU Maritime Initiative"

Hypothesis

This study assumes that the carbon reduction pathways and carbon pricing proposed under the IMO's mid-term measures will result in increased fuel cost burdens for the shipping sector. Based on this premise, the study developed the following hypotheses to analyze cost changes for different transition pathways.

First, the study relies on annual fuel consumption data collected by the IMO DCS.[5] For this study, fuels are grouped into three categories—fossil fuels (e.g., HFO, MGO, LFO), biofuels (e.g., B30, bio-methanol), and e-fuels—based on their shared characteristics, such as technologies, GHG intensity, and transition potential. This classification enables a structured evaluation of how different policy scenarios impact cost structures within fuel categories that exhibit similar energy intensities and pricing structures. Policy applicability and commercial maturity are also taken into consideration.

Second, biofuels face several practical constraints. While biofuels are theoretically advantageous as drop-in fuels that can be integrated into existing infrastructure, their real-world application is constrained by limited production capacity, environmental concerns,[6] and price volatility. Notably, classified as Sustainable Aviation Fuel (SAF), biofuels are treated as a strategic resource for meeting global emission reduction targets. Due to stiff competition from the aviation sector, the shipping industry may be priced out of the market, making it difficult to secure a stable supply of biofuels at reasonable prices. Therefore, the study applies a conservative estimate for biofuel costs to account for these limitations.[7]

Additionally, concerns remain about the potential negative impacts of biofuels on food production and land use, particularly when biomass feedstocks are sourced from the agriculture or forestry sectors. As awareness grows around ecosystem preservation and sustainability, biofuels are being assessed from a life-cycle perspective, and the emission factors for biofuels can vary significantly depending on the type of feedstock and the production method used.[8] This can lead to questions about its GHG reduction potential and undermine policy consistency. In response, the IMO has established the GESAMP Working Group on the Life Cycle GHG Intensity of Marine Fuels, which is working to enhance relevant guidelines by conducting scientific reviews of LCA

5 IMO 2021 "Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS
6 Korean Register (KR), "Current Status and Prospects of Biofuels as Marine Fuels" (2024)
7 Argus Article 2025 "Biomethanol-methanol diff widens, UK demand ticks up"
8 Solutions for Our Climate (SFOC), "Environmental Risks of Bridge Shipping Fuels and Transition plans of Korea, China, and Japan" (2024)

methodologies, standardizing emissions reporting, and incorporating sustainability indicators such as indirect land-use change (ILUC). In line with these efforts, this study measures the life-cycle emissions of fuels using the GHG emission factors established under the FuelEU Maritime, which currently provides the most comprehensive data on emission factors.

Third, the study limits the annual fuel transition rate to 10%. Given the technical, logistical, and industrial constraints, this study assumes that no more than 10% of total fuel consumption can be switched to cleaner fuels every year compared to the base year of 2025. Achieving fuel transitions at scale requires significant structural changes—including ship retrofitting, expansion of fuel supply infrastructure, and upgrades to port facilities—all of which are difficult to implement in the short term. Currently, the annual global shipbuilding capacity accounts for 7.5% of total fleet capacity worldwide (DWT).[9] Even when considering retrofits, a rapid shift to cleaner fuels remains unlikely. The model applies a 10% cap to account for these practical constraints—such as the time required to develop supporting technologies and infrastructure—and also leaves room for some flexibility in implementing fuel transitions. By incorporating this cap, the model avoids making overly optimistic assumptions on fuel transitions, which in turn ensures that the study outcomes remain grounded in operational realities.

Fourth, transport demand is held constant across all scenarios. This assumption allows for a more accurate assessment of decarbonization policies by isolating fuel mix changes from fluctuations in total energy demand. In reality, transport volume and energy consumption in the shipping sector are influenced by various external factors, such as global economic growth, evolving trade patterns, and international regulations. However, incorporating these variables into the model would complicate efforts to evaluate the direct impact of fuel transition policies quantitatively. By fixing transport demand across all scenarios, this study enables a direct scenario-based comparison of how different fuel choices and policy measures influence decarbonization outcomes in the shipping industry.

Fifth, fuel prices and emissions factors are treated as exogenous variables and assumed to remain constant over time, without accounting for time-series variation. By keeping these values fixed across all scenarios, the analysis allows for a more direct comparison of outcomes and fuel choice changes across different scenarios.

9 Clarksons Research Data 2010~2024 newbuilding volume measured in DWT (Last accessed: March 24, 2025)

Sixth, international regulations, including the IMO's mid-term measures, may be implemented at varying paces and with different standards across regions. For example, the European Union (FuelEU Maritime and EU ETS), the United Kingdom (UK ETS), the United States (IRA), and major shipping nations such as China, Japan, and South Korea are each adopting distinct policy approaches and emissions reduction standards. However, the study does not account for these regional differences. Instead, it treats the global shipping market as a single, unified fleet and applies consistent implementation timelines and reduction standards across all scenarios.

Finally, the surplus unit (SU) mechanism outlined in the IMO Net-Zero Framework is excluded from the model. Under the framework, ships that outperform the stricter direct compliance target (Tier 1) earn SUs equal to their positive compliance balance. Conversely, ships that fall short of the base target (Tier 2) must either pay a high carbon price of US$380 per tonne of CO_2eq or purchase SUs from overperforming vessels to offset their excess emissions. However, because the SU mechanism remains at the conceptual stage—with no concrete standards or implementation guidelines—it is not incorporated into this analysis. Instead, the study assesses changes in fuel costs and carbon prices based solely on the mid-term measures as currently defined, excluding SU trading dynamics. Additionally, the study's scope is limited to the 2028–2035 period, as this is the only timeframe for which specific annual GFI reduction targets have been established under the framework.

Based on the methodology and assumptions described above, this study conducts a cost-optimization analysis of decarbonization strategies and evaluates various policy scenarios. Through this, the study aims to identify viable decarbonization pathways and draw key policy insights.

Scenario Development

Under the mid-term measures, the IMO imposes a carbon price—paid through the purchase of remedial units (RUs)—for each tonne of CO_2 equivalent emitted beyond the GFI target, with price levels determined based on the three levels of compliance. Building on this framework, the study models three scenarios that reflect varying levels of GFI-linked carbon pricing and fuel transitions expected under current measures. The analysis is designed to evaluate the impact of various decarbonization strategies on the cost structure. Additionally, existing IMO measures—namely the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII)—are applied uniformly across all scenarios

❶ Non-Compliance Scenario (Business As Usual, BAU)

This scenario assumes that current technology and market trends continue, regardless of the GFI targets established under the IMO's mid-term measures. In this scenario, there are no changes to existing fuel consumption patterns and no restrictions on the use of fossil or alternative fuels, with no additional policy interventions. As a result, ships fail to meet both the base and the stricter direct compliance target, and, therefore, are subject to both the lower carbon fee of \$100/tCO_2eq (RU 1) and the higher fee of \$380/tCO_2eq (RU 2). This scenario serves as a reference point for evaluating the feasibility of market-driven decarbonization and understanding how cost structures evolve in the absence of policy interventions.

❷ Base Target Scenario (Base Target)

This scenario models the base target trajectory outlined in the IMO's mid-term measures. It represents a more balanced compliance pathway, in which the industry makes a gradual fuel transition and pays a carbon fee of \$100/tCO_2eq. It serves as a benchmark for evaluating whether the IMO's measures can strike an effective balance—ensuring industry acceptance while providing sufficient incentives to drive meaningful actions—by factoring in both fuel switching costs and the carbon price burden. This scenario reflects the practical transition strategy currently under discussion in the international community.

❸ Stricter Target Scenario (Direct Compliance Target)

This scenario assumes ambitious implementation of the IMO's mid-term measures, in which the stricter direct compliance target is met entirely through fuel transition without relying on carbon pricing. In this scenario, there is no carbon price; instead, emission reductions are entirely achieved by switching to e-fuels. As a result, the additional costs stem solely from higher operational costs associated with fuel switching rather than from carbon prices.

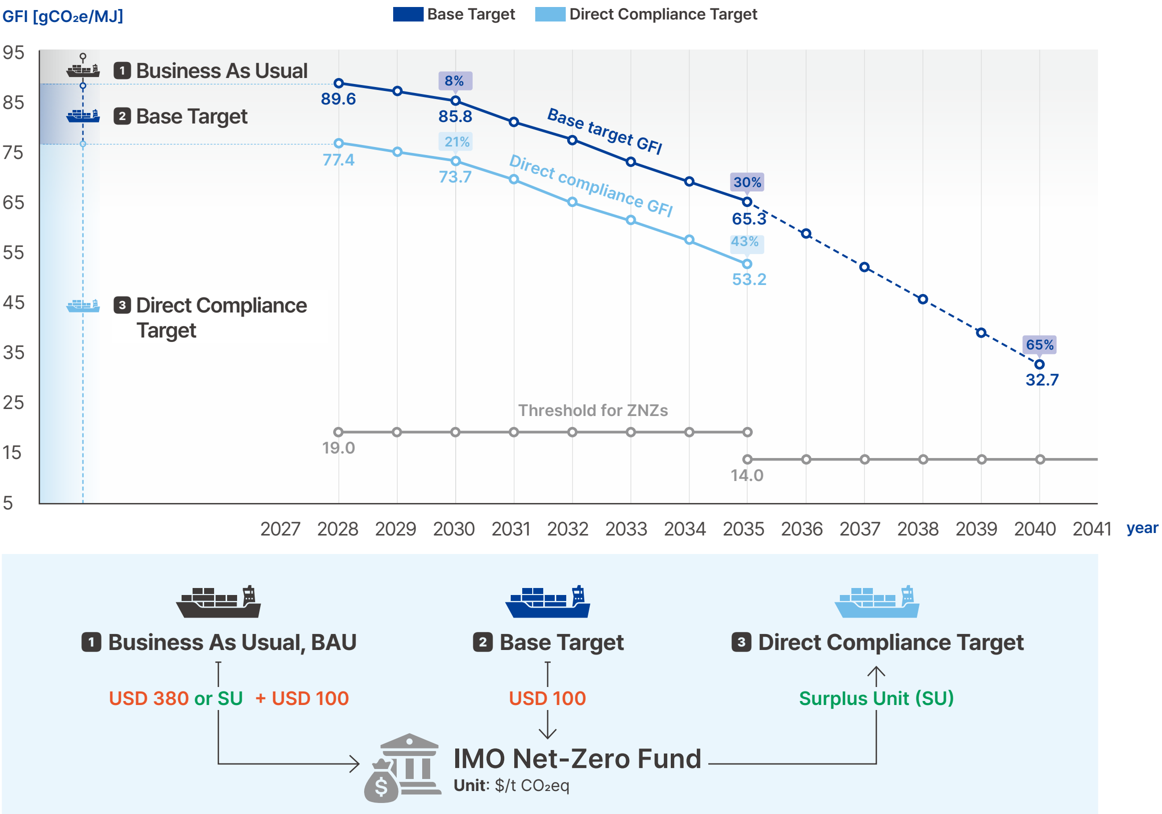
3. Results

This study quantitatively evaluates and compares the transition pathways, carbon emissions, and total cost changes for the scenarios outlined above. Each scenario reflects a distinct decarbonization strategy, resulting in different energy mixes and levels of economic burden. Through this analysis, the study evaluates various policy approaches and examines their financial and environmental implications.

Example of Fuel Cost Projection

Under the IMO Net-Zero Framework, the IMO imposes carbon price—paid through the purchase of remedial units (RUs)—for each tonne of CO_2 equivalent emitted beyond the GFI target, with price levels determined based on the three levels of compliance, as illustrated in **[Figure 1]** below.

[Figure 1] RU Classifications Under the IMO Mid-Term Measures



Based on this classification, RU is calculated using the following equation.

[Figure 2] RU Calculation Formula

$$RU = \underbrace{\left(GFI_{Base} - GFI_{Direct}\right) \times Tier1_{cost} \times \frac{LCV}{10^6}}_{RU\ 1(T1)} + \underbrace{\left(GFI_{Fuel} - GFI_{Base}\right) \times Tier2_{cost} \times \frac{LCV}{10^6}}_{RU\ 2(T2)}$$

RU	Additional cost per tonne of fuel under the carbon regulation ($/ton-fuel)
GFI_{Base}	Tier1 GFI target for the given year (gCO_2eq/MJ)
GFI_{Direct}	Tier2 GFI target for the given year (gCO_2eq/MJ)
GFI_{Fuel}	GHG intensity of the fuel for the given year (gCO_2eq/MJ)
$Tier1_{cost}$	Tier1 carbon price (e.g., $100/tCO_2eq$)
$Tier2_{cost}$	Tier2 carbon price (e.g., $380/tCO_2eq$)
LCV	Lower calorific value of the fuel (MJ/ton-fuel)

Based on these standards, the annual carbon price (RU) for HFO is calculated as shown in **[Table 2]** below.

[Table 2] Estimated Annual Carbon Price for HFO (numbers are rounded down to the nearest whole number)

Year	IMO GFI		Carbon Price (RU)		
	Tier1 Direct [gCO_2eq/MJ]	Tier2 Base [gCO_2eq/MJ]	RU 1 (T1) [$]	RU 2 (T2) [$]	Total RU [$]
2028	77	90	49	31	80
2029	76	88		60	109
2030	74	86		89	138
2031	70	82		152	201
2032	65	78		215	264
2033	61	74		278	327
2034	57	69		341	391
2035	53	65		405	454

* Conventional fossil fuels such as HFO have the highest GFI and are subject to the highest level of carbon price, resulting in a steep increase in cost burden. As shown in **[Table 2]**, the projected carbon price for HFO in 2035 is estimated at $454 per tonne, which adds cost equivalent to approximately 95% of the fuel price (based on the fuel's baseline price of $475 in 2025).

A. Fuel Mix by Scenario

Fuel transition in the global shipping sector is shaped by two key dynamics: the structural phase-out of fossil fuels and the gradual adoption of alternative fuels. To capture these dynamics, this study classifies fuels into three categories—fossil fuels, biofuels, and e-fuels—and compares transition pathways and structural characteristics across different scenarios. The results show that all three scenarios begin with the same fuel mix in the 2025 baseline year, as they are modeled to prioritize fuel cost optimization and assume unrestricted use of all fuel types. However, starting in 2028—when the new GHG reduction mandates take effect—the fuel mix begins to diverge across scenarios, depending on regulatory stringency and policy design. The timing of the transition and the type of fuels used for transition also vary by scenario, influenced by several factors, including the presence of emissions reduction obligations, the level of the carbon price, and the strength of policy signals.

However, it is essential to note that the cost-optimization analysis in this study is based on a linear programming model, which results in an outcome that is overly concentrated on a narrow set of fuel types. The fuel mix presented in this study is an outcome of this mathematical modeling, and, therefore, should be interpreted with this structural limitation in mind. In reality, a range of unstructured variables—such as policy flexibility, the maturity of fuel supply chains, and the pace of technology adoption—can affect the outcome. Accordingly, this study is not intended to forecast absolute outcomes; it focuses on understanding the relative impact of varying long-term strategies and policy signals on decarbonization pathways.

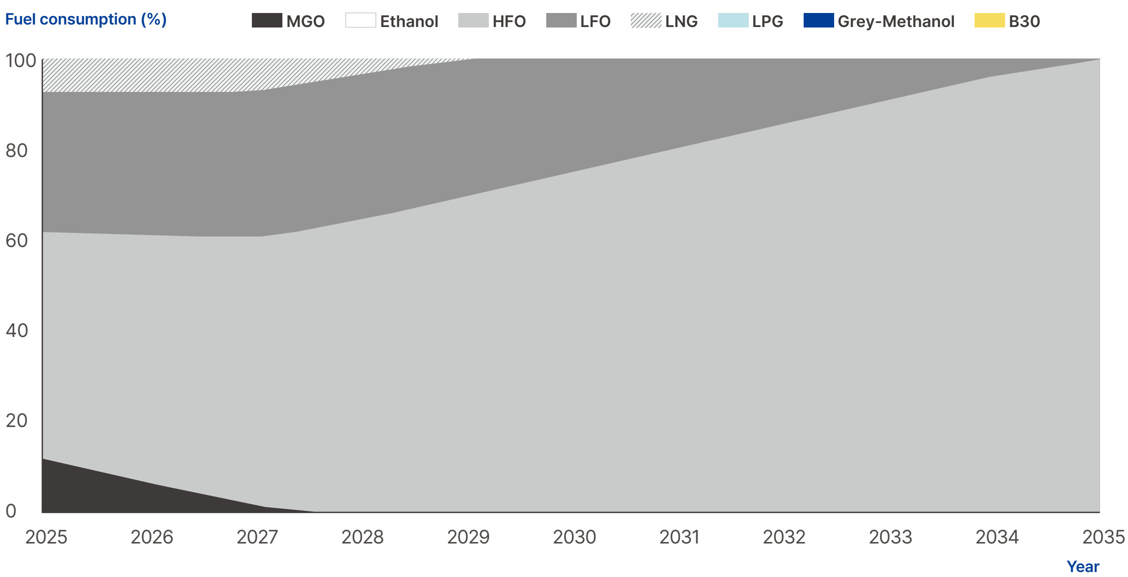
1 Non-Compliance Scenario

The Non-Compliance scenario assumes that no emissions reduction obligations are introduced. As a results, this scenario sees a continued heavy reliance on fossil fuels and, consequently, most minor changes in the fuel mix. The projected changes in fuel mix presented in this study are direct outcomes of cost-optimization modeling, so these results may be overly concentrated on certain fuel types due to structural limitations. Based on the assumption that there is unrestricted use of all fuel types, this study identifies the optimal fuel mix for minimizing fuel costs for each year from the base year of 2025 through 2035.

Under this scenario, the industry opts for the most cost-efficient fuel during the initial years. The share of HFO in the fuel mix increases over time, reaching 100% by 2035. As such, fossil fuels dominate the entire fuel mix, while alternative fuels do not enter the market. However, this result should not be interpreted as a forecast of the actual future industry landscape, but rather as an outcome of a cost-optimization model that inherently suppresses the adoption of higher-cost alternatives.

Under this scenario, a high level of carbon fee (both RU1 and RU2) is imposed. However, this pricing policy fails to trigger fuel transition. Instead, shipping companies absorb the carbon fee as part of their overall operating costs and ultimately pass it on to consumers. Meanwhile, e-fuels are not adopted due to their high costs. These findings suggest that without sufficient regulatory incentives, the industry is likely to shift back toward fossil fuels. This underscores a critical insight: unless policy tools—such as carbon pricing or greenhouse gas emissions trading schemes—are introduced to enhance the competitiveness of alternative fuels, market forces alone are unlikely to drive fuel transitions.

[Figure 3] Non-Compliance Scenario – Changes in Marine Fuel Mix by Year



❷ Base Target Scenario

The Base Target scenario models a gradual transition trajectory in line with the IMO's mid-term measures, and imposes a carbon price of \$100/tCO_2eq. This policy structure provides price signals and incentives that encourage shipping companies to avoid emissions, driving progressive shifts in the fuel mix.

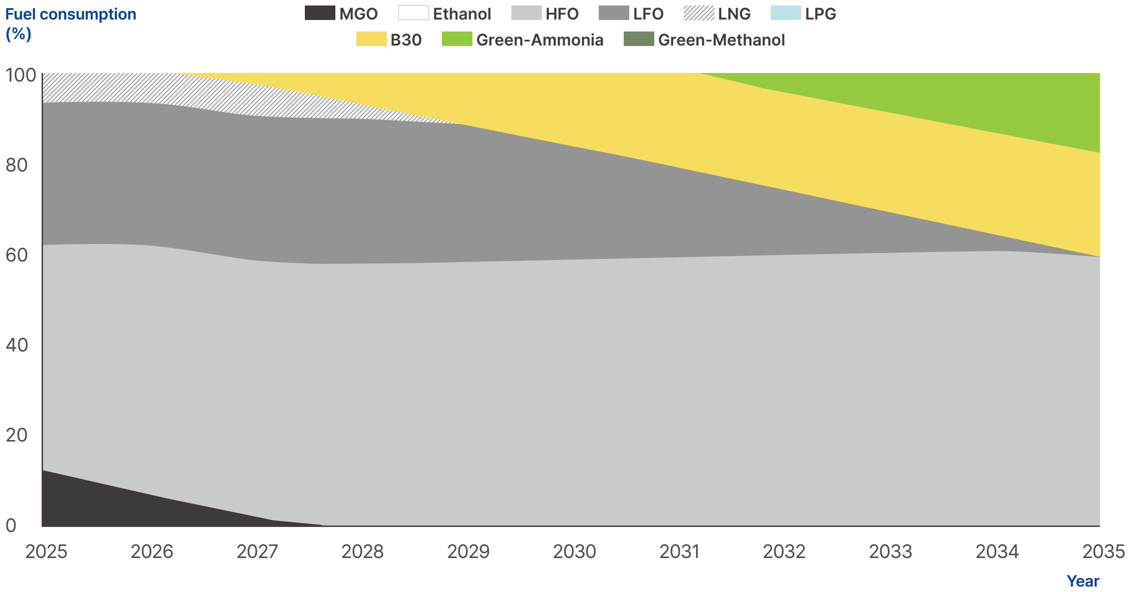
For the base year of 2025, this scenario assumes unrestricted use of all fuel types, similar to the Non-Compliance scenario. However, from 2027 onwards, the model incorporates practical limitations—such as relative fuel costs, the pace and feasibility of energy transitions, and moderate regulatory pressures. The results show that while conventional fuels, such as HFO and LFO, dominate the fuel mix in the early years, their share gradually declines over time, and the market slowly shifts toward alternative fuels.

In 2025, HFO and LFO together account for over 80% of total fuel consumption, followed by MGO (12.4%) and LNG (6.8%). From 2027 onward, however, the share of biofuels (B30) increases significantly and reaches approximately 23% by 2035—due to their competitiveness as drop-in fuels. Among e-fuels, e-ammonia (also known as green ammonia)—despite its high cost—emerges as a key zero-emission option for meeting emissions reduction targets. It begins to have a meaningful presence in the fuel mix in 2032, eventually reaching a 17.5% share by 2035.

In the Base Target scenario, notable structural changes are observed across different fuel types, each exhibiting a distinct adoption timeline, growth trajectory, and strategic significance. Although HFO remains the cheapest fuel, its share in the fuel mix gradually declines due to regulatory incentives, such as environmental regulations. This suggests that fuel choices are increasingly driven by regulatory incentives rather than purely by cost factors. Meanwhile, alternative fuels like biofuels (B30) demonstrates a potential for market entry. In particular, drop-in fuels—which do not require modifications to existing infrastructure—show a moderate growth trajectory due to their lower transition costs. However, the overall pace of adoption remains limited, highlighting that the market is constrained by structural barriers, including technology readiness, inadequate supply chain infrastructure, and uncertainties surrounding fuel prices.

This scenario demonstrates that gradual fuel diversification and decarbonization are achievable when supported by adequate policy incentives and a stable fuel supply. However, fossil fuels, including HFO, still account for more than half of the fuel mix. This highlights the structural limitations of this scenario and suggests that market mechanisms alone are unlikely to drive a full-scale fuel transition within a short timeframe.

[Figure 4] Base Target Scenario - Changes in Marine Fuel Mix by Year



❸ Stricter Target Scenario

The Stricter Target scenario models full compliance with the more rigorous direct compliance target outlined in the IMO's mid-term measures. In this scenario, emission reduction targets are achieved solely through fuel switching, without external financial incentives such as carbon pricing. Also, emission intensity is measured on a full lifecycle (well-to-wake) basis. Under these stringent regulatory conditions, the industry is projected to phase out fuels that exceed the established emissions thresholds. This underscores the significantly greater influence of regulatory pressure over market-driven factors in shaping fuel choices. As a result, this scenario exhibits the most significant changes in the fuel mix.

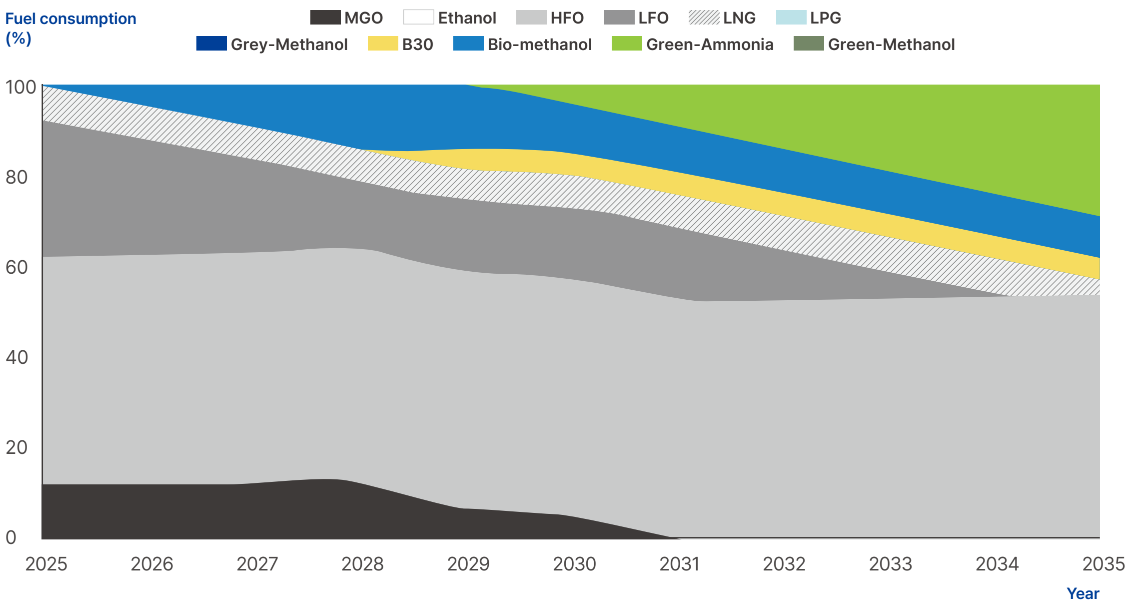
One of the most notable developments in this scenario is the growth trajectory of bio-methanol. The fuel enters the market early, making its first appearance in 2026 with a share of 4.5%, and steadily expands its share to approximately 9.5% by 2035. This trend can be interpreted as a case where tightened regulations are driving fuel transitions—

especially since bio-methanol does not appear in the previous scenarios. Such expansion of bio-methanol is likely due to its high emissions reduction potential and drop-in compatibility, making it a compelling option for meeting policy-driven demand. Notably, bio-methanol appears to serve as a transitional fuel, gaining momentum before e-fuels, such as green ammonia and green methanol, begin to enter the market later in the scenario.

Meanwhile, LNG fails to show a sustained upward trajectory in this scenario, which is contrary to industry expectations. By 2035, its share is expected to remain at just 3.1%. While this represents only a modest decline compared to other scenarios, it also lacks any clear signs of sustained growth. This outcome suggests that under stricter regulatory conditions, LNG loses its relative competitiveness, both in terms of cost-effectiveness and its ability to support compliance with maritime regulations.

Unlike in other scenarios, MGO does not experience a sharp decline in its share and continues to represent a meaningful portion of the fuel mix through 2030. This is primarily due to the rapid reduction in the average emission intensity of the fuel mix, driven by its early adoption of low-carbon fuels, which creates room for limited use of higher-emission fuels like MGO. In the Stricter Target scenario, MGO functions as a viable compliance option when used in combination with lower-emission fuels—which suggests that within an optimized framework that accounts for policy flexibility and systemic constraints, limited use of higher-emission fuels can be strategically managed within the bounds of regulatory compliance.

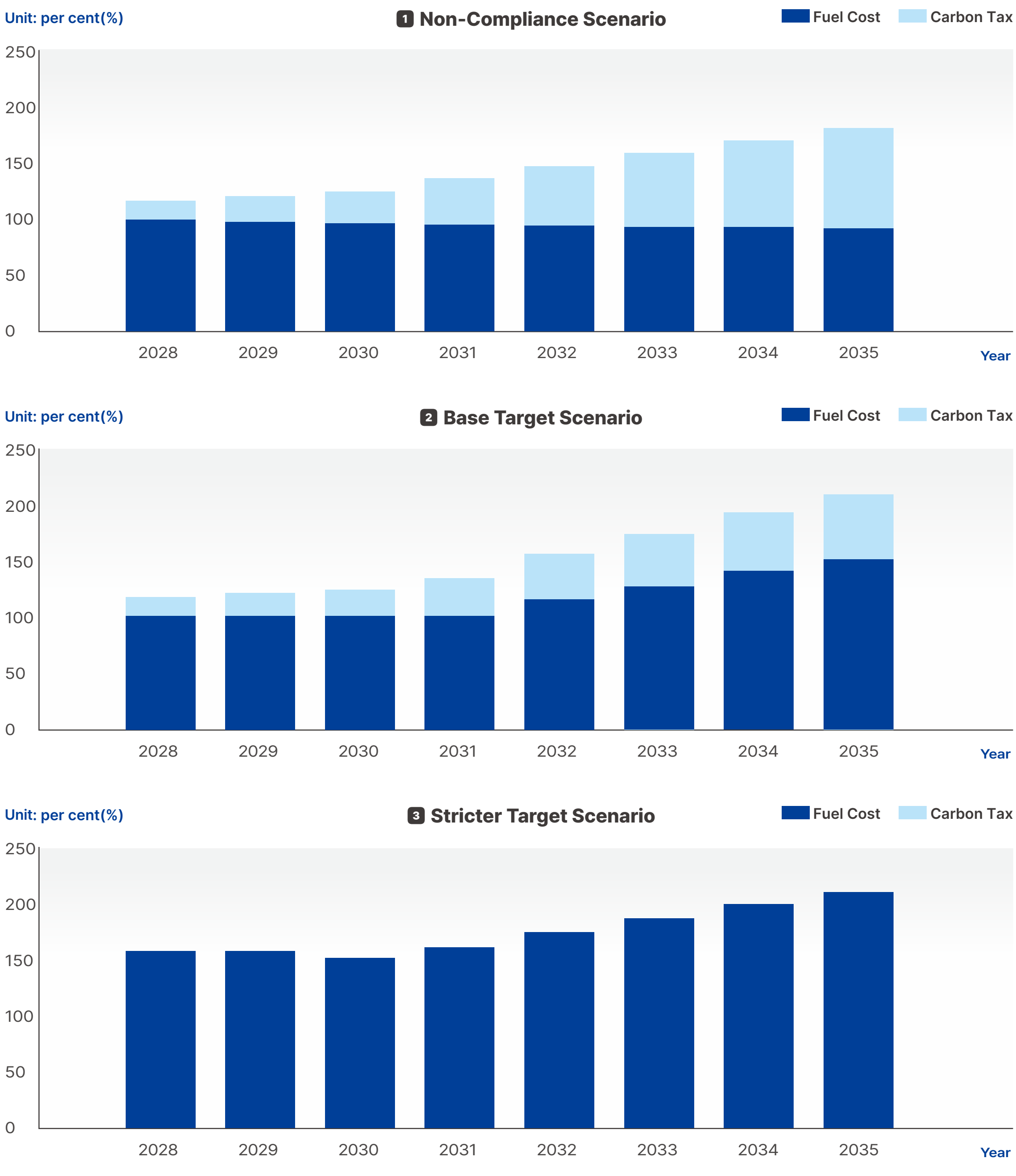
[Figure 5] Sticter Target Scenario - Changes in Marine Fuel Mix by Year



B. Fuel Cost and Carbon Price by Scenario

This section presents a comparative analysis of how fuel costs and carbon prices evolve across the three scenarios. Different fuel mixes across these scenarios result in varying cost structures, with different proportions of fuel costs and carbon prices. By examining these differences, the study aims to evaluate the effectiveness of the mid-term measures—focusing specifically on their institutional limitations and their capacity to incentivize fuel switching.

[Figure 6] Changes in Fuel Cost and Carbon Price by Decarbonization Scenario



* All values are expressed as relative percentages, with the 2028 fuel cost under the Non-Compliance scenario set as the baseline (100). The purpose is to compare year-by-year changes in fuel costs and carbon taxes visually.

[Figure 6] illustrates the annual changes in fuel costs and carbon prices across the three scenarios. In the Non-Compliance scenario, the industry continues to rely heavily on conventional fossil fuels, resulting in the lowest initial fuel costs. However, as carbon fees accumulate under the mid-term measures, its total cost rises sharply over time. While this scenario may appear economically advantageous in the short term, the growing carbon price burden significantly undermines its cost-effectiveness in the medium to long term.

In the Base Target scenario, the fuel mix includes a modest share of alternative fuels, resulting in consistently higher fuel costs compared to the Non-Compliance scenario. Although the carbon fee is set at a relatively moderate rate of $100/t$CO_2$eq—lower than in the Non-Compliance scenario—the cost savings from reduced carbon fees are insufficient to offset the higher abatement costs for lower-emission fuels. As a result, total costs in this scenario fall between those observed in the Non-Compliance and Stricter Target scenarios. The Base Target scenario reflects a balanced compliance pathway, in which the industry accepts a moderate level of fuel switching costs in exchange for reduced carbon fees, aiming to strike a balance between regulatory compliance and cost efficiency. Here, the IMO's mid-term measures are accepted at the minimum level.

The Stricter Target scenario shows an early uptake of alternative fuels, which is essential for meeting the stringent reduction targets. This aggressive shift toward e-fuels leads to higher fuel costs compared to other scenarios. However, in the absence of carbon fees, the growth in annual costs follows a stable trajectory—unlike in other scenarios where carbon fees increase sharply after 2030. This cost stability can be advantageous for long-term budgeting and investment planning while offering greater predictability in decarbonization strategies and enhancing the overall credibility of the policy framework.

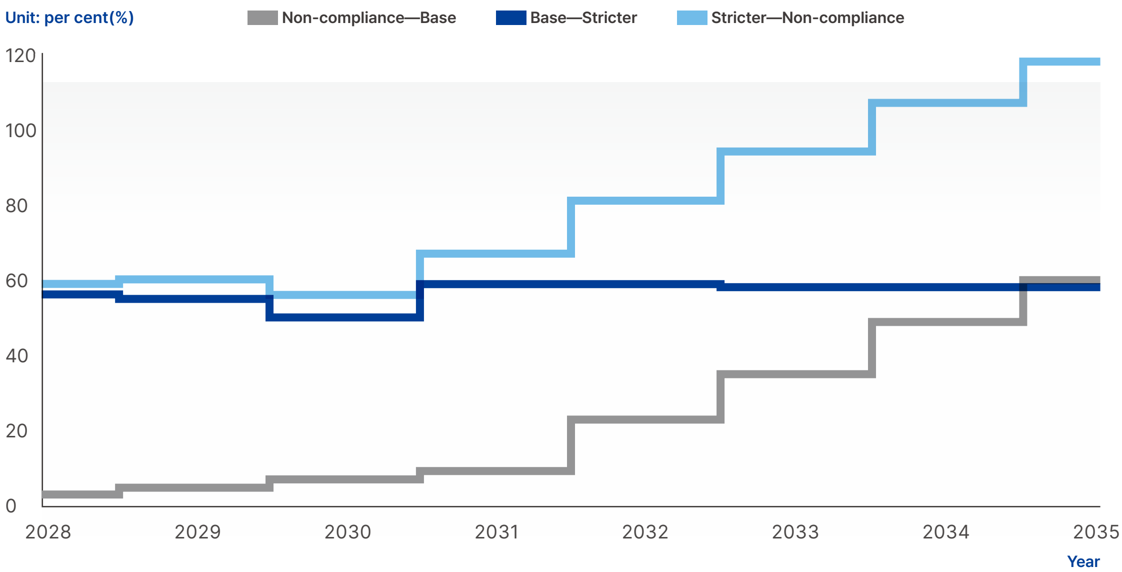
However, the study finds that under the current structure of the IMO's mid-term measures through 2035, the Stricter Target scenario—which most rigorously pursues emissions reductions—incurs the highest total costs. This outcome suggests that this policy framework may create a regressive structure, in which those most committed to the reduction targets bear the most significant short-term economic burdens. It also indicates that the incentive mechanisms embedded in the mid-term measures may be insufficient to deliver the intended outcomes.

Nevertheless, the mid-term measures—including the carbon pricing mechanism—can serve as a meaningful starting point for guiding the global shipping industry toward its 2050 net-zero goal. The policy measures can be made more effective through enhanced incentive mechanisms, such as by introducing surplus unit (SU) standards or more stringent GFI reduction factors. While this analysis highlights the current measures' limitations in providing economic benefits of switching to cleaner fuels in the short term, it also demonstrates the need to consider the various decarbonization pathways that the IMO's mid-term measures aim to incentivize.

C. Comparative Cost Analysis

The cost analysis presented above provides a foundation for evaluating how the IMO's mid-term measures influence fuel costs and overall cost structures over time. While the Non-Compliance scenario initially shows the lowest total cost, it experiences a steep cost increase over time due to escalating carbon fees. In contrast, the Stricter Target scenario incurs higher costs initially but exhibits moderate changes and follows a more stable trajectory throughout. Positioned between these two extremes, the Base Target scenario serves as a buffer pathway, allowing shipping companies to spread out the fuel switching costs as they adopt a more progressive compliance strategy. These insights offer a valuable basis for assessing which approach can most effectively support the shipping sector's net-zero goal—particularly in a context where the mid-term measures are expected to become more stringent over time.

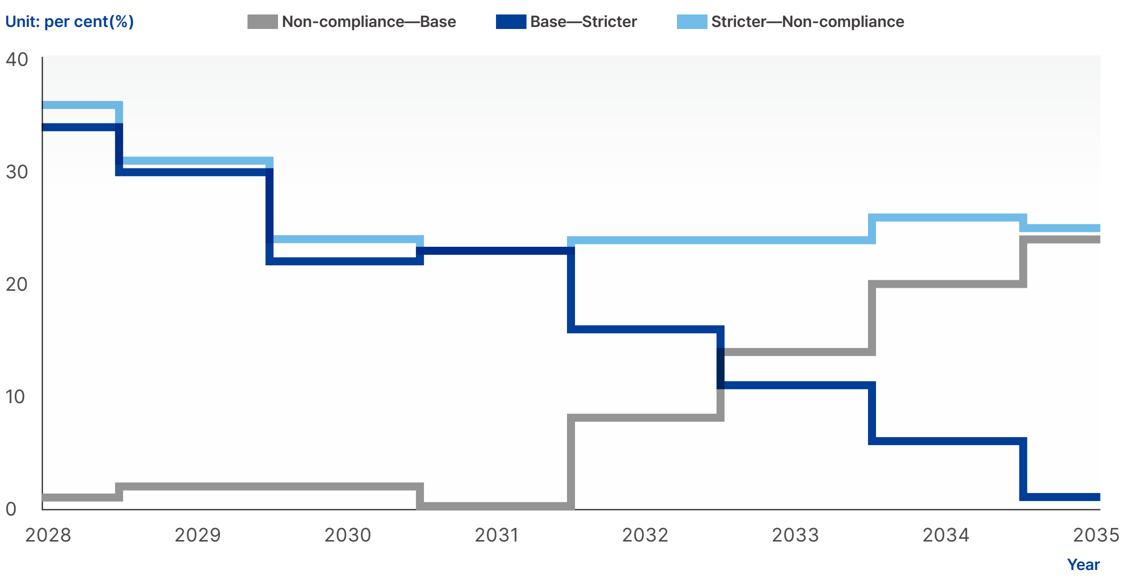
[Figure 7] Changes in Relative Fuel Cost Differences Between Scenarios



[Figure 7] illustrates the relative changes in fuel costs across the three scenarios, expressed as percentages. This chart provides an intuitive comparison of how different policy approaches impact fuel costs over time, focusing on relative trends rather than absolute values. The analysis compares the relative changes in fuel costs among the three scenarios compared to the base year of 2028. The results reveal a growing divergence in fuel costs as time progresses.

The fuel cost gap between the Non-Compliance and Base Target scenarios begins at approximately 3% in 2028 and steadily widens to around 60% by 2035. This suggests that following the Non-Compliance pathway makes transitioning to the Base Target scenario increasingly costly over time, primarily due to a sharp annual increase in fuel costs. In contrast, the gap between the Base and Stricter Target scenarios remains relatively stable at around 60% throughout the analysis period. Although the Stricter Target scenario entails higher upfront costs, it does not show sharp increases in fuel costs and thus offers greater cost stability. The most significant divergence is observed between the Non-Compliance and Stricter Target scenarios: the gap starts at roughly 60% in 2028 and doubles to 120% by 2035. These findings suggest that remaining on the Non-Compliance pathway could result in an exponentially widening fuel cost gap compared to the Stricter Target scenario.

[Figure 8] Changes in Relative Total Cost (Fuel Cost + Carbon Price) Differences Between Scenarios



The gap between scenarios becomes even more pronounced when carbon price is incorporated into the model. **[Figure 8]** illustrates the relative changes in total costs, which represent the sum of fuel costs and carbon fees (RUs) imposed under the IMO's mid-term measures. As in the previous analysis, the relative changes are compared against the base year of 2028.

The Non-Compliance and Base Target scenarios begin with virtually no difference, showing only a 1% gap in 2028. However, due to carbon fees imposed under the IMO's mid-term measures, total costs rise sharply over time, causing the gap to widen to 24%

by 2035. This increase is steeper than the trend observed in the earlier analysis focused solely on fuel costs. In contrast, the Base Target and Stricter Target scenarios start with a significant cost gap of 34% in 2028. Over time, however, this gap steadily narrows and trends toward negative values by 2035. This suggests that while the Stricter Target scenario involves higher transition costs in the early years, the cumulative savings from avoided carbon fees can ultimately result in lower total costs compared to the Base Target scenario. These findings indicate that the Base Target scenario is not merely a transitional phase, but a strategic pathway that enables the industry to spread out and gradually absorb the costs associated with transitioning toward the Stricter Target scenario.

Lastly, the total cost gap between the Stricter Target and Non-Compliance scenarios narrows from approximately 36% in 2028 to around 25% by 2035. Initially, the gap is substantial due to higher fuel costs seen in the Stricter Target scenario. However, as the Non-Compliance scenario continues to rely heavily on fossil fuels, it faces a steady rise in total costs driven by accumulating carbon fees, which quickly narrows the gap observed in the initial compliance period.

In conclusion, while focusing solely on current costs may make the Non-Compliance scenario appear economically advantageous in the short term, this ultimately undermines compliance flexibility for shipping companies due to the compounding carbon price burden and deferred transition costs. The total cost structures observed in this study suggest that the Non-Compliance pathway is likely to become the least competitive option towards 2035. In contrast, beginning with the Base Target scenario and gradually transitioning toward the Stricter Target scenario enables the industry to spread out the upfront costs over time, while benefiting from greater cost predictability and stability throughout the decarbonization journey. As such, the figures presented in this study do more than simply compare total costs—they offer a quantitative basis for making an optimal choice in terms of timing and speed of fuel transitions. The results suggest that, if the transition is inevitable, taking early action is the most rational strategy.

4. Conclusions and Implications

The study reveals both the effectiveness and structural limitations of the IMO's mid-term measures, as demonstrated by the transition pathways and cost structures projected under the current policy framework. Notably, the Stricter Target scenario—which most rigorously pursues emission reduction goals—paradoxically results in the highest cost burden. This suggests a potentially regressive policy structure, where stronger compliance leads to short-term economic disadvantages. However, it is essential to note that this analysis does not account for the reward mechanisms outlined in the Net-Zero framework, such as the surplus unit (SU) trading scheme. Given the remaining uncertainties surrounding these measures, the study takes a conservative approach to forecasting cost structures. The findings suggest that the GFI-linked pricing mechanism currently approved by the IMO may be insufficient on its own to drive meaningful fuel transitions.

Nevertheless, the IMO's mid-term measures hold significance for the global shipping industry, providing a starting point for moving toward the 2050 net-zero goal. They can be made more effective through institutional improvements—such as refining the SU criteria, strengthening GFI targets for both the base target and the stricter direct compliance target through 2040, and implementing robust reward mechanisms. In particular, the design of the SU pricing and incentive systems will be crucial in encouraging early transitions. Ultimately, the success of the mid-term measures as an effective transition policy hinges on the clarity of their design and implementation. The policy must provide strong reward signals, along with appropriate incentives to drive meaningful changes.

To be effective, the IMO's mid-term measures must be supported by complementary national policies. Given that fuel cost disparities remain a major barrier to transition, there is a pressing need for concrete support measures to accelerate the development of ZNZ fuels and to establish reliable supply and distribution infrastructure at major ports. To ease the high upfront costs of fuel transitions, governments must go beyond subsidizing green shipbuilding and provide targeted support for vessels operating on e-fuels or other ZNZ fuels. This may include compensation for the incremental fuel costs, tax incentives, or expanded access to green financing.

With a national commitment to achieving net-zero emissions from global shipping by 2050, the Korean government must take a proactive role in ongoing IMO negotiations—particularly in shaping institutional frameworks that ensure the effective implementation of the stricter direct compliance target. The surplus unit system, in particular, must function not merely as a regulatory tool but as a predictable and credible market mechanism that incentivizes meaningful GHG reduction efforts. Realizing this potential will require strong policy and financial support. A well-defined SU pricing and trading scheme can provide tangible benefits to those that move towards the Stricter Target scenario early on, which in turn enable domestic companies to develop concrete, actionable roadmaps for a phased transition toward decarbonization.

Finally, while the IMO's mid-term measures impose structural burdens on the global shipping industry by mandating fuel transitions, they also represent a critical inflection point on the long road toward decarbonization. As the first international regulation to establish GHG emission limits and carbon pricing, these measures provide essential guidance on which fuels to use, when, and how. In addition to setting a strategic direction for fuel choices across the industry, these measures can shape early alternative fuel markets through collective action and create opportunities for first-mover advantage.

The global shipping industry stands at a critical juncture in its decarbonization journey. While transitional fuels—such as LNG and biofuels—may remain viable in the short term under current mid-term measures, this is likely to change over time as fuel cost disparities grow and regulatory standards become more stringent. Continued reliance on fossil fuels will only escalate the future burden of transitioning to ZNZ fuels to meet the increasingly stringent targets set by the IMO. Adopting the Base Target scenario as a practical starting point and gradually advancing toward the Stricter Target scenario offers a rational pathway that offers both economic feasibility and operational flexibility. The IMO's mid-term measures provide the industry's first structured framework for navigating this transition. The choice is clear: act now or face higher costs and tighter constraints later. Ultimately, the path forward will be shaped by the strategic choices shipping companies make today and the commitment of regulators to support those efforts.

Appendix:
Annual Changes in Marine Fuel Mix by Scenarios

Non-Compliance Scenario – Changes in Marine Fuel Mix by Year

Unit: %

Fuel Type	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
MGO	12.41	7.05	1.52								
Ethanol	0.00										
HFO	49.56	54.61	59.71	64.87	70.10	75.38	80.58	85.81	91.07	96.37	100.00
LFO	31.09	31.43	31.78	32.13	29.90	24.62	19.42	14.19	8.93	3.63	
LNG	6.84	6.92	6.99	3.00							
LPG	0.02										
Grey-Methanol	0.00										
B30	0.08										

※ **18P** **[Figure 3]** Graph Data

Base Target Scenario - Changes in Marine Fuel Mix by Year

Unit: %

Fuel Type	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
MGO	12.41	6.97	1.44								
Ethanol	0.00										
HFO	49.56	54.61	57.04	57.67	58.32	58.99	59.37	59.75	60.13	60.52	59.12
LFO	31.09	31.43	31.78	32.13	29.82	24.53	19.33	14.10	8.84	3.54	
LNG	6.84	6.92	6.99	2.91							
LPG	0.02										
B30	0.08	0.08	2.75	7.29	11.86	16.48	21.30	21.44	22.12	22.26	23.39
Green-Ammonia								4.71	8.90	13.67	17.49
Green-Methanol	0.00										

※ **20P** **[Figure 4]** Graph Data

Sticter Target Scenario - Changes in Marine Fuel Mix by Year

Unit: %

Fuel Type	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
MGO	12.41	12.54	12.68	12.82	7.38	5.42	0.53				
Ethanol	0.00										
HFO	49.56	50.10	50.65	51.21	51.79	52.38	52.71	53.05	53.39	53.74	54.09
LFO	31.09	25.83	20.51	15.13	15.30	15.47	15.57	10.85	6.00	0.68	
LNG	6.84	6.92	6.99	7.07	7.15	7.23	7.28	7.32	7.37	7.42	3.11
LPG	0.02	0.02	0.02	0.02	0.20	0.02	0.02	0.02	0.02	0.20	0.02
Grey-Methanol	0.00										
B30	0.08	0.08	0.08	0.09	4.58	4.63	4.66	4.69	4.72	4.75	4.78
Bio-Methanol		4.51	9.06	13.01	13.16	10.36	10.00	10.06	9.70	9.76	9.51
Green-Ammonia						4.49	9.23	14.00	18.80	23.63	28.49
Green-Methanol				0.65	0.62						

※ **21P** **[Figure 5]** Graph Data

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Solutions for Our Climate (SFOC) is an independent nonprofit organization that works to accelerate global greenhouse gas emissions reduction and energy transition. SFOC leverages research, litigation, community organizing, and strategic communications to deliver practical climate solutions and build movements for change.