SFO°C
Solutions for Our Climate

° Report

Shipping Decarbonization Continues

South Korea's Choices amid IMO Delay

SFO°C

Shipping Decarbonization Continues:

South Korea’s Choices amid IMO Delay

Publication Date	**February 2026**
Author	**Yumin Han** | Shipping Program | yumin.han@forourclimate.org
Modelling	**Hyeryun Chi** | PLANiT
	Sanghyun Hong | PLANiT
Design	**sometype**

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.

Executive Summary

At the second extraordinary session of the International Maritime Organization's (IMO) Marine Environment Protection Committee (MEPC) in October 2025, member states did not reach an agreement on adopting the Net-Zero Framework (NZF), resulting in a one-year postponement and increased uncertainty around the framework's detailed design and implementation timeline. This delay, however, does not signal a departure from the IMO's overarching objective of achieving net-zero GHG emissions from international shipping by 2050. Decarbonization of international shipping has already entered a structural transition phase, driven by policy, market, and industry dynamics.

Global orders for alternative-fuel vessels tripled in 2023 compared to 2022 and have remained at similarly elevated levels through 2025, signaling a sustained shift in investment trends. At the same time, the regional regulations—including the EU Emissions Trading System (ETS) and FuelEU Maritime—are already in force, imposing ongoing emissions-reduction requirements across the sector. Europe is a core trade route for Korean shipping companies, placing them directly within the scope of these regulations.

In parallel, compliance pressures under the IMO's Carbon Intensity Indicator (CII) are intensifying, particularly for older bulk carriers and tankers, where the risk of D or E ratings is increasing. Against this backdrop, despite the adjournment of the NZF, the Korean shipping industry is entering a critical transition phase marked by fleet renewal and new vessel orders, underscoring the growing importance of strategic decisions aligned with medium- to long-term decarbonization pathways.

Therefore, this study assesses potential fuel transition pathways and associated cost structures for the Korean shipping industry, assuming that the NZF is ultimately implemented. Using scenario-based modelling, the analysis categorizes shipping companies' compliance strategies into three scenarios—**Baseline, Proactive**, and **Market-optimal**—based on differing levels of regulatory ambition. In addition, **Policy Intervention scenarios** are layered onto each compliance pathway to examine the effects of government action. Specifically, the analysis assumes a reduction in the cost of zero- and near-zero-emission (ZNZ) fuels (e.g., e-fuels) driven by public policy support and evaluates how such interventions alter fuel transition trajectories and overall cost burdens for shipping companies.

The results indicate that large-scale adoption of e-fuels becomes viable only when regulatory requirements are combined with supportive public policies. Under a **Policy Intervention scenario** in which e-fuel prices decline by 30% between 2028 and 2035, e-fuel uptake accelerates markedly, more than doubling its share of total fuel consumption. By 2035, e-fuels account for 32% of total fuel use under the **Policy-Intervened Market-optimal scenario**, compared with 28% under the **Proactive scenario** without policy support. This demonstrates that even when shipping companies prioritize market conditions over maximizing emissions reductions, targeted cost support can significantly accelerate both the pace and scale of the fuel transition.

Policy-driven reductions in e-fuel prices also significantly reduce total shipping costs. Under the **Market-optimal scenario**, e-fuels account for only 11% of total fuel use by 2035 in the absence of policy intervention, but this share increases to 32% with policy support. Despite higher e-fuel uptake, total costs are approximately USD 1,544 million lower under the **Policy Intervention scenario**. This underscores that the high cost of e-fuels remains the principal barrier to decarbonization in shipping, and that public cost support can serve as a decisive lever to accelerate the transition.

These findings highlight the central role of government action in advancing the decarbonization of international shipping. The transition to e-fuels poses a structural challenge that individual shipping companies alone cannot address, particularly in the early stages, when high costs and supply uncertainties constrain uptake. Accordingly, governments play a critical role in enabling the transition by supporting e-fuel production and supply chains, developing port infrastructure, and providing financial and fiscal incentives for investment in ZNZ vessels.

In conclusion, the postponement of the IMO NZF should not be interpreted as a signal to slow down decarbonization efforts, but rather as a strategic window to prepare for an inevitable industrial transition and potentially more stringent future emissions requirements. Policy gaps that delay the adoption of ZNZ fuels risk increasing long-term costs and eroding the competitiveness of the shipping sector. For the Korean shipping industry to secure sustainable competitiveness in the global decarbonization transition, the government and industry must proactively define the direction and pace of the transition together, rather than passively waiting for clearer international regulatory signals.

Table of Contents

I. Introduction

In April 2025, the International Maritime Organization (IMO) took an important step toward establishing a legally binding global framework to reduce greenhouse gas (GHG) emissions from ships. The IMO Net-Zero Framework (NZF), approved by the Marine Environment Protection Committee at its 83rd session (MEPC 83), is intended to be incorporated into draft amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI.

The NZF introduces mid-term GHG emissions reduction measures that require ships of 5,000 gross tonnage (GT) and above engaged on international voyages to progressively reduce their attained annual GHG fuel intensity (GFI). Under NZF, ships that fail to meet the requirements must purchase Remedial Units (RUs), while those that exceed the requirements can generate Surplus Units (SUs). This market-based mechanism is intended to facilitate the uptake of lower GHG-intensity fuels in international shipping.

The NZF was originally scheduled for formal adoption at the second extraordinary MEPC session in October 2025, ahead of its planned entry into force in 2028. However, the IMO adjourned the session, citing insufficient consensus among member states. The extraordinary session is expected to reconvene within 12 months, while the timeline and detailed implementation guidelines will be discussed at MEPC 84 in 2026.

1. Maritime Decarbonization in Korean Shipping

The IMO's decision to delay adoption of the NZF was far more than a procedural delay; it reflected unresolved political, policy, technological, and economic tensions. Key issues included limited readiness among developing countries and small and medium-sized shipping companies, nascent supply infrastructure and technology for alternative fuels, the need for detailed rules governing the RU-SU trading mechanism, and persistent disagreement among member states over the allocation of climate mitigation responsibilities.

Another major concern is the cost and administrative burden stemming from overlapping regulations. Once the NZF is implemented alongside the EU Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation—both fully in force since 2025—shipping companies are likely to face dual compliance obligations.

Against this backdrop of heightened regulatory uncertainty, Korea is in a particularly constrained position. The country depends heavily on maritime transport, which carries 98% of its international trade, and it is also the world's sixth-largest shipping powerhouse. Although there is a strong imperative to keep pace with global decarbonization and shipping transition trends, Korea faces several structural constraints.

First, Korea's internationally operating fleet is directly exposed to the EU ETS and FuelEU Maritime, as a significant share of the routes call at European ports. Under the EU ETS, the proportion of a ship's total GHG emissions subject to regulatory obligations is scheduled to increase to 40% in 2025, 70% in 2026, and 100% by 2027. FuelEU Maritime imposes penalties for noncompliance with the GHG intensity targets. Layering the NZF on top of these regional regulatory frameworks is therefore likely to impose additional costs on the Korean shipping sector.

Second, transition strategies adopted by the Korean government and the shipping industry raise feasibility concerns. Many rely on liquefied natural gas (LNG) as an interim fuel. However, LNG's full lifecycle GHG intensity differs only marginally from that of conventional fossil fuels, and methane slip[1] from LNG-fueled vessels further erodes any emission reduction benefits. Given these limitations, LNG is unlikely to be considered a sustainable transition option under the IMO's pathway toward global maritime net-zero by 2050.

Third, Korea's adoption of zero- and near-zero-emission (ZNZ) fuels is still in its early stages due to limited commercial viability, unstable supply, and insufficient infrastructure. Within the current domestic policy context, ZNZ fuels are unlikely to become a scalable alternative in the short term. The lack of technological and infrastructure maturity may further burden the shipping industry as it prepares for the NZF implementation.

These constraints should be understood in the context of the cumulative burden created by the IMO's short-term GHG reduction measures already in force, as well as the rising cost pressure from overlapping EU regulations. At the same time, the IMO's 2050 Net-Zero goal remains in place regardless of the delay in adopting the NZF.

While the one-year postponement may provide a limited window for additional preparation, the NZF will impose strict demands on the industry. Meeting the GFI targets will require a fundamental shift in fuel use that goes beyond operational optimization. These challenges underscore the need for industry-wide preemptive action well before the NZF measures are implemented.

1 Methane slip is the emission of unburned methane from ship engines using methane-based fuels such as LNG. As methane has a much higher global warming potential (GWP) than CO_2, even small amounts of slip can substantially affect the overall GHG.

2. Continuity of IMO GHG Regulations

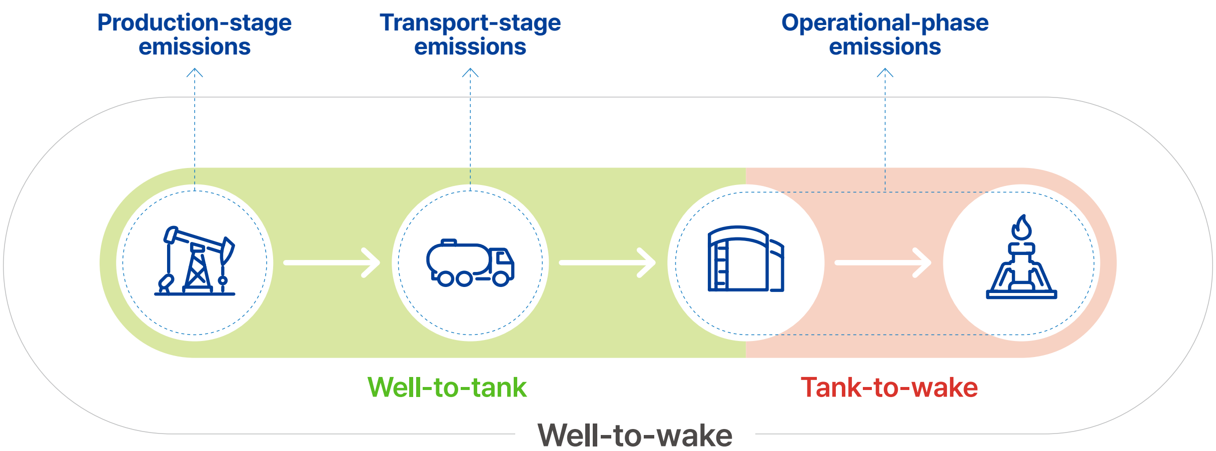
Since January 1, 2023, the IMO's short-term measures have required all ships of 5,000 GT and above to report their Carbon Intensity Indicator (CII). The CII calculates a ship's carbon dioxide (CO_2) emissions intensity using actual operational data, including fuel consumption, distance traveled, and deadweight tonnage. Ships are rated against a reference benchmark and a required reduction factor that becomes more stringent over time. Vessels that fail to meet the required performance level may be subject to corrective actions, verification, and even operational limitations.

The reduction factor—known as the "Z-factor"—specifies the required annual operational CII reduction relative to the 2019 reference level for a given year. At MEPC 83, the IMO set the 2030 Z-factor at 21.5%, with interim values determined for the intervening years.

The CII regulation, with its data-driven focus on improving operational efficiency, is a foundational component of the IMO's decarbonization agenda. However, concerns have been raised about potential administrative and regulatory overlap between the CII and the NZF, which were originally expected to be adopted in October 2025.

A central distinction is the scope of emissions. The NZF introduces GFI accounting for well-to-wake emissions using lifecycle assessment (LCA) methodologies, whereas the CII considers only tank-to-wake CO_2 emissions. This mismatch has heightened concerns about duplicated reporting requirements and compliance complexity.

[Figure 1] Lifecycle Emissions for Shipping Fuel under IMO Regulations



Even with the postponement of the NZF, the IMO's short-term measures remain in effect and continue to tighten. Another key requirement, in force since 2023, is the Energy Efficiency Existing Ship Index (EEXI), which requires existing ships to improve energy efficiency through technical measures such as engine power limitation (EPL) or the installation of energy-saving devices (ESDs).

Korean shipping companies, however, risk falling behind. Concerns have been repeatedly raised that many aging bulk carriers and tankers may receive CII ratings of D or E, requiring them to submit and implement corrective action plans. According to Korea Register's 2024 CII verification results, most ships rated C or below were bulkers, tankers, LNG carriers, and Ro-Ro cargo ships, accounting for more than half the total.[2] Recent research similarly suggests that Korean tankers and Ro-Ro cargo ships face a higher risk of being rated D or below than the global average.[3]

Lower ratings can have far-reaching implications beyond administrative burden. Poorly rated ships may lose competitiveness in the charter market and be pressured to accept lower charter rates or less favorable terms. Although some operators attempt to improve ratings through speed optimization, such short-term operational adjustments can increase long-term costs, as reduced efficiency may require additional vessels to maintain service levels.

[Figure 2] Korea's CII Rating Distribution by Ship Type

YEAR	2023		2024	
	A~B	C~E	A~B	C~E
Container Ship	44%	56%	61%	39%
Bulk Carrier	26%	74%	25%	75%
Tanker	39%	61%	41%	59%
LNG Carrier	41%	59%	40%	60%
GAS Carrier	53%	47%	60%	40%
General Cargo Ship	57%	43%	66%	34%
RO-RO Ship	9%	91%	11%	89%
Others	80%	20%	70%	30%

Source: Korean Register

2 Jinhee, K, *2024 IMO DCS/CII Verification Results and Status*, KR Decarbonization Magazine, Vol 8, 2024.

3 Jueun, H. *Global Top 100 Shipping Companies by Environmental Performance (2025) – Is Korea's Shipping Ready for the Net-Zero Era?* Solutions For Our Climate, 2025, p. 22, 24.

Importantly, the IMO’s short-term measures and the NZF are not separate tracks; they form a continuum within the IMO’s phased transition strategy. While the CII targets operational carbon intensity, the GFI directly addresses GHG intensity across the fuel lifecycle. Similarly, while the EEXI focuses on improving vessel energy efficiency, the GFI is designed to drive a fundamental transition toward ZNZ fuels.

In this context, vessels that fail to comply with the short-term measures are likely to face compounded regulatory burdens once the NZF takes effect. To enhance alignment with the NZF, the revisions to the CII standards are also under discussion at the IMO, including a potential shift toward assessing emissions on a life-cycle basis.

Using quantitative analysis, this report examines the implications of NZF for Korea's shipping sector and assesses the industry's policy readiness for NZF's planned 2028 implementation. Based on findings, this research also explains the significance of NZF's one-year adjournment and proposes compliance strategies and policy recommendations to help both the industry and the government navigate the increasingly comprehensive decarbonization requirements.

II. Methodology & Scenarios

1. Data

This study's quantitative assessment of how the IMO's short-term measures and NZF affect Korean shipping is based on commercial operations data from the Clarksons Research. The dataset covers Korean-operated vessels with a gross tonnage of 5,000 GT or more engaged in international voyages as of 2024. In total, it includes approximately 870 ships[4], with key operational variables such as annual fuel consumption and total distance traveled. To ensure data integrity, ships without verified carbon footprint data as of 2024 are excluded. Vessels in the order book as of the same year are included and reflected according to their delivery year.

Cost projections for fossil and alternative fuels rely on market prices as of June 2025, supplemented by scenario assumptions from the Methanol Institute.[5] Fuel-specific GHG emissions intensity is calculated using LCA. Well-to-tank emission factors follow the FuelEU Maritime standards. Baseline fuel GFI values were derived from both FuelEU Maritime reference averages and widely adopted global benchmarks, in order to reflect variations in production locations and differences in engine efficiency.[6] Tank-to-wake factors are taken from IMO values. The analysis covers CO_2, methane (CH_4), and nitrous oxide (N_2O), with emissions aggregated using 100-year global warming potentials (GWP100) to enable consistent comparison across fuel types.

2. Analysis Methodology

To quantify the financial burden that compliance with global GHG regulations may impose on Korean shipping, this paper develops an optimization model based on mixed-integer linear programming (MILP). The model identifies the least-cost combination of fuels and engines by ship type over a multi-year planning horizon.

4 *The Strategy for International Shipping Decarbonization* (2023), published by Korea's Ministry of Oceans and Fisheries, also covers ocean-going vessels of 5,000 GT or above (867 ships in total). To ensure comparability in scale and scope, this study uses data points that are broadly consistent with, but not identical to, those used in the Strategy.

5 Methanol Institute, *Economic Value of Methanol for Shipping under FuelEU Maritime and EU ETS*, 2024.

6 European Commission, *FuelEU Maritime Initiative*, 2023.

The objective function of the optimization model minimizes total costs, defined as the sum of: (1) fuel costs required for vessel operation; (2) the cost of RUs purchased when ships fall short of the IMO's annual emissions targets; and (3) net revenues from SUs generated through over-compliance, which are treated as offsets that reduce total costs. By jointly integrating operating costs, compliance penalties, and rewards, the model determines an optimal long-term pathway for shipping companies, including which fuel to select and when to replace the engine.

The model is subject to the following constraints:

1) In any given year, each ship selects a single engine option and can use only fuels compatible with that engine.
2) The fuel utilization ratio must sum to 100%, subject to fuel-specific minimum and maximum bounds.
3) Ships may switch fuels at most once per year, after meeting a minimum operating period requirement.
4) Lifecycle GHG intensity must meet the IMO's annual targets; RU penalties and SU credits are computed accordingly.
5) Ships enter the analysis only after their built year.

Under these cost and operational constraints, the model generates practical outputs for the Korean shipping industry, including optimal fuel mix trajectories, engine retrofit and upgrade pathways, and expected compliance costs.

3. Assumptions

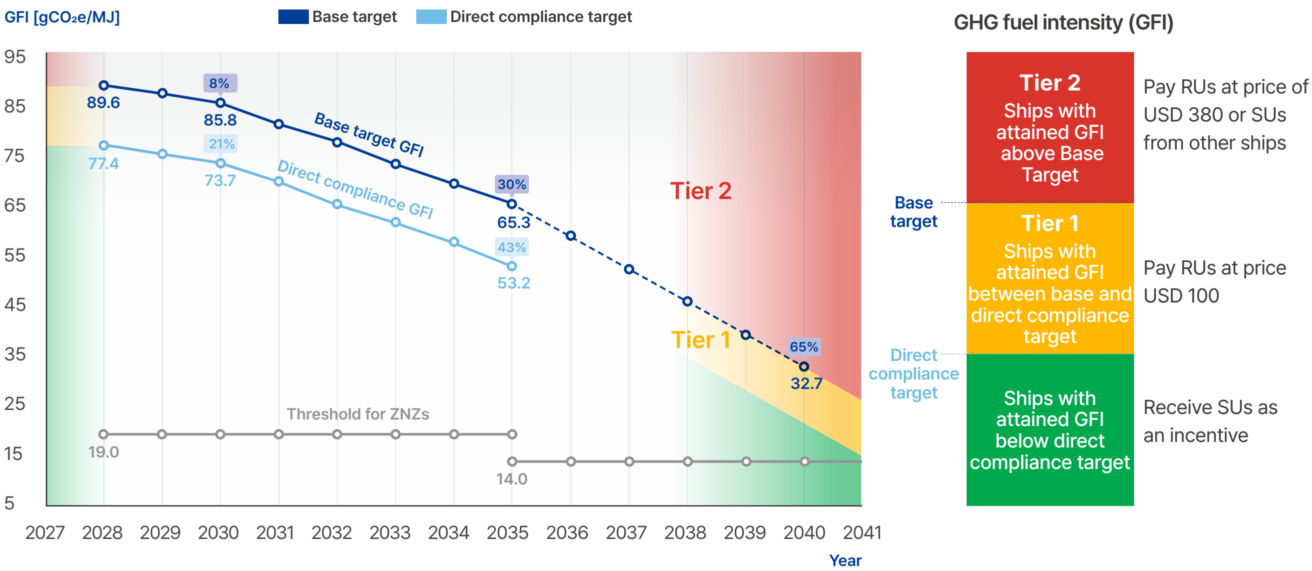
To maintain internal consistency and interpretability of results, the analysis adopts the following assumptions.

First, the NZF's core design and price parameters are assumed to remain unchanged despite the one-year delay in formal adoption. The delay is treated as affecting the timing of implementation rather than the substance of the measures. A Tier 1 RU (for direct compliance deficit) is set at \$100/tonne CO_2e, while a Tier 2 RU (for base compliance deficit) is set at \$380/tonne CO_2e. Because the NZF has not yet specified SU credit values, SU credits are assumed to be \$380/tonne CO_2e.

At the same time, the delay could increase long-term price pressure because the same reduction targets may need to be achieved over a shorter timeframe, while the decarbonization obligation under the 2030 IMO Strategy[7] on Reduction of GHG Emissions from Ships remains unchanged. Accordingly, this report applies the agreed price path while evaluating the structural impacts of upside risks to RU/SU pricing.

Second, fossil and alternative fuel prices are assumed to remain constant over the study horizon, excluding inflation and oil price volatility. However, ZNZ fuel costs (e.g., e-fuel) could decline as a result of government sustainability policies, even when those policies operate indirectly through infrastructure investment, R&D support, or enabling systems. The analysis includes policy intervention scenarios in which e-fuel costs decline linearly from 2028 to 2035 by up to 30%.

[Figure 3] **Key Elements of the IMO Net-Zero Framework**



Third, fuel efficiency gains from compliance with EEXI and CII are capped at 10%. This is treated as an achievable improvement based on 2024 fuel consumption levels and observed industry responses, including speed optimization, engine power limitation, and the adoption of energy-saving devices. The cap reflects the view that substantially larger gains are unlikely given technological, economic, and operational constraints.

7 The revised 2023 IMO Strategy on Reduction of GHG Emissions from Ships sets a net-zero emissions target by or around 2050. It also establishes emissions reduction targets relative to 2008 levels: at least 20% (striving for 30%) by 2030, and at least 70% (striving for 80%) by 2040. In addition, the Strategy also calls for zero or near-zero GHG emission technologies, fuels, and/or energy sources to account for at least 5% (striving for 10%) of the energy used by international shipping by 2030.

Fourth, transport demand is assumed to remain constant across all scenarios.

Together, these assumptions provide a coherent analytical basis that ensures practicality and consistency of the results. However, real-world market conditions may diverge from these parameters. The results should therefore be interpreted as strategic guidance under varying degrees of regulatory stringency and differing levels of policy support, rather than as point forecasts.

4. Scenario Development

The analysis evaluates compliance-cost and fuel-transition pathways for the Korean shipping industry, explicitly reflecting the linkage between the IMO's short-term measures (EEXI and CII) and the NZF (the GFI-based regulations). Six simulation cases are constructed by combining (1) the IMO's base and direct compliance targets and (2) the presence or absence of government policy support. Four scenarios are then selected for in-depth discussion.

[Figure 4] 6 Simulation Cases and 4 Scenarios Selected for In-Depth Analysis

Policy Intervention	Level of compliance		
	BAU (noncompliance)	Direct target compliance	Base target compliance
X	❶ **Baseline scenario** Tier 1 & 2 compliance	❷ **Proactive scenario** Earn SU credits	❸ **Market-optimal scenario** Tier 1 compliance
O	❹ **Policy intervention scenario**		
	(with 30% drop in e-fuel costs) **D30 Baseline scenario**	(with 30% drop in e-fuel costs) **D30 Proactive scenario**	(with 30% drop in e-fuel costs) **D30 Market-optimal scenario**

❶ Baseline Scenario (Noncompliance)

The **Baseline scenario** assumes current fuel consumption patterns continue and shipping companies remain slow to switch fuels, while complying only with the minimum requirements of short-term measures. Under the NZF, companies must purchase Tier 2 RUs to cover the base target compliance deficit, with the cost burden rising over time. In the absence of government support, companies bear the full compliance obligation. This scenario illustrates the fundamental limits of a passive response and serves as a benchmark for comparison.

❷ Proactive Scenario (Direct Compliance)

This scenario assumes shipping companies take a proactive transition approach and meet the direct compliance targets. Shipping companies optimize their fuel mix to minimize their use of fossil fuels. As a result, RU penalties are avoided, and any SU credits generated are assumed to have only a limited effect on overall costs. Because no policy support is assumed, the scenario reflects a case in which proactive transition efforts increase operating costs, primarily through higher fuel expenditures.

❸ Market-Optimal Scenario (Base Compliance)

In this scenario, with no government support, companies pursue a market-based strategy to reduce total costs. In the **Proactive scenario**, fuel costs exceed the RU costs observed under the **Baseline scenario**. Accordingly, the **Market-Optimal scenario** assumes a more gradual pace of fuel transition, while adopting a strategic approach that balances cost considerations and regulatory compliance at a level sufficient to meet the NZF's base GFI targets.

Companies optimize fuel choices while also using market instruments. They adopt an economically efficient fuel mix based on alternative fuel prices and RU/SU transaction costs, and they purchase RUs to a limited extent where this reduces total costs. The result is a blended compliance strategy that meets regulatory requirements while minimizing overall expenditure.

❹ Policy Intervention Scenario (D30)

This scenario assumes that comprehensive, government-led sustainability policies reduce ZNZ fuel costs. Under the current NZF design, alternative fuel costs, which are often the dominant component of operating expenses, can exceed RU prices. As a result, aggressive emissions reductions may increase total costs in the absence of policy support.

To test the extent to which policy support can change this cost structure, the scenario assumes a linear decline in e-fuel costs of up to 30% by 2035 relative to 2028 levels. The analysis then examines how policy support that reduces operational costs can shift the relative attractiveness of transition pathways and reshape compliance cost dynamics.

Results for all six cases are presented, with a detailed focus on the interaction between policy support and cost structure in the four selected scenarios.

III. Results

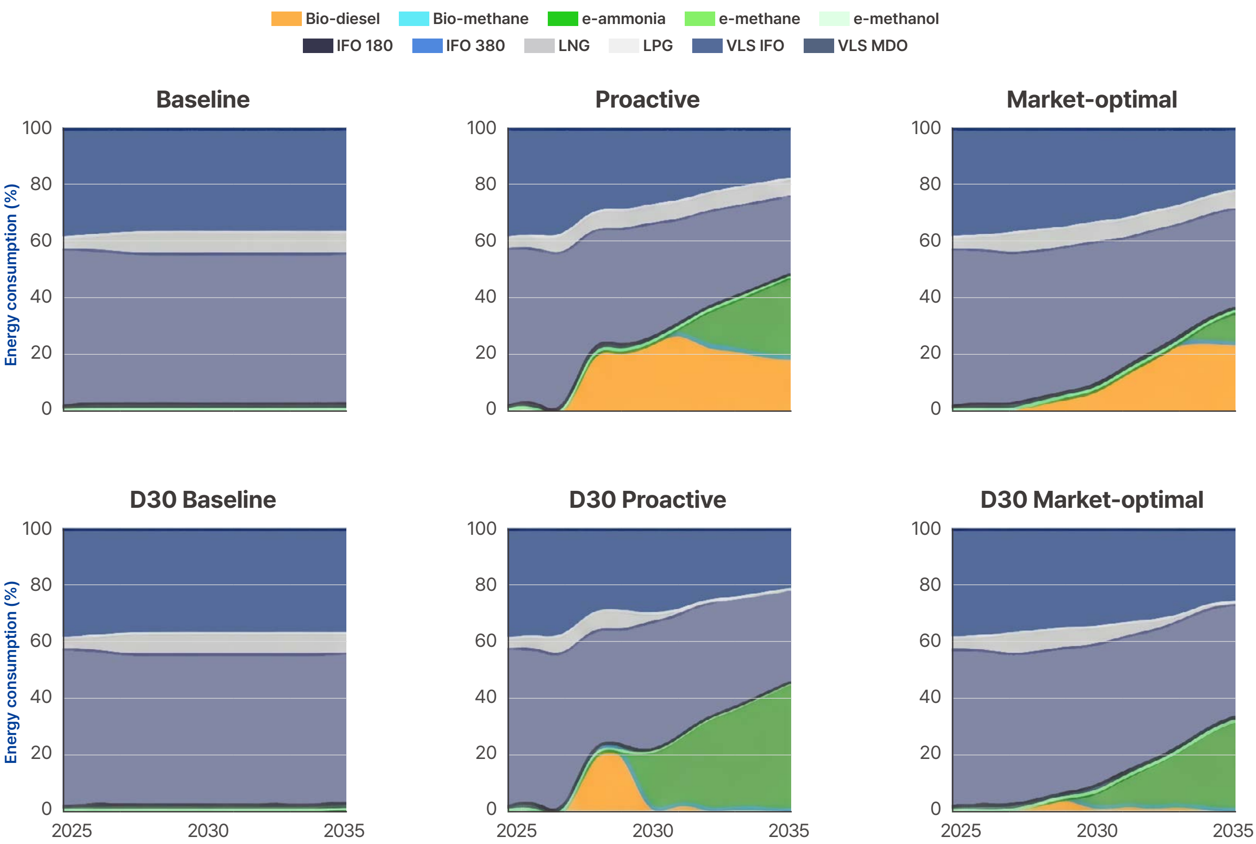
The results below summarize the projected fuel transition pathways and the combined fuel and compliance costs under each scenario.

1. Fuel Mix by Scenario

This section compares projected annual fuel mix trajectories through 2035 across four representative scenarios. The figure below illustrates expected adoption patterns for alternative fuels under the NZF—specifically, the pace and scale of uptake—assuming an initial improvement in fuel efficiency driven by the short-term measures.

Overall, the results suggest that fuel transition pathways are primarily shaped by two factors: regulatory stringency and the extent of policy support.

[Figure 5] Projected Annual Fuel Mix by Scenario



In the **Baseline scenario**, the fuel mix remains largely unchanged through 2035. Conventional fossil fuels retain a dominant position, while the volume of alternative fuels increases only marginally, largely reflecting limited adoption in newbuild orders.

Notably, even in the **D30 Baseline**—where government policies reduce e-fuel costs by 30%—the overall fuel mix shows little movement. This indicates that price support alone is insufficient to shift an entrenched fossil-fuel structure unless shipping companies pursue more proactive transition strategies.

In other words, government policy can reduce obstacles; however, it cannot replace the need for widespread behavioral change across the sector. Without better compliance incentives, the transition is unlikely to gain significant momentum.

In the **Proactive scenario**, shipping companies shift fuels early to meet the GFI requirements. Here, the regulatory signal is strong enough to prompt rapid restructuring of the fuel mix despite a higher operating cost burden. Biodiesel serves as a transitional option until around 2028, after which e-fuels become the dominant choice. As a result, reliance on fossil fuels declines quickly, increasing the likelihood of meeting direct compliance targets.

In the **D30 Proactive**, the same transition occurs more quickly. Companies begin adopting e-fuels from the outset rather than relying on biodiesel as an interim step. This suggests that government support does more than reduce cost burdens; it can materially accelerate the shift toward ZNZ fuels.

In the **Market-optimal scenario**, shipping companies transition only to the extent required to meet the base targets. Alternative fuel use increases beginning around 2028, but both the pace and scale of adoption are constrained. As a result, fuel transition occurs but at a modest scale, and a fossil fuel-dominated fuel mix persists for a considerable period.

However, once policy support is introduced, the trajectory changes. In the **D30 Market-optimal**, policy interventions that reduce e-fuel prices by a fixed margin led to a faster expansion of alternative fuel use. As the price effect takes hold, the fuel mix increasingly converges toward that of the **Proactive scenario**. For example, by 2035, e-ammonia accounts for approximately 28% of total fuel consumption under the **Proactive**, compared with about 32% under the **D30 Market-optimal**. This indicates that even when shipping companies pursue cost-minimizing strategies aligned with market conditions, public support can substantially accelerate and deepen the fuel transition.

Taken together, the **Policy Intervention scenario** results show that price support functions not only as a lever to reduce fuel costs but also as a catalyst that can shape the timing and scale of the transition. In particular, lower e-fuel prices emerge as a decisive factor in enabling earlier and broader adoption of ZNZ fuels. Under the **D30 Market-optimal**, e-ammonia uptake remains limited, reaching only about 4% of the fuel mix by 2030. By contrast, under the **D30 Proactive**, e-ammonia adoption begins early in the NZF regulatory period and rises to nearly 18% by 2030.

This divergence indicates that policy support affects not only cost outcomes but also the underlying transition dynamics. When industry decarbonization efforts are complemented by government measures that reduce e-fuel prices, the transition shifts toward faster and more widespread deployment of ZNZ fuels.

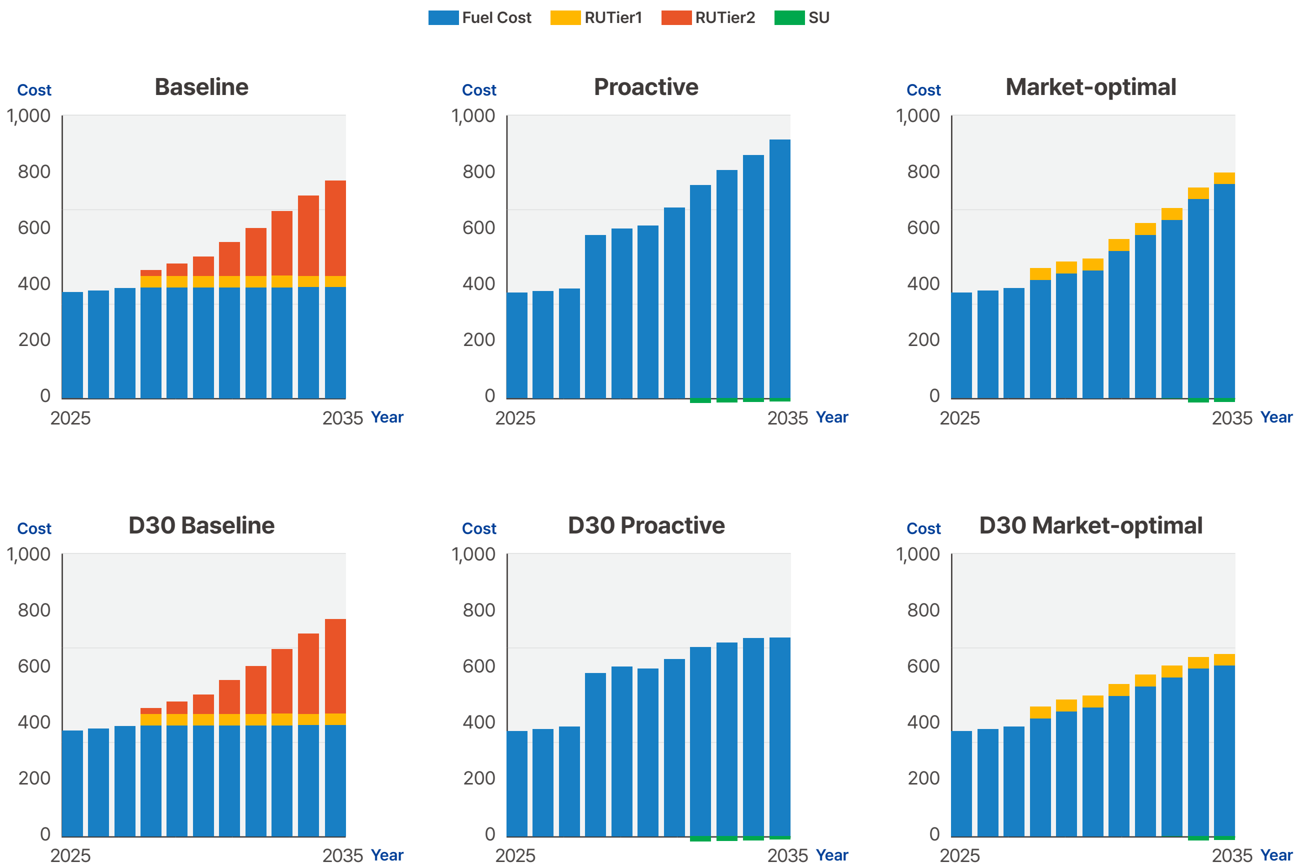
Across the **Policy Intervention scenarios**, ZNZ fuel use more than doubles, and the fuel mix shifts away from fossil fuels substantially faster than in the non-D30 cases. At the same time, the results also highlight an important constraint on policy effectiveness: without regulatory pressure, price reductions alone have a limited ability to induce large-scale transition. To enable pricing support to function as more than a subsidy and as a strategic policy tool that triggers and sustains decarbonization, the industry must already be moving through a compliance-driven transition, supported by technological readiness and investment.

2. Fuel and Compliance Costs by Scenario

This section compares the economic implications of transition choices and the regulatory burden of non-compliance across scenarios. The figure below presents projected cost trajectories through 2035, including fuel costs, RU penalties, and SU credits.

[Figure 6] Projected Annual Fuel and Compliance Costs by Scenario

Unit: USD 10M



In the **Baseline scenario**, RU penalties apply from the first year of NZF implementation, since the primary compliance effort is limited to operational efficiency improvements. RU costs increase over time, and Tier 2 RU expenses accumulate rapidly, reaching a level comparable to fuel costs by 2035.

Importantly, the RU price levels assumed here apply only through 2030. Starting in 2031, new prices are expected to apply, to be determined at MEPC 86 (scheduled for 2027 under the original timeline). The Z-factors for the base and direct compliance targets for 2036-2040 will also be set at that stage and are expected to tighten in line with the NZF, with the "no backsliding" principle. These pending updates imply that actual regulatory costs borne by the shipping companies could ultimately exceed those reflected in this analysis.

In the near term, the **Baseline scenario** may appear to be the lowest-cost option because future RU prices and long-term Z-factors remain uncertain. Over time, however, this advantage erodes. As regulatory stringency increases, the cumulative cost of non-compliance is likely to rise sharply and may eventually exceed fuel costs.

In the **Proactive scenario**, rapid adoption of alternative fuels increases fuel expenditures from the outset. In 2028, when the NZF takes effect, fuel costs are estimated to be about 1.4 times those of the **Baseline scenario**. However, no RU costs are incurred under this scenario, and from 2032 onward, the accumulation of SU credits creates potential for further reductions in total costs. Overall, the **Proactive scenario** involves higher upfront costs but offers a strategy that eliminates regulatory risk and positions shipping companies to capture longer-term value.

The **Market-optimal scenario** falls between the preceding scenarios. Both fuel costs and RU costs accrue, but the slower pace of fuel transition helps smooth total costs and reduce volatility. This pathway represents a practical middle ground for companies that cannot transition immediately, while keeping RU liabilities within a manageable range.

In the **Policy Intervention scenario**, reduced e-fuel prices mitigate increases in fuel costs, allowing companies to comply with the NZF requirements without incurring RU penalties. In some cases, companies can also generate revenue through SU credits. This finding indicates that sustainability policies can function as more than conventional fiscal support, as they can materially alter the shipping sector's medium- to long-term cost structure.

Although the **Baseline scenario** may appear cost-effective in a point-in-time comparison, such snapshots are insufficient for evaluating strategic trade-offs. Comparing scenarios requires tracking the evolution of total costs over time and understanding how distinct cost structures form and compound.

Under the **Policy Intervention scenarios**, aggregate costs through 2035 are highest for **D30 Baseline** (USD 7,780M), followed by **D30 Proactive** (USD 6,995M) and **D30 Market-optimal** (USD 6,393M). These RU cost estimates are based on current policy assumptions. Actual costs could increase significantly if further delays narrow the compliance window or if additional regulatory stringency is introduced. This represents an upside risk that would disproportionately affect companies that are slower to adapt.

By contrast, fuel cost trajectories are more predictable because they are anchored in observable market prices and can decline over time as technologies mature and policy support expands. RU costs, however, are inherently more exposed to regulatory revisions and market dynamics, creating potentially unbounded upside risk.

Ultimately, assessing the strategic impact of each scenario requires an examination of how costs evolve over time, beyond their face value. A clear understanding of cost composition and cost trajectories is essential for balancing sustainability objectives, regulatory exposure, and long-term economic outcomes across scenarios.

IV. Implications

1. Implications for Structural Constraints in Korean Shipping

The structural challenges identified in the introduction are examined in light of the modeling results, with particular attention to their implications for cost structures and compliance pathways. Beyond theoretical analysis, this assessment considers how these findings apply within the current regulatory and market context.

First, regulatory overlap can compound compliance costs across multiple layers. Because the model developed in this study does not explicitly incorporate the direct cost impacts of EU regulations, the **Baseline scenario** appears to be the lowest-cost pathway within the defined model scope. However, in the actual regulatory environment, regional compliance costs would interact with the NZF, leading cumulative expenditures to rise sharply once overlapping obligations are taken into account.

This dynamic reveals a structural vulnerability specific to the Korean shipping sector: the longer the transition is delayed, the more rapidly delay costs escalate relative to proactive transition costs. In other words, what appears to be a cost-minimizing strategy in the short term may, under conditions of regulatory overlap, evolve into a disproportionately burdensome pathway over time.

Second, an LNG-centered transition strategy is unlikely to deliver the emissions reductions required under the NZF. Because LNG lifecycle emissions vary widely depending on engine type, fuel origin, and upstream energy inputs, this study applies the average lifecycle emission factors defined under FuelEU Maritime. The scenario outputs show no meaningful increase in LNG use across the model horizon. Across all scenarios for the Korean fleet, LNG accounts for less than 10% of the fuel mix, indicating limited cost-competitiveness and strategic relevance within the modeled transition pathways. In policy intervention cases, LNG use even declines as ZNZ fuels scale up.

These results point to LNG's limited effectiveness in meeting GFI targets and in reducing full lifecycle GHG intensity at the required pace. Moreover, LNG use can undermine decarbonization objectives through methane slip and methane leakage, emitting one of the main super pollutants with a substantially higher GWP100 than CO_2. Taken together, the findings reaffirm that LNG is an unlikely candidate for a durable transition fuel under the NZF, and any residual benefits are likely to diminish as regulatory stringency increases.

These structural limitations are unlikely to be fundamentally resolved in the case of e-LNG. Although e-LNG offers a theoretical advantage in that CO_2 emissions during the production process can be reduced, the fuel's physical composition remains methane. As a result, risks associated with methane leakage during transport and methane slip during combustion persist. This suggests that, from a life-cycle GHG mitigation perspective, e-LNG struggles to secure a structural advantage over other ZNZ fuels. Furthermore, investment in e-LNG is likely to extend the lifespan of existing fossil-fuel-based LNG infrastructure, thereby increasing the risk of fossil fuel lock-in. Consequently, its alignment with mid- to long-term decarbonization strategies is considered limited.

Third, e-fuels emerge as a viable transition pathway only when regulatory pressure is combined with proactive green policy intervention. Under the **Market-optimal scenario**, which meets the NZF base target, a 30% policy-driven reduction in e-fuel prices advances adoption to around 2030 and roughly doubles their share of total fuel use. By 2035, the difference in total system costs between the **Market-optimal scenario** with and without government intervention amounts to approximately USD 1,544M. This indicates that reducing ZNZ fuel prices through policy can substantially ease the cost burden of fuel transition for shipping companies.

2. Strategic Recommendations for Maritime Decarbonization

The one-year adjournment of NZF does not meaningfully reduce the long-term regulatory burden. Even if formal adoption is delayed, the IMO's 2050 Net-Zero Strategy and associated GFI reduction pathway remain intact. If shipping companies treat the postponement as a reason to slow down, the eventual compliance burden is likely to increase rather than decrease.

Furthermore, the debate over including upstream emissions in the CII calculation is happening at the IMO level, shifting the focus from current operational emissions to the LCA approach.[8] If implemented, this will allow the CII and GFI to support each other more effectively while minimizing perceived duplication and enhancing regulatory consistency.

8 Korea Maritime Cooperation Center. (2025). IMO CII Revisions and Industry Responses.

In this regard, the most immediate priority for shipping companies is to strengthen compliance with short-term measures, particularly the CII requirements, which already define Z-factor targets through 2030. Shipping companies should maximize operational and technical efficiency through operational optimization, energy-saving devices, and engine power limitation to improve near-term ratings and lay the foundation for the upcoming NZF.

At the same time, companies should use the current interlude to prepare for the structural transition. This means securing future access to ZNZ fuels through global supply planning, developing capital investment roadmaps for next-generation vessels, and expanding bunkering and related infrastructure. The postponement should not be interpreted as an opportunity to delay, but as a narrowing window to act before stricter requirements take effect.

The analysis also highlights the enabling role of public policy. Transitioning to ZNZ fuels requires coordinated investment in vessel retrofits, bunkering systems, and scalable fuel supply chains, often simultaneously. These shifts involve substantial upfront capital and technological uncertainty, limiting the capacity of individual companies to pursue their own roadmaps.

Yet the Korean government has not established a concrete policy framework specifically targeting ZNZ fuel deployment. Existing policy efforts primarily support the construction and deployment of eco-friendly vessels and related infrastructure. Because LNG-fueled vessels are also classified as "eco-friendly"[9], public resources are distributed across fuel pathways with differing long-term decarbonization potential. Meanwhile, dedicated policy instruments to develop ZNZ fuel supply chains or directly incentivize the use of ZNZ fuels, including e-fuels, remain limited. This policy gap constrains shipping companies' ability to recognize ZNZ fuels as a viable operational alternative.

A more coordinated strategy is therefore required, focused on price stability, supply expansion, and infrastructure readiness. Policy instruments could include investment in e-fuel production capacity, reductions in renewable energy costs, port modernization, targeted fiscal incentives, and expanded green finance. Early and sustained public coordination will be essential to anchor credible transition pathways.

9 Yumin, H. (2023). *Limitations of LNG in Shipping Decarbonization*. Solutions For Our Climate.

V. Conclusion

This research examines the structural constraints faced by Korean shipping amid heightened regulatory uncertainty following the delayed adoption of the NZF, and it evaluates projected decarbonization pathways for international shipping. The analysis indicates that the one-year postponement does not reduce GHG reduction obligations. The IMO's short-term measures are already in force, and they operate alongside regional regulations. If shipping companies defer transition planning and execution, cost and compliance burdens are likely to compound over time.

Key findings are as follows:

1) While the **Baseline scenario** may appear cost-effective in the near term, cumulative regulatory penalties can eventually exceed the higher operational expenditures associated with fuel switching, particularly if RU prices rise non-linearly over time. This highlights the inherent vulnerability of delaying fuel transition.

2) LNG-centered transition strategies are unlikely to meet GFI requirements due to LNG's lifecycle emissions profile and may further undermine reduction targets through methane slip. Accordingly, LNG is unlikely to serve as a sustainable transition fuel under tightening decarbonization targets in global shipping.

3) ZNZ fuels such as e-fuel can scale meaningfully when regulatory pressure is paired with policy support. E-fuel price support materially reshapes the timing and scale of adoption, underscoring the government's essential role in shaping the market.

Taken together, the results suggest that Korea's maritime decarbonization trajectory will depend on aligning company-level transition strategies with a coherent national policy framework. In the mid-term, this requires strengthening supply chains, infrastructure readiness, and coordinated transition planning. Over the longer term, stable regulatory signals and financial support mechanisms will be critical to sustaining industry-wide transformation.

The postponement of the NZF should therefore be treated as a strategic inflection point. If proactive compliance is combined with coordinated policy support, Korean shipping can mitigate long-term risk, safeguard competitiveness, and position itself to participate in the emerging global fuel transition.

References

- European Parliament & Council of the European Union. (2023). *Regulation (EU) 2023/1805 of the European Parliament and of the Council*. Official Journal of the European Union.
- Jinhee, K. (2024). *2024 IMO DCS/CII Verification Results and Status*. KR Decarbonization Magazine, Vol 8.
- Jueun, H. (2025). *Global Top 100 Shipping Companies by Environmental Performance (2025) – Is Korea's Shipping Ready for the Net-Zero Era?* Solutions For Our Climate.
- Korea Maritime Cooperation Center. (2023). *Guidebook for Upgrading CII Rating*.
- Korea Maritime Cooperation Center. (2025). *IMO CII Revisions and Industry Responses*.
- Korea Maritime Cooperation Center. (2025). *Guidebook on the Amendment of the MARPOL Convention for IMO Mid-Term Measures 「Net-Zero Framework」*.
- Methanol Institute. (2024). *Economic value of methanol for shipping under FuelEU Maritime and EU ETS*. Methanol Institute.
- Smith, T., Frosch, A., Fricaudet, M., Langer, P., Cooper, T., Rehmatulla, N., & Oluteye, D. (2025). *An overview of the discussions from IMO's Marine Environment Protection Committee Extraordinary Session and Intersessional Working Group on GHGs 20th session, London, UK*.
- Yumin, H. (2023). *Limitations of LNG in Shipping Decarbonization*. Solutions For Our Climate.

Appendix:
Annual Changes in Marine Fuel Mix by Scenarios

Baseline

Unit: %

Fuel	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
IFO 180	1.32	2.12	2.08	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
IFO 380	55.64	54.73	53.78	53.36	53.36	53.36	53.36	53.36	53.36	53.36	53.36
LNG	4.04	4.77	6.53	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25
LPG	0.42	0.41	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VLS IFO	38.47	37.86	37.09	36.82	36.82	36.82	36.82	36.82	36.82	36.82	36.82
VLS MDO	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Grand Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Proactive

Unit: %

Fuel	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Bio-diesel	0.00	0.00	0.00	18.01	20.55	23.04	26.70	22.85	21.24	19.27	18.52
Bio-methane	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.02	0.01	0.00	0.01
e-ammonia	0.00	0.00	0.00	0.00	0.00	0.05	1.68	11.36	17.29	23.54	28.75
e-methane	0.00	0.00	0.00	0.70	0.70	0.70	0.70	0.69	0.70	0.70	0.69
e-methanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.02	0.00	0.01
IFO 180	1.32	2.13	2.08	2.03	2.03	1.53	1.46	1.23	1.05	0.88	0.65
IFO 380	55.87	54.96	54.01	42.36	41.02	40.65	36.95	34.07	31.90	29.63	27.32
LNG	3.63	4.37	6.15	6.32	6.32	6.32	6.32	6.29	6.29	6.29	6.25
LPG	0.42	0.42	0.41	0.42	0.42	0.42	0.39	0.41	0.41	0.42	0.41
VLS IFO	38.63	38.01	37.24	30.08	28.88	27.24	25.72	23.03	21.08	19.26	17.40
VLS MDO	0.12	0.11	0.11	0.08	0.08	0.05	0.04	0.00	0.00	0.00	0.00
Grand Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Market-optimal

Unit: %

Fuel	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Bio-diesel	0.00	0.00	0.00	2.00	4.05	6.48	12.05	17.62	23.15	24.10	23.41
Bio-methane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.05	0.01
e-ammonia	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.43	6.11	11.32
e-methane	0.00	0.00	0.00	0.07	0.67	0.70	0.72	0.70	0.70	0.69	0.69
e-methanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
IFO 180	1.32	2.12	2.08	1.90	1.50	1.65	1.54	1.94	1.92	1.39	1.22
IFO 380	55.64	54.73	53.78	52.45	51.59	50.63	46.42	43.06	39.65	36.88	34.92
LNG	4.04	4.77	6.53	7.18	6.69	6.69	6.68	6.66	6.36	6.36	6.32
LPG	0.42	0.41	0.40	0.41	0.41	0.41	0.42	0.42	0.42	0.38	0.42
VLS IFO	38.47	37.86	37.09	35.89	35.00	33.34	32.08	29.45	27.32	23.95	21.70
VLS MDO	0.12	0.11	0.11	0.09	0.09	0.06	0.05	0.05	0.05	0.04	0.00
Grand Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

D30 Baseline

Unit: %

Fuel	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
e-methane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59
IFO 180	1.32	2.12	2.08	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
IFO 380	55.64	54.73	53.78	53.36	53.36	53.36	53.36	53.36	53.36	53.36	53.36
LNG	4.04	4.77	6.53	7.25	7.25	7.25	7.25	7.25	7.25	7.25	6.66
LPG	0.42	0.41	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
VLS IFO	38.47	37.86	37.09	36.82	36.82	36.82	36.82	36.82	36.82	36.82	36.82
VLS MDO	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Grand Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

D30 Proactive

Unit: %

Fuel	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Bio-diesel	0.00	0.00	0.00	18.01	20.55	2.23	2.15	0.67	0.65	0.59	0.22
e-ammonia	0.00	0.00	0.00	0.00	0.00	18.25	23.26	31.24	35.83	40.52	45.31
e-methane	0.00	0.00	0.00	0.70	0.70	0.34	0.19	0.07	0.00	0.00	0.00
e-methanol	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.05	0.00	0.00
IFO 180	1.32	2.13	2.08	2.03	2.03	0.73	0.68	0.73	0.40	0.46	0.46
IFO 380	55.87	54.96	54.01	42.36	41.02	45.19	43.13	40.72	38.34	35.40	32.64
LNG	3.63	4.37	6.15	6.32	6.32	3.08	1.67	0.69	0.08	0.00	0.00
LPG	0.42	0.42	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.41	0.42
VLS IFO	38.63	38.01	37.24	30.08	28.88	29.68	28.42	25.46	24.24	22.62	20.94
VLS MDO	0.12	0.11	0.11	0.08	0.08	0.08	0.04	0.00	0.00	0.00	0.00
Grand Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

D30 Market-optimal

Unit: %

Fuel	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Bio-diesel	0.00	0.00	0.00	2.30	4.65	1.64	2.02	1.64	1.89	0.75	0.22
Bio-methane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
e-ammonia	0.00	0.00	0.00	0.00	0.00	4.73	9.24	14.53	19.56	27.31	32.24
e-methane	0.00	0.00	0.00	0.09	0.32	0.29	0.22	0.12	0.05	0.04	0.05
e-methanol	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.02	0.02	0.01
IFO 180	1.46	2.37	2.36	2.00	1.72	2.36	2.31	1.73	1.73	1.74	1.68
IFO 380	55.68	55.16	55.28	54.34	53.24	51.65	49.24	47.01	44.95	42.40	39.49
LNG	3.69	3.65	3.64	3.56	3.38	3.09	2.19	1.46	0.50	0.47	0.46
LPG	0.47	0.46	0.46	0.47	0.47	0.47	0.49	0.49	0.47	0.49	0.49
VLS IFO	38.58	38.22	38.12	37.14	36.10	35.71	34.20	32.93	30.78	26.75	25.36
VLS MDO	0.13	0.13	0.13	0.11	0.11	0.06	0.06	0.05	0.05	0.05	0.00
Grand Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

SFOC

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.