Navigating Environmental Compliance: Maritime Fleet Renewal Under Fuel Market Uncertainty

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Abstract: International shipping is entering a period in which fleet investment, fuel-market development, and climate regulation must be managed jointly. We study long-horizon fleet renewal planning for a liner company facing tightening decarbonization targets and uncertain alternative-fuel markets. We develop a ship-resolved optimization model that coordinates discrete renewal actions (energy-efficiency retrofits, dual-fuel conversions, and end-of-life replacement) with annual fuel deployment across compatible fuels, subject to ship-level technology constraints and fleetwide caps on low-/zero-carbon fuel availability. Regulatory compliance is represented through a modular mapping that captures fuel-intensity standards with deficit payments, surplus crediting, and targeted rewards for eligible fuels, enabling comparison across regulatory architectures. We solve a deterministic model under given fuel cost and supply trajectories and a scenario-based stochastic extension in which near-term retrofit choices are made before fuel-market conditions are revealed, to examine how fuel markets and regulation jointly shape decision strategies. Numerical study on an Asia–Europe liner service shows that limited low-carbon fuel availability is a first-order constraint: cost-optimal pathways shift toward efficiency everywhere, with scarce low-carbon volumes targeted to ships with longer remaining life, and continued reliance on compliance-unit purchases during the transition. Under a hybrid regulatory environment and fuel scarcity, allocating limited volumes to keep more ships near a Base target is often preferred to pushing a few ships into surplus-credit regions. Explicit uncertainty modeling yields a more selective, hedged early retrofit portfolio than mean-trajectory planning, delivering modest expected-cost gains but materially lower downside risk. Finally, standard-based regulatory designs induce earlier technology commitment and sustained fuel switching, while a pure levy can yield persistent emissions payments with weaker structural decarbonization when the price signal declines, highlighting the role of standards and incentives in shaping transition pathways.

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1. Introduction

International shipping underpins global supply chains, moving over 80% of world merchandise trade by volume (UNCTAD 2025). It is also a significant and growing source of greenhouse gas (GHG) emissions, accounting for nearly 3% of global anthropogenic CO_2 (IMO 2020). Without additional measures, these emissions are projected to rise as seaborne trade expands. Given shipping's macroeconomic role, tightening climate targets, and long asset lifetimes, oceangoing fleet investment decisions are both economically critical and environmentally consequential.

In 2023, the International Maritime Organization (IMO) adopted a revised GHG Strategy calling for net-zero emissions "by or around 2050" (IMO 2023b). Negotiations on global mid-term measures have since advanced along two tracks: technical instruments such as a goal-based GHG fuel standard (GFS) that limits the GHG intensity of ship energy use, and economic instruments that price emissions (e.g., levies or market-based mechanisms) to internalize emissions cost and create demand signals for low- and zero-carbon fuels. The Net-Zero Framework (NZF) emerged as a hybrid, combining a global GFS with emissions pricing and targeted rewards for zero and near-zero (ZNZ) fuels (IMO 2025). Although approved in principle, NZF formal adoption was deferred, leaving uncertainty around final design and timing. Several states and industry coalitions continue to advocate a global price-based measure such as a carbon levy/contribution, with IMO discussions spanning a wide range of fee levels, including proposals around 100 USD/tCO_2e (IMO 2023a). Regional measures are also advancing, including the EU ETS extension to maritime transport and FuelEU Maritime (EC 2023, 2024). Together, these developments create uncertainty about future carbon-price exposure, regulatory stringency, and fuel-demand signals across trades and time.

For shipping companies, this uncertainty creates interrelated planning challenges. Ships are long-lived assets, yet regulatory requirements and fuel-market conditions can shift quickly. Early commitment to a fuel pathway risks lock-in as targets tighten, while delaying decisions can increase compliance exposure. Firms must also choose among alternative fuels facing uncertain prices, constrained volumes, and uneven infrastructure build-out across regions. While comparative studies of GHG-reduction fuels and technologies find no single option dominates across cost and life-cycle performance (Bouman et al. 2017, Lindstad et al. 2021, Zou and Yang 2023), much of the evidence relies on static total cost of ownership (TCO) comparisons that assume deterministic fuel costs and sufficient supply. Conversely, fleet-renewal models under uncertainty often employ stylized regulation (e.g., a uniform carbon price) rather than the coupled technical-and-economic architectures now emerging. These gaps motivate ship-level renewal models that integrate alternative fuel choices with joint fuel cost–supply uncertainty under realistic compliance mechanisms.

Against this backdrop, shipping companies face a practical question: how should fleets be renewed and decarbonized as fuel markets and climate regulation evolve? Ships ordered in the 2020s and 2030s will still operate when targets tighten, so misjudging timing or technology can lead to stranded assets, costly retrofits, or high carbon-cost exposure. We develop a fleet renewal planning framework for a liner company that jointly optimizes discrete renewal actions (energy efficiency retrofits, dual-fuel conversions, replacement) and annual fuel deployment, under joint uncertainty in fuel costs and availability. The model supports consistent comparisons across regulatory designs, including technical standards, levies, and hybrid schemes. We first solve a deterministic perfect foresight benchmark, and then extend it to a scenario-based stochastic setting, reporting expected costs, downside risk, and compliance outcomes under alternative regulatory setups (NZF, pure levy, and one-tier GFS+pricing). While many factors influence transition choices (e.g., technology maturity, yard capacity, capital costs), *fuel costs* and *supply availability* are often among the most consequential drivers of feasibility and economics (Achtnicht, Bühler, and Hermeling 2012, Zwaginga et al. 2024); accordingly, we focus on their joint uncertainty.

The analysis addresses five research questions: **Deterministic baseline (RQ1):** Under perfect foresight of fuel costs, availability, and regulatory targets, what renewal pathway—defined by retrofit/replacement timing, fuel-system choice, and energy efficiency (EE) measures—minimizes total cost? **Sensitivity (RQ2):** How do fuel cost and supply assumptions shift the optimal pathway and compliance outcomes? **Fuel uncertainty (RQ3):** How do optimal strategies and cost/compliance exposures change under uncertain fuel costs and availability? **Value of stochastic planning (RQ4):** What is the impact of explicit uncertainty modeling relative to the perfect-foresight plan? **Regulatory comparison (RQ5):** How do alternative regulatory setups—NZF (two-tier), one-tier GFS+pricing, and pure levy—change renewal pathways and long-run outcomes? By answering these questions, the paper moves beyond static TCO comparisons and one-off scenarios toward uncertainty-aware fleet investment and fuel-transition planning under evolving regulation.

This work makes the following key contributions:

- **Ship-level renewal model:** A ship-level, multi-period fleet renewal framework that optimizes retrofit timing/type and end-of-age replacement choice across competing fuel-system pathways and EE measures, under explicit compliance-cost accounting.
- **Joint fuel cost–supply uncertainty:** A scenario-based stochastic extension capturing joint uncertainty in alternative-fuel costs and availability, enabling evaluation of expected performance and downside exposure under fuel-market volatility and scarcity.

- **Unified regulatory representation:** A modular regulatory mapping capturing technical and economic measures, allowing alternative setups to be analyzed by switching parameters on/off, illustrated for an NZF-type hybrid, a one-tier fuel standard with pricing, and a pure levy.
- **Decision-relevant outputs:** Renewal pathways, sensitivities, and tail-risk metrics that quantify how fuel markets and regulatory assumptions drive strategy.
- **Case-study evidence:** A representative liner-service application with calibrated cost/supply trajectories, contrasting stochastic plans with perfect-foresight benchmarks.

The remainder of the paper is organized as follows. Section 2 reviews related literature and positions this study's contribution. Section 3 presents the fleet renewal model under a general regulatory setup (deterministic and stochastic). Section 4 describes the case study, data, fuel cost–supply scenario construction, and regulatory parameterization. Section 5 reports results aligned with RQ1–RQ5, covering deterministic baselines and sensitivities, value of stochastic planning, and regulatory comparisons. Section 6 concludes and outlines directions for future research.

2. Literature Review

Research relevant to this work spans three strands: (i) fleet renewal under uncertainty, (ii) techno-economic assessment of fuels and EE options, and (iii) analyses of shipping decarbonization measures. This section reviews each strand and positions this paper's contribution.

2.1. Fleet Renewal Under Uncertainty

Fleet renewal is a strategic problem shaped by large capital outlays, long asset lifetimes, and exposure to uncertain market and regulatory conditions. Early studies largely relied on deterministic mixed-integer formulations, with uncertainty explored through scenario testing or sensitivity analysis (Christiansen et al. 2013, Pantuso, Fagerholt, and Hvattum 2014). More recent work uses stochastic programming and related approaches, which often outperform deterministic expected-value planning benchmarks (Bakkehaug et al. 2014, Pantuso, Fagerholt, and Wallace 2016).

A growing stream incorporates environmental regulation and market uncertainty, showing that market-based measures can materially shift renewal timing and technology choice (Patricksson, Fagerholt, and Rakke 2015, Zhu et al. 2018). Recent studies move closer to alternative-fuel transition and consider fuel and carbon-price uncertainty, reinforcing the value of fuel flexibility and early hedging (Lagemann et al. 2023, Loennechen et al. 2024, Wang and Çağatay Iris 2025).

Complementary liner-shipping OR studies show that service design and operations (routing/scheduling, speed, bunkering) shape effective fuel costs and feasibility through refueling opportunities and port access (e.g., Agarwal and Ergun 2008, Wang and Meng 2012, Brouer et al. 2014).

As shipping shifts to alternative fuels, these linkages tighten as competitiveness depends on both prices and accessible volumes. Johansen, Holst, and Ropke (2025) connect liner design with fuel uptake and sourcing, emphasizing both costs and availability are uncertain and decision-relevant.

Despite these advances, two aspects remain under-modeled: joint uncertainty in low-/zero-carbon fuel costs and availability, and the policy detail of emerging hybrid measures that couple fuel-intensity standards with incentives/penalties. A further gap concerns decision granularity. Many models evaluate compliance at an aggregated fleet level, while emerging regulations such as the NZF assess compliance at the ship level, creating heterogeneous incentives across ships by age, remaining lifetime, and retrofit feasibility. Our work addresses these gaps with a ship-resolved renewal and operational model aligned with ship-level compliance and joint cost–supply uncertainty.

2.2. Alternative Marine Fuels and TCO-Based Assessments

A parallel literature evaluates alternative marine fuels, including LNG, methanol, ammonia, hydrogen, and advanced bio-/e-fuels, typically using techno-economic or TCO frameworks under assumed fuel costs, emissions factors, and regulatory conditions. The central finding is consistent: low- and zero-carbon fuels can deliver large emissions reductions, but near- and mid-term economics remain challenging and highly sensitive to learning, scale-up, and regulatory support (Balcombe et al. 2019, Ammar 2019, Lindstad et al. 2021, Zou and Yang 2023).

Recent empirical and industry work provides fuel-cost and emissions-factor ranges useful for scenario design. Lagouvardou et al. (2023) quantify marginal abatement costs and show how market-based measures shift relative competitiveness. Industry and class-society reports synthesize plausible ranges for costs, well-to-wake emissions, scalability, and infrastructure readiness, emphasizing near-term uptake is constrained by both cost and sustainable fuel availability (DNV 2023, ClassNK 2026). Corridor-focused assessments similarly stress the role of regulatory clarity and reliable access to volume at scale (Rotterdam–Singapore Green Corridor 2024). Industry analytics further indicate that fuel expenditures dominate total costs for deep-sea segments under low- and zero-carbon pathways and that cost gaps are highly sensitive to fuel production costs and carbon-price assumptions (GMF 2022b, UMAS 2023). Together, these findings motivate treating fuel-market uncertainty and supply constraints as key drivers of fleet investment risk.

While this literature grounds fuel-cost spreads, transition hierarchies, and the role of energy-efficiency measures, many studies remain comparative-static or route-specific, often treating fuel availability as non-binding and addressing uncertainty via limited sensitivity tests. This motivates integrated renewal models that link early retrofit commitments with later adaptive fuel-use and replacement decisions under joint uncertainty in fuel costs and availability.

2.3. Shipping Decarbonization Policies and Investment Implications

The IMO's 2023 GHG Strategy envisages mid-term measures that combine a goal-based fuel standard with GHG pricing (IMO 2023b). The MEPC 83 approved NZF operationalizes this by pairing tightening fuel-intensity targets with pricing and incentive features, including a two-tier structure and revenue recycling (IMO 2025). These features shape renewal decisions through the trade-off between investing to over-comply and purchasing compliance units. The IMO-commissioned Comprehensive Impact Assessment (CIA) evaluates candidate measures and consolidates assumptions on ships, retrofit options, technology pathways, and costs (DNV 2024a). Our work complements this global perspective with a single-company, ship-level planning aligned with ship-level compliance.

Regionally, the EU ETS extension to maritime and FuelEU Maritime further shape incentives and effective fuel costs through carbon pricing, tightening intensity limits, and flexibility mechanisms such as pooling and credit trading (EC 2023, 2024). Yet most policy assessments remain sector- or corridor-level and rarely compare alternative global architectures (standard-plus-pricing versus a simplified levy) within an integrated company-level renewal model under joint fuel cost and supply uncertainty. This motivates our ship-resolved framework for comparing renewal timing, fuel pathways, and compliance outcomes across benchmark regulatory configurations.

3. Fleet Renewal Planning Under General Regulatory Framework

Over the coming decades, ocean-going fleets must be renewed under tightening regulations that will erode competitiveness of conventional ships. Shipping companies have several levers: (i) EE retrofits (e.g., hull/propeller upgrades, waste-heat recovery, wind assistance), (ii) retrofitting alternative(alt-) fuel systems (e.g., LNG, methanol, ammonia) to enable bio-/e-fuel use when available, and (iii) scrap and replace older ships with alt-fuel newbuilds. Each option comes with different capital and operating costs, fuel flexibility, emissions performance, and feasible age windows. Uncertainty is particularly acute for low-/zero-carbon fuels, which remain early in deployment with limited production, uneven bunkering, and evolving supply chains, making both relative fuel costs and reliable availability uncertain and directly affecting operating feasibility and pathway choice.

We study the problem from a liner shipping company's perspective. Liner shipping is a natural starting point because it is an early adopter of alt-fuel ships and typically operates homogeneous fleets on fixed schedules between major bunkering hubs, making early investment in new designs and fuel infrastructure operationally and commercially viable. At the same time, schedule integrity and capacity commitments limit fleet size adjustments to fuel cost or supply shocks. This makes liner shipping a natural context for studying fleet renewal under fuel cost and supply uncertainty.

The core planning problem is as follows. Over a multi-period horizon, the liner company decides for each ship, in eligible renewal periods, whether to keep the ship as-is, undertake EE retrofits, convert to an alt-fuel configuration, or scrap and replace with a newbuild, and in parallel allocates each ship's annual energy demand across compatible fuels subject to fuel availability. Regulatory trajectories (e.g., GHG intensity targets, levy) are treated as given, while fuel costs and availability of low-/zero-carbon fuels are uncertain. The key trade-off is between early fuel/technology commitment to reduce compliance exposure and preserving flexibility as fuel markets evolve.

We model a fixed-size fleet, replacing end-of-life ships with capacity-equivalent newbuilds. This allows us to isolate the transition decisions of interest—retrofit and fuel-system choices, fuel switching under supply constraints, and compliance-cost exposure—from demand-driven fleet expansion or chartering. Capacity growth, when needed, mainly adds new ships and poses the same fuel-system choice problem for incremental newbuilds. Given the initial fleet state, feasible renewal options and their costs/effects, fuel cost–supply paths and emission factors, and regulatory parameters, the model minimizes discounted capital, operating, fuel, and compliance costs under deterministic trajectories or fuel-market scenarios. Outputs include an optimal multi-period renewal pathway and fuel-use plan with associated cost, emissions, and compliance outcomes. We next introduce notation and present the deterministic and scenario-based stochastic formulations.

3.1. Problem Setting and Notation

Let $T = \{1, 2, \ldots, T_{\max}\}$ be a discrete-time planning horizon (typically annual periods). The liner company operates a fleet of ships indexed by $s \in S$, where each s represents a fleet position maintained over the horizon. When ship s reaches its end-of-life period, denoted by life_s, it is replaced by a newbuild that inherits index s. **Assumption 1 (fixed-size fleet):** Number of ships in the fleet is fixed over time, so total shipping capacity is maintained: end-of-life ships are replaced by capacity-equivalent newbuilds. Retrofits may reduce effective cargo capacity (e.g., due to added tank space), which we account for through an opportunity cost term in the ship's operating cost.

Technology states. Let K denote the set of technology states, and let $K_s \subseteq K$ be the states feasible for ship s. A technology state summarizes the ship's configuration (initial or retrofitted), installed fuel system (conventional or alt-fuel), any cargo capacity loss (e.g., from larger tanks), and the resulting annual energy requirement (EE upgrades typically reduce energy use). Each ship begins in an initial state k_s^0 and can transition to other states via retrofit or replacement. Feasibility can vary over time. Let $K_{s,t} \subseteq K_s$ denote the states ship s may occupy in period t, capturing technology availability (states enter only after commercial availability) and age constraints (replacement states become feasible at end-of-life). Thus, in period t the choice for ship s is restricted to $k \in K_{s,t}$.

Energy requirement. For each ship–state pair, let $E^{\text{req}}_{s,k}$ (gigajoules GJ/year) be the annual energy requirement, capturing baseline design and renewal effects (EE retrofits imply lower $E^{\text{req}}_{s,k}$ than the initial state k^0_s). Let $\delta^{\text{cap}}_{s,k} \in [0, 1)$ denote the capacity-loss fraction (e.g., from alt-fuel tanks). Rather than imposing a separate capacity constraint, we monetize this loss (e.g., chartering to cover lost slots) and include it in the ship's fixed operating cost.

Renewal options. We distinguish two classes of renewal options for each ship s:

R^{ret}_s: set of feasible *retrofit options* for ship s, including EE-only retrofits, alt-fuel conversions, and combined alt-fuel plus EE retrofits. We assume retrofits do not extend the ship's technical lifetime, which remains governed by hull age and condition.

R^{rep}_s: set of *replacement options* (scrap-and-replace) for ship s. Each option corresponds to a newbuild (conventional or alt-fuel, with or without EE) that replaces the retiring ship with the same nominal capacity. If an alt-fuel design requires additional tank volume (to preserve range), the newbuild may need a larger hull and thus higher energy use, reflected in $E^{\text{req}}_{s,k}$.

To capture age- and time-dependent feasibility (e.g., alt-fuel conversions only for ships younger than 10 years, or only after commercialization), let $R^{\text{ret}}_{s,t} \subseteq R^{\text{ret}}_s$ denote retrofit options admissible for ship s in period t. Let $T^{\text{ren}}_s \subseteq T$ be the set of renewal periods for ship s (e.g., dry-dockings); retrofits $r \in R^{\text{ret}}_{s,t}$ can be exercised only when $t \in T^{\text{ren}}_s$ and $t < \text{life}_s$, while replacement occurs at end-of-life ($t = \text{life}_s$). We do not allow discretionary early scrapping, to focus on feasible retrofits and mandatory end-of-life renewal without modeling resale/scrap values; early replacement can be added via an age-dependent salvage/resale credit, with retrofits admissible only before replacement.

Conceptually, each renewal option $r \in R^{\text{ret}}_s \cup R^{\text{rep}}_s$ induces a transition between technology states in K_s. For ship s, let $c^{\text{ret}}_{s,r,t}$ denote the retrofit cost of option $r \in R^{\text{ret}}_{s,t}$ if executed at the start of period t, and $c^{\text{rep}}_{s,r,t}$ denote the replacement cost of option $r \in R^{\text{rep}}_s$ if selected at the start of period t, and $c^{\text{fix}}_{s,k,t}$ denote the fixed operating cost in state k during period t, including technical O&M (operations and management) and any capacity-loss opportunity cost from $\delta^{\text{cap}}_{s,k}$. We impose two structural restrictions. **Assumption 2 (at most one retrofit):** each ship may undergo at most one retrofit before end-of-life. **Assumption 3 (no retrofits after replacement):** after replacement, the newbuild is not eligible for further retrofits. See Appendix A.1 for operational justifications.

Fuels, compatibility and emissions. Let F denote the set of fuels, including conventional fuel-oils and fossil/sustainable variants of alt-fuels (e.g., LNG, methanol, ammonia). Each state $k \in K$ permits a subset of compatible fuels $F_k \subseteq F$ determined by the installed fuel system, e.g., a conventional state permits only fuel-oils, whereas a DF-LNG state permits both fuel-oil and LNG fuels. We encode this with $\alpha_{k,f} \in \{0,1\}$, where $\alpha_{k,f} = 1$ if fuel f is usable in state k and 0 otherwise. Let $c^{\text{fuel}}_{f,t}$ denote the cost of fuel f in period t (USD/GJ), let $\overline{A}_{f,t}$ denote its fleetwide availability (GJ), and let $\text{EF}_{f,t}$ denote the emissions factor ($\text{gCO}_2\text{e/MJ}$). Together with fuel-use decisions, these parameters determine annual fuel expenditures and GHG emissions and intensity.

Regulatory framework. We model a general regulatory framework combining (i) *technical* requirements as declining GHG fuel-intensity (GFI) targets and (ii) *economic* incentives/penalties through carbon pricing, tradable compliance credits, and targeted fuel rewards. In each period, ships are assessed on their attained GFI (computed from fuel use and emissions factors). Under-compliance incurs deficit payments that rise with the shortfall to the GFI target, while over-compliance generates surplus credits that can be monetized by selling to deficit ships or carried forward subject to banking rules. Eligible fuels (e.g., e-fuels) may earn an additional reward on the surplus-credit share, strengthening incentives for early uptake beyond the baseline value of the credits. This structure generalizes "standard-and-trading" designs, where a fuel standard sets the benchmark, while pricing, credit trading, and targeted rewards translate deviations from the benchmark into penalties/incentives (e.g., an IMO NZF-type setup; see Section 4.5).

To represent tiered compliance (e.g., Tier 1/Tier 2 in NZF), let $Q = \{1, \ldots, Q_{\max}\}$ index regulatory tiers. A GFI threshold $I^{\text{GFI}}_{t,q}$ ($\text{gCO}_2\text{e/MJ}$) defines the lower boundary of tier q in period t, with $I^{\text{GFI}}_{t,1} < I^{\text{GFI}}_{t,2} < \cdots < I^{\text{GFI}}_{t,Q_{\max}}$ (lower thresholds for stricter tiers), and an associated carbon price $\pi^{\text{CP}}_{t,q} \geq 0$ ($\text{USD/tCO}_2\text{e}$). If a ship's attained GFI falls in tier q (i.e., between $I^{\text{GFI}}_{t,q}$ and $I^{\text{GFI}}_{t,q+1}$), it pays $\pi^{\text{CP}}_{t,q}$ per tCO_2e of deficit attributable to that tier, in addition to deficit payments from lower tiers. Prices typically increase with tier stringency (i.e., $I^{\text{GFI}}_{t,q_1} < I^{\text{GFI}}_{t,q_2} \Rightarrow \pi^{\text{CP}}_{t,q_1} < \pi^{\text{CP}}_{t,q_2}$).

Each period t also includes surplus-crediting. Let I^{SU}_t be the GFI threshold below which surplus units (SUs) are generated, valued at $\rho^{\text{SU}}_t \geq 0$ per SU, and let ϕ_t denote the SU banking horizon. Targeted rewards are represented by an eligible-fuel set $F^{\text{elig}}_t \subseteq F$ and an additional reward $\rho^{\text{elig}}_t \geq 0$ applied to the SU share attributable to F^{elig}_t. A ship that over-complies relative to I^{SU}_t generates SUs proportional to its GFI gap and energy use (converted to tCO_2e), which can be traded at ρ^{SU}_t or banked subject to ϕ_t, with additional reward ρ^{elig}_t for eligible-fuel SU share. ρ^{SU}_t depend on surplus–deficit trading dynamics, but is treated in the model as known exogenous input. Together, $\{I^{\text{GFI}}_{t,q}, \pi^{\text{CP}}_{t,q}, I^{\text{SU}}_t, \rho^{\text{SU}}_t, F^{\text{elig}}_t, \rho^{\text{elig}}_t, \phi_t\}$ define a period-specific regulatory policy function $\Phi_t(\cdot)$.

Discounting. All monetary quantities are discounted to the first period using a discount rate r and discount factors $\beta_t = (1+r)^{-(t-1)}$. Investment, operating, and fuel costs in period t are weighted by β_t. Regulatory compliance is assessed at the end of each period, so penalties and incentives for period t are settled at the period end (or at the start of $t+1$) and are discounted using β_{t+1}.

Decision variables. The liner decides (i) renewal actions by ship and eligible period (retrofit before end-of-life and replacement at end-of-life) and (ii) per-period (annual) deployment of each ship's energy demand across fuels, subject to fuel–technology compatibility and fuel availability. Technology states and emissions are implied by these choices. The main decision variables are:

Renewal decisions (eligible renewal periods). (i) $y^{\text{ret}}_{s,r,t} \in \{0,1\}$: equals 1 if ship s applies retrofit option $r \in R^{\text{ret}}_{s,t}$ at the start of period $t \in T^{\text{ren}}_s$ with $t < \text{life}_s$, (ii) $y^{\text{rep}}_{s,r} \in \{0,1\}$ equals 1 if ship s selects replacement option $r \in R^{\text{rep}}_s$ at the start of its end-of-life period $t = \text{life}_s$.

Fuel-use decisions (each period/year). $E_{s,f,t} \geq 0$: energy from fuel f used by ship s in period t.

3.2. Deterministic Fleet Renewal Problem

In deterministic setting, fuel costs $c^{\text{fuel}}_{f,t}$ and availability limits $\overline{A}_{f,t}$ are assumed known, with other parameters taken as given. The liner company chooses renewal and fuel-use decisions to minimize the net present value (NPV) of capital, operating, fuel and compliance costs over the horizon.

Technology and renewal constraints. Binaries $u_{s,k,t} \in \{0,1\}$ indicate whether ship s is in state k in period t. Each ship is in exactly one feasible state per period, with the initial state fixed at $t = 1$.

$$\sum_{k \in K_{s,t}} u_{s,k,t} = 1, \quad \forall s \in S,\ t \in T \quad ; \quad u_{s,k^0_s,1} = 1 \quad ; \quad u_{s,k,1} = 0, \quad \forall s \in S,\ k \in K_{s,1} \setminus \{k^0_s\}. \tag{1}$$

We link $u_{s,k,t}$ to renewal decisions for a consistent technology pathway. Each ship may retrofit at most once before end-of-life, and must be replaced exactly with one replacement option at end-of-life (assuming the horizon is not long enough for the replacement to reach its own end-of-life).

$$\sum_{t \in T^{\text{ren}}_s:\, t < \text{life}_s} \sum_{r \in R^{\text{ret}}_{s,t}} y^{\text{ret}}_{s,r,t} \leq 1, \quad \forall s \in S \quad ; \quad \sum_{r \in R^{\text{rep}}_s} y^{\text{rep}}_{s,r} = 1, \quad \forall s \in S. \tag{2}$$

Let $\kappa^{\text{ret}}_{s,r} \in K_s$ be the resulting technology state if retrofit option r is applied to ship s, and $\kappa^{\text{rep}}_{s,r} \in K_s$ the technology state after selecting replacement option r. The evolution of $u_{s,k,t}$ over time is then:

$$\begin{aligned}
u_{s,k^0_s,t} &= 1 - \sum_{\tau \in T^{\text{ren}}_s:\tau \leq t} \sum_{r \in R^{\text{ret}}_{s,\tau}} y^{\text{ret}}_{s,r,\tau} && \forall s \in S,\ t \in T \text{ with } t < \text{life}_s, \\
u_{s,\kappa^{\text{ret}}_{s,r},t} &= \sum_{\tau \in T^{\text{ren}}_s:\tau \leq t, r \in R^{\text{ret}}_{s,\tau}} y^{\text{ret}}_{s,r,\tau} && \forall s \in S,\ r \in R^{\text{ret}}_s,\ t \in T \text{ with } t < \text{life}_s, \\
u_{s,\kappa^{\text{rep}}_{s,r},t} &= y^{\text{rep}}_{s,r} && \forall s \in S,\ r \in R^{\text{rep}}_s,\ t \in T \text{ with } t \geq \text{life}_s.
\end{aligned} \tag{3}$$

Constraints (3) implement the logic that: (i) prior to any retrofit, ship s remains in its initial state k^0_s, (ii) if a retrofit r is applied in some eligible period $\tau < \text{life}_s$, the ship transitions to state $\kappa^{\text{ret}}_{s,r}$ from period τ up to (but not including) its replacement, and (iii) at end-of-life, the chosen replacement option $r \in R^{\text{rep}}_s$ fixes the post-replacement state $\kappa^{\text{rep}}_{s,r}$ in all periods $t \geq \text{life}_s$.

Energy requirement and fuel use. For each ship s and period t, the active technology state determines the annual energy requirement, which must be met by fuel use:

$$\begin{aligned}
&E_{s,t} = \sum_{k\in K_{s,t}} E^{\text{req}}_{s,k}\, u_{s,k,t} = \sum_{f\in F} E_{s,f,t} && \forall s\in S,\ t\in T,\\
&0 \le E_{s,f,t} \le \sum_{k\in K_{s,t}} \alpha_{k,f}\, E^{\text{req}}_{s,k}\, u_{s,k,t} && \forall s\in S,\ f\in F,\ t\in T,\\
&E_{f,t} = \sum_{s\in S} E_{s,f,t} \le \overline{A}_{f,t} && \forall f\in F,\ t\in T.
\end{aligned} \tag{4}$$

Constraints (4) link technology choice to ship and fleet energy use. The first defines ship energy demand from the active state and enforces energy balance, the second imposes fuel compatibility via $\alpha_{k,f}$, and the third aggregates ship fuel use and enforces the fleetwide availability cap $\overline{A}_{f,t}$.

Emissions and compliance units. Compliance is evaluated at the *ship* level. Given fuel use, period-t GHG emissions of ship s are

$$\text{GHG}_{s,t} = \sum_{f\in F} \text{EF}_{f,t}\, E_{s,f,t}, \qquad \forall s\in S,\ t\in T. \tag{5}$$

implying GFI attained $I_{s,t} = \text{GHG}_{s,t}/E_{s,t}$. Switching to lower-$\text{EF}_{f,t}$ fuels reduces both $\text{GHG}_{s,t}$ and $I_{s,t}$, while EE measures mainly reduce $\text{GHG}_{s,t}$ by lowering $E_{s,t}$ and may leave $I_{s,t}$ largely unchanged for a fixed fuel mix. Fleet-level emissions follow by aggregation, e.g., $\text{GHG}_t = \sum_{s\in S} \text{GHG}_{s,t}$.

Surplus units (SUs). Relative to the surplus threshold I^{SU}_t, define the compliance balance

$$G^{\text{tot}}_{s,t} = \frac{I^{\text{SU}}_t E_{s,t} - \text{GHG}_{s,t}}{1000}, \qquad \forall s\in S,\ t\in T, \tag{6}$$

and total SUs generated $SU^{\text{tot}}_{s,t} = \max\{G^{\text{tot}}_{s,t}, 0\}$ (tCO_2e), linearized via a standard big-M formulation (Appendix A.2). Surplus from eligible fuels is defined directly as

$$SU^{\text{elig}}_{s,t} = \frac{1}{1000} \sum_{f\in F^{\text{elig}}_t} \left(I^{\text{SU}}_t - \text{EF}_{f,t}\right) E_{s,f,t} \qquad \forall s\in S,\ t\in T. \tag{7}$$

Since F^{elig}_t is restricted to fuels with $\text{EF}_{f,t} \le I^{\text{SU}}_t$, each term $(I^{\text{SU}}_t - \text{EF}_{f,t})E_{s,f,t}$ is non-negative, so $SU^{\text{elig}}_{s,t} \ge 0$ holds automatically and no additional big-M linearization is required.

Banking and trading of SUs. Let $B^{\text{tot}}_{s,t} \ge 0$ denote banked total SUs available at the start of period t, $X^{\text{tot}}_{s,t} \ge 0$ the amount of banked SUs used to offset period-t deficits, and $SU^{\text{traded}}_{s,t} \ge 0$ the portion of period-t SUs that is traded/monetized rather than banked. The SU balance is

$$0 \le SU^{\text{traded}}_{s,t} \le SU^{\text{tot}}_{s,t} \qquad \forall s\in S,\ t\in T,$$

$$B^{\text{tot}}_{s,1} = 0 \quad ; \quad B^{\text{tot}}_{s,t+1} = B^{\text{tot}}_{s,t} + SU^{\text{tot}}_{s,t} - SU^{\text{traded}}_{s,t} - X^{\text{tot}}_{s,t} \qquad \forall s \in S,\ t \in T \setminus \{T_{\max}\},$$

$$0 \le X^{\text{tot}}_{s,t} \le B^{\text{tot}}_{s,t} \le \sum_{\tau=\max\{1,t-\phi_t\}}^{t-1} SU^{\text{tot}}_{s,\tau} \qquad \forall s \in S,\ t \in T.$$

The first constraint caps traded SUs by current-period generation. The second sets the initial bank to zero and updates the bank with newly generated SUs net of trading and offsets. The last enforces that offsets cannot exceed the bank, and only SUs from the most recent ϕ_t years may be retained.

Deficit units (DUs). For each tier $q \in Q$, gross deficit units denoted by $DU_{s,t,q} \ge 0$ are:

$$DU_{s,t,q} \ \ge\ \frac{\text{GHG}_{s,t} - I^{\text{GFI}}_{t,q} E_{s,t}}{1000} \qquad \forall s \in S,\ t \in T,\ q \in Q. \tag{8}$$

Thus $DU_{s,t,q}$ is at least the excess of emissions over the tier-q GFI threshold (scaled by energy and converted to tCO_2e). Since $DU_{s,t,q}$ is associated with non-negative penalty coefficients, it takes positive-part value at optimality. Ships may offset current-period deficits using previously banked SUs or SUs traded from over-compliant ships, but such offsets may be restricted to only a subset of tiers (e.g. Tier 2 in NZF). Let $Q^{\text{SU-off}} \subseteq Q$ be SU-offset-eligible tiers and let $\widehat{DU}_{s,t,q}$ be the *net* (post-offset) deficit and impose the following, so that $X^{\text{tot}}_{s,t}$ reduces only the deficits in $Q^{\text{SU-off}}$.

$$\begin{aligned}
&0 \le \widehat{DU}_{s,t,q} \le DU_{s,t,q} && \forall s \in S,\ t \in T,\ q \in Q,\\
&\widehat{DU}_{s,t,q} = DU_{s,t,q} && \forall s \in S,\ t \in T,\ q \in Q \setminus Q^{\text{SU-off}},\\
&\sum_{q \in Q^{\text{SU-off}}} \widehat{DU}_{s,t,q} \ \ge \sum_{q \in Q^{\text{SU-off}}} DU_{s,t,q} - X^{\text{tot}}_{s,t} && \forall s \in S,\ t \in T,
\end{aligned} \tag{9}$$

Regulatory cost. Ship-level regulatory cost in period t is then

$$C^{\text{reg}}_{s,t} = \sum_{q \in Q} \lambda_{t,q}\, \widehat{DU}_{s,t,q} \ -\ \rho^{\text{SU}}_t\, SU^{\text{traded}}_{s,t} \ -\ \rho^{\text{elig}}_t\, SU^{\text{elig}}_{s,t}, \tag{10}$$

where the first term penalizes net deficits and the latter terms credit traded (monetized) SUs and eligible-fuel rewards. Fleet-wide regulatory cost is $C^{\text{reg}}_t = \sum_{s \in S} C^{\text{reg}}_{s,t}$. To reproduce tiered pricing from $\pi^{\text{CP}}_{t,q}$, we interpret $\lambda_{t,q}$ as *incremental* penalties on successive GFI bands. With ordered thresholds $I^{\text{GFI}}_{t,1} < I^{\text{GFI}}_{t,2} < \cdots < I^{\text{GFI}}_{t,Q_{\max}}$ and increasing carbon prices $\pi^{\text{CP}}_{t,1} < \pi^{\text{CP}}_{t,2} < \cdots < \pi^{\text{CP}}_{t,Q_{\max}}$, we set

$$\lambda_{t,1} = \pi^{\text{CP}}_{t,1}, \qquad \lambda_{t,q} = \pi^{\text{CP}}_{t,q} - \pi^{\text{CP}}_{t,q-1} \quad \text{for } q \ge 2. \tag{11}$$

so that $\sum_{q \in Q} \lambda_{t,q} \widehat{DU}_{s,t,q}$ recovers the cumulative payment across tiers: if a ship's attained GFI falls in tier q, it pays the tier-q carbon price on the net deficit, plus the payments for all stricter tiers.

Appendix Table 9 summarizes the notation. The formulation can accommodate additional company-level constraints (e.g., budget caps or emissions targets), but we omit them for brevity.

Objective function. The deterministic fleet renewal problem minimizes discounted total cost:

$$\min Z^{\text{DET}} = \sum_{t\in T} \beta_t \left[\sum_{s\in S} \left(\sum_{\substack{r\in R_s^{\text{ret}}:\\ t\in T_s^{\text{ren}},\, t<\text{life}_s}} c^{\text{ret}}_{s,r,t}\, y^{\text{ret}}_{s,r,t} + \sum_{k\in K_{s,t}} c^{\text{fix}}_{s,k,t}\, u_{s,k,t} \right) + \sum_{f\in F} c^{\text{fuel}}_{f,t}\, E_{f,t} \right] + \sum_{s\in S} \beta_{\text{life}_s} \sum_{r\in R_s^{\text{rep}}} c^{\text{rep}}_{s,r,\text{life}_s}\, y^{\text{rep}}_{s,r} + \sum_{t\in T} \beta_{t+1}\, C^{\text{reg}}_t, \tag{12}$$

subject to the technology and renewal constraints (1)–(3), energy and fuel-use constraints (4), emissions and compliance accounting constraints (5)–(11), and variable domains. The full deterministic (DET) formulation in a single block is provided in Appendix B.2.

3.3. Scenario-Based Stochastic Extension

To capture fuel-market uncertainty, we extend the model to a scenario-based stochastic (STO) formulation. Let W be a finite set of scenarios with probabilities π_w ($\sum_{w\in W} \pi_w = 1$), where each scenario specifies joint fuel-cost and availability paths ($c^{\text{fuel}}_{f,t,w}, \overline{A}_{f,t,w}$), while all other parameters are scenario-independent. The STO model replicates the deterministic constraints for each w and replaces ($c^{\text{fuel}}_{f,t}, \overline{A}_{f,t}$) with ($c^{\text{fuel}}_{f,t,w}, \overline{A}_{f,t,w}$). Scenario-dependent variables are indexed by w, including renewal and fuel-use decisions, technology states, and implied emissions and compliance quantities (e.g., $y^{\text{ret}}_{s,r,t,w}$, $y^{\text{rep}}_{s,r,w}$, $E_{s,f,t,w}$, $\text{GHG}_{s,t,w}$, $SU^{\text{tot}}_{s,t,w}$, $\widehat{DU}_{s,t,q}$).

Non-anticipativity. The liner company must make *here-and-now* renewal decisions in period 1, before fuel-market conditions are realized. We therefore treat period 1 renewal choices as first-stage decisions and require them to be identical across all scenarios:

$$y^{\text{ret}}_{s,r,t=1,w} = y^{\text{ret}}_{s,r,t=1,w'} \qquad \forall s\in S,\ r\in R^{\text{ret}}_{s,t=1},\ \forall w, w'\in W. \tag{13}$$

Subsequent-period renewal actions are scenario-dependent (multi-stage recourse), reflecting that the company may adjust later renewal choices as fuel-market uncertainty unfolds. If a ship is retrofitted in period 1, Assumption 2 (at most one retrofit) precludes any further retrofit in later periods under all scenarios, while the mandatory end-of-life replacement choice remains scenario-dependent.

Stochastic objective. Under risk neutrality, we minimize expected discounted cost: $\min Z^{\text{STO}} = \sum_{w\in W} \pi_w Z^{\text{DET}}_w$, where Z^{DET}_w is the deterministic objective in (12) evaluated under scenario w (with scenario-specific fuel inputs and decision variables), subject to scenario-wise copies of the deterministic constraints (1)-(11) and non-anticipativity constraints (13). The full formulation is provided in Appendix B.3. In the numerical study, we adopt risk neutrality and assess downside cost and compliance outcomes *ex post* using a larger ensemble of fuel-market realizations.

Figure 1 summarizes the multi-period fleet renewal planning structure and highlights the first-stage (scenario-independent) renewal decisions and the scenario-dependent recourse decisions.

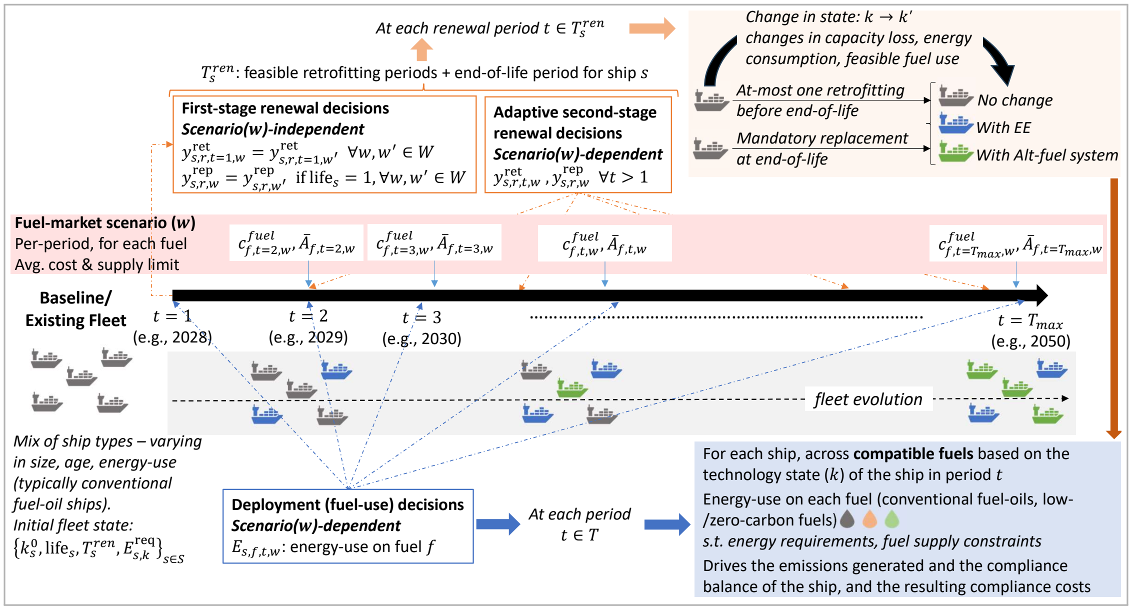


Figure 1 **Schematic of the Multi-Period Fleet Renewal Planning Under the General Regulatory Framework**

3.4. Representation of Alternative Regulatory Setups

The framework can represent a range of decarbonization measures through a unified regulatory mapping. Specifically, period-t compliance is fully determined by $\{I^{\text{GFI}}_{t,q}, \pi^{\text{CP}}_{t,q}, I^{\text{SU}}_t, \rho^{\text{SU}}_t, F^{\text{elig}}_t, \rho^{\text{elig}}_t, \phi_t\}$, which defines the regulatory mapping $\Phi_t(\cdot)$ from ship-level fuel use and emissions to deficit/surplus quantities and associated payments. Alternative architectures can be represented by reconfiguring these parameters without changing the underlying fleet-renewal model. Table 1 summarizes four regulatory setups commonly proposed for maritime: (i) NZF-type two-tier GFS with carbon pricing and surplus incentives (and ZNZ rewards), (ii) one-tier GFS with carbon pricing and surplus incentives (and ZNZ rewards), (iii) a pure carbon levy, and (iv) a pure GFS with a strict non-compliance penalty. Formally, each setup p corresponds to a specific configuration of $\{I^{\text{GFI}}_{t,q}, \pi^{\text{CP}}_{t,q}, I^{\text{SU}}_t, \rho^{\text{SU}}_t, F^{\text{elig}}_t, \rho^{\text{elig}}_t, \phi_t\}$, and hence to a regulatory function $\Phi^{(p)}_t(\cdot)$.

Extensions and generalizations. The framework is modular: renewal constraints define feasible technology and fuel-deployment pathways, while the regulatory module maps fuel use and emissions to deficit/surplus quantities and payments. This structure supports extensions—such as endogenous capacity growth/chartering, early retirement with salvage values, more granular (e.g., hub-specific) fuel-availability constraints, alternative credit/banking and offset rules, and risk-averse objectives (e.g., CVaR)—without changing the core renewal model. Details are in Appendix C.

3.5. Solution approach

DET is a mixed-binary linear problem with binary renewal/state variables and continuous fuel-use, emissions, and compliance variables. Although such models are computationally challenging, for

Table 1 Alternative Regulatory Setups through Parameter Configurations

Regulatory setup	Key parameter configuration
IMO NZF: two-tier GFS + carbon pricing + SU incentive and ZNZ reward (IMO (2025), see Figure 2)	$Q = \{1,2\}$ with $I^{\text{GFI}}_{t,1} < I^{\text{GFI}}_{t,2}$ and $0 < \pi^{\text{CP}}_{t,1} < \pi^{\text{CP}}_{t,2}$; surplus threshold $I^{\text{SU}}_t = I^{\text{GFI}}_{t,1}$; SUs monetized at $\rho^{\text{SU}}_t > 0$; eligible fuels F^{elig}_t rewarded at $\rho^{\text{elig}}_t > 0$; banking horizon ϕ_t reflects NZF banking (e.g., $\phi_t = 2$); SU offsets restricted to $Q^{\text{SU-off}} = \{2\}$.
One-tier GFS + carbon pricing + SU incentive and ZNZ reward (IMO 2024b)	$Q = \{1\}$ with single target/surplus threshold $I^{\text{SU}}_t = I^{\text{GFI}}_{t,1}$ and $\pi^{\text{CP}}_{t,1} > 0$; SUs monetized at $\rho^{\text{SU}}_t > 0$; eligible fuels F^{elig}_t rewarded at $\rho^{\text{elig}}_t > 0$; $Q^{\text{SU-off}} = \{1\}$; ϕ_t as desired.
Pure (economic-measure) carbon levy (IMO 2024a, 2022)	$Q = \{1\}$ with $I^{\text{GFI}}_{t,1} = 0$ and $\pi^{\text{CP}}_{t,1} = p^{\text{levy}}_t$; switch off surplus incentives $\rho^{\text{SU}}_t = \rho^{\text{elig}}_t = 0$. The regulatory term reduces to p^{levy}_t times total emissions.
Pure (technical-measure) GFS with non-compliance penalty (IMO 2024c)	$Q = \{1\}$ with single target $I^{\text{GFI}}_{t,1}$ and a large penalty $\pi^{\text{CP}}_{t,1} \gg 0$; switch-off incentives $\rho^{\text{SU}}_t = \rho^{\text{elig}}_t = 0$, yielding a pure performance standard with no over-compliance incentives.

Notes. Each setup can be implemented by selecting values for $\{I^{\text{GFI}}_{t,q}, \pi^{\text{CP}}_{t,q}, I^{\text{SU}}_t, \rho^{\text{SU}}_t, F^{\text{elig}}_t, \rho^{\text{elig}}_t, \phi_t, Q^{\text{SU-off}}\}$.

our case-study instances with limited fleet size, horizon, and option set, a commercial solver obtains optimal solutions within 1–2 hours, which is acceptable for such long-horizon strategic problems.

STO scales with $|W|$ and includes non-anticipativity constraints, making the full mixed-binary model difficult to solve even for moderately large scenario sets. We therefore adopt a restricted first-stage approach: solve each scenario deterministically (ignoring non-anticipativity), collect the resulting optimal period-1 renewal decisions into a candidate set, and then solve a reduced STO in which first-stage choices are restricted to this set. For our instances, the reduced STO objective value is within 1% of a lower bound from relaxing non-anticipativity (i.e., scenario-wise optimization and taking probability-weighted average of the optimal objective values), indicating the restriction captures most of the fully non-anticipative value while remaining computationally manageable.

4. Numerical Study

We apply the framework to a deep-sea Asia–Europe liner service that, while marketed as an alliance loop, is operated by a single carrier. We therefore model it as a single-company fleet and study renewal and fuel switching under tightening decarbonization measures. The framework also extends to a fixed fleet across multiple services by specifying ship-level annual energy requirements and treating deployment as exogenous, or endogenizing assignment via service-level capacity constraints. The numerical study uses public-source techno-economic inputs and scenario-based fuel cost and supply trajectories. For regulation, we focus on the IMO NZF and benchmark it against a one-tier NZF variant and a pure carbon levy without explicit GFI targets.

The planning horizon spans 2028–2050 ($T = \{2028, \ldots, 2050\}$), with 2028 as the potential start of global mid-term measures (NZF). We model annual decision points for renewal and fuel deployment, and extend the horizon to 2050 to align with mid-century targets and to capture long-lived investment effects under tightening requirements.

4.1. Liner Service and Baseline Fleet

The case study is based on the French Asia Line 6 (FAL6) Asia–North Europe deep-sea container service within the Ocean Alliance network (CMA CGM 2025). Since deployed ships are owned and operated by Evergreen Group, we treat the loop as a stylized single-carrier weekly service and analyze unilateral renewal and fuel-choice decisions while holding the service pattern fixed.

Table 2 Existing Fleet at the Start of the Planning Horizon (2028): Ship Characteristics and Baseline inputs

Ship index	Capacity (TEU)	Age (yr)	Annual energy (PJ/yr)	Initial fuels	NB CAPEX (mUSD)
S01	23,992	7	1.07	VLSFO, bio/e-diesel	203
S02	24,000	6	1.07	VLSFO, bio/e-diesel	203
S03	23,992	7	1.07	VLSFO, bio/e-diesel	203
S04	24,000	4	1.07	VLSFO, bio/e-diesel	203
S05	23,992	7	1.07	VLSFO, bio/e-diesel	203
S06	24,004	3	1.07	VLSFO, bio/e-diesel	203
S07	24,000	6	1.07	VLSFO, bio/e-diesel	203
S08	23,992	7	1.07	VLSFO, bio/e-diesel	203
S09	24,000	6	1.07	VLSFO, bio/e-diesel	203
S10	24,000	6	1.07	VLSFO, bio/e-diesel	203
S11	23,992	6	1.07	VLSFO, bio/e-diesel	203
S12	23,992	6	1.07	VLSFO, bio/e-diesel	203
S13	24,000	6	1.07	VLSFO, bio/e-diesel	203
S14	20,388	10	1.04	VLSFO, bio/e-diesel	184
S15	20,388	9	1.04	VLSFO, bio/e-diesel	184

Notes. Capacities and ages from FAL6 service flyer (CMA CGM 2025). Energy demand estimated from Fourth IMO GHG Study (IMO 2020). Newbuild (NB) CAPEX estimates from SeaWeb. PJ represents peta joules.

Table 2 summarizes the 15-ship fleet deployed on FAL6: 13 ultra-large ships (about 24,000 TEU) and 2 slightly smaller ships (about 20,400 TEU). The fleet is relatively young. We assume a 25-year technical lifetime, after which ships are replaced. For each ship, we specify its 2028 age and annual energy requirement (treating 2028 as the baseline operating year). In the baseline/initial state, all ships use conventional bunker fuels and drop-in variants, represented by very-low sulfur fuel oil (VLSFO) and bio-/e-diesel. Non-fuel OPEX (crew, maintenance, insurance) is set to 2% of newbuild CAPEX (Drewry 2022, DNV 2024a), implying baseline annual OPEX of 3.6–4.0 million USD per ship. Baseline energy requirements are held constant unless altered by retrofit/replacement. If desired, time-based efficiency improvements can be added via exogenous scaling factors.

4.2. Renewal Options

Each ship may undergo at most one retrofit and is replaced at its technical lifetime. Renewal options combine an EE package that reduces propulsion energy demand and installation of DF systems that enable switching between conventional and alt-fuels. While many EE measures exist, we represent them as a single aggregated EE package to keep the analysis tractable. The assumed EE retrofit

Table 3 Renewal Options (Retrofit and Replacement)

Option	Compatible fuels (post-renewal)	CAPEX (% conv. NB)	OPEX (% base)	TEU loss (% nominal TEU)	Age limit (yr)
Retrofit EE	VLSFO, bio/e-diesel	36	106	0.0	15
Retrofit DF-LNG + EE	VLSFO, bio/e-diesel, fossil/bio/e-LNG	60	122	2.0	10
Retrofit DF-methanol + EE	VLSFO, bio/e-diesel, fossil/bio/e-methanol	47	113	4.0	10
Retrofit DF-ammonia + EE	VLSFO, bio/e-diesel, blue/e-ammonia	54	118	7.3	10
Replace with DF-LNG + EE	VLSFO, bio/e-diesel, fossil/bio/e-LNG	140	122	0.0	25
Replace with DF-methanol + EE	VLSFO, bio/e-diesel, fossil/bio/e-methanol	131	113	0.0	25
Replace with DF-ammonia + EE	VLSFO, bio/e-diesel, blue/e-ammonia	136	118	0.0	25

Notes. EE, CAPEX, and OPEX inputs follow DNV (2024a) (EE provides 28% energy savings). Retrofit CAPEX includes a 50% installation premium. Age limits follow GMF (2022a). TEU-loss estimates (SEA-LNG 2020, MMMCZCS 2022) reflect capacity reductions from added tank/machinery space and are monetized via an opportunity-cost term. The associated opportunity cost is calibrated proportionally to TEU charter rate estimates, with lost TEUs evaluated as (capacity-loss fraction)×(nominal ship capacity). Replacements are assumed capacity-equivalent.

reduces propulsion energy demand by 28%. We include DF systems because liner operators are prioritizing fuel-flexible designs to hedge uncertainty (Lindstad et al. 2021, Maersk 2023, Hapag-Lloyd 2025). Nevertheless, the framework can readily accommodate multiple EE packages or single-alt-fuel options if needed. Table 3 summarizes the renewal options considered.

We consider EE-only retrofits, DF+EE retrofits, and replacement with DF+EE newbuilds. Replacement is limited to DF+EE, reflecting that when the fleet under consideration retires (post-2040) purely conventional NBs are unlikely to be competitive under tightening regulation, and that high EE performance will be standard. We note, however, that as fuel-pathway uncertainty narrows in the 2040s–2050s, replacement could shift toward mono-fuel designs; our DF NB assumption is a conservative flexibility choice, and mono-fuel options can be added straightforwardly. All retrofit options are assumed feasible from 2028. Onboard carbon capture and storage (OCCS) can abate tank-to-wake emissions without large-scale fuel switching, reducing compliance exposure when low-/zero-carbon fuel supply and infrastructure are constrained. While not modeled here, it can be added as a retrofit option by parameterizing capture rate, energy and space/weight penalties, added CAPEX/OPEX (including CO_2 handling), and CO_2 offloading/storage costs and constraints.

As summarized in Table 3, each option is characterized by compatible fuels, energy-savings (relative to baseline), investment cost (as a fraction of conventional NB CAPEX), resulting OPEX (as a fraction of baseline OPEX), age limits (retrofit cutoff or design life), and any capacity loss. We assume EE entails no TEU loss. Replacement newbuilds are capacity-equivalent, and any added energy requirement from larger hull/tankage is captured in the energy-savings parameter. These options are available to each ship subject to age limits, and renewal decisions determine both the ship's energy demand and feasible fuel mix under the market and regulatory conditions considered.

Table 4 **Projected Fuel Costs and Uncertainty Ranges (USD/GJ)**

Fuel	2028	2030	2035	2040	2045	2050
VLSFO	18.5 [10.5, 26.4]	18.1 [10.3, 25.9]	17.3 [9.9, 24.8]	16.5 [9.4, 23.6]	15.6 [8.9, 22.3]	14.7 [8.4, 21.1]
Bio-diesel	30.7 [26.1, 35.3]	31.6 [26.8, 36.3]	33.7 [28.6, 38.8]	35.8 [30.5, 41.2]	38.1 [32.4, 43.9]	40.4 [34.4, 46.5]
e-diesel	76.9 [36.2, 117.7]	74.1 [34.8, 113.3]	66.6 [31.3, 101.8]	59.1 [27.8, 90.4]	51.6 [24.2, 78.9]	44.1 [20.7, 67.4]
Fossil LNG	15.7 [8.9, 22.4]	15.7 [8.9, 22.4]	15.6 [8.9, 22.3]	15.5 [8.9, 22.2]	15.5 [8.8, 22.1]	15.4 [8.8, 22.0]
Bio-LNG	28.9 [24.6, 33.2]	29.7 [25.2, 34.1]	31.7 [27.0, 36.5]	33.8 [28.7, 38.9]	36.1 [30.7, 41.5]	38.4 [32.6, 44.1]
e-LNG	65.7 [32.2, 99.2]	63.5 [31.1, 95.8]	59.4 [29.1, 89.6]	55.3 [27.1, 83.5]	50.9 [25.0, 76.9]	46.6 [22.8, 70.4]
Fossil methanol	11.8 [6.8, 16.9]	11.8 [6.8, 16.9]	11.8 [6.8, 16.9]	11.7 [6.7, 16.8]	11.7 [6.7, 16.8]	11.6 [6.6, 16.6]
Bio-methanol	22.6 [18.3, 26.9]	23.1 [18.8, 27.5]	24.4 [19.8, 29.1]	25.7 [20.8, 30.6]	27.4 [22.2, 32.6]	29.0 [23.5, 34.5]
e-methanol	69.6 [32.0, 107.2]	66.1 [30.4, 101.8]	61.9 [28.5, 95.3]	57.6 [26.5, 88.7]	53.1 [24.4, 81.8]	48.6 [22.4, 74.9]
Blue ammonia	38.3 [15.3, 61.3]	36.2 [14.5, 58.0]	35.3 [14.1, 56.5]	34.4 [13.8, 55.0]	33.7 [13.5, 54.0]	33.1 [13.2, 52.9]
e-ammonia	41.7 [22.1, 61.3]	39.6 [21.0, 58.2]	36.4 [19.3, 53.6]	33.3 [17.6, 48.9]	29.9 [15.9, 44.0]	26.6 [14.1, 39.1]

Notes. Values are mean [lower, upper]. For 2028, bounds follow Lagouvardou et al. (2023), Loennechen et al. (2024) and mean is the midpoint. For later years, means follow fuel-specific cost trends from DNV (2024a), with bounds preserving the 2028 proportional spread.

4.3. Fuels, GHG intensities, Costs and Supply

We consider conventional and alt-fuels relevant for deep-sea shipping: VLSFO, bio/e-diesel, fossil/bio/e-LNG, fossil/bio/e-methanol, blue/e-ammonia. For each year, we specify: (i) well-to-wake (WTW) GHG intensities of fuels, (ii) projected unit fuel costs with lower/upper bounds, and (iii) projected aggregate supply levels with lower/upper bounds for bio-, e-, and blue-fuels, scaled to the representative fleet. These exogenous inputs feed into the fuel cost–supply scenario generation procedure described in Section 4.4. For brevity, WTW intensities are reported in Appendix Table 10: fossil fuels are held constant, while bio- and e-fuels decline toward near-zero by 2050.

Table 4 reports projected unit-cost trajectories and bounds. Following the literature, we use production costs rather than market prices, which are harder to project and depend on evolving supply–demand conditions. In the stochastic setting, these bounds define scenario supports, with realizations sampled within each interval and the deterministic trajectory interpreted as the mean.

To capture limited availability of low- and zero-carbon fuels, we impose exogenous supply caps for three aggregate categories: bio-fuels (bio-diesel, bio-LNG, bio-methanol), e-fuels (e-diesel, e-LNG, e-methanol), and blue fuels (blue-ammonia). We model supply at this aggregated level because fuel-specific availability is highly uncertain, and because carriers plan around fuel pathways. Once compatible technology is in place, they can substitute within a category and allocate scarce volumes to the most accessible option as supply conditions evolve. Global shipping fuel-supply trajectories from DNV (2024a) are scaled to the representative fleet by the ratio of the FAL6 fleet's baseline annual energy use to projected global shipping energy demand (≈0.14%). Because FAL6 calls at major bunkering hubs, accessible supply could exceed a purely proportional allocation, the scaled values should therefore be interpreted as conservative. Table 5 reports the resulting fleet-level availability envelopes, imposed as annual upper bounds on category energy use.

Table 5 Annual Low- and Zero-Carbon Fuel Supply Availability for the Representative Fleet (PJ/year)

Category	2028	2030	2035	2040	2045	2050
Bio-fuels	0.11 [0.08,0.40]	0.56 [0.14,0.56]	1.68 [0.28,2.80]	2.80 [0.42,5.05]	3.64 [0.56,7.43]	4.49 [0.70,9.81]
e-fuels	1.04 [0.00,1.99]	1.12 [0.00,2.10]	1.33 [0.07,2.38]	1.54 [0.14,2.66]	3.50 [0.21,4.84]	5.47 [0.28,7.01]
Blue-fuels	0.03 [0.00,0.08]	0.14 [0.00,0.28]	0.42 [0.00,0.77]	0.70 [0.00,1.26]	1.26 [0.00,2.24]	1.82 [0.00,3.22]

Notes. Values are mean [lower, upper]. In DNV (2024a), e-fuel and blue-fuel totals include hydrogen; since hydrogen is not modeled here (ammonia is treated as the preferred hydrogen carrier), category totals are assigned to the fuels retained in this work. Under the lower-bound trajectory, combined bio/e/blue supply can cover about 1% of the fleet's annual demand in 2030, 3% in 2040, and 6% in 2050; under mean trajectories, 11%, 31%, and 73%; and under upper bounds, about 18%, 56%, and 125% (exceeding total demand) by 2050.

4.4. Fuel Costs and Supply Scenario Generation

We model fuel-market uncertainty using joint scenarios for (i) fuel costs for all fuels and (ii) supply availability of low-/zero-carbon fuel categories, constructed over 2028–2050 from the mean and bound trajectories in Tables 4 and 5. We generate 100 *training* scenarios for solving the stochastic model and 100 independent *test* scenarios for out-of-sample evaluation. For brevity, we summarize scenario generation procedure here; sample cost and supply paths are shown in Appendix D.2.

Fuel-cost scenarios. For each fuel f and year t, let $c^L_{f,t}$ and $c^U_{f,t}$ be the lower and upper bounds. We sample uniformly within these bounds, independently across fuels and with perfect time dependence within each fuel: draw one $U_{f,w} \sim \text{Unif}(0,1)$ for each fuel f and scenario ω, and set $c^\omega_{f,t} = c^L_{f,t} + U^\omega_f (c^U_{f,t} - c^L_{f,t}), \forall t \in T,\ f \in F$. Holding U^ω_f constant over t preserves each fuel's deterministic time profile while inducing persistent cross-scenario differences in relative fuel costs.

Fuel-supply scenarios. Supply uncertainty is modeled at the fuel-category level $g \in$ {bio-fuels, e-fuels, blue-fuels}. For each year t and category g, we take take lower/upper bounds $S^L_{g,t}$, $S^U_{g,t}$ and mean $S^0_{g,t}$ from Table 5. For each scenario w, we compute average category cost $\bar{c}^\omega_{g,t}$ (averaged across fuels in g) and normalize it to $z^\omega_{g,t} \in [0,1]$, where larger $z^\omega_{k,t}$ indicates higher cost. Category supply in scenario w is then generated by $S^\omega_{g,t} = S^U_{g,t} - \left(S^U_{g,t} - S^L_{g,t}\right) (z^\omega_{g,t})^{\eta_{g,t}}$, with curvature parameter $\eta_{g,t}$ calibrated so that the expected supply under the mean-cost realization is close to $S^0_{g,t}$. This ensures $S^\omega_{g,t} \in [S^L_{g,t}, S^U_{g,t}]$ and induces lower supply when category costs are high and vice versa.

4.5. Regulatory Setup

We consider that the liner company is subject to the IMO NZF, which combines declining GFI targets, carbon pricing through remedial units (RUs), trading and limited banking of SUs, and a targeted reward for ZNZ fuels. The NZF specifies two GFI trajectories: a *Base* target and a stricter *Direct-compliance/Strive* target. Each ship compares its attained annual GFI to these thresholds. If attained GFI exceeds the Base target, the gap to Base is covered with Tier 2 RUs (or, if cheaper, by purchasing SUs from over-compliant ships), and the remaining shortfall to the Direct-compliance

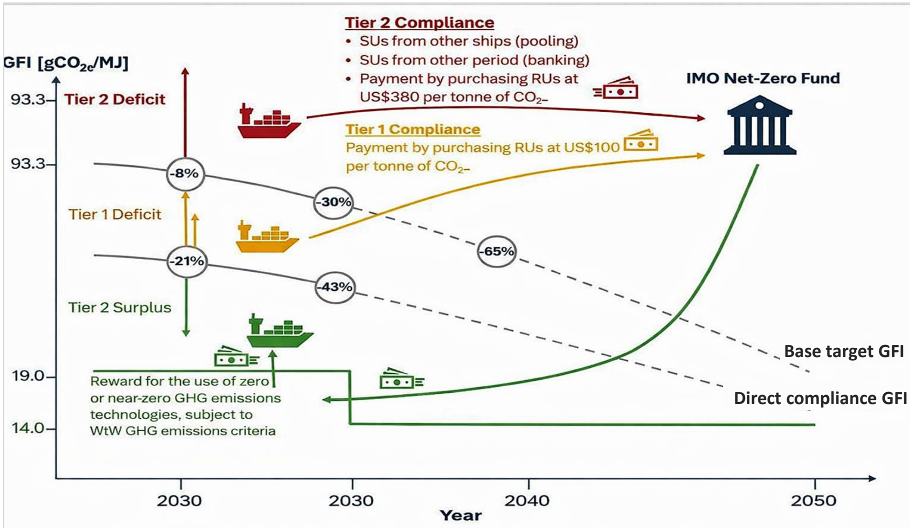


Figure 2 **Approved NZF at MEPC 83 (source: ABS (2025))**

Note. RU prices beyond 2030, GFI targets beyond 2035, and ZNZ reward rates are yet to be finalized.

is covered with Tier 1 RUs. If attained GFI lies between the Base and Direct-compliance, only Tier 1 RUs are required on the shortfall to Direct-compliance. If attained GFI falls below Direct-compliance, the ship generates SUs that may be traded or banked for future offsets. ZNZ-eligible fuel use earns an additional reward financed from NZF revenues. Since reward details remain unsettled, we adopt a technology-centric interpretation (GMF 2025) and treat e-fuels (with WTW intensities below the Direct-compliance target) as ZNZ-eligible, while excluding bio-fuels on the grounds that they already benefit enough from SU incentives. Figure 2 summarizes the approved NZF features, and Appendix D.3 reports the parameter values and calibration details.

4.6. Discounting

All monetary quantities are discounted to 2028 using a constant rate of $r = 3\%$ (Lagouvardou et al. 2023). The discount factor for a cost incurred in year t is $\beta_t = (1 + r)^{-(t-2028)}$. Ship-replacement CAPEX is annualized over asset life, with annualization and terminal-credit details in Appendix D.4.

4.7. Computational Approach

We solve all instances with GUROBI. For the FAL6 case (15 ships, 23 annual periods), the DET model has a few thousand decision variables and solves to proven optimality within 1–2 hours on a standard workstation, which is acceptable for long-horizon planning. The STO model is substantially larger as it scales with $|W|$ and enforces non-anticipativity. We therefore adopt the restricted first-stage procedure in Section 3.5; for our instances, the resulting objective is within 1% of a lower bound from relaxing non-anticipativity, while remaining computationally manageable.

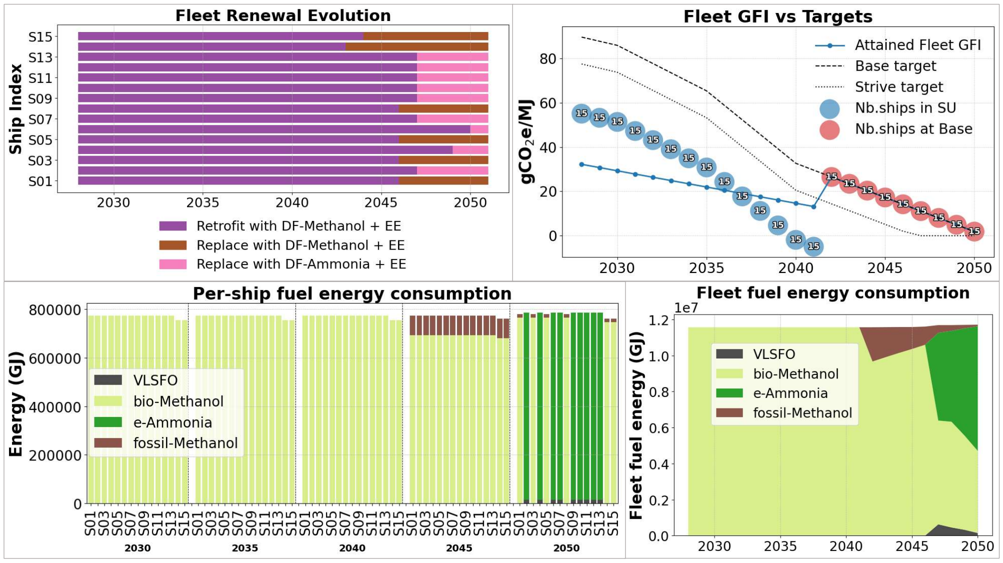


Figure 3 **Deterministic Results Without Fuel-Supply Constraints**

Note. Fuel costs follow the mean trajectories in Table 4; no limits imposed on fuel supply.

5. Results

The analysis proceeds in four steps. (i) a deterministic baseline under mean fuel cost and supply trajectories, (ii) sensitivity to fuel cost and supply assumptions, (iii) comparison of stochastic and deterministic strategies in terms of cost, risk, and compliance outcomes, and (iv) comparison of alternative regulatory setups (NZF, one-tier GFS with pricing and incentives, and a pure levy).

5.1. Deterministic Fleet Renewal

Mean fuel costs and supplies in Tables 4–5 are assumed to materialize. We first solve an unconstrained benchmark with no fuel supply limits, and then impose supply caps to quantify how scarcity changes renewal and fuel-use choices. For each case, we report the optimal renewal and fuel usage plans, attained (average) fleet GFI, and the distribution of ships in SU/Tier 1/Tier 2 regions.

No fuel-supply constraints. The resulting optimal total discounted cost over 2028–2050 is 7,210 m(million)USD with the detailed results summarized Figure 3.

1. Early retrofits and methanol pathway. In 2028, all ships retrofit to DF-methanol+EE. The EE package lowers energy use at modest cost, which is valuable when the optimal fuel mix relies on higher-cost bio-/e-fuels. With unconstrained low-carbon fuel access and under the assumed NZF parameters and mean cost trajectories, near-100% bio-methanol is cost-effective until the late 2040s, keeping ships in the SU region (below Direct-compliance) and generating SUs through about 2041.

2. Shift from over-compliance to Base-target operation. From around 2042, tightening GFI targets raise the cost of sustaining over-compliance and and reduce the marginal value of additional SUs.

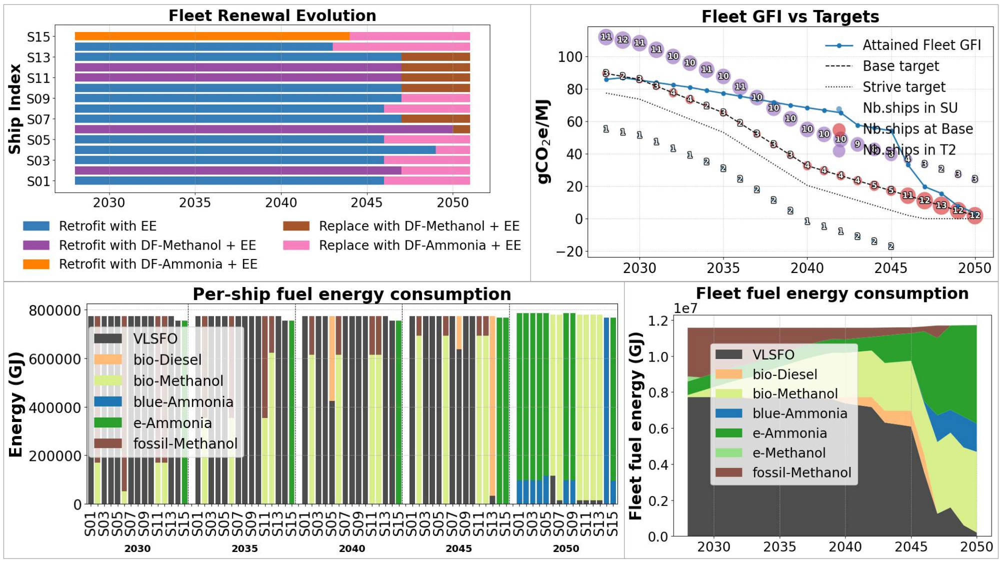


Figure 4 **Deterministic Results With Fuel-Supply Constraints**

Note. Supply of bio-/e-/blue-fuel categories is capped at the mean trajectories in Table 5; fossil fuels are unconstrained.

The cost-minimizing response is therefore to move up from the SU region and track the Base targets by blending fossil and bio-methanol rather than sustaining large surpluses.

3. Late-horizon replacement mix. Replacement depends on retirement timing. Ships retiring by about 2046 are replaced with DF-methanol+EE, as methanol blends remain cost-effective over the remaining horizon. While later retirements shift toward DF-ammonia+EE as targets tighten and e-ammonia blends become more cost-effective under the assumed cost trajectories.

Overall, without supply limits the DET pathway follows a methanol-first transition with fleetwide DF-methanol+EE retrofits, early over-compliance through bio-methanol, track Base targets from early 2040s, and a late-horizon tilt toward ammonia-capable newbuilds as targets tighten, with EE playing a key role in reducing the volume of costly low-carbon fuel required.

With low-carbon fuel-supply constraints. We next cap annual bio-/e-/blue-fuel availability at the mean trajectories in Table 5, while keeping fossil fuels unconstrained to reflect practical sourcing and ensure feasibility. Relative to the no-supply case, scarce low-carbon fuel volumes must be rationed across ships and years, with residual demand met by fossil fuels, raising the optimal cost to 8,514 mUSD (18% above the no-supply case). Figure 4 summarizes the resulting pathway.

1. EE everywhere, selective DF. In 2028, ten ships take EE-only retrofits, four retrofit to DF-methanol+EE, and one to DF-ammonia+E (one of the smaller and younger ships, which helps justify the higher CAPEX under limited early e-fuel availability). More generally, younger ships are prioritized for DF retrofits to maximize payback, while scarce low-carbon fuels are allocated to this small DF subset and EE is applied broadly to reduce required low-carbon fuel volumes.

2. Fossil-heavy fuel mix under caps. VLSFO dominates into the early 2040s, with limited uptake of fossil/bio-methanol and e-ammonia. Within-category supply scarcity steers uptake toward the most cost-effective options (bio-methanol and e-ammonia), leaving DF-LNG unattractive.
3. Higher deficits, limited surplus. Fleet GFI falls but stays above Base for much of the 2030s–2040s, implying sustained RU purchases. Limited low-carbon fuels pull a subset of ships toward Base, and SU generation is largely curtailed (only one ship in SU region) relative to the no-supply case.

Overall, binding supply constraints shift the strategy from fleet-wide fuel switching for over-compliance to an "EE everywhere, low-carbon fuels where they matter most" approach, with deeper decarbonization delayed until bio- and e-fuel availability expands later in the horizon.

At the mean category caps (Table 5) that grant FAL6 fleet a proportional share of projected global maritime fuel availability, remain insufficient to track the Base GFI targets even with EE retrofits and selective DF conversions. While an Asia–Europe service calling at major bunkering hubs could secure a larger-than-proportional share, this would necessarily reduce access for other trades while global production remains constrained. This underscores that meeting NZF's tightening GFI targets at scale will require credible long-term regulatory signals to accelerate low-carbon fuel investment.

5.2. Sensitivity of Renewal Pathways to Fuel Supply and Costs

The deterministic baseline indicates that, under the mean category-level supply caps, the fleet cannot track the Base GFI target for much of the horizon, so we test how availability and relative fuel costs shift total costs, attained GFI, and renewal choices. Detailed results are provided in Appendix E.1.

Supply sensitivity (scale-up of bio/e/blue caps). Scaling mean supply caps from "1x" to "2x" reduces discounted total cost by about 4% (USD 327 million), while moving from "1x" to the unconstrained case reduces cost by about 15% (USD 1.3 billion). Higher supply supports broader DF uptake (especially DF-methanol+EE), whereas under tight supply DF-ammonia can concentrate scarce e-fuels on a small subset of ships. Fleet GFI improves overall but need not be monotone: at "5x", abundant bio-methanol makes it cheaper to spread low-carbon volumes across more ships and operate nearer the Base target (rather than a few ships in SU region), slightly increasing early-year GFI while lowering total cost. Full plots and renewal details are in Appendix E.1.

Cost sensitivity (under mean supply caps). Under mean cost trajectories in Table 4, bio-methanol drives DF-methanol retrofits, but shifting relative costs can change the preferred DF pathway. In an LNG-favorable case (bio-LNG at its lower-bound costs, others at mean), the plan shifts materially toward DF-LNG+EE retrofits and bio-LNG becomes the primary low-carbon fuel within the bio-fuels cap. In an ammonia-favorable case (e-ammonia at its lower-bound costs), DF-ammonia uptake increases only modestly (to two DF-ammonia+EE retrofits), because of limited e-fuel availability, dampening the technology response. Supporting figures are in Appendix E.1.

Joint fuel cost–supply sensitivity (scenario-wise deterministic solves). Across 100 jointly generated cost–supply scenarios, discounted total cost varies widely, with a best–worst spread on the order of 30%. Mid-2030s fuel use and DF pathway choice vary by scenario (conventional, LNG-, or methanol-based) depending on the joint realization. Fleet GFI shows substantial dispersion, with most scenarios exceeding Base targets during the transition (mid-2030s to mid-2040s), implying sustained compliance-unit purchases. Average fleet composition transitions gradually from conventional to DF, with DF-methanol and DF-LNG prominent early, DF-ammonia expanding later, and DF-ammonia dominating by 2050. Scenario summaries are reported in Appendix E.1.

5.3. Stochastic Fleet Renewal Under Fuel-Market Uncertainty

The sensitivity analysis shows that renewal pathways are highly sensitive to fuel supply and relative fuel costs. Supply expansion lowers total cost and shifts DF uptake and timing, modest cost changes can flip the preferred early pathway (e.g., methanol vs. LNG), and joint cost–supply uncertainty yields a wide spread in total cost (nearly 30%) and attained fleet GFI. This implies a liner company cannot rely on a single deterministic fuel-market view, but needs first-period (2028) retrofit choices that hedge across plausible outcomes, trading higher upfront CAPEX against uncertain future fuel and compliance costs, while later renewal and fuel-use decisions adapt as uncertainty unfolds.

We solve the scenario-based STO model (Section 3.3) using 100 training scenarios (Section 4.4). With 15 ships and 5 first-stage options each, the full first-stage space has $5^{15} \approx 30.5$ billion combinations, making a direct solve impractical. We therefore use the restricted first-stage method: pooling optimal 2028 decisions from 100 single-scenario deterministic solves yields 95 distinct configurations, and we solve the reduced STO model over this pool. Figure 5 compares the resulting 2028 STO decisions with DET. The STO expected discounted total cost is 8,102 mUSD.

Relative to DET, which retrofits entire fleet in 2028, STO retrofits only a subset in 2028 and defers the rest, with roughly half the ships following a wait-and-see strategy. The STO plan is age-structured: ships near the DF-retrofit age limit (e.g., S14, S15) are converted to DF-methanol+EE to preserve access to low-carbon methanol over their remaining life, some older ships (e.g., S01, S08) take EE-only because they are unlikely to recover DF CAPEX before retirement, and among the newest ships (e.g., S04, S06), STO selects DF retrofits, reflecting the higher value of fuel flexibility for long-lived assets. Overall, STO is less aggressive than DET, prioritizing DF where remaining

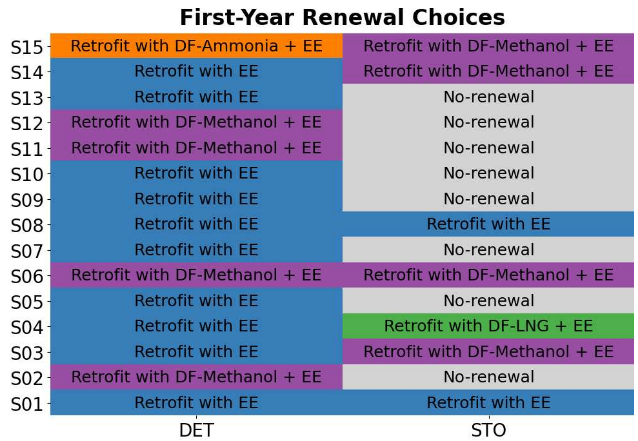


Figure 5 **First-Stage (Year 2028) Renewal Decisions: DET (Deterministic) vs. STO (Stochastic)**

lifetime and flexibility value are highest and using EE-only plus deferred renewal elsewhere to preserve optionality across different fuel pathways under uncertain future costs and supply.

Since STO is solved approximately over a reduced set of first-stage decisions, its objective value of 8,102 mUSD is an upper bound (UB) on the true optimum. We compute a lower bound (LB) by relaxing non-anticipativity (13), solving a deterministic problem for each scenario and averaging the optimal costs; this yields 8,055 mUSD, implying an optimality gap of about 0.6%.

5.4. Value of Stochastic Planning

The results above show that accounting for fuel-market uncertainty changes optimal first-stage renewal relative to a deterministic plan. To assess whether this improves performance, we compare DET and STO out-of-sample (OoS) over 100 *test* scenarios generated as in Section 4.4. For each test scenario, we fix period-1 renewal decisions to the DET or STO plan and re-optimize all subsequent renewal and operational decisions under scenario-specific fuel costs and supply trajectories.

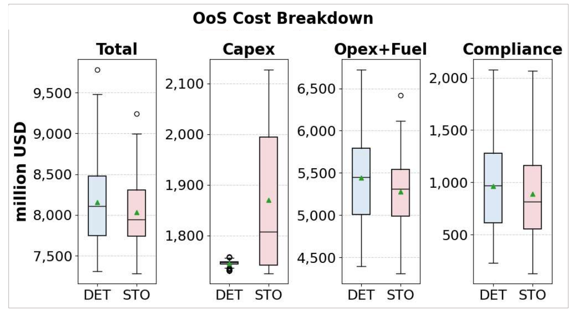
Cost and downside risk. Table 6 and Figure 6 summarize OoS cost outcomes. STO delivers lower cost in 69 of 100 scenarios and provides downside protection: worst-case cost falls from 9,783 to 9,240 mUSD (5.6%) and the mean of the worst 10% scenarios drops by 3.4%. Mean cost declines from 8,153 to 8,034 mUSD (1.5%), while best-case outcomes are essentially unchanged (0.4% lower), indicating that STO does not sacrifice performance in favorable futures to gain robustness.

Total cost volatility also falls materially, with standard deviation decreasing by 18.6%. As Figure 6 shows, STO has a lower center, a shorter upper tail, a narrower interquartile range, and fewer high-cost outliers than DET. Under DET, CAPEX is nearly scenario-invariant because all ships are retrofitted in 2028 and we restrict at most one retrofit per ship; subsequent replacement choices may vary across scenarios, but the resulting CAPEX changes only modestly. Under STO, CAPEX is

Table 6 OoS Total Cost Performance

OoS Metric	DET	STO	Improv.
Nb. Scenarios dominated	31	69	123%
Max. cost	9,783	9,240	5.6%
Mean of worst 10%	9,186	8,870	3.4%
Mean	8,153	8,034	1.5%
Min. cost	7,312	7,282	0.4%
Std. dev.	521	424	18.6%

Notes. Total costs are in mUSD.



Notes. y-axis scales are different across components.

Figure 6 OoS Cost Distribution

higher on average and more variable because the plan follows a wait-and-see approach and invests in different DF technologies across scenarios to preserve flexibility, which lowers OPEX+fuel and compliance costs and compresses the upper tail of total cost. Overall, stochastic planning delivers modest expected savings but materially reduces downside risk and cost variability.

Fleet transition patterns. Figure 7 compares the average OoS fleet composition, aggregated over the 100 test scenarios. Under DET, all 15 ships retrofit in 2028, so the incumbent-fleet mix is largely fixed across scenarios: in 2030 and 2040, about two-thirds remain conventional-with-EE and the rest are DF-methanol/ammonia, while by 2050 conventional ships are essentially phased out and the fleet is dominated by DF-ammonia/methanol. STO yields a more gradual and diversified transition. In 2030, more ships remains conventional and the DF mix is more balanced, with DF-LNG appearing alongside DF-methanol/ammonia rather than upfront commitment to DF-methanol. By 2040, the conventional share falls while the DF mix remains more diversified than DET. By 2050, DET and STO converge to same end-state fleet (about 54% DF-ammonia, 40% DF-methanol, and 6% DF-LNG on average) because the OoS evaluation fixes only the first-stage retrofits, while replacement decisions remain scenario-adaptive. Overall, stochastic planning mainly moderates early commitment and diversifies DF investments while delivering a comparable 2050 outcome.

GFI and compliance risk. Table 7 reports OoS attained fleet GFI and probability the fleet fails to meet the Base target; full paths and envelopes are in Appendix Figure 15. Both plans show substantial GFI dispersion and often fail to meet the Base target (see Appendix Figure 15). STO attains a consistently lower *mean* fleet GFI than DET over 2030–2045 (about 1–2% lower in the early 2030s, widening to nearly 5% by 2045), before converging by 2050. While non-compliance probabilities remain high, STO lowers them in 2035 and 2045 (by 9 and 2 percentage points, respectively) and is similar to DET in 2040 and 2050. Thus, the emissions value of STO planning is a modestly faster and more robust mid-horizon transition, alongside lower downside cost risk.

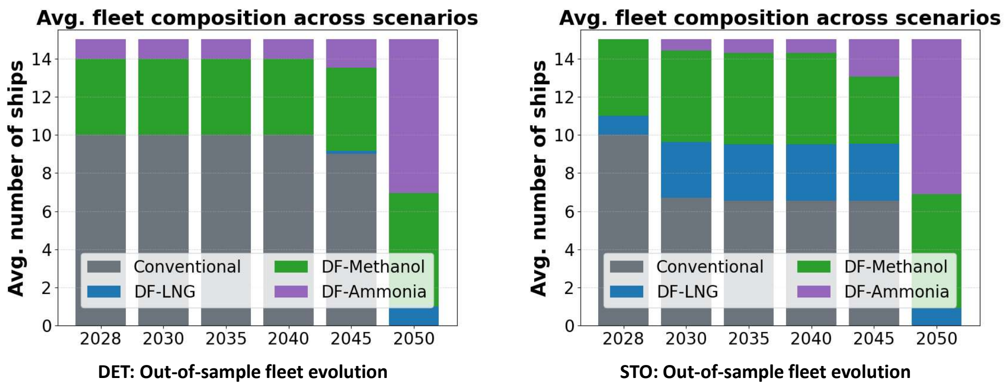


Figure 7 Average Fleet Composition Across 100 Test Scenarios: DET vs. STO

Note. Each bar shows the average number of ships by fuel system (conventional, DF-LNG/methanol/ammonia).

Table 7 OoS Average Fleet GFI and Probability of Not Meeting the Base GFI Target

Year	Attained fleet GFI (gCO_2e/MJ)			Probability of not meeting the Base GFI target		
	DET	STO	Improv.	DET	STO	Improv.
2030	83.2	82.2	1.2% lower	20%	23%	3 pp higher
2035	70.4	68.9	2.1% lower	81%	70%	9 pp lower
2040	60.8	58.9	3.1% lower	100%	100%	0 pp
2045	40.6	38.6	4.9% lower	99%	97%	2 pp lower
2050	9.1	9.0	1.1% lower	97%	97%	0 pp

Note. Probability denotes the proportion of scenarios with attained fleet GFI > Base GFI.

In summary, the stochastic plan delivers a more balanced transition than the deterministic plan. It slightly lowers expected costs while providing stronger protection against adverse fuel-market conditions, reducing downside costs and cutting cost variability. These gains stem from a more selective first-stage strategy: STO retrofits only a subset of ships and maintains a more diversified DF mix, particularly DF-methanol and DF-LNG. Emissions also improve, with lower mean fleet GFI through the 2030s–2040s, even though both plans converge to a similar low-carbon fleet and mean GFI by 2050. Overall, stochastic planning adds value mainly by reducing downside cost and compliance risk while preserving, and modestly improving, long-run decarbonization outcomes.

Results under the "2x" supply setting. We repeat the OoS evaluation under a "2x" fuel-supply envelope, where the mean and bounds of low-carbon availability are doubled and becomes sufficient to feasibly meet NZF GFI targets (Appendix Figure 11). Relaxing supply constraints amplifies the value of adaptive planning: STO is cheaper in 82 of 100 scenarios, cuts worst-case cost by 6.5%, and lowers mean cost by 2.7%. Unlike the 1x case, STO also yields lower CAPEX than DET, indicating that greater supply reduces the need for precautionary diversification and shifts value toward cost-efficient fuel and operational choices. Detailed results are in Appendix E.3.

5.5. Impact of Regulatory Design

The NZF framework, while comprehensive, is relatively complex. This section compares NZF with two simpler alternative regulatory setups: (i) a one-tier GFS with a single carbon price (retaining the SU/ZNZ structure), and (ii) a pure levy with no fuel-intensity standard. We omit an "isolated" GFS with high non-compliance penalties (Table 1) because early binding fuel-supply constraints can make compliance infeasible and penalties would mechanically dominate total costs.

One-tier GFS + RU/SU/ZNZ. This setup collapse the two-tier structure into a single GFI target trajectory and RU price while keeping SU pricing and ZNZ reward assumptions unchanged. We calibrate the one-tier parameters period-by-period: one-tier GFI target is set to the midpoint of the NZF targets $I_t^{\text{GFI,one-tier}} = \left(I_t^{\text{Base}} + I_t^{\text{Direct-compliance}}\right)/2$, and then choose $\pi_t^{\text{RU,one-tier}}$ so that, for a VLSFO-operated ship, the implied compliance surcharge per unit energy matches the NZF

$$\underbrace{\frac{(I_t^{\text{VLSFO}} - I_t^{\text{Base}})\,\pi_{t,2}^{\text{Tier 2}}}{1000} + \frac{(I_t^{\text{Base}} - I_t^{\text{Direct-compliance}})\,\pi_{t,1}^{\text{Tier 1}}}{1000}}_{\text{Effective VLSFO cost under NZF}} = \underbrace{\frac{(I_t^{\text{VLSFO}} - I_t^{\text{GFI,one-tier}})\,\pi_t^{\text{RU,one-tier}}}{1000}}_{\text{Effective VLSFO cost under one-tier GFS}},$$

where intensities I are in gCO_2e/MJ and prices π are in USD/tCO_2e. Consistent with NZF assumption, one-tier SU price is set equal to $\pi_t^{\text{RU,one-tier}}$. ZNZ reward rates and eligible-fuel set are kept unchanged; the difference is that incentives are now defined relative to $I_t^{\text{GFI,one-tier}}$.

Pure Levy. This setup isolates the economic measure by removing GFI targets and SU/ZNZ incentives, and instead applies a uniform levy on WTW emissions. To match the overall economic burden, we calibrate a time-varying levy to the NZF-implied *average abatement cost* relative to a business-as-usual (BAU) case with no regulatory measures. Using the same 100 training scenarios as in the NZF-based stochastic analysis, let $C_{t,w}^{\text{tot,NZF}}$ and $C_{t,w}^{\text{tot,BAU}}$ denote scenario-specific optimal total discounted costs in period t under NZF and BAU, and let $\text{GHG}_{t,w}^{\text{NZF}}$ and $\text{GHG}_{t,w}^{\text{BAU}}$ be the corresponding fleet emissions. For each period t, we set the levy rate $p_t^{\text{levy}} = \frac{\sum_{w\in W^{\text{train}}} \alpha_w (C_{t,w}^{\text{tot,NZF}} - C_{t,w}^{\text{tot,BAU}})}{\sum_{w\in W^{\text{train}}} \alpha_w (\text{GHG}_{t,w}^{\text{BAU}} - \text{GHG}_{t,w}^{\text{NZF}})}$, so that p_t^{levy} reflects the expected marginal emissions abatement cost under NZF and yields a levy comparable in total cost impact, while abstracting from technical standard and incentive structure.

Appendix Table 13 summarizes the setups: one-tier RU price $\pi_t^{\text{RU,one-tier}}$ rises from 292 (2030) to 378 (2050); levy rate p_t^{levy} equals 141 (2030), 196 (2035), 289 (2040), 189 (2045), 103 (2050).

5.5.1. Regulatory Comparison (NZF vs One-Tier vs Pure Levy). Figure 8 compares the three setups. NZF and One-Tier, with tightening GFI targets and pricing/incentives, yield similar cost and decarbonization trajectories. Pure Levy provides a uniform emissions-price signal but does not replicate the pathway-shaping effects of a tightening standard and surplus-credit incentives.

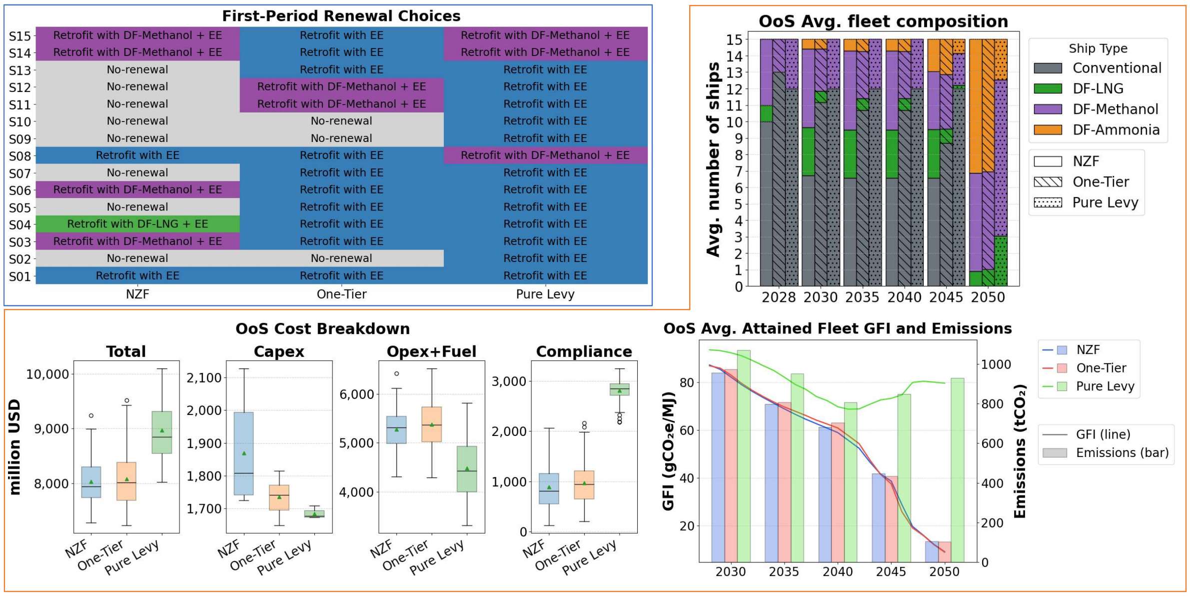


Figure 8   Under Alt-Regulatory Setups: (top-left) First-Period Renewal, (top-right and bottom) OoS Outcomes

Total cost and downside exposure. NZF and One-Tier deliver lower OoS total costs than Pure Levy and have similar cost distributions, while the levy has a higher mean and heavier upper tail. Under NZF/One-Tier, technology and fuel-mix shifts, supported by SU monetization and ZNZ incentives, mitigate the regulatory burden. Under Pure Levy, the fleet remains exposed to persistent emissions charges, increasing expected and tail costs. The cost gap is driven mainly by *levy payments*: fossil-heavy operation persists, so payments rise without a commensurate increase in fuel or investment costs, yielding a high-payment rather than high-transition-cost pathway.

Attained GFI and emissions. NZF and One-Tier drive sustained reductions in fleet GFI and emissions. Pure Levy delivers weaker reductions under the NZF-implied abatement-cost calibration because levy-driven switching is threshold-based: if the levy does not close fuel cost gaps, the model stays with the cheaper fossil option, whereas NZF/One-Tier sustain incentives via deficit pricing, surplus monetization, and ZNZ rewards. Under our levy calibration, emissions can even *rebound after 2040* as the levy rate declines. Moreover, without crediting for partial uptake beyond direct emissions savings, the levy-only regime tends to concentrate on fossil variants (e.g., fossil- vs e-methanol) rather than blend toward low-carbon fuels.

Fleet composition. Consistent with GFI and emissions results, NZF and One-Tier shift the fleet from conventional to alt-fuel-capable ships. One-Tier builds capability more slowly through the mid-2040s, but both regimes support substantial DF-methanol/ammonia uptake, enabling operation on low-GFI fuels as targets tighten and supply expands. Under Pure Levy, the transition is slower

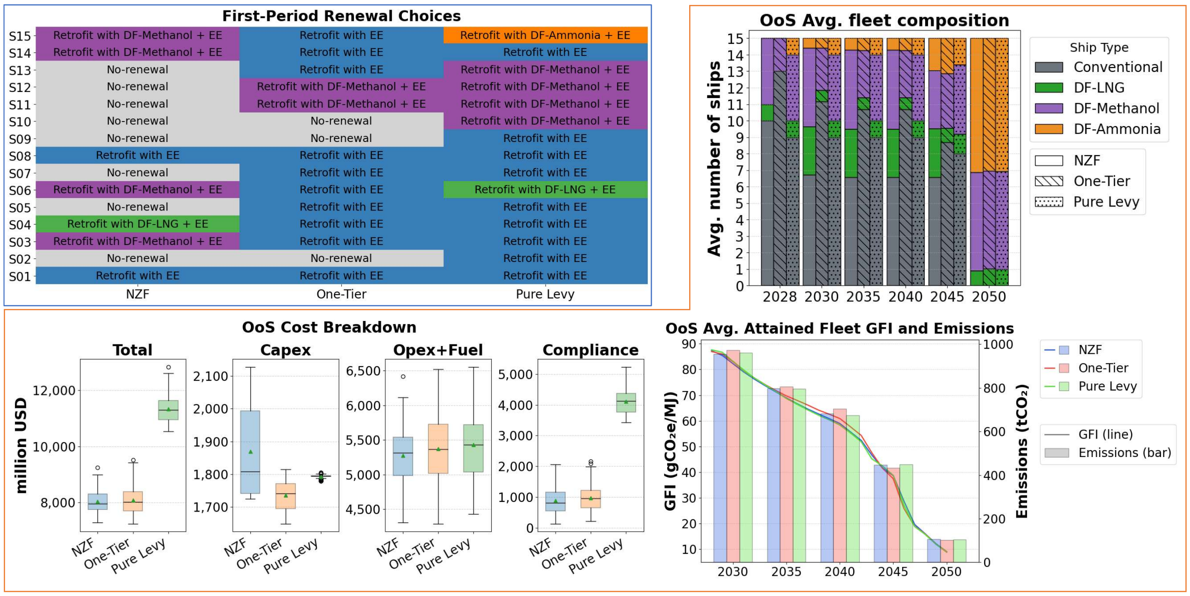


Figure 9 “High-Levy” Case: (top-left) First-Period Renewal, (top-right and bottom) OoS Outcomes

and fleet remains conventional longer. Even when DF appear (as replacements are restricted to DF), they operate mostly on fossil fuels as weaker late-horizon levy rates reduce incentives to switch, so capability does not translate into use. Overall, standard-based regimes provide stronger and more persistent incentives for both technology commitment and fuel switching.

NZF vs One-Tier. In this case study, One-Tier is near-equivalent to NZF for the liner, with similar costs and compliance outcomes but a simpler structure, suggesting the main signal comes from the tightening GFI targets with pricing and surplus incentives rather than the tiering structure. One-Tier may weaken fund revenues if SUs offset deficits too freely, which can be addressed by requiring a *non-offsettable* share of deficits to be settled via RUs.

5.5.2. Levy Sensitivity. As seen above, levy calibrated to the NZF-implied abatement-cost signal yields limited decarbonization because fleet operations remain largely fossil-based. This baseline levy path is relatively low and non-monotone (141 USD/tCO_2e (2030), 196 (2035), 289 (2040), 189 (2045), 103 (2050)), weakening transition incentives. We therefore test a higher levy path, tuned (by trial-and-error) to match NZF/One-Tier OoS GFI and emissions trajectories: 340 (2030), 380 (2035), 390 (2040), then 385 (2045) and 370 (2050). Figure 9 summarizes the results.

Despite a similar decarbonization trajectory under high levy rates, Pure Levy is substantially more expensive: OoS mean total cost is about 40% higher than NZF/One-Tier, driven mainly by *levy payments*. CAPEX and OPEX+fuel are broadly similar across setups, but levy payments stay high because the fleet remains fossil-heavy during the transition and there are no SU monetization

Table 8 Key Takeaways for Shipping Companies and Policymakers

Shipping Companies
1. **Plan for binding low-carbon supply**: expect rationing and compliance-unit purchases; apply EE broadly and target scarce low-carbon fuels to younger ships and highest-payoff years/ships.
2. **Use scarce fuel to manage deficits**: when SU value is limited, it can be cheaper to keep more ships near the Base target than to push a few deep into the SU region.
3. **Hedge early, commit selectively**: under joint cost–supply uncertainty, a diversified and less aggressive first-period (*here-and-now*) retrofit portfolio reduces downside risk and volatility versus mean-trajectory planning.
4. **More supply reduces the need to overbuild flexibility**: with expanded fuel availability, stochastic planning can avoid premature DF overinvestment and rely on fuel access to lower total cost, even if compliance payments rise slightly.
5. **Preserve pathway optionality**: use DF where remaining life and flexibility value are high; defer irreversible commitments on short-lived ships.
Policymakers
1. **Targets require fuel scale-up**: tightening GFI trajectories need credible long-horizon signals that accelerate production, infrastructure, and certification.
2. **Scarcity changes firm behavior**: limited low-carbon fuel volumes are allocated to reduce broad Base deficits rather than maximize SU generation; target design should anticipate this rationing response.
3. **Standards shape pathways more than pricing alone**: Technical standards (like GFS) with SU incentives can induce earlier commitment and sustained switching, while levies can yield "high-payments, low-transition" outcomes if price signals weaken.
4. **Simplicity can be feasible**: one-tier standards can be near-indifferent to two-tier NZF for firm outcomes, but may need explicit revenue safeguards (e.g., a mandatory RU-offsettable deficit share).
5. **Targeted rewards support additionality and early market formation**: focusing incentives on long-term scalable fuels (e.g., e-ammonia) can sustain gradual early uptake, enabling learning and infrastructure scale-up so these fuels become cost-effective in the late 2040s and support sector-wide net-zero goals.

effects or ZNZ-type rewards to offset e-fuel uptake. By contrast, NZF and One-Tier reduce net compliance costs through surplus incentives and by rewarding eligible e-fuel use even without over-compliance, which becomes increasingly important as e-fuel uptake rises in the late 2040s. Consistent with this, the levy case retrofits nearly all ships in 2028, mainly via EE, as a robust way to reduce energy use (and levy exposure) regardless of which low-carbon fuels materialize.

Taken together, the results show that pricing alone does not generally replicate the decarbonization pathway of standard-plus-incentive designs at comparable cost. NZF/One-Tier deliver lower long-run costs and stronger decarbonization by reshaping incentives over time: tightening targets raise the value of low-GFI capability, and surplus-credit monetization strengthens earlier commitment. While NZF and One-Tier are similar in aggregate outcomes, NZF tends to pull forward adoption, whereas One-Tier achieves comparable results with a simpler compliance structure.

Based on all the above results, Table 8 summarizes key managerial and policy takeaways.

6. Conclusions

This paper develops a ship-resolved fleet renewal planning model from an individual liner company's perspective. The framework jointly optimizes discrete renewal actions (EE retrofits, DF conversions, and end-of-life replacement) and annual fuel deployment across compatible fuels, subject to ship-level technology constraints and fleetwide limits on low- and zero-carbon fuel availability. Ship-level compliance is represented through a unified regulatory mapping capturing tightening GHG fuel-intensity requirements with deficit payments, surplus-crediting, and targeted rewards for eligible fuels. We extend the deterministic model to a scenario-based stochastic program in which near-term retrofit decisions are made before fuel-market uncertainty is revealed, while later renewal and fuel-use decisions adapt to realized fuel cost and supply trajectories. To maintain tractability, we solve the stochastic model using a restricted first-stage subset method that draws first-period renewal decisions from a candidate pool generated by single-scenario deterministic solves.

We apply the model to a stylized Asia–Europe deep-sea liner service (15 ships, fixed weekly loop) using public techno-economic inputs and joint scenarios for fuel costs and category-level fuel availability. Three insights emerge. First, fuel availability is a first-order constraint: a proportional share of projected global low-carbon supply can be insufficient to meet tightening GFI targets, shifting the strategy toward “EE everywhere, low-carbon fuels where they matter most” and increasing reliance on compliance-unit purchases in the early and mid-horizon. Second, uncertainty affects investment timing and technology choice: relative to a mean-trajectory deterministic plan, stochastic planning yields a more selective, hedged first-stage retrofit portfolio with modest expected-cost savings but materially lower downside risk and cost volatility out of sample. Third, regulatory architecture shapes pathways: standard-based designs (NZF and a simpler One-Tier variant) induce earlier technology commitment and more sustained fuel switching, whereas a pure levy can produce a “high-payments” outcome with persistent compliance charges and limited decarbonization, especially when price signal weakens over time. One-Tier variant is largely cost- and compliance-indifferent to the two-tier NZF, suggesting scope to simplify compliance architecture while ensuring revenue adequacy (e.g., a mandatory share of deficits settled through RU purchases).

Methodologically, the results show that a compact stochastic programming model, combined with a first-stage subset approach and structured cost–supply scenario generation, can yield decision-relevant insights at the level of an individual liner company. Natural extensions include: (i) a multi-service setting with endogenous ship allocation and redeployment, (ii) richer regulatory modeling with endogenous RU/SU prices, trading frictions, banking value, and explicit fund revenue rules, and (iii) enhanced uncertainty and operations, including correlated cost–supply processes, learning dynamics, risk-averse objectives (e.g., CVaR), and port/region-level fuel access and contracting with lead times and yard-capacity constraints.

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Appendix A: Additional Modelling Assumptions and Technical Details

This appendix provides additional rationale for structural restrictions and technical details used in the formulation.

A.1. Rationale for Renewal-Action Restrictions

Assumption 2 (at most one retrofit). Major retrofits (EE packages and/or alt-fuel conversions) are typically planned as a single dry-dock campaign to limit off-hire time and consolidate yard work, class approvals, and equipment integration. Many retrofit elements are spatially and structurally interdependent (e.g., tank arrangement, piping, ventilation, machinery layout), so repeated conversions can require substantial rework and additional downtime. The business case also weakens as hull age increases and remaining life shrinks. While multiple retrofits are possible in principle, they are uncommon for deep-sea vessels, so we restrict each ship to at most one retrofit before end-of-life.

Assumption 3 (no retrofits after replacement). Replacement decisions correspond to ordering a newbuild with the selected fuel system and EE package integrated at design. Immediate post-delivery retrofits are atypical and can conflict with commissioning, warranties, and performance guarantees. From a modelling standpoint, allowing post-replacement retrofits would expand the action space with limited added realism for the horizon considered.

A.2. Linearization of Surplus-Unit Generation and Big-M Bounds

Let $SU^{\text{tot}}_{s,t} = \max\{G^{\text{tot}}_{s,t}, 0\}$ denote total SUs (tCO_2e). We implement this positive-part relation using a standard big-M linearization:

$$\begin{aligned} &G^{\text{tot}}_{s,t} - M^{\text{tot}}_{s,t}(1 - b^{\text{tot}}_{s,t}) \le SU^{\text{tot}}_{s,t} \le G^{\text{tot}}_{s,t} + M^{\text{tot}}_{s,t}(1 - b^{\text{tot}}_{s,t}) && \forall s \in S,\ t \in T, \\ &0 \le SU^{\text{tot}}_{s,t} \le M^{\text{tot}}_{s,t}\, b^{\text{tot}}_{s,t} && \forall s \in S,\ t \in T, \\ &b^{\text{tot}}_{s,t} \in \{0, 1\} && \forall s \in S,\ t \in T, \end{aligned} \tag{14}$$

where $b^{\text{tot}}_{s,t}$ indicates whether $G^{\text{tot}}_{s,t}$ is non-negative. Specifically, when $b^{\text{tot}}_{s,t} = 0$, the second line enforces $SU^{\text{tot}}_{s,t} = 0$; when $b^{\text{tot}}_{s,t} = 1$, the first line enforces $SU^{\text{tot}}_{s,t} = G^{\text{tot}}_{s,t}$.

Choice of $M^{\text{tot}}_{s,t}$. From (6), the maximum feasible value of $G^{\text{tot}}_{s,t}$ occurs when emissions are minimized (in the limit, $\text{GHG}_{s,t} = 0$), yielding

$$G^{\text{tot}}_{s,t} \le \frac{I^{\text{SU}}_t E_{s,t}}{1000}.$$

Under (4), $E_{s,t}$ equals the energy requirement implied by the active technology state, and is therefore bounded by $\max_{k \in K_{s,t}} E^{\text{req}}_{s,k}$ (maximum energy requirement across feasible technology states for ship s). A conservative and time-consistent choice is thus

$$M^{\text{tot}}_{s,t} = \frac{I^{\text{SU}}_t \cdot \max_{k \in K_{s,t}} E^{\text{req}}_{s,k}}{1000}, \qquad \forall s \in S,\ t \in T,$$

or, more simply, $\max_{k \in K_s}$ if $K_{s,t} = K_s$ for all t. This bound is valid for all feasible fuel mixes and technology states, and can be tightened further if sharper bounds on $E_{s,t}$ are available (e.g., using period-specific feasibility sets or known state restrictions).

Appendix B: Notation and Full model Formulations

B.1. Notation

Table 9 Fleet-Renewal Problem Notation

Symbol	Description
Sets and indices	
S	Set of ships (fleet positions), index s
$T = \{1, \ldots, T_{\max}\}$	Set of periods (years), index t
K	Set of technology states, index k
$K_s \subseteq K$	Technology states feasible for ship s over the planning horizon
$K_{s,t} \subseteq K_s$	Technology states feasible for ship s in period t
R_s^{ret}	Retrofit options for ship s
$R_{s,t}^{\text{ret}} \subseteq R_s^{\text{ret}}$	Retrofit options admissible for ship s in period t
R_s^{rep}	Replacement options for ship s
$T_s^{\text{ren}} \subseteq T$	Eligible renewal (dry-docking) periods for ship s
F	Set of fuels, index f
$F_k \subseteq F$	Fuels compatible with technology state k
$F_t^{\text{elig}} \subseteq F$	Fuels eligible for targeted rewards in period t
$Q = \{1, \ldots, Q_{\max}\}$	Set of regulatory tiers, index q
$Q^{\text{SU-off}} \subseteq Q$	Tiers whose deficits may be offset using SUs
Parameters	
$k_s^0 \in K_s$	Initial technology state of ship s
$\kappa_{s,r}^{\text{ret}} \in K_s$	Post-retrofit state under option r for ship s
$\kappa_{s,r}^{\text{rep}} \in K_s$	Post-replacement state under option r for ship s
life_s	End-of-life period of ship s
$E_{s,k}^{\text{req}}$	Annual energy requirement of ship s in state k
$c_{s,r,t}^{\text{ret}}$	Retrofit capital cost of option r for ship s at the start of period t
$c_{s,r,\text{life}_s}^{\text{rep}}$	Replacement capital cost of option r for ship s at the start of end-of-life period life_s
$c_{s,k,t}^{\text{fix}}$	Fixed operating cost of ship s in state k in period t (including capacity-loss opportunity cost)
$c_{f,t}^{\text{fuel}}$	Cost of fuel f in period t
$\overline{A}_{f,t}$	Fleet-wide availability cap for fuel f in period t
$\text{EF}_{f,t}$	Well-to-wake emission factor of fuel f in period t
$\alpha_{k,f} \in \{0, 1\}$	Compatibility indicator (1 if f usable in state k)
$I_{t,q}^{\text{GFI}}$	GFI threshold defining lower boundary of tier q
$\pi_{t,q}^{\text{CP}}$	Emissions/carbon price for deficits associated with tier q
I_t^{SU}	Surplus-intensity threshold
ρ_t^{SU}	Incentive per traded/monetized SU
ρ_t^{elig}	Reward per SU associated with eligible-fuel
ϕ_t	Effective SU-banking horizon (years)
$\lambda_{t,q}$	(Tiered/ladder structure) Incremental penalty coefficient derived from $\pi_{t,q}^{\text{CP}}$
β_t	Discount factor (time value of money)
Decision variables	
$y_{s,r,t}^{\text{ret}} \in \{0, 1\}$	1 if retrofit option r is applied to ship s at the start of period t
$y_{s,r}^{\text{rep}} \in \{0, 1\}$	1 if replacement option r is chosen for ship s at its end-of-life
$u_{s,k,t} \in \{0, 1\}$	1 if ship s is in technology state k in period t
$E_{s,f,t} \geq 0$	Energy from fuel f used by ship s in period t
$E_{f,t} \geq 0$	Fleet-wide use of fuel f in period t
$\text{GHG}_{s,t} \geq 0$	GHG emissions of ship s in period t
$DU_{s,t,q} \geq 0$	Gross deficit units of ship s corresponding to tier q in period t
$\widehat{DU}_{s,t,q} \geq 0$	Net (post-offset) deficit units of ship s corresponding to tier q in period t
$SU_{s,t}^{\text{tot}} \geq 0$	Total surplus units of ship s generated in period t
$SU_{s,t}^{\text{elig}} \geq 0$	Surplus units of ship s associated with eligible fuels in period t
$SU_{s,t}^{\text{traded}} \geq 0$	Traded/monetized SUs by ship s in period t
$B_{s,t}^{\text{tot}} \geq 0$	Total banked SUs available for ship s at start of period t
$X_{s,t}^{\text{tot}} \geq 0$	Banked SUs used by ship s to offset its deficits in period t
$C_{s,t}^{\text{reg}}$	Regulatory cash flow of ship s in period t
$Z^{\text{DET/STO}}$	Discounted total cost (objective for deterministic/stochastic model)

B.2. Deterministic (DET) Formulation

$$\min\ Z^{\mathrm{DET}} = \sum_{t\in T}\beta_t\left[\sum_{s\in S}\Big(\sum_{r\in R^{\mathrm{ret}}_{s,t}} c^{\mathrm{ret}}_{s,r,t}\, y^{\mathrm{ret}}_{s,r,t} + \sum_{k\in K_{s,t}} c^{\mathrm{fix}}_{s,k,t}\, u_{s,k,t}\Big) + \sum_{f\in F} c^{\mathrm{fuel}}_{f,t}\, E_{f,t}\right] + \sum_{s\in S}\beta_{\mathrm{life}_s}\sum_{r\in R^{\mathrm{rep}}_s} c^{\mathrm{rep}}_{s,r,\mathrm{life}_s}\, y^{\mathrm{rep}}_{s,r} + \sum_{t\in T}\beta_{t+1}\, C^{\mathrm{reg}}_t$$

s.t. *Technology and renewal:*

$$u_{s,k,t},\, y^{\mathrm{ret}}_{s,r,t},\, y^{\mathrm{rep}}_{s,r},\, b^{\mathrm{tot}}_{s,t} \in \{0,1\} \quad \forall s,k,r,t,$$

$$\sum_{k\in K_{s,t}} u_{s,k,t} = 1 \quad \forall s,t, \quad ; \quad u_{s,k^0_s,1} = 1 \quad ; \quad u_{s,k,1} = 0 \quad \forall k \in K_{s,1}\setminus\{k^0_s\}, s,$$

$$\sum_{t\in T^{\mathrm{ren}}_s:\, t<\mathrm{life}_s}\ \sum_{r\in R^{\mathrm{ret}}_{s,t}} y^{\mathrm{ret}}_{s,r,t} \le 1 \quad \forall s \quad ; \quad \sum_{r\in R^{\mathrm{rep}}_s} y^{\mathrm{rep}}_{s,r} = 1 \quad \forall s,$$

$$u_{s,k^0_s,t} = 1 - \sum_{\tau\in T^{\mathrm{ren}}_s:\, \tau\le t}\ \sum_{r\in R^{\mathrm{ret}}_{s,\tau}} y^{\mathrm{ret}}_{s,r,\tau} \quad \forall s,\ t<\mathrm{life}_s,$$

$$u_{s,\kappa^{\mathrm{ret}}_{s,r},t} = \sum_{\tau\in T^{\mathrm{ren}}_s:\, \tau\le t,\ r\in R^{\mathrm{ret}}_{s,\tau}} y^{\mathrm{ret}}_{s,r,\tau} \quad \forall s,\ r\in R^{\mathrm{ret}}_s,\ t<\mathrm{life}_s,$$

$$u_{s,\kappa^{\mathrm{rep}}_{s,r},t} = y^{\mathrm{rep}}_{s,r} \quad \forall s,\ r\in R^{\mathrm{rep}}_s,\ t\ge \mathrm{life}_s,$$

Energy requirement and fuel use:

$$E_{s,t} = \sum_{k\in K_{s,t}} E^{\mathrm{req}}_{s,k} u_{s,k,t} = \sum_{f\in F} E_{s,f,t} \quad \forall s,t,$$

$$0 \le E_{s,f,t} \le \sum_{k\in K_{s,t}} \alpha_{k,f} E^{\mathrm{req}}_{s,k} u_{s,k,t} \quad \forall s,f,t,$$

$$E_{f,t} = \sum_{s\in S} E_{s,f,t} \le \overline{A}_{f,t} \quad \forall f,t,$$

Emissions and surplus-unit generation:

$$\mathrm{GHG}_{s,t} = \sum_{f\in F} \mathrm{EF}_{f,t}\, E_{s,f,t} \quad \forall s,t,$$

$$G^{\mathrm{tot}}_{s,t} = \frac{I^{\mathrm{SU}}_t E_{s,t} - \mathrm{GHG}_{s,t}}{1000} \quad \forall s,t \quad ; \quad G^{\mathrm{tot}}_{s,t} - M^{\mathrm{tot}}_{s,t}(1-b^{\mathrm{tot}}_{s,t}) \le SU^{\mathrm{tot}}_{s,t} \le G^{\mathrm{tot}}_{s,t} + M^{\mathrm{tot}}_{s,t}(1-b^{\mathrm{tot}}_{s,t}) \quad \forall s,t,$$

$$SU^{\mathrm{tot}}_{s,t} \le M^{\mathrm{tot}}_{s,t} b^{\mathrm{tot}}_{s,t} \quad \forall s,t,$$

$$SU^{\mathrm{elig}}_{s,t} = \frac{1}{1000}\sum_{f\in F^{\mathrm{elig}}_t} (I^{\mathrm{SU}}_t - \mathrm{EF}_{f,t})\, E_{s,f,t} \quad \forall s,t,$$

Banking, trading and offsets:

$$0 \le SU^{\mathrm{traded}}_{s,t} \le SU^{\mathrm{tot}}_{s,t} \quad \forall s,t,$$

$$B^{\mathrm{tot}}_{s,1} = 0 \quad \forall s \quad ; \quad B^{\mathrm{tot}}_{s,t+1} = B^{\mathrm{tot}}_{s,t} + SU^{\mathrm{tot}}_{s,t} - SU^{\mathrm{traded}}_{s,t} - X^{\mathrm{tot}}_{s,t} \quad \forall s,\ t<T_{\max},$$

$$0 \le X^{\mathrm{tot}}_{s,t} \le B^{\mathrm{tot}}_{s,t} \le \sum_{\tau=\max\{1,\,t-\phi_t\}}^{t-1} SU^{\mathrm{tot}}_{s,\tau} \quad \forall s,t,$$

Deficit units and ladder pricing:

$$DU_{s,t,q} \ge 0 \quad \forall s,t,q \quad ; \quad DU_{s,t,q} \ge \frac{\mathrm{GHG}_{s,t} - I^{\mathrm{GFI}}_{t,q} E_{s,t}}{1000} \quad \forall s,t,q,$$

$$0 \le \widehat{DU}_{s,t,q} \le DU_{s,t,q} \quad \forall s,t,q \quad ; \quad \widehat{DU}_{s,t,q} = DU_{s,t,q} \quad \forall s,t,\ q\in Q\setminus Q^{\mathrm{bank}},$$

$$\sum_{q\in Q^{\mathrm{bank}}} \widehat{DU}_{s,t,q} \ge \sum_{q\in Q^{\mathrm{bank}}} DU_{s,t,q} - X^{\mathrm{tot}}_{s,t} \quad \forall s,t,$$

$$C^{\mathrm{reg}}_{s,t} = \sum_{q\in Q} \lambda_{t,q} \widehat{DU}_{s,t,q} - \rho^{\mathrm{SU}}_t SU^{\mathrm{traded}}_{s,t} - \rho^{\mathrm{elig}}_t SU^{\mathrm{elig}}_{s,t} \quad \forall s,t \quad ; \quad C^{\mathrm{reg}}_t = \sum_{s\in S} C^{\mathrm{reg}}_{s,t} \quad \forall t.$$

B.3. Scenario-Based Stochastic (STO) Formulation

$$\min\ Z^{\mathrm{STO}} = \sum_{w\in W}\pi_w\Bigg\{\sum_{t\in T}\beta_t\Big[\sum_{s\in S}\Big(\sum_{r\in R^{\mathrm{ret}}_{s,t}} c^{\mathrm{ret}}_{s,r,t}\, y^{\mathrm{ret}}_{s,r,t,w} + \sum_{k\in K_{s,t}} c^{\mathrm{fix}}_{s,k,t}\, u_{s,k,t,w}\Big) + \sum_{f\in F} c^{\mathrm{fuel}}_{f,t,w}\, E_{f,t,w}\Big]$$

$$+ \sum_{s\in S}\beta_{\mathrm{life}_s}\sum_{r\in R^{\mathrm{rep}}_s} c^{\mathrm{rep}}_{s,r,\mathrm{life}_s}\, y^{\mathrm{rep}}_{s,r,w} + \sum_{t\in T}\beta_{t+1}\, C^{\mathrm{reg}}_{t,w}\Bigg\}$$

s.t. *Technology and renewal (scenario-wise):*

$$u_{s,k,t,w},\ y^{\mathrm{ret}}_{s,r,t,w},\ y^{\mathrm{rep}}_{s,r,w},\ b^{\mathrm{tot}}_{s,t,w}\in\{0,1\}\quad \forall s,k,r,t,w,$$

$$\sum_{k\in K_{s,t}} u_{s,k,t,w}=1\quad \forall s,t,w\quad ;\quad u_{s,k^0_s,1,w}=1\quad ;\quad u_{s,k,1,w}=0\quad \forall k\in K_{s,1}\setminus\{k^0_s\},s,w,$$

$$\sum_{t\in T^{\mathrm{ren}}_s:\, t<\mathrm{life}_s}\ \sum_{r\in R^{\mathrm{ret}}_{s,t}} y^{\mathrm{ret}}_{s,r,t,w}\le 1\quad \forall s,w\quad ;\quad \sum_{r\in R^{\mathrm{rep}}_s} y^{\mathrm{rep}}_{s,r,w}=1\quad \forall s,w,$$

$$u_{s,k^0_s,t,w}=1-\sum_{\tau\in T^{\mathrm{ren}}_s:\, \tau\le t}\ \sum_{r\in R^{\mathrm{ret}}_{s,\tau}} y^{\mathrm{ret}}_{s,r,\tau,w}\qquad \forall s,w,\ t<\mathrm{life}_s,$$

$$u_{s,\kappa^{\mathrm{ret}}_{s,r},t,w}=\sum_{\tau\in T^{\mathrm{ren}}_s:\, \tau\le t,\ r\in R^{\mathrm{ret}}_{s,\tau}} y^{\mathrm{ret}}_{s,r,\tau,w}\qquad \forall s,w,\ r\in R^{\mathrm{ret}}_s,\ t<\mathrm{life}_s,$$

$$u_{s,\kappa^{\mathrm{rep}}_{s,r},t,w}=y^{\mathrm{rep}}_{s,r,w}\qquad \forall s,w,\ r\in R^{\mathrm{rep}}_s,\ t\ge \mathrm{life}_s,$$

Energy requirement and fuel use (scenario-wise):

$$E_{s,t,w}=\sum_{k\in K_{s,t}} E^{\mathrm{req}}_{s,k}u_{s,k,t,w}=\sum_{f\in F}E_{s,f,t,w}\quad \forall s,t,w,$$

$$0\le E_{s,f,t,w}\le \sum_{k\in K_{s,t}}\alpha_{k,f}E^{\mathrm{req}}_{s,k}u_{s,k,t,w}\quad \forall s,f,t,w,$$

$$E_{f,t,w}=\sum_{s\in S}E_{s,f,t,w}\le \overline{A}_{f,t,w}\quad \forall f,t,w,$$

Emissions and surplus-unit generation (scenario-wise):

$$\mathrm{GHG}_{s,t,w}=\sum_{f\in F}\mathrm{EF}_{f,t}\,E_{s,f,t,w}\quad \forall s,t,w,$$

$$G^{\mathrm{tot}}_{s,t,w}=\frac{I^{\mathrm{SU}}_t E_{s,t,w}-\mathrm{GHG}_{s,t,w}}{1000}\ \forall s,t,w\ ;\ G^{\mathrm{tot}}_{s,t,w}-M^{\mathrm{tot}}_{s,t}(1-b^{\mathrm{tot}}_{s,t,w})\le SU^{\mathrm{tot}}_{s,t,w}\le G^{\mathrm{tot}}_{s,t,w}+M^{\mathrm{tot}}_{s,t}(1-b^{\mathrm{tot}}_{s,t,w})\ \forall s,t,w,$$

$$SU^{\mathrm{tot}}_{s,t,w}\le M^{\mathrm{tot}}_{s,t}b^{\mathrm{tot}}_{s,t,w}\quad \forall s,t,w,$$

$$SU^{\mathrm{elig}}_{s,t,w}=\frac{1}{1000}\sum_{f\in F^{\mathrm{elig}}_t}(I^{\mathrm{SU}}_t-\mathrm{EF}_{f,t})\,E_{s,f,t,w}\quad \forall s,t,w,$$

Banking, trading and offsets (scenario-wise):

$$0\le SU^{\mathrm{traded}}_{s,t,w}\le SU^{\mathrm{tot}}_{s,t,w}\quad \forall s,t,w,$$

$$B^{\mathrm{tot}}_{s,1,w}=0\quad \forall s,w\quad ;\quad B^{\mathrm{tot}}_{s,t+1,w}=B^{\mathrm{tot}}_{s,t,w}+SU^{\mathrm{tot}}_{s,t,w}-SU^{\mathrm{traded}}_{s,t,w}-X^{\mathrm{tot}}_{s,t,w}\quad \forall s,w,\ t<T_{\max},$$

$$0\le X^{\mathrm{tot}}_{s,t,w}\le B^{\mathrm{tot}}_{s,t,w}\le \sum_{\tau=\max\{1,t-\phi_t\}}^{t-1} SU^{\mathrm{tot}}_{s,\tau,w}\quad \forall s,t,w,$$

Deficit units and ladder pricing (scenario-wise):

$$DU_{s,t,q,w}\ge 0\quad \forall s,t,q,w\quad ;\quad DU_{s,t,q,w}\ge \frac{\mathrm{GHG}_{s,t,w}-I^{\mathrm{GFI}}_{t,q}E_{s,t,w}}{1000}\quad \forall s,t,q,w,$$

$$0\le \widehat{DU}_{s,t,q,w}\le DU_{s,t,q,w}\quad \forall s,t,q,w\quad ;\quad \widehat{DU}_{s,t,q,w}=DU_{s,t,q,w}\quad \forall s,t,w,\ q\in Q\setminus Q^{\mathrm{bank}},$$

$$\sum_{q\in Q^{\mathrm{bank}}}\widehat{DU}_{s,t,q,w}\ge \sum_{q\in Q^{\mathrm{bank}}}DU_{s,t,q,w}-X^{\mathrm{tot}}_{s,t,w}\quad \forall s,t,w,$$

$$C^{\mathrm{reg}}_{s,t,w}=\sum_{q\in Q}\lambda_{t,q}\widehat{DU}_{s,t,q,w}-\rho^{\mathrm{SU}}_t SU^{\mathrm{traded}}_{s,t,w}-\rho^{\mathrm{elig}}_t SU^{\mathrm{elig}}_{s,t,w}\quad \forall s,t,w\quad ;\quad C^{\mathrm{reg}}_{t,w}=\sum_{s\in S}C^{\mathrm{reg}}_{s,t,w}\quad \forall t,w,$$

First-period non-anticipativity: $y^{\mathrm{ret}}_{s,r,1,w}=y^{\mathrm{ret}}_{s,r,1,w'}$; $u_{s,k,1,w}=u_{s,k,1,w'}\quad \forall s,\ r\in R^{\mathrm{ret}}_{s,1},\ k\in K_{s,1},\ \forall w,w'\in W.$

Appendix C: Extensions and Generalizations

The framework is modular: fleet-renewal constraints define feasible technology and fuel-deployment pathways, while the regulatory module maps fuel use and emissions to deficit/surplus quantities and payments. This separation enables several extensions without changing the core structure.

Endogenous capacity growth and chartering. To reflect demand growth, the model can allow additional fleet positions (new ships) to be introduced over time, or include charter-in/out decisions to adjust capacity. In such cases, the key strategic lever remains the fuel-system choice for incremental capacity under the same regulatory and fuel-market conditions, while the extension mainly adds capacity-balance constraints and corresponding capital/charter costs.

Early retirement with salvage/resale values. Replacement can be generalized beyond end-of-life by allowing discretionary early scrap-and-replace decisions with age-dependent salvage/resale credits. This expands the replacement option set and adds salvage accounting, while leaving the regulatory and fuel-switching structure unchanged.

Richer fuel-availability structure. The current fleetwide fuel caps $\overline{A}_{f,t}$ can be refined to represent location- or hub-specific availability (and, if needed, contractual supply), capturing the geographic unevenness of low- and zero-carbon fuel supply and its implications for feasible fuel switching.

Alternative compliance and credit rules. The regulatory module can incorporate additional design features such as alternative SU banking/expiry rules, limits on SU offsets by tier, and differentiated reward rates across eligible fuels/pathways by modifying $\Phi_t(\cdot)$ and the associated accounting constraints.

Risk-averse objectives. Beyond the risk-neutral expected-cost objective, the scenario-based model can include risk measures such as CVaR on total discounted cost or compliance costs, preserving the scenario structure while adding auxiliary variables and constraints.

Appendix D: Case-study Inputs and Parameter Calibration

D.1. WTW Emission Factors

Table 10 WTW GHG Emission Factors (gCO_2e/MJ).

Fuel	2028	2030	2035	2040	2045	2050
VLSFO	92.1	92.1	92.1	92.1	92.1	92.1
Bio-diesel	61.1	55.6	41.7	27.8	13.9	0.0
e-diesel	1.3	1.1	0.9	0.6	0.3	0.0
Fossil LNG	84.8	84.8	84.8	84.8	84.8	84.8
Bio-LNG	15.5	14.1	10.5	7.0	3.5	0.0
e-LNG	1.7	1.5	1.1	0.8	0.4	0.0
Fossil methanol	101.7	101.7	101.7	101.7	101.7	101.7
Bio-methanol	32.2	29.3	22.0	14.6	7.3	0.0
e-methanol	1.0	0.9	0.7	0.4	0.2	0.0
Blue ammonia	29.5	28.2	24.9	21.6	18.3	15.0
e-ammonia	5.3	4.8	3.6	2.4	1.2	0.0

Notes. 2028 values follow Lagouvardou et al. (2023), Loennechen et al. (2024). Bio- and e-fuels are assumed to reach near-zero WTW intensity by 2050, and blue-ammonia follows the trajectory in DNV (2024a). Intermediate-year values are linearly interpolated.

D.2. Illustration of Sampled Fuel-Cost and Supply Scenarios

This appendix provides a visual illustration of the scenario-generation procedure described in Section 4.4. The left panel plots example fuel-cost trajectories obtained by fuel-wise sampling within the annual lower/upper bounds while preserving each fuel's time profile (perfect time dependence within fuel). The right panel plots the corresponding fuel-category availability trajectories, generated via a monotone mapping that links category supply to scenario-specific category cost levels so that higher (lower) costs induce lower (higher) availability, while respecting the annual lower/upper supply envelopes.

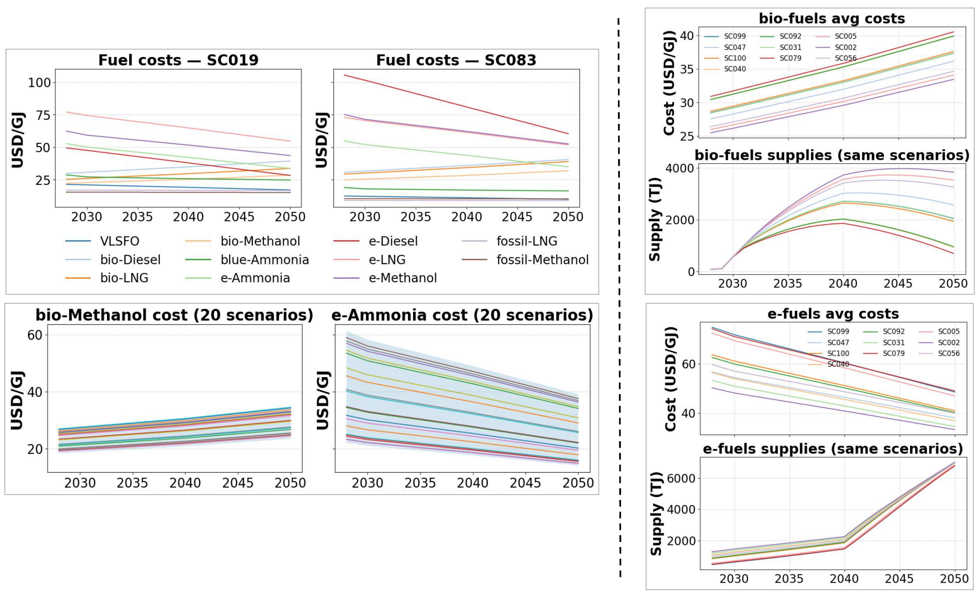


Figure 10 (left-panel) Sample Fuel-Cost Scenarios; (right-panel) Sample Fuel-Category Supply Scenarios

D.3. NZF parameter calibration and assumptions

Base and Direct-compliance GFI targets for the 2028–2035 period and the Tier 1/Tier 2 RU prices up to 2030 are aligned with the values agreed in the NZF. Beyond these years, we extrapolate the two GFI trajectories smoothly to 2050 and hold Tier 1 and Tier 2 RU prices at 100 and 380 USD/t-CO_2e, respectively. SU trading prices are capped by the Tier 2 RU price and depends on the SU market supply-demand dynamics. For the sake of this study, we assume that SU price is conservatively set at Tier 2 RU price. For the reward eligible ZNZ fuels, we take the technology-centric approach (GMF 2025) of rewarding only e-fuels (which typically have GFI lower than direct-compliance target), while excluding bio-fuels on the grounds that their costs are generally lower and SU incentives are presumed sufficient, and several studies raise concerns about the long-term sustainability of certain bio-fuel pathways. The ZNZ reward path is calibrated from a conservative revenue assumption of ∼11 billion USD/year in RU proceeds (GMF 2025), with 50% earmarked for ZNZ rewards, combined with an optimistic ZNZ uptake trajectory (2% in 2028, 10% in 2030, 50% in 2040, 90% in 2050; *e.g.*, DNV, 2024). Back-calculation yields a time-varying reward that is intentionally moderate to mitigate IMO Fund insolvency risk while still providing a meaningful signal for e-fuel deployment.

Table 11 NZF: GFI Targets (gCO_2e/MJ), RU Prices, Reward Rates (USD/tCO_2e)

Year	Base GFI	Direct-compliance GFI	Tier 1 RU	Tier 2 RU	ZNZ reward
2028	89.6	77.4	100	380	381
2030	85.8	73.7	100	380	80
2035	65.3	53.2	100	380	37
2040	32.7	20.5	100	380	61
2045	17.3	5.1	100	380	200
2050	1.9	0.0	100	380	0

Notes. Targets to 2035 follow the approved NZF; beyond 2035 they are extrapolated so the Base target approaches zero by 2050 while maintaining a constant 13 ppt gap to the Direct-compliance target. RU prices are assumed constant over the horizon. The reward-rate path is calibrated from a conservative revenue assumption (GMF 2025) and an optimistic ZNZ uptake trajectory (DNV 2024b) to limit NZF fund insolvency risk.

D.4. Capital-Cost Annualization and Terminal-Credit Treatment

Capital outlays for ship replacements are converted to an equivalent annual cost (EAC) over the ship's tehnical life ($L = 25$ years). For a one-time investment K commissioned in year τ, the EAC is

$$\mathrm{EAC}(K, L, d) \;=\; K\,\frac{d(1+d)^L}{(1+d)^L - 1}.$$

To ensure only the within-horizon portion is accounted, the model accrues the EAC stream from τ up to $T_{\max} = \min\{\tau + L - 1,\, 2050\}$. Equivalently, if $\tau + L - 1 > 2050$, a terminal credit equal to the present value (at 2028) of the unexpired EAC payments from 2051 to $\tau + L - 1$ is deducted:

$$\mathrm{PV\_credit} \;=\; \sum_{t=2051}^{\tau+L-1} \frac{\mathrm{EAC}(K, L, d)}{(1+d)^{\,t-2028}}.$$

This treatment allocates CAPEX proportionally to the share of the asset's life that lies inside the 2028–2050 planning horizon, while preserving intertemporal consistency across options.

Appendix E: Additional Results

E.1. Sensitivity Results

Sensitivity to fuel supply. We vary low-carbon fuel availability while holding fuel costs at their mean trajectories. The case "1x" corresponds to the baseline proportional allocation (mean category-level supplies in Table 5), while "2x"–"5x" uniformly scale annual bio-, e-, and blue-fuel supplies by factors of two to five. Figure 11 reports the resulting changes in discounted total cost, attained fleet GFI, and the renewal choices as the supply multiplier increases.

1. Costs fall as supply expands. Increasing fuel availability relaxes the binding supply caps and allows greater use of cost-effective low-carbon fuels. Doubling supply from "1x" to "2x" reduces discounted total cost by about 4% (USD 327 million), while moving from the baseline case "1x" to the unconstrained case ("No limit") lowers cost by roughly 15% (USD 1.3 billion).

2. Renewal shifts toward broader DF uptake, especially methanol. Higher supply supports more aggressive retrofit and replacement: as availability rises from "1x" to "2x" and then to "3x/4x", more ships retrofit to DF-methanol+EE and DF-ammonia+EE, enabling larger volumes of methanol- and ammonia-based fuels. In low-supply cases, DF-ammonia retrofits help concentrate scarce e-fuels on a small subset of ships; as bio-fuel availability expands, the plan shifts toward DF-methanol, particularly for younger ships, because sufficient bio-methanol makes methanol-based operation

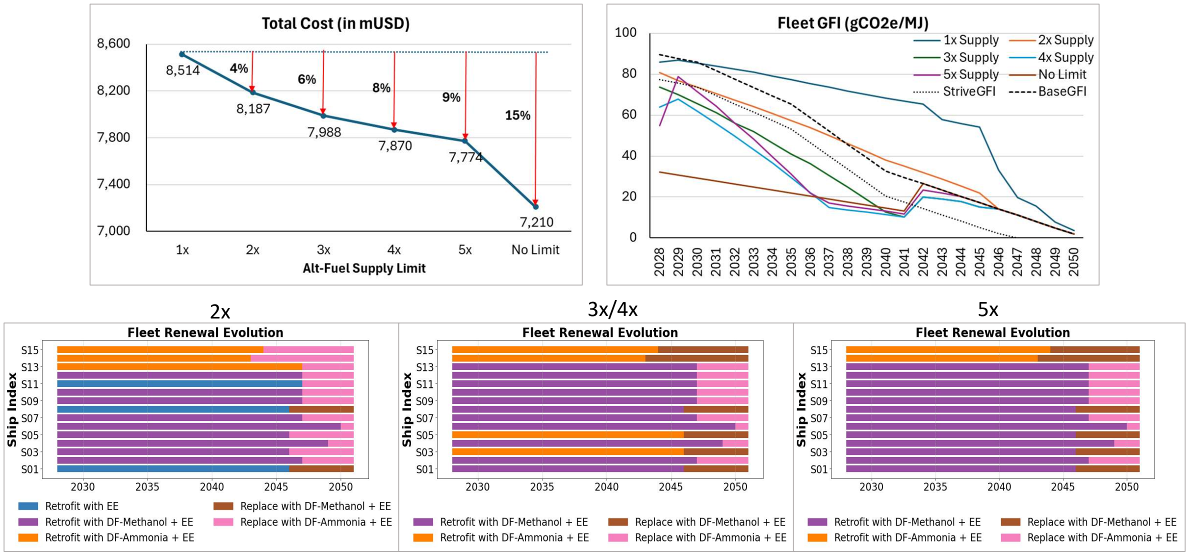


Figure 11 Sensitivity to Low-Carbon Fuel Supply

Note. “1x” corresponds to mean supplies in Table 5; “2x”–“5x” scale these supplies by factors of two to five, with fuel costs fixed at their mean trajectories.

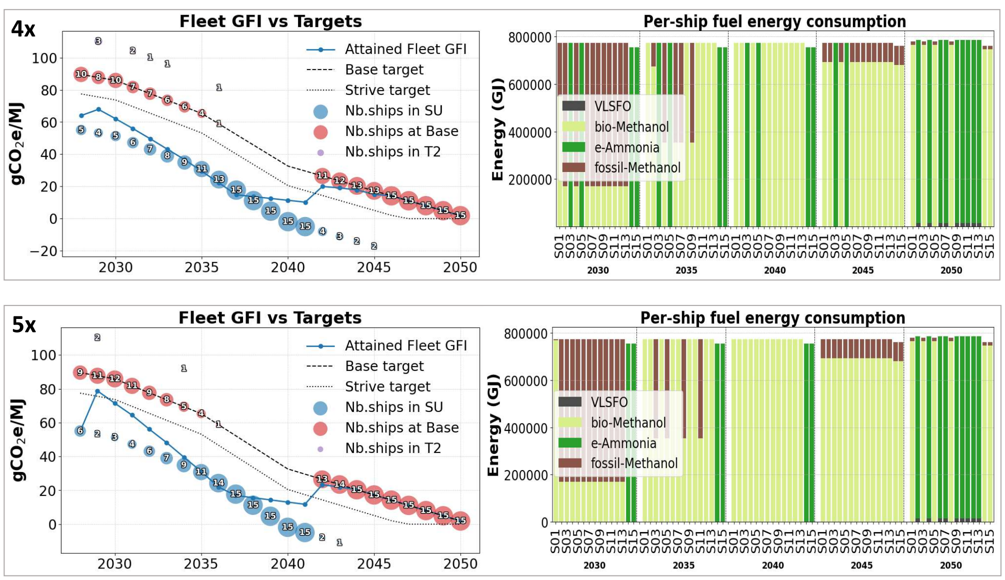


Figure 12 “4x” vs. “5x” Supply: Attained GFI and Fuel-Use

broadly cost-effective. “3x” and “4x” yield identical renewal plans, indicating that the incremental supply, especially in the early years, is still not sufficient to justify an additional retrofit, because the extra low-carbon fuel would not be used at levels that offset the additional (retrofitting) capital cost. At “5x”, further supply growth supports more extensive DF-methanol uptake, with a visible shift away from DF-ammonia retrofitting.

3. GFI improves overall but is not strictly monotone. More supply generally lowers fleet GFI by enabling more low-carbon fuel use, but the cost-minimizing outcome need not be monotone in supply. In Figure 11, moving from “4x” to “5x” slightly increases early-year GFI. (see Figure 12) Under “4x”, limited volumes are concentrated on a few

DF-ammonia ships operating in the SU region on high shares of e-ammonia. Under "5x", added bio-methanol makes it cheaper to spread low-carbon fuel across more ships and operate closer to the Base target using fossil/bio-methanol blends, rather than maintaining a small number of ships in over-compliance on 100% e-ammonia. This shifts retrofits (from DF-ammonia toward DF-methanol) and fuel use (from e-ammonia toward bio-methanol), yielding lower cost but a slightly higher fleet GFI in those years.

Sensitivity to fuel cost. We next investigate how relative fuel costs influence preferred pathways, keeping the mean supply caps. As seen in section 5.1, under the assumed mean cost trajectories, bio-methanol is the dominant low-carbon fuel and thus drives retrofits to DF-methanol, because it offers a lower marginal abatement cost than other low-carbon fuels. To test how sensitive this outcome is to fuel cost assumptions, we consider two alternative cases: (1) *LNG-favorable* case, where bio-LNG is set to follow its lower-bound cost trajectory in Table 4, while all other fuels retain their mean cost paths, (2) *ammonia-favorable* case, where e-ammonia follows its lower-bound cost trajectory, again with all other fuels kept at their mean paths. Figure 13 reports the resulting renewal and fuel-use patterns, highlighting how the optimal technology choices shift when either bio-LNG or e-ammonia becomes comparatively more competitive.

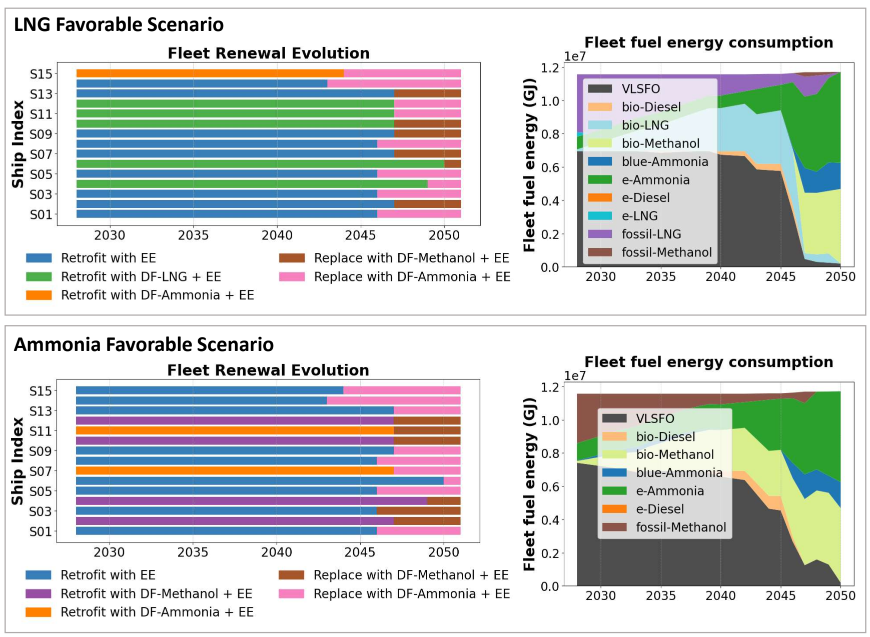


Figure 13 Sensitivity to Fuel Costs: LNG- and Ammonia-Favorable Cost Scenarios.

Note. In the LNG-favorable case, bio-LNG follows its lower-bound cost trajectory in Table 4 and other fuels follow their mean trajectories. In the ammonia-favorable case, e-ammonia follows its lower-bound trajectory and other fuels follow their mean paths.

1. LNG-favorable costs. When bio-LNG follows its lower-end cost path, the optimal plan shifts markedly toward DF-LNG+EE retrofits in 2028. Several ships that adopt DF-methanol+EE under the mean-cost case (Figure 4) instead convert to DF-LNG+EE, and bio-LNG becomes the primary low-carbon fuel (within the bio-fuels supply cap). This shows that, when low-carbon volumes are not overly tight, relative fuel costs can materially change the preferred DF pathway, even though the overarching strategy of combining EE with low-carbon fuels remains.

2. Ammonia-favorable costs. Lower e-ammonia costs increase the attractiveness of DF-ammonia systems, but the shift is smaller: only two ships retrofit to DF-ammonia+EE (up from one in Figure 4). The limited e-fuel supply availability restricts how many vessels can exploit the cheaper ammonia pathway, so most ships still follow a methanol-based strategy. Overall, supply constraints dampen the technology response to more favorable ammonia costs.

Sensitivity to fuel cost and supply. Finally, we assess the impact of combined uncertainty in fuel costs and supply levels. We consider 100 jointly generated fuel cost–supply scenarios, as described in Section 4.4, and solve the deterministic model for each scenario. The detailed scenario distributions (costs, fuel mix, fleet GFI, and average fleet composition) are reported in the Figure 14. Across these scenarios, four key observations emerge. First, total cost is highly sensitive to fuel-market outcomes, with the spread between best- and worst-case scenarios on the order of 30%. Second, the cost-effective fuel pathway in the mid-2030s varies widely across scenarios, with different realizations favoring conventional, LNG-based, or methanol-based operation depending on the joint cost–supply conditions. Third, attained fleet GFI shows wide dispersion with most scenarios exceeding the Base targets during the transition period (mid-2030s to mid-2040s), implying sustained reliance on compliance-unit purchases (RUs or SUs). Fourth, the average fleet composition shifts gradually from conventional toward a mix of DF technologies: DF-methanol and DF-LNG appear prominently in early retrofit years, DF-ammonia enters later and expands over time, and by 2050 the fleet is dominated by DF-ammonia followed by DF-methanol, with DF-LNG playing a more limited role and conventional-only ships largely phased out.

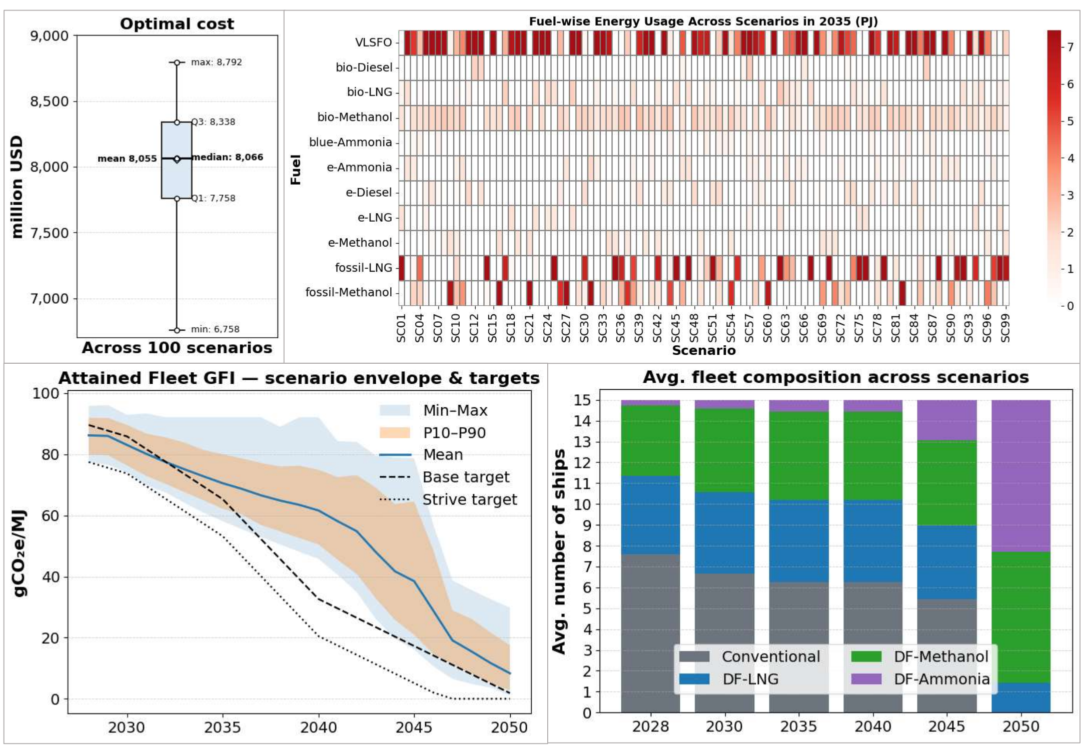


Figure 14 Optimal DET Outcomes Across 100 Random Fuel Cost–Supply Scenarios

Note. Panels show (i) the distribution of discounted total costs, (ii) the 2035 fuel mix, (iii) the attained fleet GFI envelope relative to the Base and Direct-compliance targets, and (iv) average fleet composition by technology in selected years.

E.2. Out-of-Sample Fleet GFI Envelopes

Figure 15 compares the out-of-sample attained fleet GFI under the deterministic (DET) and stochastic (STO) first-stage plans. For each year, the shaded bands show the min–max envelope and the P10–P90 range (10th and 90th percentiles) across the 100 test scenarios, while the solid line reports the mean attained GFI and the dashed/dotted lines show the Base and Direct-compliance GFI targets. These envelopes complement the summary statistics reported in Table 7 by illustrating how fuel cost–supply uncertainty translates into a wide dispersion of possible fleet GFI trajectories over the transition period.

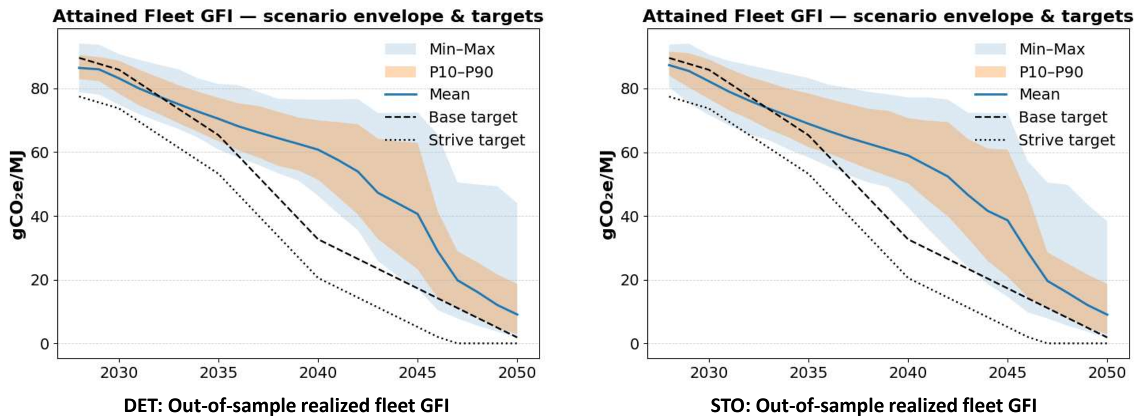


Figure 15 Realized Fleet GFI Across Test Scenarios Under DET and STO First-Stage Plans

Note. Strive targets refer to Direct-Compliance GFI targets

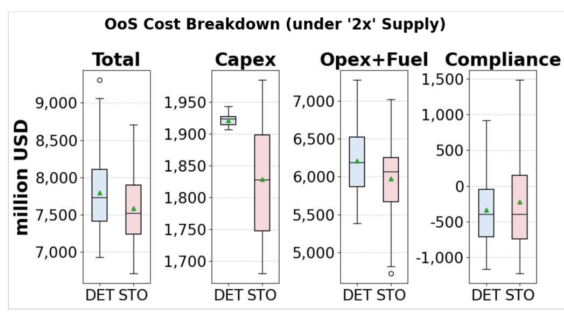
E.3. Outcomes under 2x Supply Case

This appendix reports (i) first-period renewal plans under the deterministic (DET) and stochastic (STO) models and (ii) out-of-sample outcomes evaluated on 100 jointly generated fuel cost–supply scenarios. The out-of-sample tests use the 2x supply setting, where the lower, mean, and upper bounds in Table 5 are scaled by a factor of two.

Table 12 OoS Total Cost Performance

OoS Metric	DET	STO	Improv.
# scenarios dominated	18	82	356%
Max. cost	9,305	8,704	6.5%
Mean of worst 10%	8,779	8,550	2.6%
Mean	7,794	7,582	2.7%
Min. cost	6,928	6,707	3.2%
Std. dev.	507	499	1.6%

Notes. Total costs are in mUSD.



Notes. Cost (y-) axis scales are different across components. -ve compliance costs implies the ZNZ rewards exceed the compliance payments.

Figure 16 OoS Cost Distribution

Figure 17 reports the first-period renewal plans, out-of-sample average fleet composition and attained fleet GFI for the DET and STO strategies under the 2x setting.

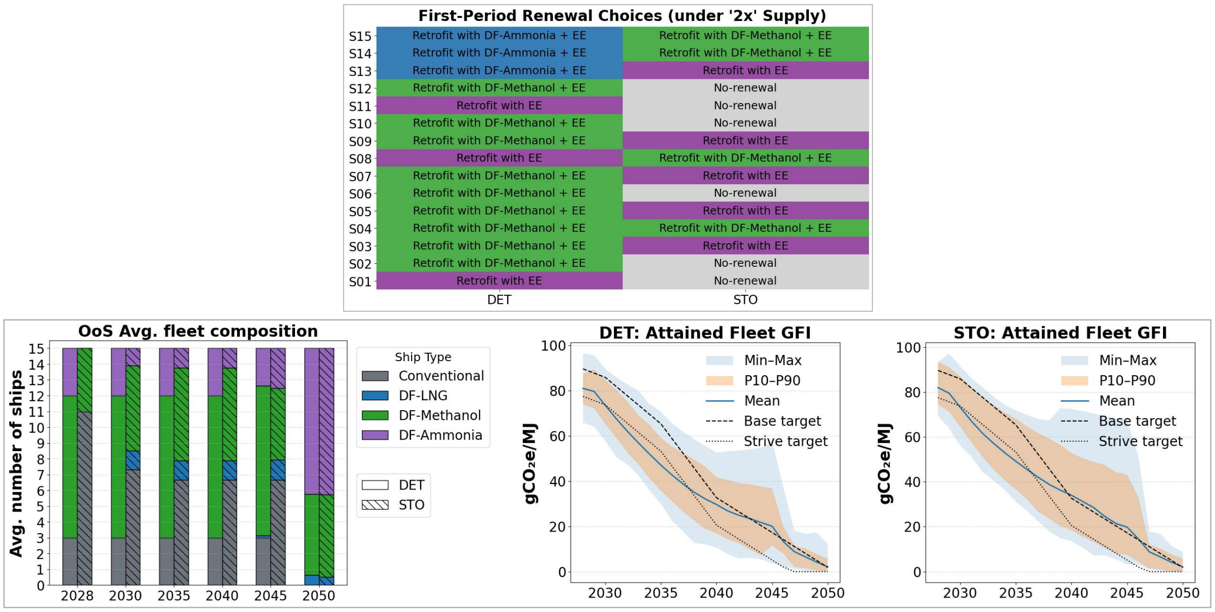


Figure 17 **Outcomes Under 2x Supply Case: DET vs. STO First-Period Renewal Plans and OoS Outcomes**

Appendix F: Alternative Regulatory Setup Details

Table 13 **Alternative Regulatory Setups Used in the Comparison Experiments**

Reg. parameter	IMO NZF (Two-Tier GFS + RU/SU/ZNZ)	One-Tier GFS + RU/SU/ZNZ	Pure Levy
GFI targets (gCO_2e/MJ)	Base: 86(2030) → 65(2035) → 33(2040) → 17(2045) → 2(2050) Direct-compliance: 74(2030) → 53(2035) → 21(2040) → 5(2045) → 0(2050)	Only one GFI trajectory: 80(2030) → 59(2035) → 27(2040) → 11(2045) → 1(2050)	–
Carbon pricing (USD/tCO_2e)	Tier 2 RU: 380 and Tier 1 RU: 100 (held constant to 2050) Applied to deficits relative to the GFI targets.	RU price: 292(2030) → 347(2035)→ 363(2040) → 367(2045) → 378(2050) Applied to deficits relative to the GFI target.	Levy: 142(2030) → 195(2035) → 286(2040) → 187(2045) → 102(2050) Uniform price on emissions (zero baseline).
SU incentives	SU price assumed at Tier 2 RU price (380 USD/tCO_2e)	SU price assumed at the RU price	–
ZNZ rewards (for e-fuels)	As in Table 11	Same as IMO NZF	–

Notes. "–" denotes the instrument is absent in that setup.