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Navigating IMO Net-Zero Framework: Potential Challenges and Refinements

Working Paper

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Executive Summary

Highlights:

- The IMO Net-Zero Framework is a significant step toward maritime decarbonization but raises concerns about incentive adequacy, cost gap closure, and long-term sustainability.
- Analysis shows potential under-utilization of surplus units (SUs) under the current system, which may weaken financial signals for investing in zero and near-zero emission (ZNZ) fuels.
- Refinements such as Reverse Compliance Trading (reversing SU trading flexibility from Tier-2 to Tier-1) or Differentiated Deficit Balancing (using uniform RU pricing but requiring multiple SUs or RUs to balance each Tier-2 deficit) can improve SU utilization, increase investment certainty, and strengthen decarbonization incentives.
- The ability to maintain sufficient and predictable revenue flows to the IMO Net-Zero Fund is crucial for funding ZNZ rewards and just transition measures, especially under varying fleet compliance strategies.
- A more flexible and targeted compliance structure can help avoid over-subsidization of transitional fuels (e.g., biofuels) and ensure robust, equitable support for long-term, sustainable shipping decarbonization.

This working paper critically assesses the recently approved IMO Net-Zero Framework, which sets out both Base and Direct Compliance (Strive) greenhouse gas intensity (GFI) targets for international shipping from 2028 onwards. While the framework represents an important milestone in the sector's decarbonization journey, there remain substantial questions about its effectiveness in closing the cost gap between conventional fuels and zero and near-zero emission (ZNZ) alternatives, as well as its ability to provide predictable incentives and secure sufficient revenue to fund a just transition.

The analysis draws on a range of future fuel transition scenarios published by DNV and Lloyd's Register, covering both conservative and ambitious pathways. It highlights several structural challenges in the current mechanism, such as the risk of surplus compliance units (SUs) under-utilization that introduces uncertainty for shipowners investing in cleaner fuels, and the potential over-subsidization of biofuels. In practice, these issues may reduce the mechanism's effectiveness in stimulating early and deep decarbonization, slow industry investment in greener technologies, and threaten the financial sustainability of the Net-Zero Fund. Scenario modelling demonstrates that, without careful calibration, the current framework could inadvertently lock in less sustainable fuels or limit the sector's ability to exceed even the minimum (Base) compliance targets.

To address these challenges, the paper proposes two targeted refinements to the compliance structure. First, introducing Reverse Compliance Trading—where Tier-1 deficits can be met with SUs, complemented by SU buyback option—would help ensure SUs are fully utilized, providing shipowners with greater certainty and value for investing in over-compliance. Second, Differentiated Deficit Balancing, where Tier-2 compliance requires multiple SUs or RUs per deficit unit but at a uniform RU price across both tiers, could improve SU utilization, minimize over-subsidization, and deliver more predictable revenue flows. Together, these refinements aim to create a more robust, equitable, and flexible regulatory environment—one that aligns industry incentives with long-term decarbonization goals and supports a smoother, more confident transition to sustainable shipping.

1. Introduction

The maritime sector is at a pivotal juncture in its decarbonization journey. With international shipping responsible for nearly 3% of global greenhouse gas (GHG) emissions, the International Maritime Organization (IMO) has introduced progressively ambitious measures to align with global climate objectives. Most recently, at the 83rd session of the Marine Environment Protection Committee (MEPC 83), member states approved the IMO Net-Zero framework, comprising a Global Fuel Standard (GFS), and a two-tier compliance and GHG pricing mechanism. These measures are designed to drive significant reductions in the GHG intensity of international shipping starting from 2028, signalling a major step toward the sector's long-term transition to net zero.

This paper aims to critically examine the effectiveness of the IMO Net-Zero Framework in advancing maritime decarbonization. Specifically, it assesses whether the framework offers sufficient and predictable incentives for the adoption of zero and near-zero emission fuels, addresses key concerns such as cost gap closure and surplus unit utilization, and ensures adequate revenue to support just transition objectives—each essential for the sector's decarbonization. The analysis draws on projected maritime energy transition pathways from leading industry reports, including DNV and Lloyd's Register (LR), to robustly test the framework under various plausible scenarios. The paper further proposes and evaluates refinements that can potentially strengthen the framework and can inform the future IMO deliberations. While this study incorporates a range of credible scenario projections that are well-aligned to achieve the IMO's decarbonization targets, as well as fuel cost and emission factor assumptions from established sources, the results and implications remain contingent on the underlying scenario and parameter choices adopted. Nevertheless, the analysis identifies potential hurdles that may arise as these scenarios unfold, underscoring the need for the framework to be robust and adaptable.

2. Key Elements of the IMO Net-Zero Framework

The approved IMO Net-Zero Framework features a two-tier compliance mechanism, provisions for pooling, banking, purchasing, and surrendering compliance units, and a centralized framework for collection and disbursement of compliance revenues.

Two-Tier Compliance: The GFS establishes annual GHG fuel intensity (GFI) targets, benchmarked to a baseline of 93.3 gCO_2e/MJ on a well-to-wake (WtW) basis. Each year, two targets are set: a more stringent **Direct Compliance (or Strive) Target** and a less stringent **Base Target**. Both targets become stricter over time through "Z-factors" (reduction factors): for Base Target, the Z-factor increases from 4% in 2028 to 8% by 2030 and 30% by 2035; for Direct Compliance Target, the Z-factor rises from 17% in 2028 to 21% in 2030 and 43% by 2035. A ship's annual GFI attained is assessed against these targets.

- **Over-Compliance:** Ships with GFI attained lower than Direct Compliance Target generate Surplus Units (SUs) that can be banked for up to two subsequent reporting periods, transferred to another ship to offset its Tier-2 deficit, or voluntarily cancelled as a contribution to mitigation efforts.
- **Two-Tier Under-Compliance:** Ships failing to meet Direct Compliance Target but achieve Base Target incur a Tier-1 deficit, which must be offset by purchasing Tier-1 Remedial Units (RUs) at a fixed price (100 \$/t-CO_2e until 2030). Ships exceeding Base Target incur both Tier-1 and Tier-2 deficits. Tier-2 deficit can be balanced by SUs acquired from other ships, using SUs that are banked

from previous periods, or by purchasing Tier-2 RUs at a higher price (380 \$/t-CO_2e until 2030). **Tier-1 deficits cannot be offset with SUs**, ensuring a direct penalty.

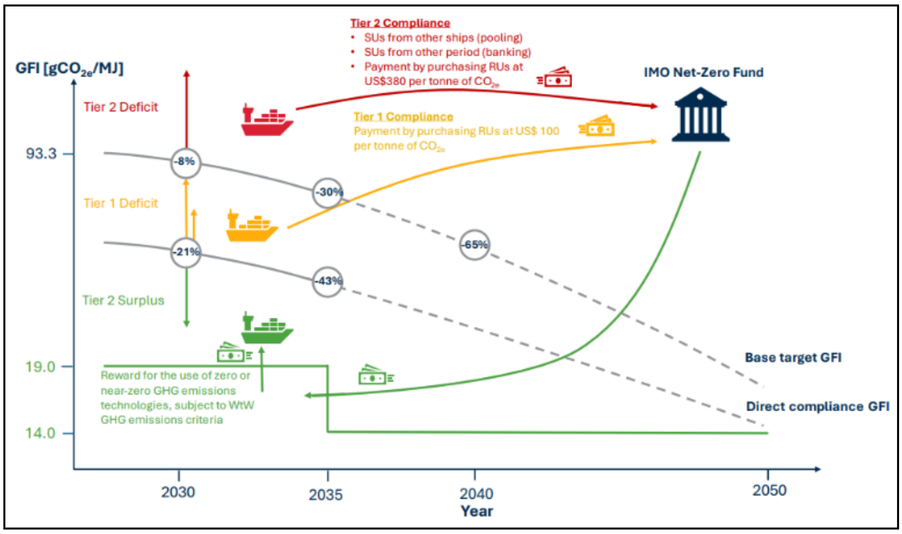

Figure 1: Overview of IMO Net-Zero Framework. (Source: New Brief 2025, ABS)

Revenue Collection and Disbursement: All revenues from RU sales (from both Tier-1 and Tier-2) are collected into a IMO Net-Zero Fund, which are ring-fenced for three principal purposes within the boundaries of the energy transition in shipping: *(1) ZNZ Rewards:* Incentives to ships using zero or near-zero GHG emission fuels, technologies, or energy sources (ZNZs), provisionally defined as those with GFI ≤19 gCO_2e/MJ (tightening to ≤14 gCO_2e/MJ from 2035). Eligible vessels receive financial rewards from the Fund, proportional to their GHG reductions. The reward formula and implementation methodology will be finalized by 2027. *(2) Just and Equitable Transition:* Supporting mitigation, adaptation, food security, and capacity-building in developing states, with emphasis on LDCs and SIDSs, and (3) Cover the administration and operational costs of the Fund and its Governing Board.

Cost Gap Closure: The IMO Net-Zero framework aims to meet the emissions targets of the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, accelerate the uptake of ZNZs, and support a just and equitable transition. Closing the cost gap between conventional and ZNZ fuels is therefore essential to reducing financial barriers, encouraging early adopters, and mobilizing the investment needed to achieve these decarbonization goals. A central element in accelerating ZNZ uptake is the use of financial incentives—primarily through the two-tier emissions pricing and ZNZ rewards. Ships exceeding the set GFI targets are required to purchase SUs or RUs, imposing a financial cost on excess emissions. Conversely, vessels that outperform GFI targets generate SUs proportional to their emissions reductions and may qualify for ZNZ rewards, providing financial incentives for low-emission operations. **SU trading provides compliance flexibility but creates uncertainty for shipowners, as the supply, demand, and market value of SUs can fluctuate each year**. Although the Tier-2 RU price sets an upper limit for the SU trading price, unpredictability in SU demand and value makes it harder for shipowners to plan low-carbon investments with confidence. In contrast, once established, ZNZ rewards will provide predictable incentives for ZNZ adoption, offering greater certainty for long-term investments. However, the reward disbursements are subject to the revenues collected from RU sales.

While the IMO's new regulations represent a significant step toward maritime decarbonization, critics express concerns about their effectiveness in accelerating the transition. Key issues include whether the measures provide **sufficient incentives for adopting ZNZ fuels** and effectively bridge the cost gap with conventional fuels to stimulate substantial investment. There are also concerns about possible **over-subsidization of fuels such as crop-based biofuels**, which may yield only temporary emission reductions while risking adverse outcomes resulting higher net emissions. Additionally, doubts remain over whether the framework will generate **sufficient revenue to support a just and equitable transition**. These issues highlight the need for further refinement of the Net-Zero Framework to ensure it promotes sustainable fuels and technologies. It is important to note that the IMO still needs to decide on many practical aspects of the Net-Zero Framework's implementation in upcoming sessions, and some of these outstanding concerns may yet be addressed as further details are finalized. In this working paper, we analyse these concerns, evaluate the likely impact of the framework under different transition scenarios, and offer recommendations to address the identified challenges.

3. Compliance Mechanism Assessment

- The study compares a Moderate Transition (LR-Hydrogen) scenario aligned with Base targets, an Accelerated Transition (DNV-Ammonia Reduced CCS) scenario aligned with Strive targets and an Intermediate Transition scenario (average of Moderate and Accelerated Transition scenarios).
- The Accelerated Transition scenario generates 30–50% unutilized SUs due to trading restrictions (only offsetting Tier-2 deficits) and the Intermediate Transition Scenario generates 7–32% unutilized SUs, reducing financial incentives and risking system inefficiency.
- Current SU and RU pricing structures significantly overcompensate biofuels like Bio-Methane, even after accounting for unutilized SUs, potentially encouraging unsustainable adoption.
- e-Ammonia cost gaps are modest under ideal SU utilization but rise sharply (requiring rewards up to \$181/t-CO_2e) when SUs remain unsold, highlighting the need for targeted ZNZ reward supplements.
- Compliance revenues and required rewards vary significantly by energy scenario (\$8.4–22.4B), indicating the need for a more adaptive and robust mechanism to balance incentives and prevent

As mentioned earlier, the IMO has set clear trajectories for maritime decarbonization, defining Base and Strive (direct compliance) targets from 2028 through 2035. These targets are specified by annual Z-factors, which specify percentage reductions from the baseline GFI of 93.3 gCO_2e/MJ. The IMO's approved Z-factors maintain a consistent 13 percentage point (pp) gap between the Base and Strive targets up to 2035. With 2040 Base target set at a Z-factor of 65%, we linearly extrapolated the Z-factor trajectories beyond 2035—maintaining the 13-pp gap between Base and Strive—for completeness, while **focusing our analysis primarily on the more clearly defined period from 2028 to 2035**.

3.1 Projected Fuel Transition Scenarios

Depending on how key factors such as fuel costs, technological advancements, and infrastructure evolve in response to the IMO Net-Zero Framework, numerous industry transition pathways are plausible. As it is not practical to analyze every scenario individually, this study draws on five representative fuel transition scenarios, informed by the projections from DNV (Maritime Forecast to 2050, 2024) and LR (The Future of Maritime Fuels, 2023). Notably, DNV's scenarios—developed using their detailed GHG pathway model—also informed the IMO's comprehensive impact assessment of mid-term measures and the recommended Net-Zero Framework. These scenarios, detailed below, span a broad spectrum of possible technological and fuel adoption pathways, providing a robust foundation to assess the implications of the approved compliance mechanism:

1. **DNV-Ammonia Scenario:** Assumes significant adoption of ammonia as a marine fuel, driven by its favourable cost structure as a long-distance energy carrier, the already substantial level of seaborne ammonia trade, and the limited availability of sustainable carbon for carbon-based e-fuels. CCS (Carbon Capture and Storage) technologies are assumed to play a substantial role.
2. **DNV-Methanol Scenario:** Assumes early adoption and expansion of bio-methanol, enabled by cost advantages for first movers over other biofuels, followed by a shift to e-methanol as biofuel availability becomes constrained.
3. **DNV-Ammonia Reduced CCS Scenario:** A variant of the DNV-Ammonia scenario, in which CCS contributions are adjusted significantly downward (from approximately 34% to about 8%). Consequently, greater reliance is placed on uptake of bio- and e-fuels.
4. **DNV-Methanol Reduced CCS Scenario:** Similar adjustment as above applied to the DNV-Methanol scenario, reducing CCS contribution and emphasizing increased bio- and e-fuel adoption.
5. **LR-Hydrogen Scenario:** Projects substantial use of hydrogen-based fuels—including blue ammonia and various e-fuels—alongside a gradual decline in fossil fuel use.

Detailed visual representations of fuel-mix trajectories in these scenarios, from 2025 to 2050, are provided in the Appendix which clearly illustrate the fuel transition paths. DNV's projections are calibrated to achieve the IMO's emissions reduction targets—20% by 2030 and 70% by 2040—through GFI requirements, without assuming any pooling or GHG pricing mechanisms. These projections are grounded in seaborne trade growth assumptions aligned with the OECD_RCP2.6_G (low growth) and SSP2_RCP2.6_L (high growth) scenarios from the Fourth IMO GHG Study. Notably, these same growth scenarios were also referenced in several key proposals (e.g., ISWG-GHG 18/2/1 [Japan] and ISWG-GHG 18/2/12 [China et al.]) that informed recommendations for Z-factors prior to MEPC 83. The LR-Hydrogen scenario is based on average trends from fuel-mix projections reported in the literature between 2020-2022 by sources such as IEA, IRENA, DNV, UMAS, ABS, Clarksons Research, the Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, and Ricardo Energy & Environment.

GFI projections for these scenarios—calculated as the global average GFI using the fuel-level formula $\sum_{fuels}(WTW_{fuelGFI} \times \text{Energy Uptake}_{fuel})/\text{Total energy uptake}$ and shown in ***Figure 2***—indicate that all five pathways lead to substantial emission reductions by 2050. However, focusing on the **critical period from 2028 to 2035**—where IMO provides explicit regulatory numbers (Z-factors and RU prices)—reveals notable distinctions. The four DNV scenarios consistently meet or slightly surpass the more ambitious Strive targets, while the LR scenario remains aligned with the Base targets during this period.

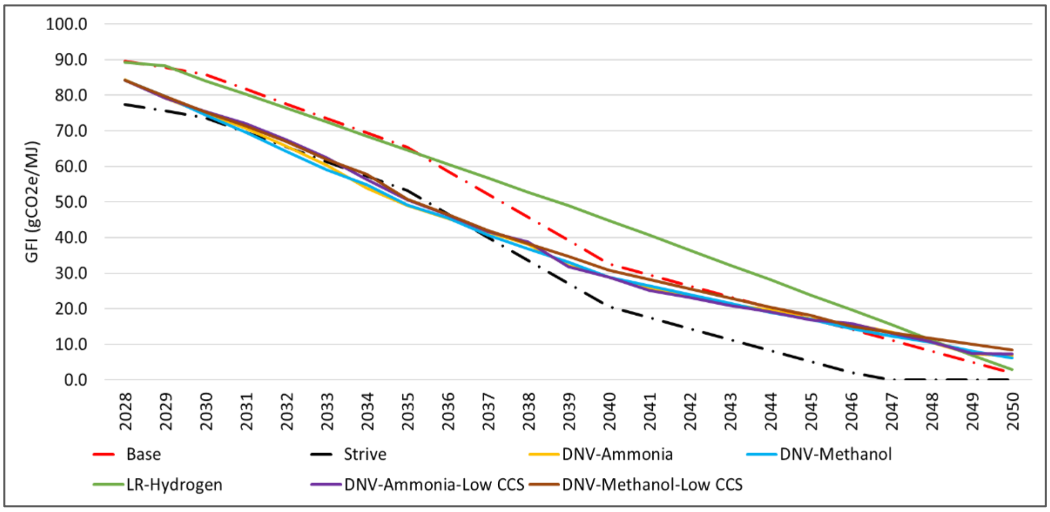

Figure 2: Approved Base & Strive Trajectories and GFI projections for the five selected transition scenarios.

DNV has also projected additional scenarios, including a 'Bio and Fossil Fuels with CCS' scenario (66% biofuel uptake and no e-fuel by 2050) and a 'Hydrogen' scenario (68% e-fuels by 2050, including 21% e-hydrogen), with GFI trajectories similar to the DNV scenarios discussed above. Similarly, LR has reported a biofuels scenario (79% biofuel and 16% e-fuel uptake by 2050), which also results in GFI outcomes closely matching those of the LR-Hydrogen scenario. These scenarios are excluded from further analysis due to long-term biofuel sustainability concerns, the greater likelihood of ammonia and methanol becoming dominant maritime fuels over hydrogen (aligned with the results from a study by UMAS & UCL, 2025, which conducted a TCO modelling on different fuel choices), and because their GFI trajectories closely mirror those of the main scenarios—meaning the results and implications would not differ significantly.

To facilitate a comprehensive comparative analysis while maintaining ease of understanding, we selected two scenarios from the above that represent opposite ends of projected GFI outcomes: the **DNV-Ammonia Reduced CCS scenario** and the **LR-Hydrogen scenario**. The LR-Hydrogen scenario—hereafter the '**Moderate Transition**' scenario—serves as a practical baseline, reflecting an industry approach on meeting only the minimum Base targets through a conservative fuel transition pathway, relying on a mix of fossil fuels and emerging alternatives to achieve compliance. In contrast, the DNV-Ammonia Reduced CCS scenario—hereafter the '**Accelerated Transition**' scenario—represents an ambitious upper bound, with the industry pushing toward deep decarbonization by maximizing low-carbon fuel uptake and utilizing all available resources—excluding significant CCS reliance. The rationale for selecting this scenario over other DNV scenarios is twofold: first, ammonia stands out as one of the most economically viable alternative fuels; and second, minimizing reliance on CCS—whose efficiency, scalability, and cost remain uncertain—offers a more realistic benchmark for assessing the highest decarbonization level achievable with current technological and supply constraints.

These two selected scenarios differ notably in their (please see ***Figure A1*** and ***Figure A2*** in the Appendix):

- **Energy demand trajectories**. The Moderate Transition scenario (LR-Hydrogen) projects global maritime energy consumption starting at about 9 EJ (Exa Joules) and gradually increasing to about 11 EJ by 2050. While the Accelerated Transition scenario (DNV-Ammonia Reduced CCS scenario) begins at a higher level of around 11 EJ and decreases slightly to about 10 EJ by 2050.
- **Fuel adoption pathways**. The Moderate Transition scenario (LR-Hydrogen) projects substantial use of fossil fuels (such as LSFO, HFO, and LNG) during the initial transition period (2028–2035), whereas the Accelerated Transition scenario (DNV-Ammonia Reduced CCS scenario) relies significantly on biofuels from early on. This early biofuel uptake, coupled with the higher total energy demand in the Accelerated Transition scenario, results in significantly more SUs compared to the Moderate Transition scenario. However, the demand for RUs across both compliance tiers remains comparable between the two scenarios, as a result of which the GFI attained is relatively lower in the Accelerated Transition scenario (see ***Table 1*** for more details).
- **Timing and nature of e-fuel adoption**. The Moderate Transition scenario (LR-Hydrogen) foresees early integration of both biofuels and e-fuels starting in 2028, whereas the Accelerated Transition scenario (DNV-Ammonia Reduced CCS scenario) does not project any e-fuel adoption until after 2035. These critical differences have important implications for SU generation, utilization, and revenue flows within the compliance framework.

As outlined above, the Moderate and Accelerated transition scenarios align with the Base GFI and strive GFI trajectories, respectively, during the critical period from 2028 to 2035. To provide a more comprehensive assessment of the Net-Zero Framework, we also introduce an '**Intermediate Transition**' scenario, with a GFI outcome falling between the Base and Strive trajectories (***Figure 3***).

This scenario is simulated by averaging the fuel uptakes of the Moderate and Accelerated scenarios. For example, if the projected VLSFO uptake is 8 EJ in the Moderate scenario and 6 EJ in the Accelerated scenario, the Intermediate Transition scenario projects a VLSFO uptake of (8+6)/2 = 7 EJ.

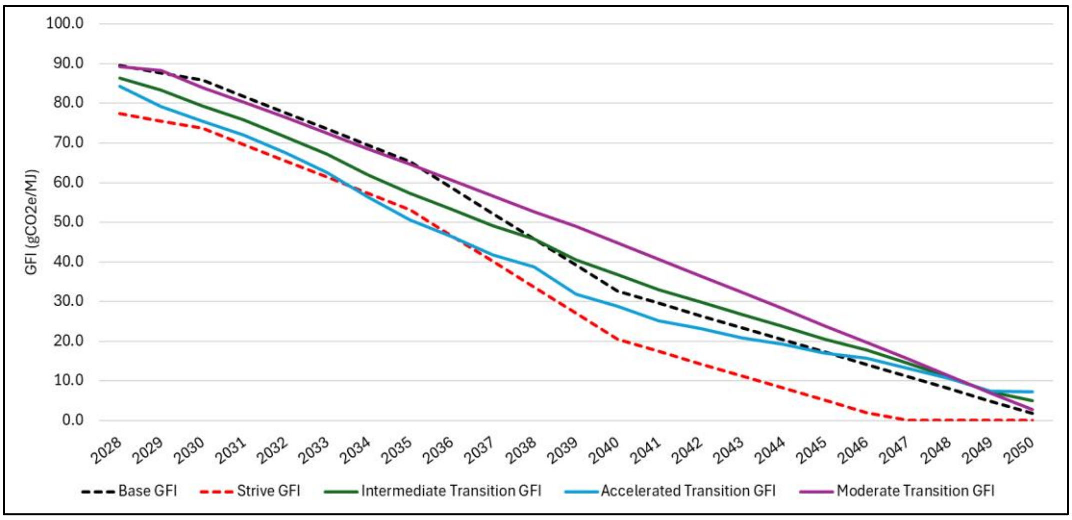

Figure 3: GFI projections for Accelerated, Moderate and Intermediate transition scenarios.

3.2 Scenario Analysis – Compliance Mechanism Assessment

Under the current Net-Zero framework, SU trading (or pooling) is permitted only to offset Tier-2 deficits. In the Accelerated and Intermediate Transition scenarios, this restriction leads to a substantial buildup of **unutilized SUs**—defined as the SUs remaining after all Tier-2 deficits are offset via SU trading, calculated as **(SUs generated – SUs traded)**. During 2028–2035, unutilized SUs account for 31%–50% of annual SUs generated in Accelerated Transition scenario, and 7%–32% in Intermediate Transition scenario, as shown in ***Figure 4***. That is, these scenarios generate a surplus of SUs that significantly exceeds the Tier-2 deficits, leaving many over-compliant ships unable to find under-compliant counterparts to trade with. This can potentially weaken the financial incentives intended by the compliance mechanism, as shipowners may not be fully rewarded for over-compliance (as also noted by other studies such as the UMAS & UCL, 2025). Without adequate market or industry adjustments—such as ships reducing green fuel use and reverting to cheaper fossil fuels to mitigate surplus SUs—these scenarios suggest that SUs alone may not deliver the desired incentives for low-carbon investment, due to the risk of unutilized SUs.

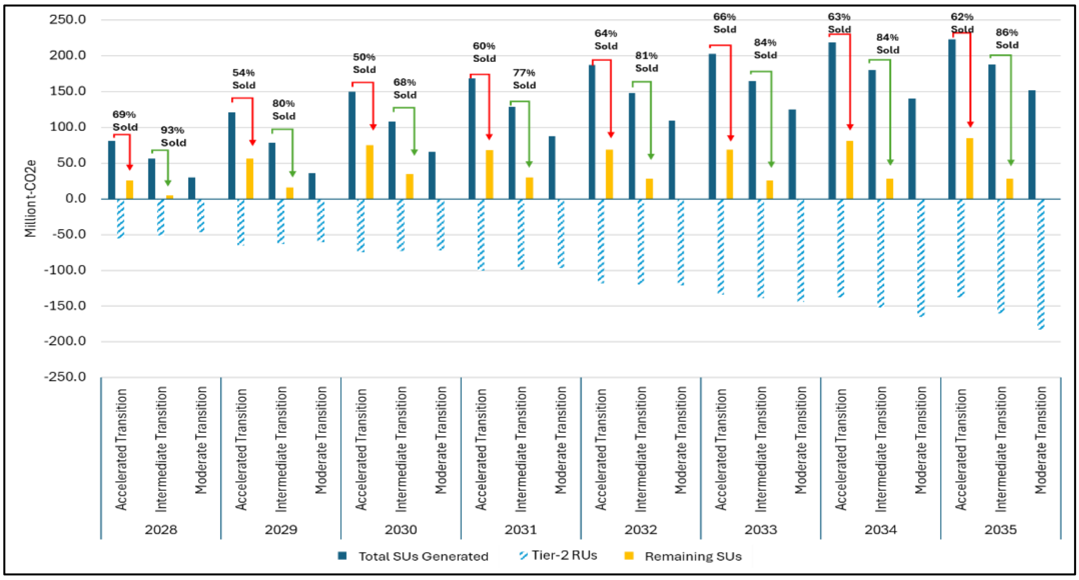

Figure 4: Share of SUs remaining under the scenarios (no Remaining SUs in Moderate Transition scenario).

It should be noted that the above compliance unit calculations are conducted at the fuel-level and detailed in the Appendix. However, the IMO Net-Zero Framework assesses compliance at the individual ship level. Because projecting ship-level GFI across the global fleet is complex, our analysis uses a fuel-level approach. While significant unutilized SUs are seen at the fuel-level, these would likely be lower when assessed at the ship level, especially when ships primarily use fossil fuels. For example, if a ship uses 8 PJ (peta joules) of VLSFO (with a GFI of 96 gCO_2e/MJ) and 1 PJ of e-ammonia (with a GFI of 1 gCO_2e/MJ) in 2028, the fuel-level calculation yields 76 SUs generated from e-ammonia, 51 Tier-2 deficit and 97 Tier-1 deficit units from VLSFO—resulting in 25 unutilized SUs after offsetting Tier-2 deficits. However, at ship level, the attained GFI is 85.4 gCO_2e/MJ—compared to the 2028 Base and Strive GFI targets of 89.6 and 77.4 gCO_2e/MJ, respectively—the ship falls into Tier-1, generating only 72 Tier-1 deficit units and no SUs. This discrepancy arises because, at the ship level, there is greater flexibility: the aggregation of a ship's fuel mix allows deficits and surpluses to be offset internally, reducing unutilized SUs. Such internal pooling is not captured in fuel-level calculations, which treat each fuel separately and therefore do not reflect the true compliance outcomes possible at ship-level.

Further analysis using the IMO approved RU prices—100 $/t-$CO_2e$ for Tier-1 and 380 $/t-$CO_2e$ for Tier-2— highlights a **potential risk of over-subsidization, particularly for biofuels**. As shown in ***Table 1***, Bio-Methane (used here as a representative low-cost biofuel) could be substantially overcompensated by the SU trading incentive. Its effective cost (fuel cost + compliance cost), after trading SUs at the Tier-2 RU price, can drop to just 19%–50% of the effective cost of LSFO, making Bio-Methane much cheaper than conventional fuels. Even after adjusting for unutilized SUs—where only traded SUs provide a financial benefit, and unutilized SUs (distributed proportionally among SU-generating ships) do not contribute to cost gap closure—Bio-Methane still remains overcompensated, with an effective cost around 57%–81% of LSFO's effective cost. In other words, even with a 50% price increase, Bio-Methane remains over-subsidized (assuming SUs can be sold at 380 $/t-$CO_2e$).

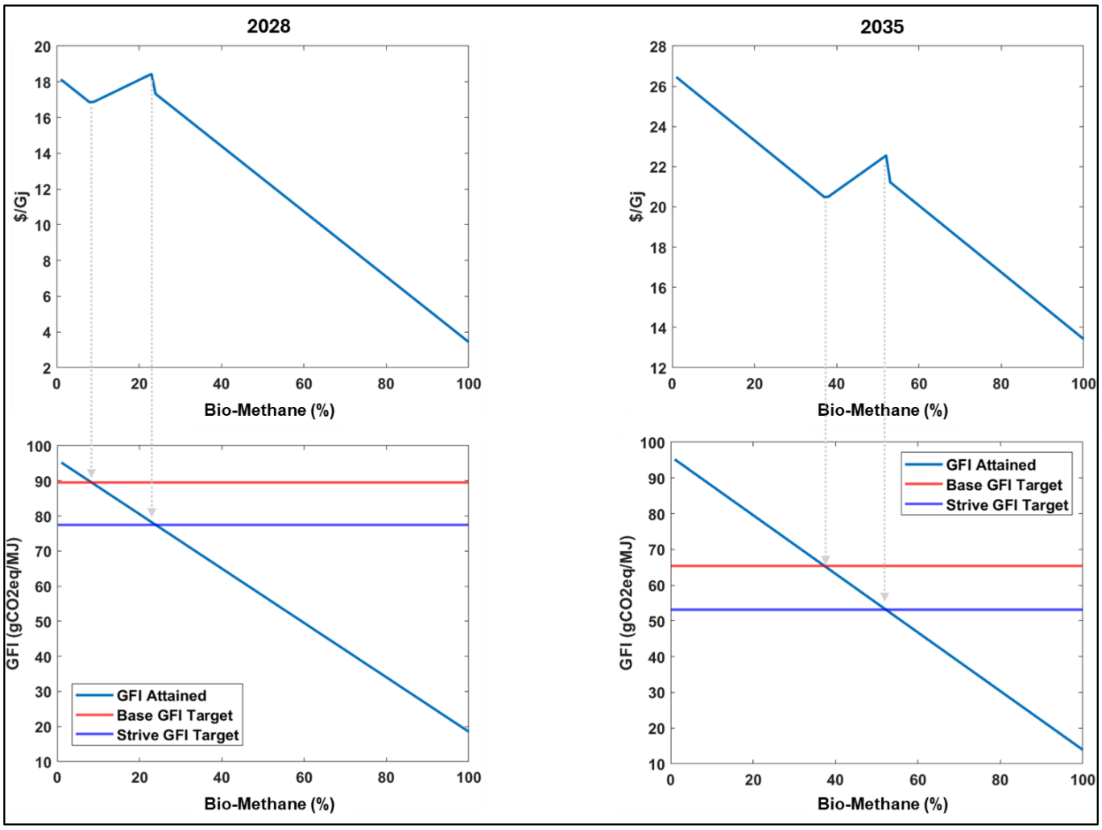

Figure 5: Changes in effective fuel cost and attained GFI with increasing Bio-Methane uptake.

Figure 5 illustrates how effective fuel cost changes with increasing bio-Methane percentages. Over-subsidization becomes a concern primarily when ships predominantly use biofuels, resulting in an attained GFI below the Strive GFI target and thus generating SUs. In such cases, SU incentives could further encourage biofuel use. However, if biofuel usage results in an attained GFI above the Strive GFI target, no SUs are generated and therefore no over-subsidization concern arises. Still, the potential for biofuels to become significantly cheaper due to over-subsidization may drive shipping companies toward heavy biofuel use, which could have unintended adverse effects such as deforestation, indirect land-use change resulting in increased net emissions (as also highlighted in other studies such as T&E, 2025).

For e-fuels like e-ammonia (e-NH_3)—the lowest-cost e-fuel—the **current RU pricing structure is generally sufficient to close the cost gap**. Under ideal conditions, where all SUs are utilized (i.e., all SUs generated can be monetized through SU trading), the effective cost of e-NH_3 is about 86%–108% of LSFO's effective cost, nearly bridging the cost gap. However, when unutilized SUs are considered, the SU incentive drops substantially and the effective cost of e-NH_3 rises to 114%–172% of LSFO's effective cost, indicating that further targeted rewards would be needed to close the remaining cost gap.

These economic evaluations are based on detailed fuel cost projections from the DNV CIA Task 2 report, complemented by fuel emission factors sourced from FuelEU-2023, Maritime Decarbonization Strategy-2022 by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS), and MEPC 81/16/Add.1 (2024). Related supporting information and figures are provided in the Appendix.

Based on the scenario analysis, it is **likely that no additional subsidies might be needed to support biofuel adoption**. In fact, the **current compliance structure may potentially overcompensate biofuels like Bio-Methane**, highlighting the **need to recalibrate RU pricing levels or refine the SU trading mechanism**. Without such adjustments, there is a risk of incentivizing unsustainable levels of biofuel adoption, which could lead to negative consequences such as increased deforestation, indirect land-use change, and ultimately higher net GHG emissions. These potential refinements are discussed further in subsequent sections. In contrast, the **adoption of e-fuels may still require additional targeted incentives to close the cost gap to conventional fuels**. Under ideal conditions where all SUs generated can be monetized from SU trading, the required supplemental rewards for e-fuels—especially e-NH_3—are minimal, ranging from \$5 to \$20 per t-CO_2e. However, in scenarios with significant unutilized SUs, these supplemental rewards could rise substantially, reaching \$72 to \$181 per t-CO_2e in the Accelerated Transition scenario and \$15 to \$130 per t-CO_2e in the Intermediate Transition scenario, to compensate for the diminished financial incentive from unutilized SUs.

The revenues collected and ZNZ reward dynamics across the Accelerated, Intermediate, and Moderate Transition scenarios highlight key structural contrasts in how the mechanism performs across different decarbonization (fuel-mix) trajectories. The Accelerated Transition scenario is projected to generate \$8.4 to \$11.5 B (billion) in annual compliance revenue between 2028 and 2035 (***Figure 6)*** which is broadly inline with the revenues projected in T&E, 2025. However, due to the lack of projected e-fuel uptake during this period, no ZNZ reward disbursements are triggered until after 2035 (and, as discussed, biofuels require no rewards since SU trading incentives alone close their cost gap). Additionally, the significant accumulation of unutilized SUs in this scenario indicates that the SU trading mechanism may not fully compensate green fuel users, underscoring the **need for a stronger ZNZ reward signal from the IMO**. The Intermediate Transition scenario, which reflects a midpoint trajectory between the Accelerated and Moderate scenarios, generates total compliance revenues between \$9.6 and \$11.2 B for 2028–2035. In contrast to the Accelerated scenario, the Intermediate scenario includes moderate e-fuel uptake. Calibrating reward rate to close the remaining cost gap after the SU incentive—under conditions of full SU utilization (and), ZNZ reward disbursements remain minimal at approximately \$0.1 B; however, when accounting for the impact of unutilized SUs, these required disbursements increase significantly, ranging from \$0.1 to \$6.8 B over the same period. The Moderate Transition scenario, in contrast, consistently achieves higher GFI values, resulting in larger Tier-2 compliance deficits than SUs generated. It also leads to higher total compliance revenues—ranging from \$12.1 to \$22.4 B between 2028 and 2035—mainly due to more RU purchases, particularly at the higher Tier-2 RU price, to cover remaining Tier-2 deficits after SU trading. Moreover, while it still overcompensates biofuels, it also manages to nearly close the cost gap for e-NH_3, requiring only a minimal reward disbursement around \$0.1 B per year in 2028 and 2029. After this period, SU trading alone is sufficient to maintain cost parity for e-fuels, and no additional rewards are needed.

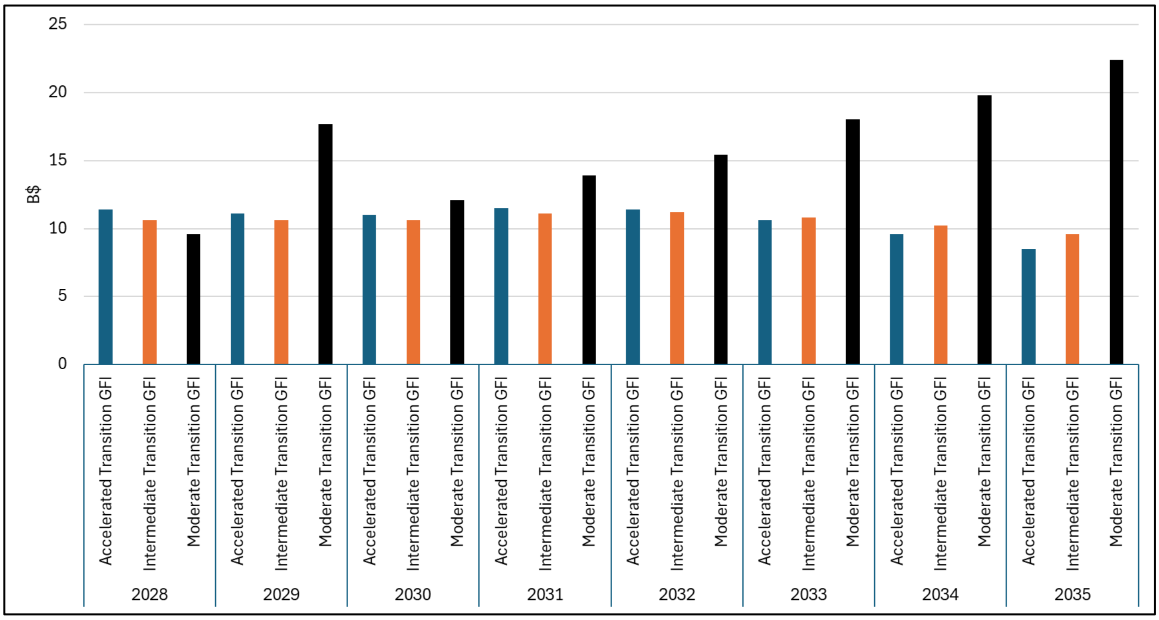

Figure 6: Compliance revenues collected across the three scenarios.

These findings illustrate the considerable variability in both compliance revenues and reward requirements across plausible future scenarios. This variability introduces significant financial risk and uncertainty for both shipowners and the Net-Zero Fund and underscores the importance of designing a compliance mechanism that is robust and adaptive to a wide range of potential industry responses.

These scenario analyses set the stage for detailed exploration of the mechanism's potential challenges and policy refinements in the following sections. Addressing the identified issues—particularly surplus SU handling, biofuel overcompensation, and e-fuel incentivization—is essential for the IMO Net-Zero framework to achieve its long-term maritime decarbonization goals effectively and economically efficiently.

Table 1: Results based on the IMO Net-Zero Framework with approved Z-factors with RU prices (100 \$/t-CO_2e for Tier-1 & 380 \$/t-CO_2e for Tier-2).

Scenario		Tier-1 Deficit Units (million t-CO_2e)	Tier-2 Deficit Units (million t-CO_2e)	Total SUs Generated (million t-CO_2e)	Remaining/Unutilized SUs (million t-CO_2e)	Remaining SUs Including 2 Years Banking (million t-CO_2e)	Generated Revenues (B\$)			Effective Cost Compared to the LSFO Cost After the Impact of SCUs (% LSFO Effective Cost)+		Necessity of Additional Rewards/Subsidies (Effects of Remaining SUs) +		
							Handling Fee (5% for transaction and 1% for banking) *	RU Sales	Total Revenue	Bio-Methane	e-NH_3	Bio-Methane (\$/t-CO_2e)	e-NH_3 (\$/t-CO_2e)	Reward Disbursement Required (B\$)
Accelerated Transition Scenario	2028	103	55	81	25	25	1.0	10.3	11.4	19% (57%)	108% (158%)	No Need	20 (139)	0 No Uptake of e-Fuels
	2029	98	65	121	56	82	1.3	9.8	11.1	22% (76%)	102% (172%)	No Need	5 (181)	0 No Uptake of e-Fuels
	2030	95	75	150	75	157	1.6	9.5	11.0	25% (81%)	96% (168%)	No Need	0 (181)	0 No Uptake of e-Fuels
	2031	95	100	168	68	200	2.0	9.5	11.5	32% (71%)	94% (144%)	No Need	0 (135)	0 No Uptake of e-Fuels
	2032	91	118	187	68	212	2.3	9.1	11.4	37% (68%)	91% (132%)	No Need	0 (109)	0 No Uptake of e-Fuels
	2033	81	134	203	69	205	2.6	8.1	10.6	42% (67%)	89% (122%)	No Need	0 (86)	0 No Uptake of e-Fuels
	2034	69	138	219	81	218	2.7	6.9	9.6	47% (70%)	87% (119%)	No Need	0 (83)	0 No Uptake of e-Fuels
	2035	58	138	223	85	234	2.7	5.8	8.4	50% (72%)	86% (114%)	No Need	0 (72)	0 No Uptake of e-Fuels
Intermediate Transition Scenario	2028	96	51	55	3	3	0.9	9.6	10.5	19% (27%)	108% (119%)	No Need	20 (45)	0.1 (0.1)
	2029	95	63	79	16	19	1.1	9.5	10.6	22% (47%)	102% (136%)	No Need	5 (89)	0.1 (1.7)
	2030	92	73	108	35	54	1.3	9.2	10.6	25% (65%)	96% (152%)	No Need	0 (130)	0 (1.9)
	2031	93	99	129	30	84	1.7	9.3	11.1	32% (58%)	94% (131%)	No Need	0 (88)	0 (1.9)
	2032	91	120	148	28	112	2.1	9.1	11.2	37% (57%)	91% (119%)	No Need	0 (63)	0 (1.4)
	2033	83	139	165	26	138	2.4	8.3	10.8	42% (57%)	89% (110%)	No Need	0 (38)	0 (1.4)
	2034	75	152	180	29	167	2.6	7.5	10.2	47% (61%)	87% (108%)	No Need	0 (33)	0 (0.7)
	2035	68	160	188	27	194	2.8	6.8	9.6	50% (63%)	86% (103%)	No Need	0 (15)	0 (6.8)
Moderate Transition Scenario	2028	88	47	30	0	0	0.5	15.5	20	19% (19%)	108% (108%)	No Need	20 (20)	0.1 (0.1)
	2029	92	61	36	0	0	0.6	18.6	19.2	22% (22%)	102% (102%)	No Need	5 (5)	0.1 (0.1)
	2030	89	72	66	0	0	1.1	11.0	12.1	25% (25%)	96% (96%)	No Need	0 (0)	0 (0)
	2031	91	97	88	0	0	1.5	12.4	13.9	32% (32%)	94% (94%)	No Need	0 (0)	0 (0)
	2032	91	121	110	0	0	1.9	13.5	15.4	37% (37%)	91% (91%)	No Need	0 (0)	0 (0)
	2033	86	144	125	0	0	2.2	15.8	18	42% (42%)	89% (89%)	No Need	0 (0)	0 (0)
	2034	81	165	140	0	0	2.4	17.4	19.8	47% (47%)	87% (87%)	No Need	0 (0)	0 (0)
	2035	77	183	152	0	0	2.6	19.8	22.4	50% (50%)	86% (86%)	No Need	0 (0)	0 (0)

∗ Note: While the IMO-approved regulations reference an SU trading transaction fee, no specific percentages are provided. We have used indicative figures from earlier proposals for completeness, but this assumption does not have any significant impact the core analysis.

+ The percentages/values in red within the parentheses indicate the cost gap closure/reward rates after accounting for unutilized SUs.

4. Potential Challenges of the IMO Net-Zero Framework

- The current mechanism potentially risks deterring shipowners from adopting green fuels due to concerns over unutilized SUs, potentially leading to increased reliance on fossil fuels.
- When shipowners adjust fuel use to eliminate unsold SUs, even the Accelerated Transition scenario regresses toward Base targets—limiting the effectiveness of the Strive trajectory, particularly problematic during the critical early phase (2028–2035).
- Current RU pricing (\$380/tCO_2e) potentially overcompensates biofuels like Bio-Methane, while e-ammonia is almost adequately incentivized—assuming no SUs go unsold.
- Reducing the Tier-2 RU price narrows biofuel overcompensation but increases required ZNZ rewards for e-fuels, shifting financial pressure to centralized funding.
- Future refinements must reduce SU sales uncertainty, set realistic yet ambitious targets, and calibrate differentiated SU and reward pricing to balance incentives across various fuel types and encourage sustainable decarbonization.

The primary objective of setting two distinct GFI trajectories—Base and Strive (Direct Compliance)—within the IMO Net-Zero Framework is to provide clear guidance on both baseline and ambitious decarbonization pathways for the shipping industry. The Base target sets a baseline level of ambition aimed at achieving the base targets set for the maritime industry in 2023 IMO strategy, while the Strive target sets a more ambitious level, envisioning the highest feasible decarbonization outcomes through accelerated production and adoption of green fuels, alongside optimal utilization of available resources, aligned with the strive targets in 2023 IMO strategy. By encouraging stakeholders to aim higher, the Strive target not only motivates greater action but also helps safeguard against the risk that the sector may fall short if only a lower Base target is set. This dual-target approach is intended to drive continuous improvements and maximize the industry's environmental performance, within realistic constraints.

However, analysis of the Accelerated Transition scenario—where Strive targets are met under the current regulatory framework—indicates uncertainty for shipowners regarding the management of SUs. Specifically, shipowners generating SUs may face ambiguity around how to monetize unutilized SUs, which could discourage investments in cleaner, higher-cost fuels. If there is a lack of confidence in sufficient market demand for SUs, some may opt to continue using cheaper fossil fuels rather than pursue more ambitious decarbonization measures. To address this, the compliance mechanism could consider provisions to support or guarantee the monetization of unutilized SUs, thereby strengthening the certainty of incentives for over-compliance. Additionally, it is important that the IMO establishes long-term GFI targets beyond 2035 to provide clear signals for sustained investment in low-carbon solutions and ensure continued progress toward the sector's decarbonization goals.

To clearly illustrate this issue, we adjusted the Accelerated Transition scenario by simulating a market reaction where shipowners reduce their use of SU-generating green fuels and proportionally increase fossil fuel use until no unutilized SUs remain, while keeping the total annual energy demand unchanged. ***Figure 7*** shows the extent of this adjustment: in 2028, eliminating unutilized SUs required a 25% reduction in green fuel uptake (bio- and e -fuels) and a corresponding 5% increase in fossil fuel consumption. By 2035, the adjustments became even more substantial, leading to a 37% decrease in green fuel use and a 35% increase in fossil fuels. It should be noted that, under the Net-Zero Framework, shipowners can bank unutilized SUs for up to two years, providing flexibility to carry them forward and offset deficits in subsequent years. For simplicity, our analysis assumes shipowners proactively adjust fuel use within the current year to eliminate surplus SUs, rather than modelling the more complex dynamics of banking and individual risk preferences of shipowners. In practice, some may choose to increase fossil fuel use in the following year(s) to achieve the same outcome.

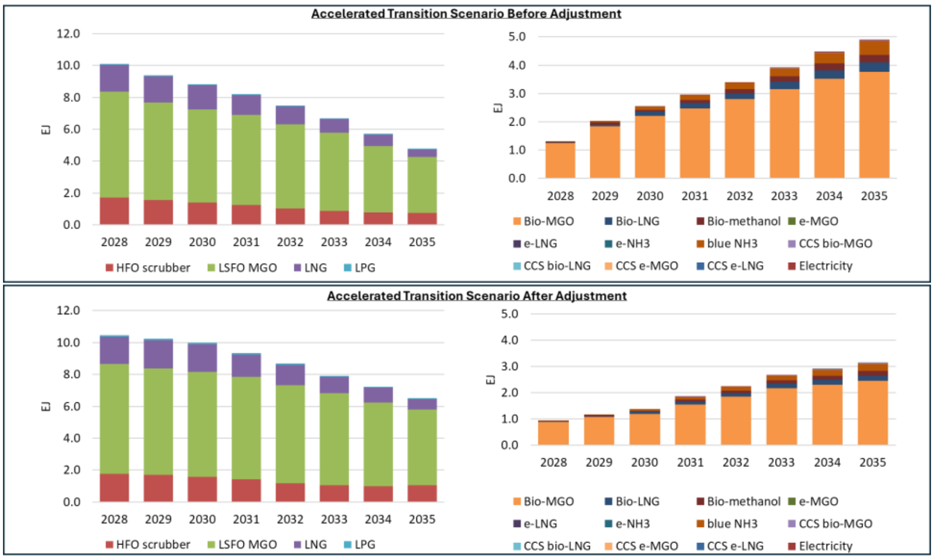

Figure 7: Market-driven adjustments in fuel uptake to eliminate unutilized SUs.

Figure 8 compares the adjusted GFI values with those from the original scenario, illustrating the potential impact of market-driven adjustments under the current mechanism. Following these adjustments, the Accelerated Transition scenario converges with the Base targets, mirroring the less ambitious Moderate Transition scenario during the key period of 2028–2035 (with no adjustment needed from 2038 onward, as surplus SUs are no longer present). This suggests that, under the current design, the mechanism may not always drive emissions reductions beyond the Base trajectory. In practice, the compliance equilibrium could tend to align with the Base targets or fall within the range between Base and Strive, particularly in the early years of implementation. This is the zone where compliance penalties are minimized and can be achieved using transitional fuels such as LNG and biofuels, or lower-cost low-carbon technologies like CCS.

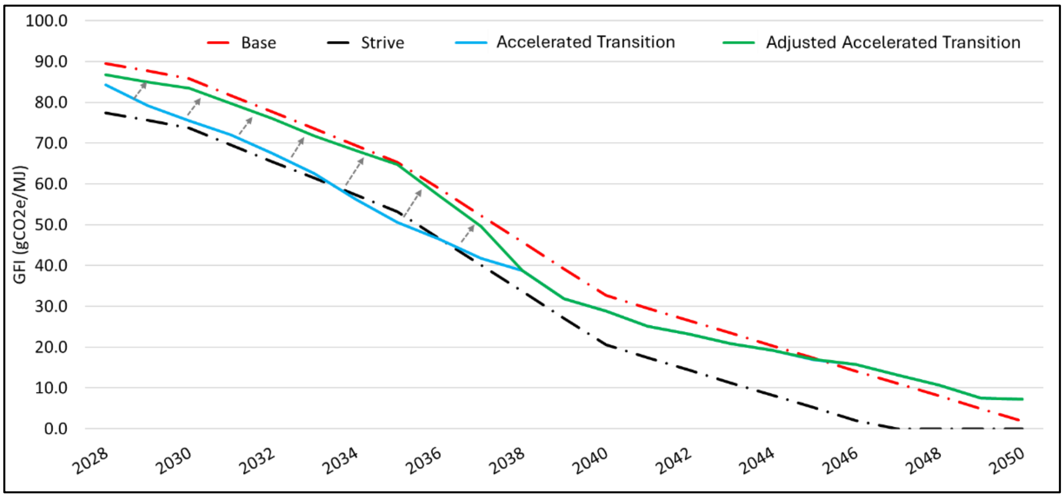

Figure 8: Scenario attained GFI comparison before and after market adjustment.

It is important to recognize that real-world factors—such as limited green fuel availability and the pace of technological advancement—already present challenges to deep maritime decarbonization. To support further progress, the regulatory mechanism can play a key role in providing shipowners the confidence to invest in and generate SUs, ideally backed by reliable demand or compensation for these units. At present, some uncertainty may remain around SU sales, which could influence shipowners' willingness to pursue more ambitious low-carbon investments. Addressing these uncertainties within the compliance framework, along with establishing clear long-term GFI targets beyond 2035, would provide stronger market signals and help keep the sector on track for deeper decarbonization.

This inherent limitation is not unique to the Accelerated Transition scenario but is evident across all DNV scenarios that reach or slightly exceed the Strive targets. Accumulated unutilized SUs cause each scenario to revert toward the Base targets during the transition period. As a result, the Strive trajectory—meant to represent maximum ambition—may become unattractive due to economic uncertainty, leading shipowners to favour the less ambitious Base trajectory, or in some cases, fall short of even that.

While the Base trajectory is nominally aligned with the 2050 net-zero goal, relying solely on it is undesirable because it defers substantial emissions reductions to later years, resulting in higher cumulative emissions and delaying early investments in green infrastructure. This is particularly problematic during the initial compliance window (2028–2035), a critical period to lock in long-term investments and scale low-carbon fuels and technologies. With comparatively less stringent targets, this phase presents a rare opportunity for cost-effective, ambitious decarbonization. Ensuring that the mechanism can incentivize over-compliance with certainty during this period would help unlock these opportunities, maintain momentum, and lower long-term decarbonization risks and costs. Establishing clear long-term GFI targets beyond 2035 would further reinforce this certainty, providing stronger market signals and greater confidence for early action as regulatory requirements tighten.

Table 2: Comparison of compliance outcomes before and after market-driven adjustment.

Scenario	Year	Tier-1 Deficit Units (million t-CO_2e)	Tier-2 Deficit Units (million t-CO_2e)	Total SUs Generated (million t-CO_2e)	Remaining SUs (million t-CO_2e)	Remaining SUs Including 2 Years Banking (million t-CO_2e)	Generated Revenues (B$)		
							Handling Fee (5% for transaction and 1% for banking)	RUs Sales	Total Revenue
Accelerated Transition Scenario	2028	103	55	81	25	25	1.0	10.3	11.4
	2029	98	65	121	56	82	1.3	9.8	11.1
	2030	95	75	150	75	157	1.6	9.5	11.0
	2031	95	100	168	68	200	2.0	9.5	11.5
	2032	91	118	187	68	212	2.3	9.1	11.4
	2033	81	134	203	69	205	2.6	8.1	10.6
	2034	69	138	219	81	218	2.7	6.9	9.6
	2035	58	138	223	85	234	2.7	5.8	8.4
Adjusted Accelerated Transition Scenario	2028	107	57	58	0	0	1.0	10.7	11.7
	2029	107	71	70	0	0	1.2	10.9	12.1
	2030	107	85	82	0	0	1.4	11.9	13.3
	2031	108	113	106	0	0	1.8	13.5	15.3
	2032	105	137	124	0	0	2.1	15.2	17.3
	2033	96	160	141	0	0	2.4	16.8	19.2
	2034	88	176	145	0	0	2.5	20.3	22.8
	2035	79	188	145	0	0	2.5	24.2	26.7

Table 2 summarizes the quantitative outcomes of the adjusted Accelerated Transition scenario. The market-driven adjustments, significantly decrease total SUs generated and increase the deficit units, thus eliminating unutilized SUs and increasing the required purchase of RUs. Consequently, total compliance revenue, for the 2028–2035 period, substantially increases, shifting from approximately $8.4–11.5 B before adjustments to around $11.7–26.7 B afterward (***Figure 9***). While this might initially seem financially beneficial, it paradoxically reflects greater reliance on fossil fuels.

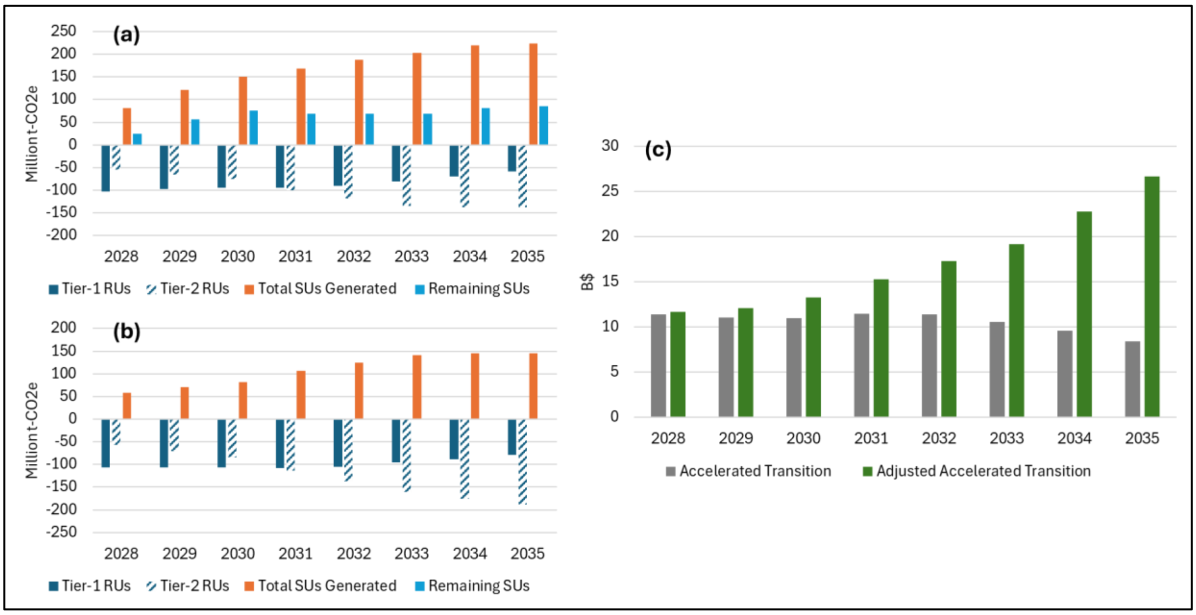

Figure 9: Compliance units in (a) original and (b) adjusted Accelerated Transition scenario; (c) Total Revenues.

The concern of biofuel overcompensation can be addressed by lowering the financial incentive from SUs, specifically by reducing the Tier-2 RU price, which sets the ceiling for SU trading. Assuming a scenario in which no SUs remain unsold—and using the fuel cost and emissions assumptions adopted in this study—we explored the impact of revising the Tier-2 RU price from the current $380/t-$CO_2$e to $200/t-$CO_2$e. This adjustment would significantly reduce the overcompensation currently observed for biofuels. Specifically, for Bio-Methane, SU trading alone would raise the effective fuel cost to 82%–97% of LSFO's effective cost, compared to the previous range of just 19%–50% in the period 2028–2035. Conversely, for e-fuels, the effective cost would rise from the current 86%–108% of LSFO's effective cost to 153%–196%, reinforcing the need for higher supplementary rewards to support their adoption. ***Figure 10*** illustrates the final effective fuel costs after applying SU and reward impacts (reward set at a level to close the remaining cost gap) under both RU price settings—$380 and $200 per t-$CO_2$e—offering a clear comparison of their respective effects on biofuel and e-fuel economics.

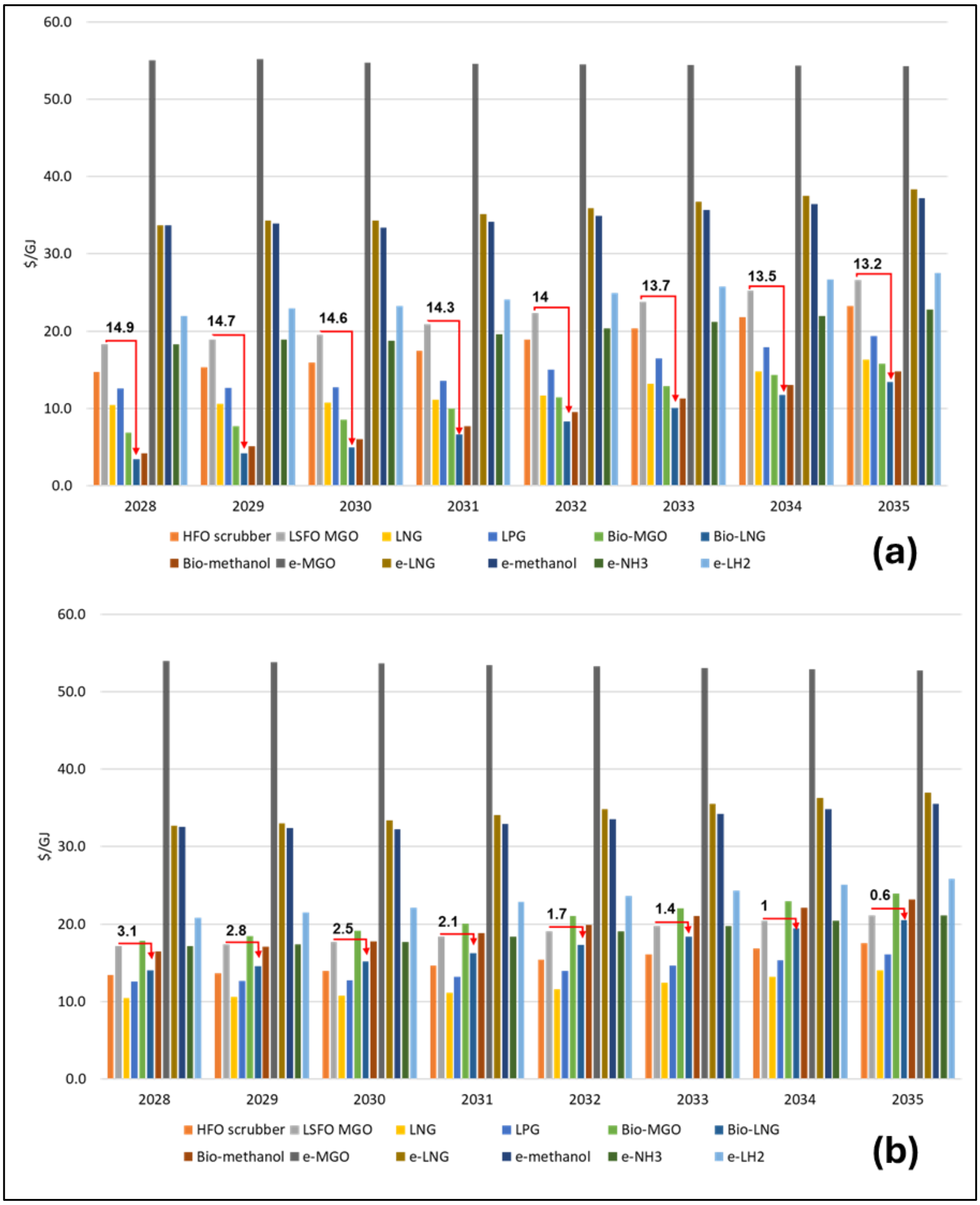

Figure 10: Fuel costs after SU incentives and rewards under two Tier-2 RU price ($/t-$CO_2$e) of: (a) 380, (b) 200.

As can be seen in ***Figure 10***, the effective fuel costs for e-fuels remain unchanged across both Tier-2 RU price settings ($200 and $380 per t-$CO_2$e) except for the years where the e-fuel is already overcompensated by the SU revenues. This is because any remaining cost gap, after accounting for SU revenues, is assumed to be fully covered by rewards. However, lowering the Tier-2 RU price from $380 to $200 significantly increases the amount of rewards required. As illustrated in ***Table 3***, annual reward disbursements would rise from $0.1 B range (~0.5% of the total revenue collected) to as high as $20.2 B (~131% of the total revenue collected) over the 2028–2035 period, underlining the trade-off between lower compliance costs and increased reliance on centralized funding to close the remaining cost gap, particularly for e-fuels. This highlights another limitation of the IMO Net-Zero framework: avoiding the overcompensation of biofuels would reduce registry revenues while simultaneously increasing the need for reward disbursements. In scenarios with early e-fuel uptake—such as the Moderate Transition scenario—this could result in disbursement requirements exceeding the revenues collected, raising concerns about the sufficiency of available funds to sustain the mechanism (as also noted in other studies such as T&E, 2025). Therefore, a carefully calibrated adjustment to RU pricing and SUs trading mechanism, in tandem with reward rates, is essential—to avoid excessive overcompensation on one side, while maintaining a balanced and sustainable reliance on centralized funding to close the remaining cost gaps for more expensive low-carbon fuels.

Table 3: Impact of SU incentives in closing cost gap and projected reward disbursements for e-fuels under different Tier-2 RU price levels

Scenario		Generated Revenues (B$)			Effective Cost Compared to LSFO Effective Cost (% Effective LSFO Cost)		Necessity of additional rewards/subsidies	
		Low RU Price ($/t-$CO_2$e)	High RU Price ($/t-$CO_2$e)	Total Revenue	Bio-Methane	e-NH_3	Reward Rate ($/t-$CO_2$e)	Reward Disbursement Required (B$)
Moderate Transition Scenario (Before Tier-2 RU Price Adjustment)	**2028**	100	380	20	**19%**	**108%**	20	0.1
	2029	100	380	19.2	**22%**	**102%**	5	0.1
	2030	100	380	12.1	**25%**	**96%**	0	0
	2031	100	380	13.9	**32%**	**94%**	0	0
	2032	100	380	15.4	**37%**	**91%**	0	0
	2033	100	380	18	**42%**	**89%**	0	0
	2034	100	380	19.8	**47%**	**87%**	0	0
	2035	100	380	22.4	**50%**	**86%**	0	0
Moderate Transition Scenario (After Tier-2 RU Price Adjustment)	**2028**	100	200	12.6	**82%**	**196%**	215	0.1
	2029	100	200	14.5	**84%**	**188%**	205	0.4
	2030	100	200	10.6	**86%**	**181%**	195	5.2
	2031	100	200	11.6	**88%**	**174%**	198	8.7
	2032	100	200	12.4	**91%**	**168%**	201	12.1
	2033	100	200	13.5	**93%**	**163%**	204	15.0
	2034	100	200	14.3	**95%**	**158%**	208	17.8
	2035	100	200	15.4	**97%**	**153%**	212	20.2

To effectively address these critical challenges, future refinements to the regulatory mechanism must ensure some key principles:

1. **Reduce uncertainty around SU generation and sales:** The mechanism should give shipowners confidence to invest in cleaner, SU-generating fuels by guaranteeing that all generated SUs will be absorbed—whether through a functioning market, a central clearinghouse, or a guaranteed buy-back arrangement. This assurance is essential to promote investment in low- and zero-carbon fuels and technologies.
2. **Realistic and achievable target-setting:** Decarbonization targets must be set based on realistic assessments of available fuel supplies and technologies. The Base target must not be so relaxed that it fails to drive meaningful environmental improvements, while the Strive target must remain ambitious yet practically achievable, representing the best-case decarbonization scenario given resource constraints.
3. **Careful calibration of SU and reward pricing:** To stimulate the uptake of biofuels and e-fuels effectively, attention must be given to setting SU and reward rates. Ideally, initial incentives should

be calibrated based on the most cost-effective biofuels and e-fuels (those closest to fossil fuel prices, e.g., Bio-Methane and e-ammonia). This ensures that operators begin adopting currently available cleaner fuels, subsequently driving greater market uptake and economies of scale. However, not all low-carbon fuels are equal in terms of production cost, scalability, and maturity. Biofuels such as Bio-Methane tend to have lower marginal costs and are closer to market readiness, whereas e-fuels like e-ammonia are still emerging technologies with higher production and infrastructure costs. Without differentiated reward levels, the mechanism risks overcompensating cheaper biofuels while under-supporting more expensive e-fuels that are essential for deep decarbonization in the long run. Introducing differentiated rewards allows the mechanism to better match incentive levels to the actual cost gap of each fuel type—ensuring fair compensation, avoiding inefficiencies, and helping build momentum across a wider range of alternative fuels. At the same time, setting incentives too high risks reducing pressure for innovation and cost reduction, while setting them too low can stall adoption and delay investment. Properly calibrated, differentiated incentives encourage broader uptake now and sustained technological progress into the future.

In conclusion, a well-structured compliance mechanism should avoid additional uncertainty or limitations that discourage ambitious decarbonization actions. Rather, it should provide clear, reliable economic signals, incentivizing continuous investment in greener fuels and technologies. Ensuring realistic yet ambitious targets, combined with a reliable mechanism to manage and absorb SUs and careful calibration of incentives, is critical for enabling meaningful, industry-wide emissions reductions aligned with IMO's long-term decarbonization vision. The next section of this paper explores specific recommendations and solutions designed explicitly to address these identified challenges.

5. Potential Refinements and Recommendations

- Reducing uncertainty around SU utilization and simplifying compliance are essential to ensure ships investing in green fuels fully realize from SU value and to streamline administration.
- Reversing SU pooling flexibility in the current two-tier structure from Tier-2 to Tier-1, and allowing surplus SUs to be sold to the GFI registry, can boost SU utilization and provide greater certainty and value for over-compliance.
- As an alternative to the current two-tier structure, a differentiated deficit balancing approach—requiring multiple SUs or RUs to balance each Tier-2 deficit while keeping RU prices uniform—can enhance SU utilization, stabilize incentives, and support steady Net-Zero Fund revenues.
- Both refinements have the potential to generate higher revenues and may require higher ZNZ rewards—especially for e-fuels—which can be supported by increased revenue flows, while also reducing the risk of over-subsidizing transitional fuels.
- Greater pooling flexibility and simpler compliance processes reduce administrative burden and improve transparency for both regulators and industry.

We propose two refinements, particularly in the two-tier compliance structure, that can potentially address the above concerns and provide more certainty to stakeholders in investing and adopting the use of low-carbon solutions essential for driving maritime decarbonization.

1. Reverse Compliance Trading with Option to Sell SUs to the GFI Registry

Under the IMO Net-Zero framework, only Tier-2 deficits can be offset by SUs (either from other ships or banked SUs), while Tier-1 deficits must be balanced by purchasing RUs. The proposed reverse compliance trading would swap these options: Tier-1 deficits could be offset using SUs, while Tier-2 deficits would require the purchase of higher-priced Tier-2 RUs from the GFI registry. Furthermore, this mechanism also includes the flexibility to sell SUs to the GFI registry at a price slightly lower than Tier-1 RU price. This ensures that SU pooling is more attractive and any unutilized SUs can then be sold to the GFI registry, providing greater certainty and value for SUs.

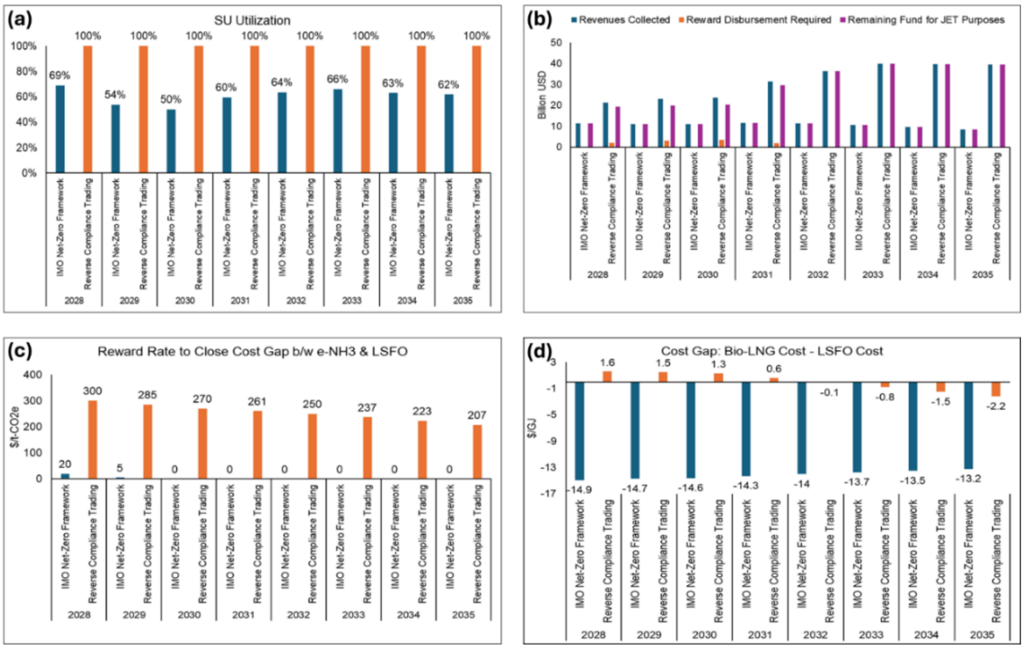

Figure 11: Implications of Reverse Compliance Trading (with SU selling option) for Accelerated Transition Scenario.

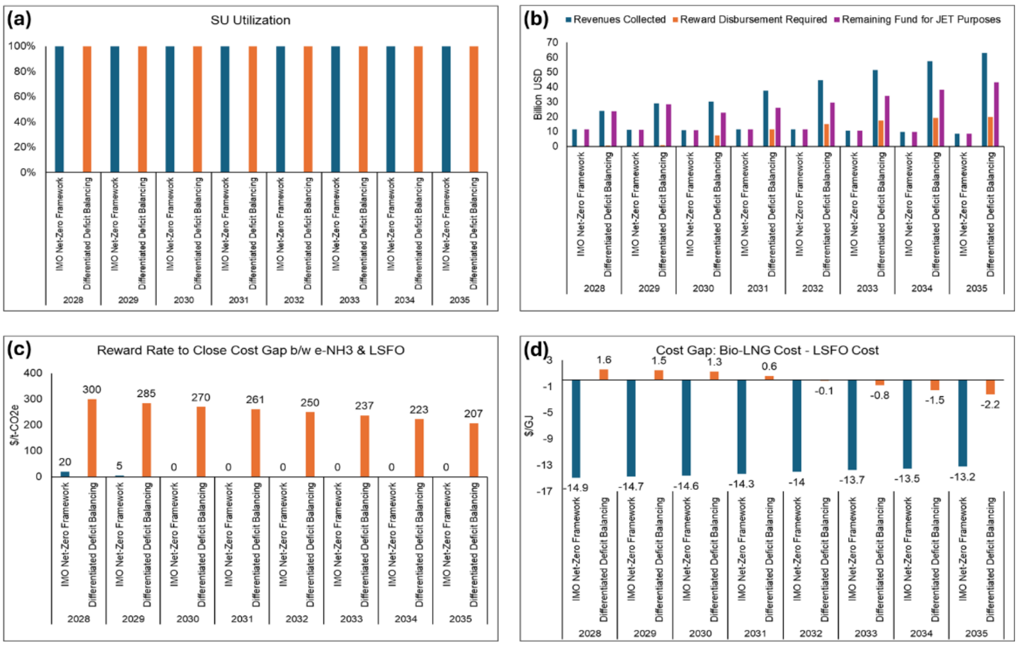

Figure 12: Implications of Reverse Compliance Trading (with SU selling option) for Moderate Transition Scenario.

Figure 11 and ***Figure 12*** present the quantitative impacts of this refined approach for the Accelerated Transition scenario and the Moderate Transition scenario, respectively. Further detailed results are provided in the Appendix ***Table A1*** and ***Table A2***. Some potential key implications of this mechanism are:

- **Potentially Greater SU Utilization**: As highlighted in ***Figure 5*** it is generally economical for ships to remain near the Base or Strive GFI targets. Due to limited availability of low-carbon green fuels in the early years, most ships are likely to stay close to the Base GFI target. As a result, it is likely that the volume of Tier-2 deficit units will be relatively lower than Tier-1 deficit units. Under the current SU trading mechanism, which allows SUs to offset only Tier-2 deficits, unutilized SUs may accumulate. Instead, allowing Tier-1 deficits to be offset with SUs could increase demand for SUs and enable deficits to be balanced using pooled or banked SUs. However, as GFI targets become stricter over time, fewer ships may be able to stay near the Base target, which could again lead to surplus SUs. In such cases, providing the option to sell surplus SUs to the GFI registry could help address under-utilization, sustain demand for SUs, enhance their value, and give shipowners greater certainty of financial returns for over-compliance.
- **Flexibility Option to Sell Unutilized SUs:** With the option to sell remaining SUs to the GFI registry, provides even greater certainty that SUs will be fully utilized. This option may not be viable under the current IMO Net-Zero Framework, where trading is limited to Tier-2. In that case, the GFI registry would need to buy the remaining SUs at the higher price closer to Tier-2 RU price, which might not be feasible due to potential limitations in the availability of funds in the Net-Zero Fund or the risk of insufficient funds remaining for JET purposes. In the Accelerated Transition scenario, as can be seen in ***Figure 11(a),*** that SU utilization increases from 50%–69% under Net-Zero Framework to 100% in this reverse trading mechanism. In the Moderate Transition scenario, as can be seen in ***Figure 12(a)***, the reverse mechanism performs equivalently to the Net-Zero Framework, since no remaining SUs are generated, thereby maintaining full SU utilization. Nonetheless, this mechanism must be implemented with caution. If a large volume of SUs is generated and remains unutilized (albeit unlikely), the Net-Zero Fund may face fiscal strain if required to buy back all surplus SUs. This could compromise its financial sustainability and undermine broader decarbonization support objectives.
- **Potentially Higher Revenues**: By restricting Tier-2 deficit units to be balanced only through the purchase of RUs at the higher Tier-2 price (\$380/t-CO_2e, 3.8 times the Tier-1 rate), this revised mechanism would likely generate significantly greater revenues for the IMO Net-Zero Fund. These increased revenues could play a critical role in supporting the JET, by providing more substantial funding for climate mitigation, adaptation, and capacity-building efforts, particularly in developing states and small island developing states. At the same time, a larger and more reliable revenue pool would enable the provision of larger or more sustained ZNZ rewards, helping to close the cost gap between conventional and ZNZs. The increased financial capacity from this approach would also enhance the Fund's flexibility in responding to changing market conditions and better support industry-wide low-carbon transitions. In the Accelerated Transition scenario, as can be seen in ***Figure 11(b),*** that total revenues, cumulative over the period 2028 to 2035, increases from 85 B\$ under current Net-Zero Framework to 255 B\$ after this refinement even after accounting for the unutilized SU buy back by the GFI registry. Similarly as can be seen in ***Figure 12(b)***, in the Moderate Transition scenario, cumulative revenues over the same period increase substantially, from 141 B\$ under the current Net-Zero Framework to 331 B\$ after this refinement.
- **Cost Gap Closure**: Under the refined mechanism, the market price for SUs would be capped at the Tier-1 RU price (\$100/t-CO_2e), which is lower than the Tier-2 RU cap applicable to SU trading

under the current Net-Zero Framework. As a result, SUs would cover a smaller portion of the cost gap ZNZ fuels. Consequently, to maintain investment attractiveness in ZNZ fuels—particularly for high-cost options such as e-fuels—a higher ZNZ reward rate would likely be required. The ability to provide and sustain these rewards will depend on the strength and adequacy of revenue flows into the Net-Zero Fund, which, as discussed above, could potentially be higher under this revised mechanism. In the Accelerated Transition scenario, as can be seen in ***Figure 11(c),*** that required reward rate for closing the cost gap of e-NH_3 to LSFO increases from 5–20 \$/t-CO_2e under current Net-Zero Framework to 207–300 \$/t-CO_2e after this refinement, which is a result of the SU component closing the cost gap to a lesser extent.

- **Potentially Mitigate Over-Subsidization:** By capping SU prices at the lower Tier-1 RU level, the refined mechanism may reduce the risk of over-subsidizing lower-cost transitional fuels such as biofuels—an issue that could arise under the current Net-Zero Framework, where higher Tier-2 RU prices enable more generous SU trading returns. The lower trading ceiling mitigates the risk of excessive financial incentives flowing to transitional or less sustainable fuels. Subject to the fuel costs and emissions factors considered in this study, it can be seen in ***Figure 11(d)***, that biofuels are not over-subsidized by the SU component until 2031, and only experience minimal over-subsidization in the years that follow.
- **Operational Simplicity**: This mechanism closely mirrors the IMO-approved two-tier structure, but reverses SU pooling flexibility. Implementation and administration remain similar, though the flexibility option of selling SUs to the GFI registry adds some complexity. In scenarios where it is expected that many ships stay in Tier-2, higher revenues could boost IMO's transition efforts but may require additional fund management resources.

Overall, this refinement offers the potential to address key challenges observed under the current Net-Zero Framework—namely, the risk of unutilized SUs, over-subsidization of lower-cost fuels, and lower revenue generation. However, a key concern must be acknowledged: restricting Tier-2 deficit compliance solely to the purchase of RUs removes the flexibility for affected ships to trade compliance via the SU market. As a result, smaller shipping companies or vessels operating in regions with limited access to decarbonization options and SU trading opportunities would be forced to pay the full RU penalty and lose the ability to manage compliance more cost-effectively through the SU trading mechanism. Careful consideration is needed to ensure that compliance pathways remain accessible and equitable across different ship types, geographies, and operator profiles.

2. Differentiated Deficit Balancing (Volumetric Multiplier)

The IMO Net-Zero Framework differentiates Tier-1 and Tier-2 deficits through RU pricing, with Tier-2 RUs priced 3.8 times higher than Tier-1 RUs—reflecting the higher penalty for exceeding the Base Target. Under this system, Tier-1 deficits must be balanced exclusively by RUs on a **one-to-one basis**, while Tier-2 deficits can be offset using either SUs or RUs, also on a one-to-one basis. An alternative approach would maintain a *uniform RU price* across both tiers but differentiate compliance stringency by adjusting the number of units required. Specifically, each Tier-1 deficit unit would still require one SU or RU (1 t-CO_2e), while each Tier-2 deficit unit would require a higher multiple—such as 3.8 SUs or RUs per unit—reflecting the original price ratio. The RU price would remain constant (for example, \$100/t-CO_2e) across both tiers. This refinement preserves the intended financial differentiation between tiers while simplifying the pricing structure. It achieves stronger compliance pressure at higher tiers through volumetric scaling rather than price escalation.

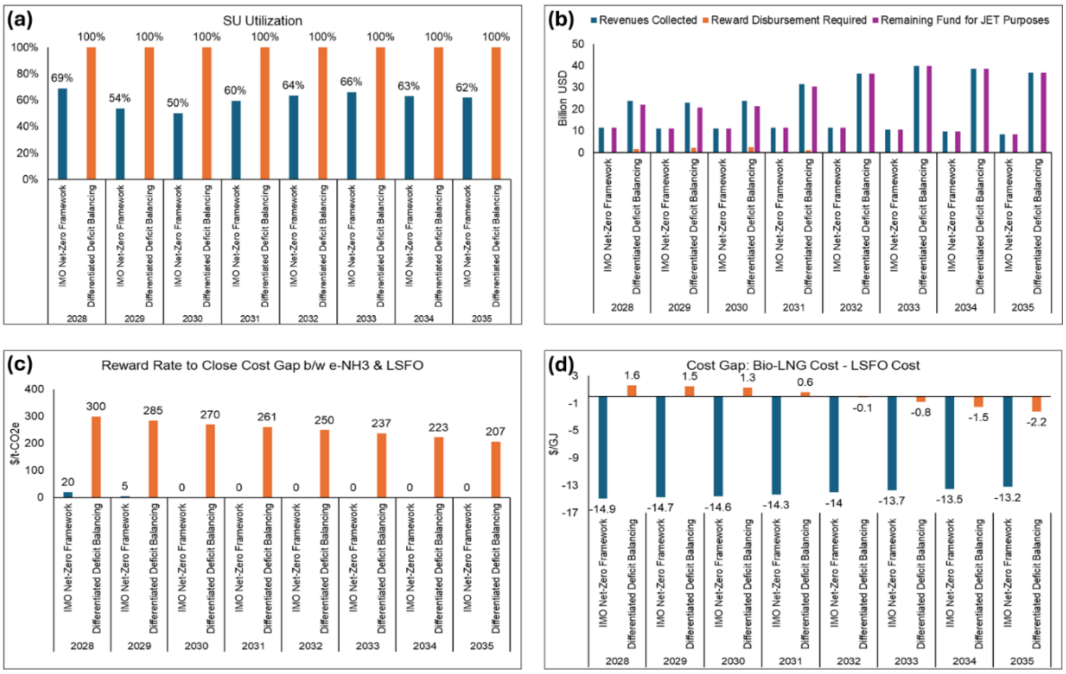

Figure 13: Implications of the Differentiated Deficit Balancing under Accelerated Transition Scenario.

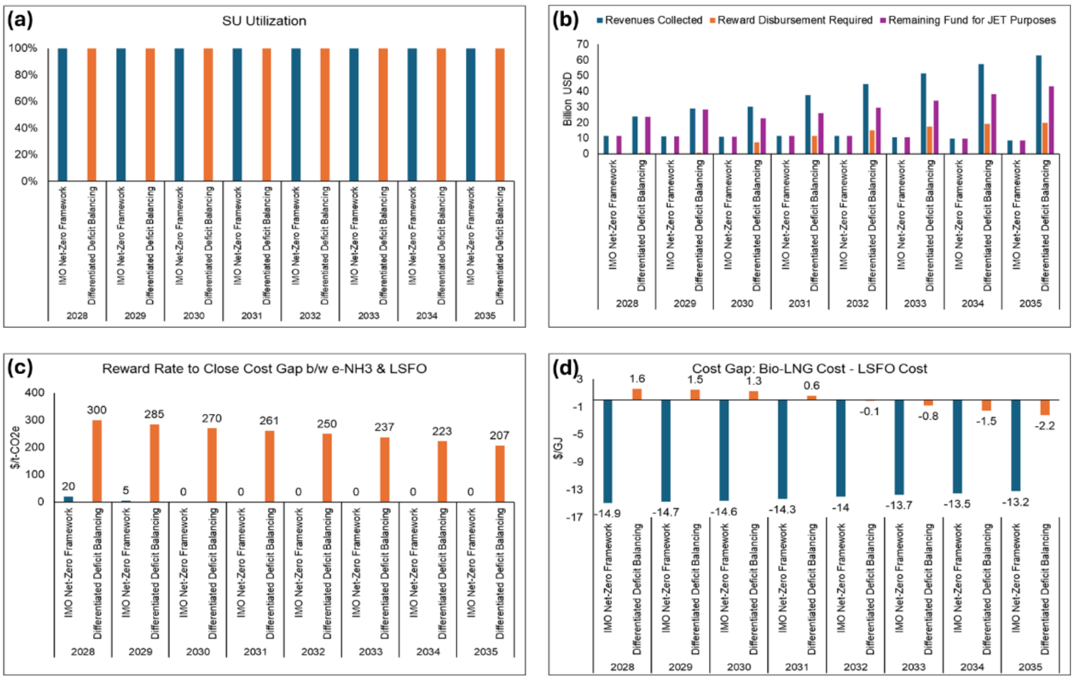

Figure 14: Implications of the Differentiated Deficit Balancing under Moderate Transition Scenario.

Figure 13 and ***Figure 14*** present the quantitative impact of this refined approach for the Accelerated Transition scenario and the Moderate Transition scenario, respectively. Further detailed results are provided in the Appendix ***Table A1*** and ***Table A2***. Some of the key implications of this refinement are:

- **Greater SU Utilization:** By requiring a higher number of SUs or RUs to offset each Tier-2 deficit unit (e.g., 3.8 units per 1 t-CO_2e), this mechanism increases overall demand for SUs. This, in turn, enhances the likelihood that surplus units generated by over-compliant ships will be fully utilized. This offers shipowners greater certainty and a stronger financial incentive to invest early in low-carbon solutions. In the Accelerated Transition scenario, as can be seen in ***Figure 13(a)*** that SU utilization increases from 50%-69% under current Net-Zero framework to 100% in this mechanism.

- **Potentially Enough Revenues:** With an increased number of deficit units needing to be balanced, it is likely that the volume of RU purchases will remain robust, helping to maintain strong revenue flows into the IMO Net-Zero Fund to support decarbonization initiatives. However, since the deficits in both tiers could be offset by SUs rather than direct RU purchases (as is the case for Tier-1 in IMO Net-Zero framework), there is a possibility that revenue generation could fall short of expectations, especially if SU supply is high. To address any potential shortfall, the mechanism could be adjusted by reintroducing restrictions on SU pooling or requiring a minimum portion of Tier-1 deficits to be settled through RU purchases. This flexibility would help ensure that the compliance system continues to generate the necessary funding for sector-wide transition efforts while still encouraging efficient SU utilization. In the Accelerated Transition scenario, as can be seen in ***Figure 13(b)***, the total revenues, cumulative over the period 2028 to 2035, increases from $85 B under current Net-Zero Framework to $254 B under this refinement considering no pooling restrictions. Similarly as can be seen in ***Figure 14(b)***, in the Moderate Transition scenario, cumulative revenues over the same period increase substantially, from 141 B$ under the current Net-Zero Framework to 331 B$ after this refinement.
- **Cost Gap Closure:** With a uniform RU price across tiers—likely set at the approved Tier-1 level (e.g., \$100/t-CO_2e)—the SU trading price ceiling will also be lower. As a result, to effectively close the cost gap between conventional and ZNZ fuels, the ZNZ reward rate would need to be higher to maintain a strong investment signal. This, in turn, would require higher revenue inflows to adequately fund more substantial incentives for ZNZ fuel adoption. In the Accelerated Transition scenario, as can be seen in ***Figure 13(c)***, that required reward rate for closing the cost gap of e-NH_3 to LSFO increases from 5–20 \$/t-CO_2e in current Net-Zero Framework to 207–300 \$/t-CO_2e under this refinement, which is a result of the SU component closing the cost gap to a lesser extent.
- **Potentially Mitigate Over-Subsidization:** With lower SU prices, this mechanism may help mitigate the risk of over-subsidizing lower-cost fuels such as biofuels—an issue that could arise under the current Net-Zero Framework with higher Tier-2 RU prices. Lower SU trading values reduce the risk of excessive financial incentives flowing to transitional or less sustainable fuels. Subject to the fuel costs and emissions factors considered in this study, it can be seen in ***Figure 13(d)***, that biofuels are not over-subsidized by the SU component until 2031, and only experience minimal over-subsidization in the years that follow.
- **Simplified Implementation and Administration:** The greater demand for SUs under this mechanism could enable the removal of current pooling restrictions, allowing SU pooling for both Tier-1 and Tier-2 deficits. This would make compliance more flexible for shipowners, reduce administrative complexity, and enhance transparency. This streamlined system would facilitate easier management and verification of compliance across the fleet, and could also promote broader participation in SU trading, making the overall mechanism more efficient and predictable.

Overall, this refinement—applying a uniform RU price with higher SU/RU quantities for Tier-2 deficits—offers a simpler, more transparent compliance system. It improves SU utilization, boosts revenue potential, and enables SU pooling across tiers, reducing administrative complexity. Unlike mechanisms that restrict compliance trading, it retains flexibility for all shipowners, including smaller players, to manage compliance via the SU market. However, lower SU values increase reliance on higher ZNZ rewards, requiring sustained fund inflows and potential safeguards to prevent revenue shortfalls.

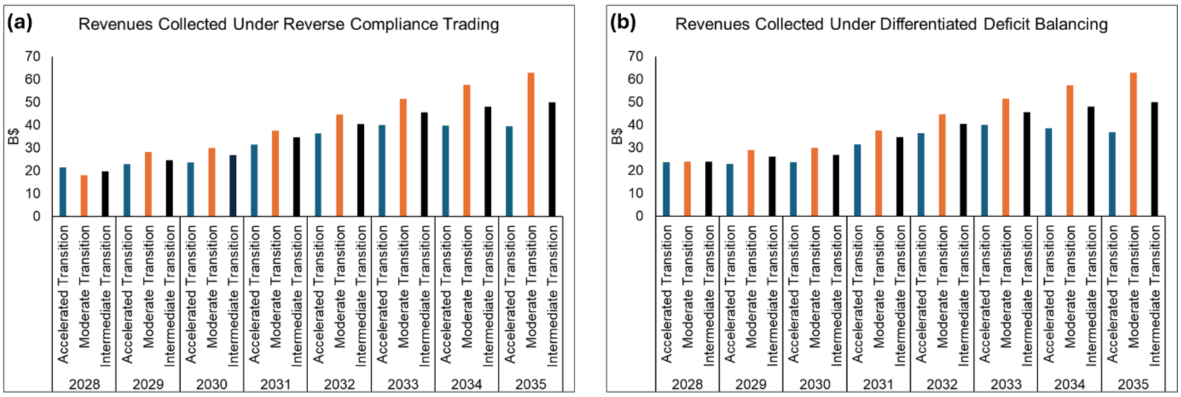

Figure 15: Revenues generated under the two refinements across the two scenarios.

Figure 15 compares the revenues generated from RU sales under the two proposed compliance framework refinements for the three transition scenarios. Compared to the IMO Net-Zero framework results in ***Figure 6***, these refinements not only increase total revenues but also significantly reduce variability across scenarios. Specifically, during 2028–2035, the annual revenue variability—measured as (maximum minus minimum revenue across scenarios, divided by maximum)—is as high as 63% under the current IMO Net-Zero framework and Differentiated Deficit Balancing, increases to 71% with Reverse Compliance Trading.

A summary comparing these mechanisms—including the IMO-approved two-tier approach—across key dimensions such as SU utilization, cost gap closure and ZNZ rewards, revenues collected, and implementation and administration is presented in the ***Table 4*****.**

Table 4: Comparison of the IMO Net-Zero framework, Reverse Compliance Trading, and Differentiated Deficit Balancing across key dimensions.

	IMO Net-Zero framework	Reverse Compliance Trading	Differentiated Deficit Balancing
Overview	**Tier-2 pooling; two-tier differentiated RU prices.**	**Swaps pooling: Tier-1 pooling; two-tier differentiated RU prices; SUs can be sold to the GFI registry.**	**Single RU price; Tier-2 deficits require multiple SUs or RUs per unit; pooling can be flexible.**
	• Each unit of Tier-1 deficit must be balanced by purchasing one RU. Each unit of Tier-2 deficit can be balanced by either by pooling one SU or by purchasing one RU. • Differentiated RU pricing: Tier-2 RU price is higher ($380/t-$CO_2e$) than Tier-1 ($100/t-CO_2e).	• Each unit of Tier-2 deficit must be balanced by purchasing one RU. Each unit of Tier-1 deficit can be balanced by either one SU pooling or purchasing one RU. • RU pricing remains differentiated and could use the same IMO-approved price levels (i.e., 100 and 380 $/t-$CO_2e$).	• Each Tier-2 deficit must be balanced by x (>1) SUs or RUs. Each Tier-1 deficit can be balanced by one SU or one RU. • Same RU price applies for both tiers (e.g.,100$/t-$CO_2e$). • Two possible variants: (1) SU pooling is restricted to Tier-2 deficits, or (2) pooling is allowed for both tiers (no restriction).
SU Utilization	**Potential high risk of SU under-utilization leading to less certainty for shipowners about financial return**.	**SU under-utilization risk is low providing shipowners more certainty.**	**High SU demand (especially if pooling is flexible) means most SUs are likely utilized, minimizing under-utilization.**
	• May result in significant SU under-utilization, since pooling is restricted to Tier-2 deficits. • If most ships remain close to Base GFI targets—as this is often most economical—fewer Tier-2 deficits are available, making under-utilization more pronounced. • Under-utilization can drive down SU market value, potentially requiring the IMO to establish a price floor to maintain incentives. • This creates uncertainty for shipowners investing in low-carbon solutions regarding the financial return from SUs.	• Lower risk of SU under-utilization, as most ships stay near Base GFI targets—often the most economical choice—leading to higher Tier-1 deficits and strong SU demand. • As GFI targets tighten, fewer ships may be able to remain near the Base target, potentially leading to surplus SUs. But allowing SU sales to the GFI registry at a price near the Tier-1 RU value can maintain financial certainty. • This flexibility is difficult to implement under the IMO-approved mechanism, where buying SUs at the higher Tier-2 RU price may not be financially viable for the Fund. • Overall, while some risk of SU under-utilization remains, it is generally low, and the option to sell surplus SUs provides greater certainty and assurance for shipowners.	• higher number of SUs required to offset Tier-2 deficits means most surplus units generated are likely to be used for compliance, making SU under-utilization minimal—especially in variants where pooling is permitted for both tiers. • In scenarios where SU generation significantly exceeds the combined Tier-1 and Tier-2 deficits, some under-utilization could occur. However, this is unlikely, particularly in the early years, as generating large volumes of SUs would require widespread adoption of ZNZ fuels, which is constrained by current costs, supply, and technology development. • Overall, this structure provides shipowners with greater assurance of financial returns on SUs and supports broader uptake of low-carbon solutions.
Cost Gap Closure & ZNZ Reward	**SU under-utilization adds uncertainty to closing the cost gap for ZNZ fuels, may risk over-compensating biofuels, and makes incentives less predictable.**	**SU utilization is more predictable, but a higher ZNZ reward may be needed to fully close the gap for expensive e-fuels, while also reducing over-compensation risks.**	**High SU utilization helps close the cost gap and provides strong incentives, though a higher ZNZ reward may be needed if RU price is low.**
	• SU under-utilization can weaken cost gap closure for high-cost e-fuels. Without provisions to monetize unutilized SUs, incentives for investing in e-fuels diminish, creating uncertainty for shipowners. • Approved RU prices may lead to over-compensation of biofuels through SUs, potentially encouraging excessive biofuel use and associated risks like deforestation and higher	• Allowing Tier-1 deficits to be offset with SUs potentially increases SU utilization and gives shipowners more predictable incentives for ZNZ investment. • The option to sell surplus SUs to the GFI registry further reduces under-utilization risk and supports cost recovery. • However, with SU trading capped at the Tier-1 RU price ($100/t-$CO_2e$), additional ZNZ rewards are needed to fully close the cost gap for high-cost fuels like e-fuels.	• Requiring multiple SUs or RUs per Tier-2 deficit (e.g., 3.8 per unit) substantially increases SU demand, so shipowners investing in ZNZ fuels can expect high SU utilization and stronger investment signals. • A higher ZNZ reward may be needed if the RU price is set lower, as this would reduce the SU trading price and the incentive from SU utilization alone. • The higher number of deficit units ensures steady RU purchases and consistent funding for the Net-Zero Fund, supporting ongoing ZNZ rewards and just transition initiatives.

<table>
<tr>
<td rowspan="2"></td>
<td rowspan="2">emissions. RU prices also over-subsidize LNG in early years, raising concerns about long-term reliance and methane slip.
• While a higher Tier-2 RU price reduces the ZNZ reward required, uncertainty over SU utilization still makes ZNZ investments risky and may shift incentives toward less sustainable options.
• Overall, SU under-utilization adds uncertainty to ZNZ adoption incentives, potentially slowing the pace and sustainability of the industry's transition.
• Preventing biofuel overcompensation requires lowering the Tier-2 RU price. However, this increases the reward needed for e-fuels, and in scenarios with early e-fuel adoption, may result in insufficient Fund revenues to cover all disbursements.</td>
<td>• Sufficient Net-Zero Fund resources and targeted rewards are essential, while lower SU prices help prevent over-compensation for lower-cost options like biofuels.
• Overall, this approach can provide more certainty on SU value and supports ZNZ investment, but closing the cost gap depends on balancing SU value with ZNZ reward rates.</td>
<td>• Overall, Differentiated Deficit Balancing can reliably close much of the cost gap between ZNZ and fossil fuels, reduces uncertainty for shipowners, and fosters stable incentives for deep sector decarbonization.</td>
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<td colspan="2">• Both Reverse Compliance Trading and Differentiated Deficit Balancing use the lower Tier-1 RU price for SU trading, which helps avoid overcompensating biofuels while generating higher revenues. These revenues are sufficient to support e-fuel rewards—even under aggressive early adoption—and can be banked in the early years for future disbursement or other fund uses.</td>
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<tr>
<td rowspan="2">Revenues Collected</td>
<td>Revenues are stable but modest due to lower Tier-1 RU price and potential SU under-utilization, possibly limiting support for transition.</td>
<td>Higher, more predictable revenues from Tier-2 RU purchases, but SU buybacks must be managed to avoid straining the Fund.</td>
<td>Robust and stable revenues from more deficit units and steady RU purchases, supporting long-term decarbonization funding.</td>
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<tr>
<td>• Ensures stable revenue, as Tier-1 deficits must be covered by RU purchases at $100/t-CO_2e. However, lower RU price means total revenue is modest—sufficient for ZNZ rewards but likely insufficient for ambitious decarbonization goals.
• SU under-utilization, especially with few Tier-2 deficits, weakens incentives for early ZNZ adoption and may require higher ZNZ rewards, straining limited funds.
• Overall, this mechanism offers stable revenue, but may not provide enough support for ambitious or equitable transition unless reward rates, incentives, and market responses are well balanced.</td>
<td>• Can generate higher revenues, as Tier-2 deficits are covered by RU purchases at the higher Tier-2 RU price ($380/t-CO_2e).
• If many ships are in Tier-2 (e.g., due to limited low-carbon options), fund revenues will rise; if most stay in Tier-1 and use SUs to offset deficits, revenue may be lower.
• Option to sell surplus SUs to the registry provides certainty but requires careful fund management to avoid undermining fund sustainability.
• Strong Tier-2 RU revenue gives the Fund capacity to offer higher ZNZ rewards and support investment in ZNZ fuels.
• With higher and more predictable revenues, this mechanism can strengthen the Fund's capacity to support decarbonization and equitable transition, though careful management is needed to keep incentives sustainable and aligned with sector goals.</td>
<td>• Requiring multiple SUs or RUs per Tier-2 deficit helps ensure a high volume of RU purchases, even as SUs are fully utilized. With more deficit units and minimal risk of SU under-utilization, this mechanism maintains steady RU purchases, helping prevent unexpected revenue gaps.
• Stable, sufficient revenues enable strong support for ZNZ rewards and JET programs.
• Should revenues be insufficient, rules can be adjusted—such as restricting pooling or requiring a minimum RU purchase—to preserve financial stability and the ability to deliver on incentive commitments.
• Overall, this mechanism is designed for stable and reliable Net-Zero Fund revenues, supporting both ZNZ incentive payments and broader equitable transition objectives.</td>
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<tr>
<td rowspan="2">Implementation & Administration</td>
<td>More complex due to dual pricing and pooling restrictions, requiring careful oversight.</td>
<td>Similar complexity as IMO-approved system, with added challenge of managing SU buybacks and larger fund flows.</td>
<td>Simplified administration with a single RU price and fewer restrictions, making compliance and oversight easier.</td>
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<tr>
<td>• Differentiated pooling restrictions and RU pricing make implementation more complex and require careful oversight.</td>
<td>• Similar admin challenges as the approved mechanism, with added complexity from managing SU sales to the registry.
• Higher revenues from Tier-2 RU purchases increase flexibility for transition support but may require more administrative resources and oversight.</td>
<td>• A single RU price and fewer pooling restrictions (variant 2) simplify implementation for both IMO and shipowners.
• Higher revenues from Tier-2 RU purchases offer more flexibility for transition support, though managing larger funds may require more administrative oversight.</td>
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6. Conclusions

This paper has critically analysed the effectiveness and challenges of the IMO Net-Zero Framework's compliance mechanism, designed to drive substantial reductions in maritime greenhouse gas emissions. While the current regulatory framework marks a significant step toward maritime decarbonization, several important limitations remain that may undermine its long-term effectiveness and efficiency, and these issues need to be carefully considered in future IMO deliberations.

A potential issue relates to the economic uncertainty that could arise from under-utilization of Surplus Units (SUs), which may create hesitation among shipowners considering investment in greener fuels. This uncertainty could limit the mechanism's effectiveness in encouraging ambitious decarbonization. Additionally, the current differentiated pricing of Remedial Units—Tier-2 at \$380/t-CO_2e and Tier-1 at \$100/t-CO_2e—may overcompensate some biofuels, such as bio-methane, while effectively closing the cost gap for e-fuels like e-ammonia. To mitigate the risk of promoting unsustainable biofuel adoption, it may be beneficial to further refine the incentive structure. Specifically, closing the cost gap through a combination of lower-priced SUs and targeted rewards for both biofuels and e-fuels could help ensure a more balanced outcome. Achieving this will require careful calibration to avoid overcompensation, while ensuring that centralized funding remains sufficient to support the necessary incentives.

Scenario analyses comparing baseline compliance (Moderate Transition scenario) and ambitious compliance (Accelerated Transition scenario) highlight structural challenges that may arise within the current mechanism. In ambitious scenarios, the accumulation of unused SUs could weaken market incentives and make deeper decarbonization more difficult. To address these potential challenges, this paper examines two possible refinements—Reverse Compliance Trading and Differentiated Deficit Balancing. These approaches can help improve SU utilization, reduce economic uncertainty, ensure more predictable incentives, and stabilize revenue flows to support the adoption of zero and near-zero emission fuels as well as just transition measures.

This study is subject to several limitations. First, our analysis is conducted at the fuel level rather than the fleet level, and does not account for vessel-specific operational or investment behaviour. Second, fuel cost assessments exclude capital expenditure (CAPEX), which may materially affect real-world fuel choices. Third, the scenarios used are based on energy projections that already incorporate the expected effects of IMO mid-term measures, rather than dynamically modelling feedback from evolving cost signals under the mechanism. While this limits the ability to simulate responsive behaviour (e.g., shifts in technology adoption in reaction to pricing signals), the selected scenarios span a broad and representative spectrum—from conservative to highly ambitious pathways—anchored in the assumptions used by the IMO itself. Finally, fuel costs and emission factors are based on the best available projections and may vary in practice. Taken together, these limitations may affect the quantitative results, but they are unlikely to alter the overall direction or qualitative insights. The comparative dynamics, incentive design challenges, and key policy implications remain robust and relevant under a wide range of plausible future conditions.

In conclusion, targeted refinements—such as improving SU utilization, calibrating targets realistically, and providing differentiated incentives for biofuels and e-fuels—are essential to strengthen the IMO framework. Implementing these changes will empower the shipping industry to pursue ambitious decarbonization with confidence, support sustained investment in sustainable technologies, and ultimately achieve meaningful, equitable, and robust maritime decarbonization.

Appendix

Table A1: Summary results of the two new proposed mechanisms, (a) Reverse Compliance Trading and (b) Differentiated Deficit Balancing under Accelerated Transition Scenario.

DNV-Ammonia-Reduced CCS (Accelerated Scenario)		Tier-1 RUs (million t-CO_2e)	Tier-2 RUs (million t-CO_2e)	Total SUs Generated (million t-CO_2e)	Total SUs Purchased by the Registry	Remaining SUs Including 2 Years Banking (million t-CO_2e)	Generated Revenues (B$)			Effective Cost Compared to the LSFO Effective Cost (% Effective LSFO Cost)		Necessity of additional rewards/subsidies		
							Handling Fee (5% for transaction and 1% for banking)	RUs Sales	Total Revenue	Bio-Methane	e-NH_3	Bio-Methane ($/t-$CO_2e$)	e-NH_3 ($/t-$CO_2e$)	Reward Disbursement Required (B$)
Reverse Compliance Trading	**2028**	103	55	81	0	0	0.4	21.0	21.4	109%	225%	27	300	2.1 No Uptake of e-Fuels
	2029	98	65	121	23	0	0.6	22.4	23.0	108%	213%	26	285	3 No Uptake of e-Fuels
	2030	95	75	150	55	0	0.7	22.9	23.7	107%	201%	24	270	3.4 No Uptake of e-Fuels
	2031	95	100	168	73	0	0.8	30.7	31.5	103%	186%	12	261	1.9 No Uptake of e-Fuels
	2032	91	118	187	96	0	0.8	35.3	36.3	100%	173%	0	250	0 No Uptake of e-Fuels
	2033	81	134	203	122	0	0.9	38.9	39.9	97%	161%	0	237	0 No Uptake of e-Fuels
	2034	69	138	219	150	0	1.0	38.6	39.7	94%	150%	0	223	0 No Uptake of e-Fuels
	2035	58	138	223	165	0	0.9	38.5	39.5	92%	141%	0	207	0 No Uptake of e-Fuels
Differentiated Deficit Balancing (Each Tier-2 deficit units is balanced by 3.8 units of SUs or RUs)	**2028**	103	209	81	0	0	0.4	23.3	23.7	109%	225%	27	300	2.1 No Uptake of e-Fuels
	2029	98	247	121	0	0	0.6	22.4	23.0	108%	213%	26	285	3 No Uptake of e-Fuels
	2030	95	285	150	0	0	0.7	22.9	23.7	107%	201%	24	270	3.4 No Uptake of e-Fuels
	2031	95	380	168	0	0	0.8	30.7	31.5	103%	186%	12	261	1.9 No Uptake of e-Fuels
	2032	91	448	187	0	0	0.8	35.3	36.3	100%	173%	0	250	0 No Uptake of e-Fuels
	2033	81	509	203	0	0	0.9	38.9	39.9	97%	161%	0	237	0 No Uptake of e-Fuels
	2034	69	524	219	0	0	1.0	37.5	38.6	94%	150%	0	223	0 No Uptake of e-Fuels
	2035	58	524	223	0	0	1.0	35.8	36.9	92%	141%	0	207	0 No Uptake of e-Fuels

Table A2: Summary results of the two new proposed mechanisms, (a) Reverse Compliance Trading and (b) Differentiated Deficit Balancing under Moderate Transition Scenario.

LR-Hydrogen Scenario (Moderate Transition Scenario)		Tier-1 RUs (million t-CO_2e)	Tier-2 RUs (million t-CO_2e)	Total SUs Generated (million t-CO_2e)	Total SUs Purchased by the Registry	Remaining SUs Including 2 Years Banking (million t-CO_2e)	Generated Revenues (B$)			Effective Cost Compared to the LSFO Effective Cost (% Effective LSFO Cost)		Necessity of additional rewards/subsidies		
							Handling Fee (5% for transaction and 1% for banking)	RUs Sales	Total Revenue	Bio-Methane	e-NH_3	Bio-Methane ($/t-$CO_2e$)	e-NH_3 ($/t-$CO_2e$)	Reward Disbursement Required (B$)
Reverse Compliance Trading	**2028**	88	47	30	0	0	0.1	18.0	18.1	109%	225%	27	300	0.4
	2029	92	61	36	0	0	0.2	28.2	28.4	108%	213%	26	285	0.8
	2030	89	72	66	0	0	0.3	29.6	29.9	107%	201%	24	270	7.4
	2031	91	97	88	0	0	0.4	37.2	37.6	103%	186%	12	261	11.6
	2032	91	121	110	19	0	0.5	44.2	44.7	100%	173%	0	250	15.1
	2033	86	144	125	39	0	0.6	50.8	51.5	97%	161%	0	237	17.5
	2034	81	165	140	59	0	0.7	56.7	57.4	94%	150%	0	223	19.2
	2035	77	183	152	75	0	0.8	62.2	63.0	92%	141%	0	207	19.8
Differentiated Deficit Balancing (Each Tier-2 deficit units is balanced by 3.8 units of SUs or RUs)	**2028**	88	180	30	0	0	0.1	23.8	23.9	109%	225%	27	300	0.4
	2029	92	234	36	0	0	0.2	28.9	29.1	108%	213%	26	285	0.8
	2030	89	272	66	0	0	0.3	29.6	29.9	107%	201%	24	270	7.4
	2031	91	369	88	0	0	0.4	37.2	37.6	103%	186%	12	261	11.6
	2032	91	461	110	0	0	0.5	44.2	44.7	100%	173%	0	250	15.1
	2033	86	548	125	0	0	0.6	50.8	51.4	97%	161%	0	237	17.5
	2034	81	626	140	0	0	0.7	56.7	57.4	94%	150%	0	223	19.2
	2035	77	697	152	0	0	0.8	62.2	63.0	92%	141%	0	207	19.8

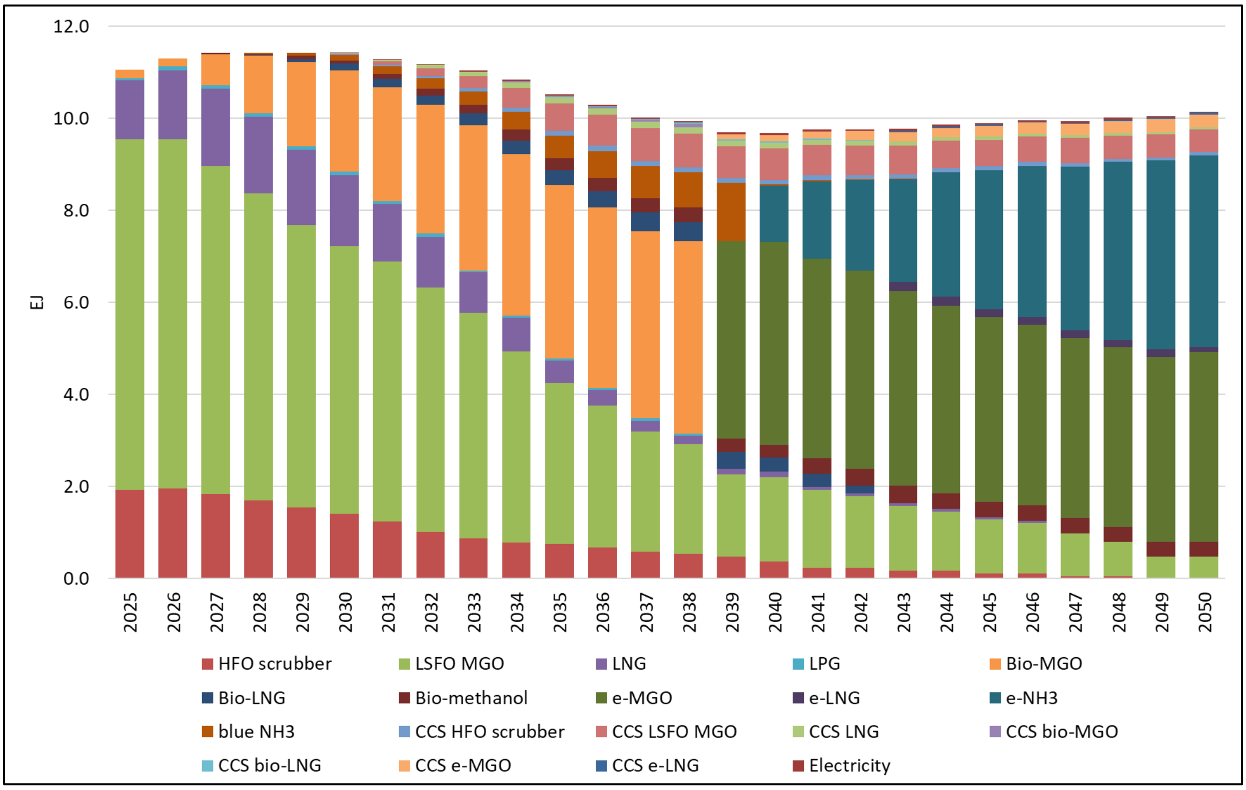

Figure A1: DNV-Ammonia-Reduced CCS Scenario.

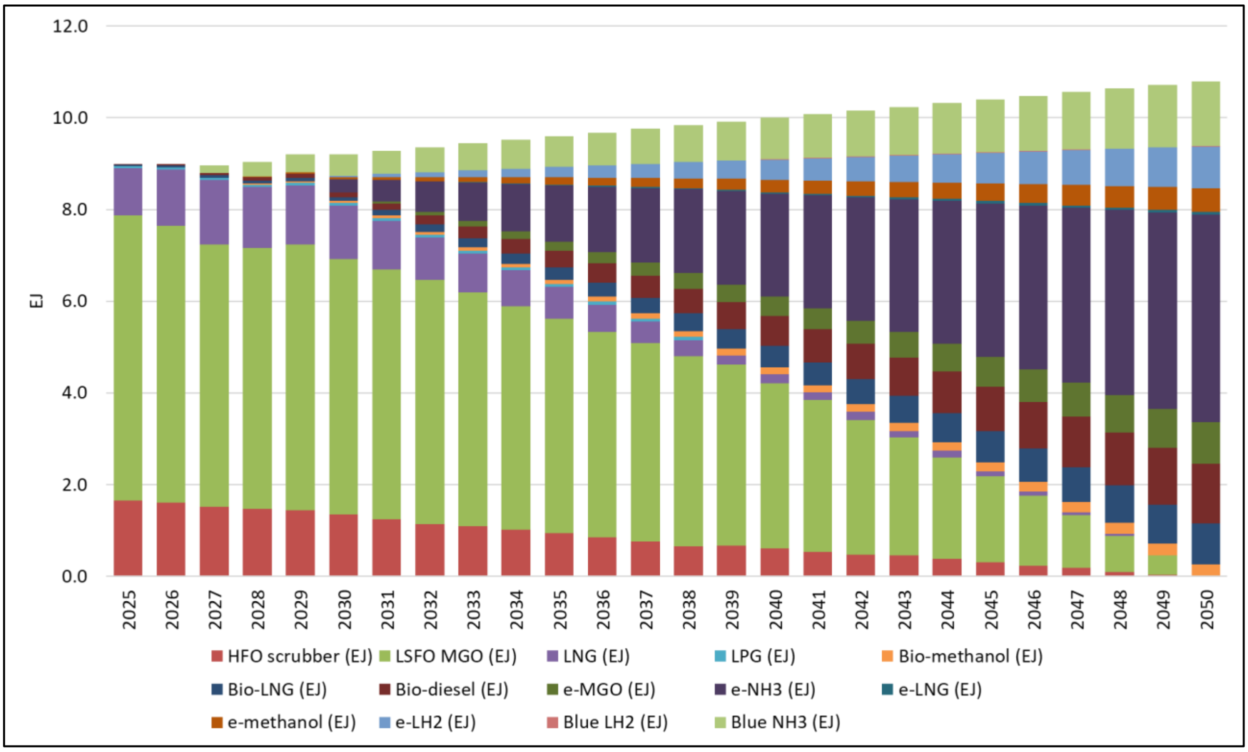

Figure A2: LR-Hydrogen Scenario.

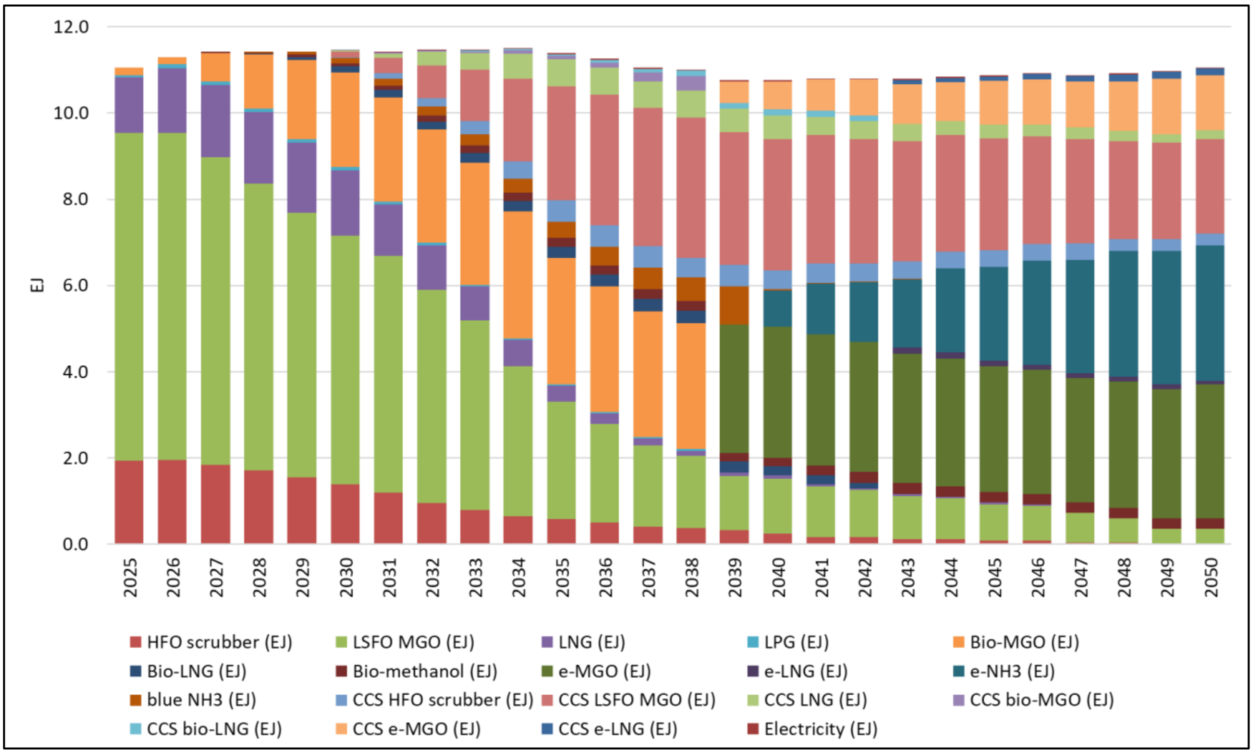

Figure A3: DNV-Ammonia Scenario.

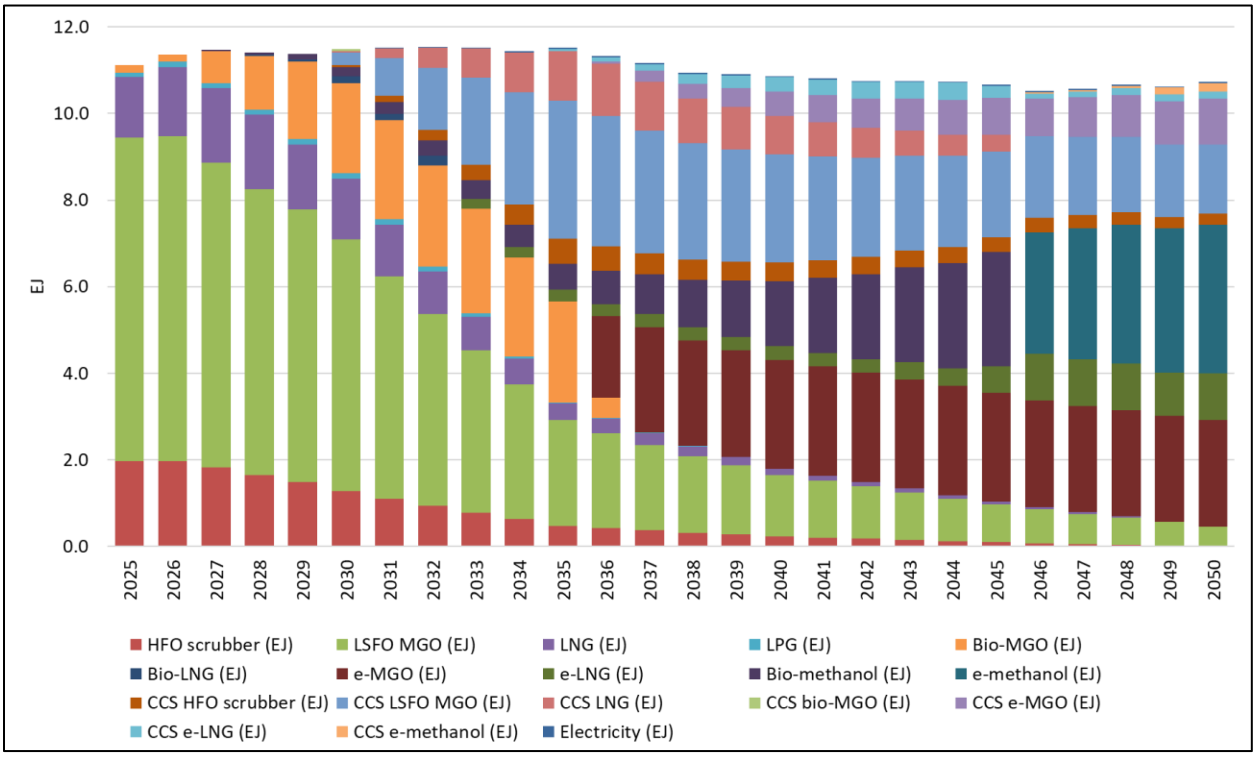

Figure A4: DNV-Methanol Scenario.

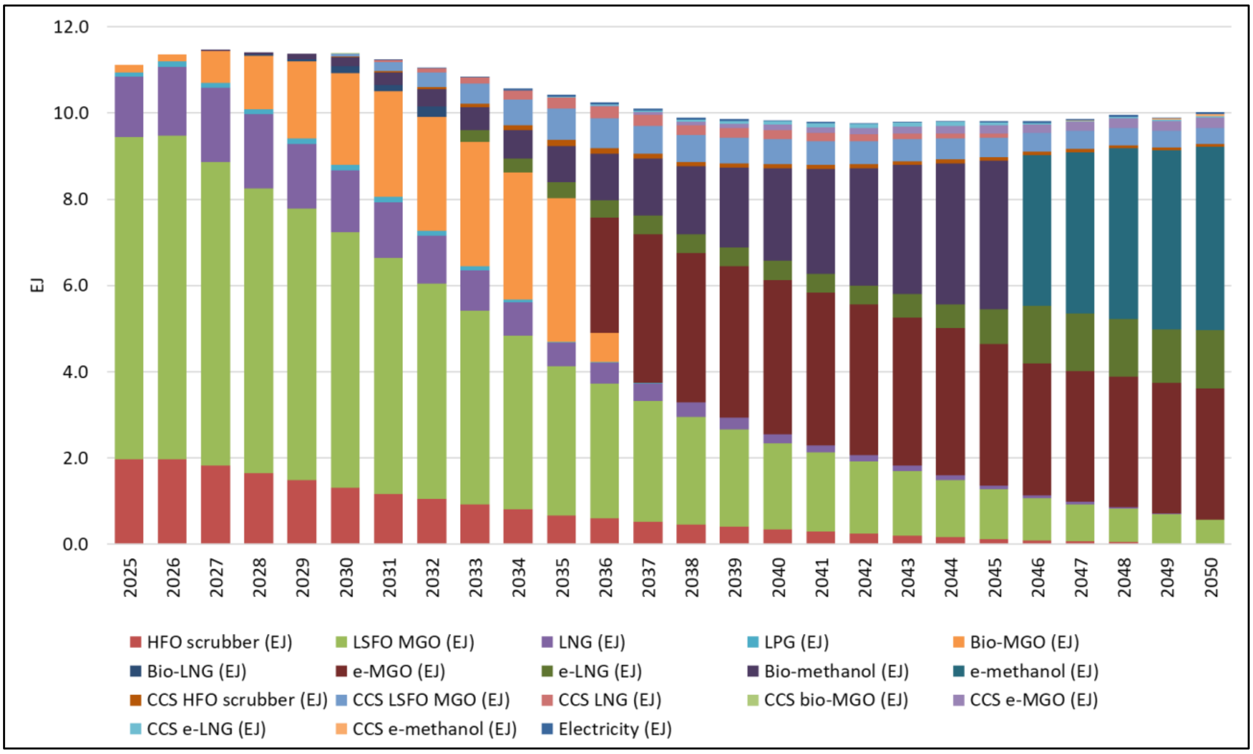

Figure A5: DNV-Methanol-Reduced CCS Scenario.

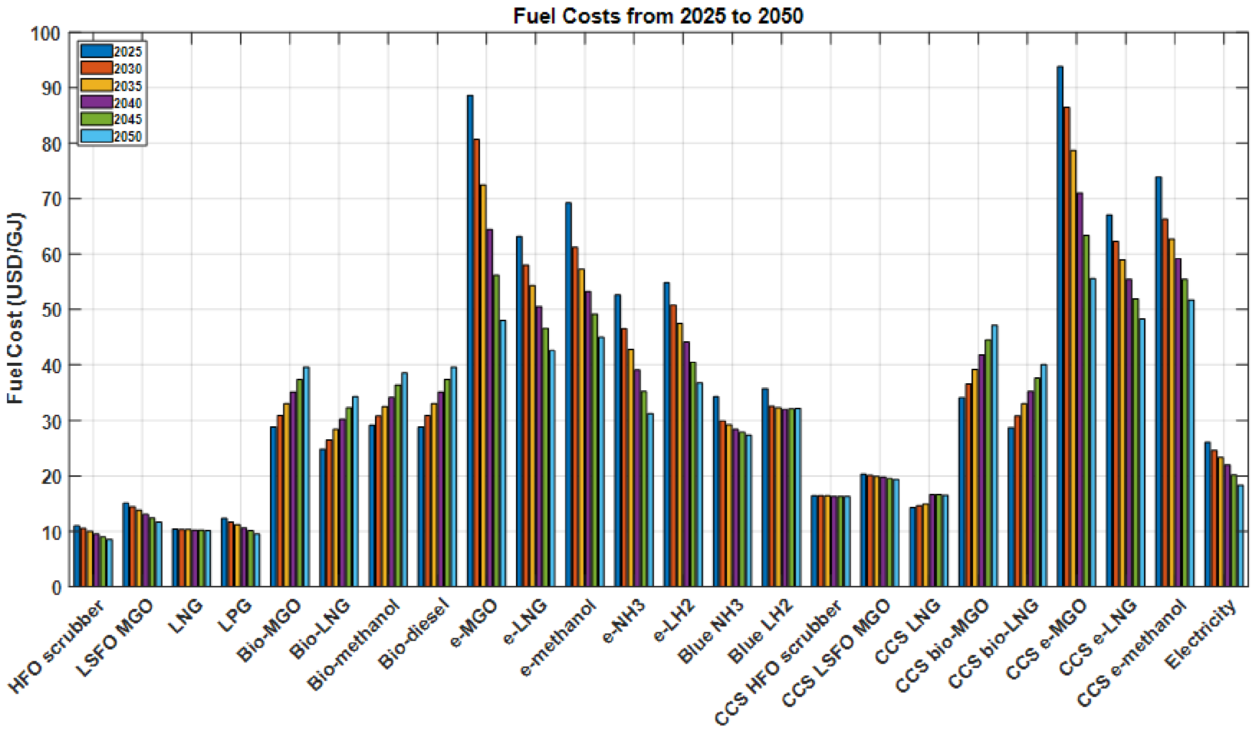

Figure A6: Fuels cost projection from 2025 to 2050.

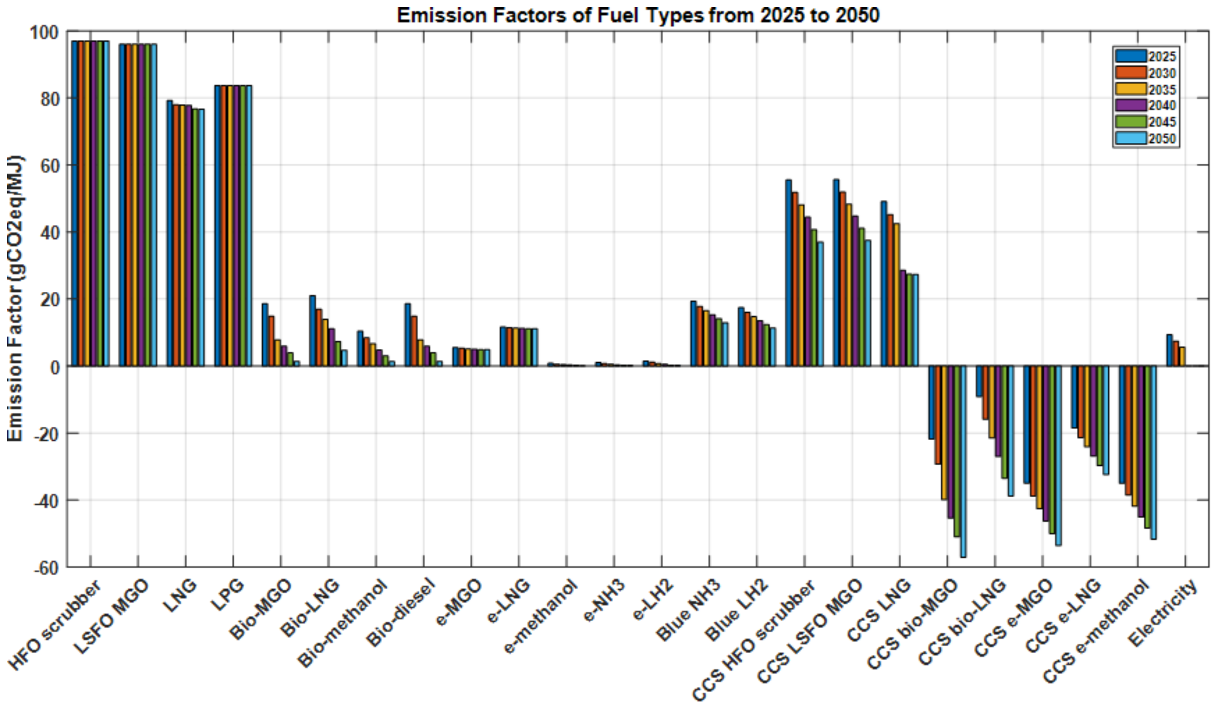

Figure A7: Fuels emission factor projection from 2025 to 2050.

Key Calculation Formulas

In line with the guidelines in the IMO Net-Zero Framework, and focusing the analysis at the fuel level, the following key calculation formulas are used in this study:

Table A3: Key Calculation Formulas.

Annual GFI Attained	$\frac{\sum_{f \in \text{all fuels}} \text{GFI}_f(\text{gCO2e/MJ}) \times \text{Annual Fuel Uptake}_f(\text{MJ})}{\sum_{f \in \text{all fuels}} \text{Fuel Uptake}_f(\text{MJ})}$
Annual SUs Generated from over-complaint fuels (with GFI < Direct Compliance Target)	$\sum_{f \in \text{over-compliant fuels}} (\text{Direct Compliance Target} - \text{GFI}_f) \times \text{Annual Fuel Uptake}_f$
Annual Tier-1 Deficit Units from Tier-1 fuels (with Direct Compliance Target < GFI < Base Target) & from Tier-2 fuels (GFI > Base Target)	$\sum_{f \in \text{Tier-1 fuels}} (\text{GFI}_f - \text{Direct Compliance Target}) \times \text{Annual Fuel Uptake}_f$ $+$ $\sum_{f \in \text{Tier-2 fuels}} (\text{Base Target} - \text{Direct Compliance Target}) \times \text{Annual Fuel Uptake}_f$
Annual Tier-2 Deficit Units from Tier-2 fuels (GFI > Base Target)	$\sum_{f \in \text{Tier-2 fuels}} (\text{GFI}_f - \text{Base Target}) \times \text{Annual Fuel Uptake}_f$
Annual Traded SUs	Minimum{SUs Generated, SU Trading Eligible Deficit Units} SU Trading Eligible Deficit Units = • Tier-2 Deficit Units for IMO Net-Zero Framework • Tier-1 Deficit Units for Reverse Compliance Trading • Tier-1 + x (e.g., 3.8) * Tier-2 Deficit Units for Differentiated Deficit Balancing
Unutilized (or Unsold) SUs	Annual SUs Generated − Annual Traded SUs

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