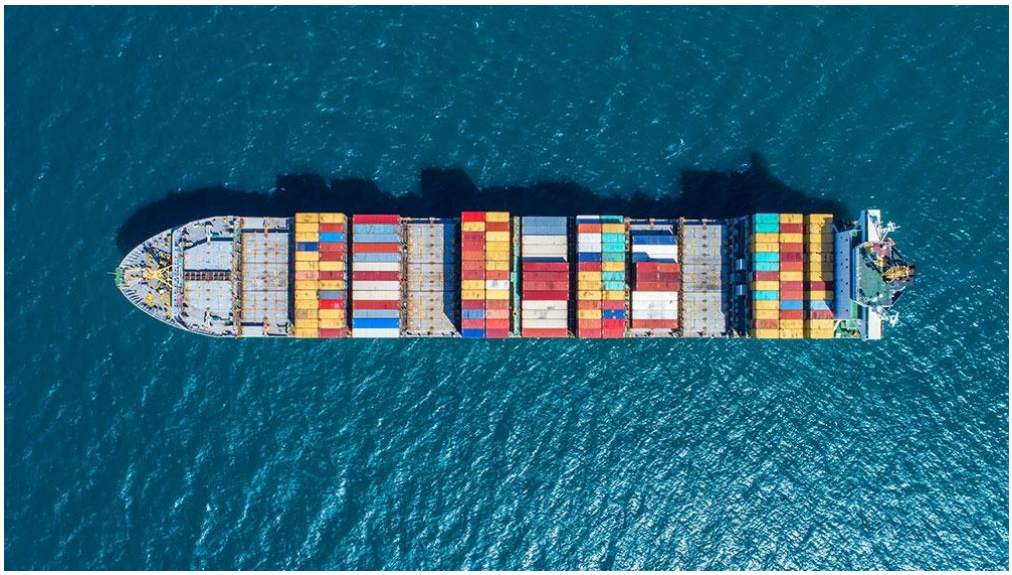
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Implications of the IMO Net-Zero Framework on Greek Shipping and Economy



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A study performed
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Abbreviations

APV	Agrophotovoltaics
ATR	Auto-thermal reforming
CAPEX	Capital Expenditure
CCUS	Carbon Capture, Utilization, and Storage
DF	Dual Fuel
DWT	Deadweight Tonnage
EC_{50}	Effective Concentration, 50% (concentration of a chemical that causes a specific biological effect in 50% of test organisms)
EPA	Environmental Protection Agency
ERPG	Emergency Response Planning Guidelines
ETS	EU Emissions Trading Scheme
EU	European Union
FID	Final Investment Decision
FLL	Fuel Lifecycle Label
FPSO	Floating Production Storage and Offloading vessel
FSU	Floating Storage Unit
GDP	Gross Domestic Product
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GFI	Greenhouse gas Fuel Intensity
GHG	Greenhouse Gas
GT	Gross Tonnage
GVA	Gross Value Added
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HSHFO	High Sulphur Heavy Fuel Oil
ICCT	International Council for Clean Transportation
IDLH	Immediately Dangerous to Life or Health
IEA	International Energy Agency
ILUC	Indirect land-use change
IMO	International Maritime Organization
ISM	International Safety Management
LCA	Life Cycle Assessment
LC_{50}	Lethal concentration, 50% (in air or water kills 50% of test organisms)
LD_{50}	Lethal dose, 50% (amount of substance that would kill 50% of test animals)
LNG	Liquified Natural Gas
MEPC	IMO's Marine Environment Protection Committee
MGO	Marine Gasoil
NZF	Net-Zero Framework
O&M	Operation and Maintenance
OCCS	Onboard Carbon Capture and Storage
PEM	Proton Exchange Membrane
PRL-MF	Port Readiness Level for Marine Fuels
PSC	Port State Control
PtM	Power-to-Methane
PV	Photovoltaics
RES	Renewable energy sources
RFNBO	Renewable Fuel of Non-Biological Origin
RNG	Renewable natural gas
RU	Remedial Unit
SFCS	Sustainable Fuels Certification Scheme
SME	Small and Medium-sized enterprise
SMR	Steam methane reforming
SNG	Synthetic natural gas
SU	Surplus Unit
TEU	Twenty-Foot Equivalent Unit
UGS	Union of Greek Shipowners
UNCTAD	United Nations Conference on Trade and Development
VLSFO	Very Low Sulphur Fuel Oil
ZNZ	Zero or Near-Zero greenhouse gas emissions fuels

Extended Summary

This report examines the implications of the proposed IMO Net-Zero Framework (NZF) for Greek shipping and the Greek economy, within the broader context of global maritime decarbonization. Greek-controlled shipping represents a structurally critical component of global trade and European energy security, accounting for a disproportionate share of the world's tanker, LNG, and bulk carrier capacity, ranging between 20-30%, relative to Greece's domestic economic size of 0.2% globally. The sector contributes materially to Greek GDP, directly via employment, foreign-exchange inflows, and maritime cluster development, as well as indirectly through regional spending and investments, while also serving as a stabilizing force during periods of macroeconomic stress.

Against this backdrop, the NZF proposes a legally binding global greenhouse gas (GHG) fuel-intensity (GFI) standard combined with an economic compliance mechanism based on remedial and surplus units. Although perceivably technology-neutral, the framework would effectively restrict incentives to only a narrow range of GHG intensities, expectedly achieved by emerging Zero- or Near-Zero (ZNZ) fuels – namely synthetic ammonia, methane and methanol, or green hydrogen – failing to support existing alternative fuels. At present, in addition to not having been fully assessed on their effectiveness, none of these fuels is available at the scale, cost, or geographic coverage required to support the existing international fleet.

Our analysis demonstrates a structural mismatch between the NZF's GFI reduction trajectory and the industrial readiness of alternative fuels. Global production of ZNZ-compliant fuels remains below one percent of shipping's annual energy demand, while scaling pathways are constrained by renewable electricity availability, electrolyzer capacity, permitting timelines, and capital intensity. Even under optimistic scenarios, meaningful supply expansion is unlikely before the mid- to late-2030s.

From an environmental systems perspective, the report finds that the production of green marine fuels is highly energy-intensive and results in significant efficiency losses. The same unit of renewable electricity achieves substantially greater CO_2 abatement when deployed directly in land-based electrification, particularly in road transport, than when routed through synthetic fuel pathways for shipping. This raises fundamental questions regarding optimal allocation of scarce renewable resources.

Economically, compliance with the NZF is shown to impose costs that, for certain vessel types, exceed the residual market value of the ships themselves, while the resulting incentives would favor payment of compliance penalties over investment in fuel conversion, especially under conditions of uncertain fuel availability and unclear reward mechanisms. The projected scale of the IMO Net-Zero Fund further introduces governance, transparency, and distributional concerns, particularly given the absence of defined rules for revenue allocation and safeguards against market distortion.

The report concludes that, while the objective of maritime decarbonization is broadly supported, the NZF in its current form risks imposing significant economic burdens on the industry, and disproportionally impacting shipping-dependent economies such as Greece, with limited near-term environmental benefit. The findings underscore the need for a more phased, technology-inclusive, and system-aware regulatory approach.

1. Impact of Greek-Owned and Greek-Operated Fleets

Greece, despite representing less than 0.5% of Global GDP, has been consistently holding a leading position in global maritime transport. Greek shipowners control the world's largest merchant fleet in terms of deadweight tonnage (DWT), over 16%, well ahead of other major maritime nations such as China and Japan[1,2]. The global reach of Greek-owned fleets also plays a decisive role in European energy security. This highlights the fleet's strategic importance not only to Greece but to the broader European geopolitical and energy landscape. This disproportionate influence reflects centuries of maritime tradition, entrepreneurial risk-taking, and adaptive business models that have allowed Greek shipowners to thrive in volatile global markets.

The sector's influence is not only economic but also deeply social, shaping employment, regional development, and Greece's international standing. Thus, as the International Maritime Organization (IMO) has prepared to adopt the Net-Zero Framework (NZF), understanding the foundational role of Greek shipping is essential for assessing the direct and broader implications of decarbonization policies.

1.1. Contribution to the Greek Economy

1.1.1. Direct and Indirect GDP Impact

Shipping is the strongest contributor to Greece's gross value added as compared to all other EU Member States. While the EU average is just 0.2%, shipping represents 3.1% of Greece's GVA, highlighting its disproportionately large role in the national economy [IOBE]. According to recent studies, the sector generates around $40 billion in annual gross revenues, with a domestic value contribution of approximately $14 billion per year. This accounts for about 7.9% of Greece's GDP, a figure that far exceeds the EU average for maritime nations, with scope to grow by an additional 20–30% ($3–4 billion per year) should structural improvements be realized[3]. This reflects not only direct operational activity, but also the strong interlinkages between shipping and other sectors such as land transport, real estate, financial services, energy, and construction. Maritime capital has historically fueled investments in aviation, oil refining, banking, and tourism, further amplifying its economic significance.

Numbers

While the EU average is just 0.2%, shipping represents **3.1% of Greece's GVA**.

Shipping contributes **7.9% of Greek GDP**, or about **$14 billion annually.**

Sector's annual turnover in Greece is estimated at **$40–50 billion**, and scope to **increase by 20–30%** in coming years.

Greece's largest source of export revenue, with over **$148 billion received** from maritime transport abroad in the last decade, equivalent to **42% of the general government's gross debt**.

[1] UNCTAD 2025 Review of Maritime Transport: Staying the course in turbulent waters.
[2] Foundation for Economic and Industrial Research (IOBE), Contribution of shipping to the Greek economy. Challenges and outlook, 2023. link
[3] D. Martinis, E. Koulouridi, M. Pacca, A. Chalofti, A. Zampelas, Greek shipping: Success factors and opportunities, 2024, link

Shipping receipts have consistently helped offset Greece's chronic trade deficits, serving as a stabilizing force during crises. For example, during the 2008 global financial downturn, shipping revenues fell sharply, but the sector maintained its global ranking and remained a critical source of foreign exchange[4].

1.1.2. Employment

Shipping directly supports 60,000 jobs in Greece, along with an additional 90,000 jobs in related sectors, for a total domestic employment footprint of about 150,000 jobs according to McKinsey[3,5]. These figures primarily reflect direct employment and closely linked onshore activities across vessel operations, port logistics, ship management, finance, insurance, and legal services. When indirect and induced effects are taken into account and employment is measured in full-time equivalents, the contribution is estimated at approximately 86,300 jobs annually, based on analysis by the Foundation for Economic and Industrial Research[2]. Seafarer employment also remains crucial, with roughly 45,900 jobs in waterborne transport. Shipping thus sustains not only economic activity but also cultural, educational, and social initiatives, reinforcing its role as a pillar of the Greek civil society.

1.2. Structural and Strategic Importance

1.2.1. Global Trade and Energy Security

Greek-owned fleets play a decisive role in securing Europe's energy needs and sustaining its wider trade flows. According to McKinsey[5], 30% of all LNG imported into Europe by sea in 2023 was transported by Greek-owned LNG carriers, while 40% of the continent's crude oil imports relied on Greek tankers. This makes the Greek fleet indispensable to Europe's energy security and diversification strategy following the decline of Russian pipeline gas, as well as to the uninterrupted flow of oil from global suppliers. With one of the world's largest and most technologically advanced groups of LNG carriers and tankers, Greek shipping ensures that Europe can access alternative energy sources quickly and reliably during times of heightened geopolitical tension.

Numbers

In Greece, the sector directly supports **60,000 jobs** and indirectly another **90,000 jobs** in related industries.

More than **200,000 foreign individuals** are employed on Greek-owned vessels globally.

Measured in full-time equivalents, **86,300 full-time jobs** in Greece are linked to shipping, with significant multiplier effects in logistics, finance, energy, and construction.

In 2023, **40% of Europe's crude oil imports** and **30% of LNG imports by sea** were carried by Greek-owned vessels.

Greece controls the world's **largest tanker and LNG fleets**, and the **second-largest dry bulk fleet**.

Greek shipowners reinvest about **$1.4 billion annually** into other domestic sectors (real estate, tourism, energy, sports) and contribute around **$400 million annually** in philanthropy.

[4] Bragoudakis, Z., Panagiotou, S. Thanopoulou, H. (2015). Greek Shipping Receipts Revisited: A Freight Market and Country Risk Perspective. SSRN Electronic Journal. doi

[5] Lloyd's List, McKinsey report underlines massive role of Greek shipping home and abroad, 2025, link

Beyond energy, Greek-owned ships underpin Europe's broader trade system by transporting the raw materials, industrial inputs, and containerized goods on which European manufacturing and consumption depend. Greece controls the world's largest bulk carrier fleet (24.9% of global share, as per UGS[6]), which carries essential commodities such as iron ore, coal, and grains across European ports, sustaining the continent's industrial base and food security. Even when flying non-EU flags, these vessels are managed largely from Greece, meaning that their operations, investment decisions, and compliance frameworks remain closely tied to European regulatory and economic structures. In effect, Greek-owned fleets operate as a strategic maritime asset for Europe, providing resilience, flexibility, and capacity that the continent would not otherwise possess.

Taken together, the scale of the Greek-owned fleet and its centrality to Europe's supply chains mean that the continent's economic stability and energy security depend significantly on Greek maritime capacity. During recent global disruptions, Greek shipowners rapidly redirected vessels to new energy routes and expanded LNG transport, helping Europe avoid severe shortages and price shocks. Their agility, investment in modern vessels, and long-standing dominance in key shipping segments make Greek shipping one of the quiet but indispensable pillars of Europe's geopolitical and economic resilience.

1.2.2. Investment Cycles and Fleet Modernization

Historically, Greek shipowners have been known for their shrewd counter-cyclical investment strategies, acquiring vessels during market downturns to capitalize on future recoveries[7,8,9]. However, the period between 2006 and 2008 marked a notable departure from this traditional approach, with unprecedented number of orders for new vessels. This surge in investment was fueled by a unique confluence of factors, including the global economic boom, blooming trade (especially driven by China), and exceptionally high freight rates, which created an impression of a sustained period of market prosperity. Readily available and low-cost credit during this period also facilitated this massive expansion.

This investment strategy, though initially propelled by market optimism, ultimately exposed the sector to significant cash-flow pressures when the global financial crisis in late 2008 caused a sudden and sharp collapse in freight rates. Nevertheless, this aggressive fleet renewal had a modernizing effect, reducing the average age of Greek-owned vessels to 14.2

[6] Union of Greek Shipowners (UGS), Annual Report 2024-2025. link
[7] Z. Bragoudakis, S. Panagiotou, H. Thanopoulou. (2013). Investment Strategy and Greek Shipping Earnings: Exploring the Pre & Post 'Ordering-Frenzy' Period. SSRN Electronic Journal. 157. 1-36. link
[8] Helen A. Thanopoulou (1996). Anticyclical Investment Strategies in Shipping — The Greek Case. In: David Hensher, Jenny King, Tae Hoon Oum (eds.), World Transport Research: Proceedings of the 7th World Conference on Transport Research, Vol. 4, pp. 209–220. Oxford: Elsevier Pergamon.
[9] Z. Bragoudakis, St. Panagiotou, H. Thanopoulou. (2015). Greek Shipping Earnings and Investment Expenditure: Exploring the Pre & Post "Ordering-Frenzy" Period. Journal of Economics and Business. 65. 3-28. link

years, well below the world average of 18.5 years, and enhancing their long-term competitiveness[10,11]. This capacity to adapt and enhance their fleets – already reflected in sustained investment in energy-efficiency improvements and carbon-intensity reduction measures, often undertaken ahead of regulatory requirements and across unconventional investment cycles – underscores the entrepreneurial resilience of Greek shipping families and their ability to navigate volatile market conditions while maintaining a dominant position in global shipping.

Numbers

The average age of the Greek controlled fleet in terms of ships now stands at **14.2 years**, in comparison to 18.5 years for the world fleet.

The Port of Piraeus is the **largest in the Eastern Mediterranean**. It ranked **4th among European container ports and 29th in the world in 2023**.

Piraeus container throughput grew from **2 million TEUs in 2010 to nearly 6 million TEUs in 2022**.

1.2.3. Fleet composition and tramp-market exposure

A defining structural feature of Greek-controlled shipping is its predominant exposure to bulk/tramp markets (dry bulk, tankers, LNG/LPG), rather than liner shipping (Table 1). The Union of Greek Shipowners (UGS)[6] characterizes Greek shipping as "predominantly engaged in the bulk/tramp sector," which is itinerant in nature and operates through a highly competitive, globally dynamic trading pattern.

*Table 1: Composition of the Greek-Controlled Fleet by Vessel Type and Typical Market Exposure[6] - The table **DOES NOT IMPLY** uniform chartering arrangements within each segment but highlights the dominant market structures that shape operational flexibility, fuel procurement, and cost-recovery mechanisms.*

Vessel segment	Global Share of Greek-controlled fleet (DWT,%)	Typical market structure	Relevance for decarbonization analysis
Bulk carriers	24.9%	Tramp (spot / time charter)	High exposure to freight cyclicality; limited and market-dependent cost pass-through
Oil tankers	29.2%	Tramp (spot / time charter)	Fuel and compliance cost allocation depends on charterparty form
Chemical and product tankers	15.4%	Tramp / semi-industrial	Greater technical constraints; cost recovery varies by contract
Gas carriers (LNG)	24.5%	Tramp / project-based	Route and terminal specificity; fuel choice constrained by nature
Gas carriers (LPG)	11%	Tramp	Exposure to fuel availability and charterer fuel clauses
Container ships	8.1%	Liner (scheduled services)	Higher ability to internalise compliance via surcharges and service contracts
Vehicles Carriers	8.2%	Liner / semi-liner	Partial cost pass-through; dependent on long-term contracts

[10] Eurobank Ergasias S.A., Economic Analysis Division. (2014, May). The Greek maritime transport industry and its influence on the Greek economy (Economy & Markets Research Paper). link

[11] Greek Shipping Co-Operation Committee, Greek Controlled Shipping: An informative report based on data provided by S&P Global Market Intelligence, link

This distinction is material for decarbonization strategy under emerging measures (including fuel-intensity standards and market-based mechanisms), because the cost pass-through, fuel-procurement control, and compliance optimization levers differ by market structure. In liner trades, compliance surcharges and green-fuel premiums can more readily be incorporated into freight-rate systems and longer-term service contracts, supported by networked bunkering strategies. By contrast, tramp segments face more fragmented and cyclical freight markets, higher volatility in chartering structures, and operational itinerancy that makes access to compliant fuels dependent on geographically uneven port readiness.

At the macro trade level, UGS also notes that bulk/tramp shipping accounts for almost 85% of global transport work (ton-miles), underscoring why decarbonization feasibility and compliance economics for Greece are tightly linked to tramp-sector realities.

Accordingly, the Greek fleet's tramp orientation is a crucial lens for assessing both the capacity for leveraging emerging scarce compliant fuels, and the restrictions in distribution of compliance costs between owners, charterers, and cargo interests across segments.

1.3. Regional and Social Impact

Greek shipping functions not only as an economic powerhouse but also as a deeply embedded social and cultural institution whose influence extends across sectors of Greek society. According to the IOBE study[2], maritime capital has historically financed the development of aviation, oil refining, banking, and tourism, demonstrating how wealth generated from shipping has been reinvested to shape multiple pillars of the modern Greek economy. These investments often fill structural gaps in national development, enabling industries to flourish in ways that would have been difficult without maritime support. In this sense, shipping serves as both a driver of economic diversification and a stabilizing force within Greece's broader productive system.

Philanthropy is another dimension through which Greek shipping exerts a profound social impact. Shipowners have long funded hospitals, universities, cultural institutions, and civil-society organizations, making the maritime community a major contributor to social welfare. McKinsey[5] emphasizes that Greek shipowners contribute approximately $400 million annually in social support initiatives, much of it routed through charitable foundations that focus on education, healthcare, and community development. This sustained philanthropic tradition strengthens social cohesion and helps compensate for public-sector limitations, particularly during crises such as the debt and pandemic years.

Greek shipping culture is also characterized by a unique blend of tradition, family ownership, and entrepreneurial agility. Many of the world's leading shipping companies remain family-operated, with direct involvement of owners in strategic decisions—a structure that McKinsey identifies as a source of resilience and adaptability in a volatile global market. This tradition supports long-term thinking, rapid decision-making, and a strong sense of corporate identity

rooted in maritime heritage. It also explains why Greek shipowners continue to reinvest heavily in Greece—around $1.4 billion annually—in sectors such as real estate, tourism, sports, and energy, creating positive spillovers across society and the domestic economy.

1.3.1. Support for Island Communities

The IMO Net-Zero Framework applies exclusively to ships of 5,000 gross tonnage and above engaged in international voyages, thereby limiting its regulatory scope to oceangoing shipping[12]. As a result, inland and purely domestic coastal shipping fall outside the direct applicability of the framework. Nevertheless, these segments are retained in this report, as the present section examines the aggregate economic and social impact of shipping on Greece, for which domestic maritime transport constitutes an integral and non-separable component.

Passenger and short-sea shipping play a vital role in sustaining Greece's island regions, which depend on maritime links for the movement of residents, goods, and tourists. The IOBE report[13], underscores that passenger shipping is essential not merely as a mode of transport but as a lifeline that guarantees year-round access to employment, healthcare, education, and public services for communities scattered across the Aegean and Ionian Seas. Statistics from 2014[13] show coastal shipping contributing an estimated **€11.8 billion** (combining the direct, indirect and induced benefits from the demand for coastal services in the domestic routes along with the catalytic effects), or **6.5% of Greece's GDP**, and supporting about **260,000 jobs**, with approximately half of the total employment in island regions tied to this sector. Without these connections, many islands – especially small or remote ones – would face severe social and economic isolation.

The economic viability of island communities is closely tied to the reliability and frequency of maritime services. Tourism, which is the principal economic driver for many islands, depends on efficient short-sea connections that can accommodate seasonal peaks while also supporting local businesses during the off-season. Maritime transport facilitates the flow of goods such as food supplies, fuel, medical equipment, and construction materials, ensuring the functioning of local economies. In this way, shipping becomes not only a transport service but a structural component of regional equity, linking the periphery to the national core.

Moreover, the role of short-sea shipping extends beyond economics by reinforcing the social fabric of island life. It enables family connectivity, supports cultural and social events, and ensures that residents can travel for essential services not available locally. This continuity is particularly valuable during emergencies or adverse weather conditions, where maritime operators often maintain routes at substantial operational cost. Thus, Greek passenger and

[12] The IMO Net-Zero Framework – FAQs, link
[13] Foundation for Economic and Industrial Research (IOBE), The contribution of coastal shipping to the Greek economy: Performance and outlook, 2014, link

short-sea shipping provide a form of territorial cohesion that is indispensable for the survival and development of island regions.

1.3.2. Development of Maritime Clusters

Greek shipping sustains a dense network of maritime-related activities that together form one of Europe's most significant maritime clusters. This cluster includes port operations, shipbuilding and repair facilities, maritime equipment manufacturing, bunkering, logistics, and a broad range of business services—such as banking, insurance, legal, and accounting—that support shipping companies. IOBE[2] highlights that maritime transport, along with these related sectors, constitutes a "vital network of activities" with major contributions to domestic income generation and employment. Shipping therefore functions as an anchor industry that stimulates growth across multiple complementary fields.

The city of Piraeus (and a few Athens suburbs) serves as the epicenter of this cluster, acting as an international hub for maritime service provision. The Port of Piraeus is the largest in the Eastern Mediterranean and ranked 4th among European container ports in 2023, with container throughput rapidly expanding from 2 million TEUs in 2010 to nearly 6 million TEUs in 2022[14,15,16]. The concentration of ship management companies, classification societies, brokers, insurers, legal firms, and logistics providers creates strong agglomeration effects that enhance efficiency and innovation. This ecosystem attracts international talent and investment, reinforcing Greece's position as a global maritime center. McKinsey[5] notes that expanding this maritime services cluster is one of the key strategic opportunities for increasing shipping's economic footprint by up to 30% in the coming years.

Beyond economic output, maritime clusters contribute to technological advancement and workforce development. Shipyards and repair facilities support innovation in green technologies, digital systems, and energy-efficient vessel designs, aligning Greek shipping with global decarbonization goals. Maritime academies, training centers, and research institutions also benefit from the proximity to industry, creating a feedback loop that strengthens the maritime knowledge base. In this broader sense, the cluster effect not only drives local growth but also reinforces Greece's global competitiveness in the shipping sector.

[14] Greek Travel Pages, Piraeus Rises to 4th Position on Europe's Top Container Ports List, 30/8/2024, link
[15] David Glass, Piraeus rises to 4th largest container port in Europe, Seatrade Maritime News, link , 4/9/2024
[16] Nassos Perrotis, 2022 Global Seaport Review: Piraeus, Greece, CBRE 2022, link

2. The IMO Net Zero Framework (NZF)

The International Maritime Organization (IMO) Net-Zero Framework (NZF) was proposed in support of the IMO 2023 GHG Strategy, aiming at achieving net-zero greenhouse gas (GHG) emissions from international shipping by or around 2050. The Net-Zero Framework, for the first time, would set a legally binding requirement under combined technical and economic measures, including a greenhouse gas fuel intensity standard and a pricing mechanism, under a new Chapter 5 of Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL) [17,18,19,20].

2.1. Scope and Applicability

The NZF applies to all ships of 5,000 gross tonnage (GT) or above engaged in international trade, regardless of flag. This broad scope was selected to cover approximately 85% of total CO_2 emissions from international shipping[17]. Exemptions are provided for non-self-propelled ships, platforms such as FPSOs, FSUs, and drilling rigs, as well as certain vessels operating exclusively on domestic routes[18,19]. Notably, the NZF is not limited to cargo or passenger vessels, but also encompasses offshore and dredging vessels, thereby extending beyond the scope of comparable regional regulations such as FuelEU Maritime[19].

The framework covers all major greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), with emissions measured in CO_2-equivalents (CO_2e) [19]. The NZF was expectedly designed to focus on performance outcomes rather than prescribing specific fuels or technologies[18]. This approach intended to allow for flexibility and innovation, with the aim of enabling shipowners to select the most suitable compliance strategies for their fleets.

2.2. GHG Fuel Intensity (GFI) Requirements

The NZF sets requirements for ships to reduce their annual greenhouse gas fuel intensity (GFI). The GFI is calculated as grams of CO_2-equivalent per megajoule (gCO_2eq/MJ) of energy used, based on a well-to-wake approach (see Section 5). This methodology accounts for emissions across the entire lifecycle of marine fuels, from extraction and processing to delivery and combustion onboard[19,21]. The NZF establishes two compliance targets for GFI: the Base Target (89.57 $gCO_{2eq.}/MJ$ for 2028), which represents a higher threshold, and the Direct Compliance Target (77.44 $gCO_{2eq.}/MJ$ for 2028), which is more stringent[22]. These targets were set to

[17] IMO approves net-zero regulations for global shipping, April 2025, link
[18] DNV: Overview of IMO's Net-ZeroFramework, link
[19] Gorrissen Federspiel, FuelIMO? The IMO approves a historic Net Zero Framework, 2025, link
[20] Countdown: How the IMO Process Works for the NZF, link
[21] UMAS/UCL, IMO's new Net Zero Framework: Assessing the potential options and costs of compliance, 2025, link
[22] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Countdown: How IMO NZF Compliance Works in Practice, October 2025, link

become progressively more demanding over time, with **annual reduction factors through 2035** and a **65% reduction for Base Target required by 2040** [18,21]. The framework provided that **the targets for the period 2036–2040 would be reviewed and set by 2032**, to align the regulatory trajectory with technological advancements and climate objectives. In parallel, the NZF defines specific thresholds for **zero or near-zero (ZNZ) GHG fuels, set at a GFI not greater than 19 gCO_2eq/MJ until 2034 and 14 gCO_2eq/MJ or less thereafter**. By limiting eligibility for financial rewards exclusively to fuels meeting these highly stringent lifecycle thresholds, the framework **effectively confines incentives to a very narrow subset of green synthetic fuels**. As demonstrated in subsequent chapters of this report, these progressively stringent GFI limits are introduced in a context where fuels capable of meeting the NZF thresholds do not yet exist at commercial scale, creating a structural gap between regulatory ambition and actual fuel availability.

The GFI metric also includes energy delivered to the ship from external sources, such as shore power, as well as wind and solar propulsion. Ships will be required to develop or update their data collection and reporting plans to include all necessary elements for GFI calculation. These plans must be verified and kept onboard, together with a Confirmation of Compliance, prior to the start of the first reporting period [18].

2.3. Compliance Mechanism: Units and Economic Measures

Compliance with the NZF is expected to be assessed on an annual basis. Ships with GFI exceeding the targets must acquire Remedial Units (RUs) to balance their emissions. Tier 1 RUs, priced at $100 per ton of CO_2eq, cover emissions between the Direct Compliance and Base Targets, while Tier 2 RUs, at $380 per ton, address emissions above the Base Target [18,19,21]. The acquisition of RUs is effected through monetary contributions to the IMO Net-Zero Fund, as per above initial unit prices set for the period 2028 – 2030, to be determined for 2031 onward by 1 January 2028. Conversely, ships that achieve a GFI below the Direct Compliance Target would be awarded Surplus Units (SUs), which serve as a positive compliance incentive. SUs will have the options to be banked for **up to two years**, transferred once to another vessel to offset a Tier 2 deficit, or cancelled as voluntary mitigation [18,19].

The NZF's unit system design is intended to provide both flexibility and accountability. In this frame, RUs would be non-transferable, and SUs would not be freely tradable commodities; their transfer being restricted to a single transaction between vessels [19]. These restrictions on SUs appear designed to reduce the scope for a speculative secondary market and to keep unit use closely tied to ship-level compliance needs. However, because SUs are generated from verified GFI performance, limiting their transferability and validity can also reduce their expected economic value and therefore weaken the incentive to invest in low-carbon fuels, unless the reward mechanism and SU utilization potential are sufficiently predictable and durable. The compliance balance for each ship is to be determined annually, and all transactions to be recorded in the IMO GFI Registry [18].

2.4. Economic Modeling and Compliance Strategies

Recent techno-economic and lifecycle assessments of alternative marine fuels consistently present a heterogeneous transition landscape, in which candidate fuels differ markedly in technological readiness, lifecycle greenhouse-gas performance, infrastructure requirements, safety profiles, and cost trajectories[23,24]. Comparative studies covering LNG, methanol, ammonia, hydrogen, biofuels, and synthetic e-fuels indicate that, while several options can reduce specific air pollutants and, under tightly defined production pathways, well-to-wake greenhouse-gas emissions relative to conventional fuels, none currently combines NZF-compliant GFI performance with widespread commercial availability, mature global bunkering infrastructure, and cost competitiveness.

In this context, a joint analysis by UMAS and the UCL Energy Institute[21] concludes that, particularly in the early years of NZF implementation, many conventional ships are likely to find it economically preferable to comply through the purchase of Remedial Units (RUs) rather than switching to low-carbon fuels, given prevailing fuel price differentials, limited supply of compliant fuels, and the capital expenditures associated with fuel conversion. While that analysis identifies ammonia-based pathways as potentially competitive under specific long-term scenarios, broader literature on alternative fuels highlights substantial sensitivities to assumptions regarding fuel production scale-up, upstream energy costs, non-CO_2 emissions, safety constraints, and infrastructure deployment[25,26,27,28].

Economic feasibility studies presented by the Korean Register[29], incorporating shipyard data and calculations, further reinforce this assessment by showing that the cost of e-fuels remains sufficiently high that, even after application of NZF penalties, synthetic fuels remain the most expensive compliance options on a total cost basis. When the capital costs of dual-fuel newbuildings or retrofits are also accounted for, these analyses indicate that even LNG dual-fuel solutions fail to achieve cost-efficient payback within commercially acceptable time horizons. As demonstrated in subsequent chapters on fuel availability, infrastructure readiness, and economic impact, this body of evidence points to a structural misalignment between the stringency of NZF GFI targets and the current technological, economic, and industrial readiness of alternative marine fuel pathways.

[23] Roux, M., Lodato, C., Laurent, A., & Astrup, T. F. (2024). A review of life cycle assessment studies of maritime fuels: Critical insights, gaps, and recommendations. *Sustainable Production and Consumption*, *50*, 69-86. doi
[24] W Zhang, J Wang, G Qin, S Kuntal, F Gong, R Yan, Review of the state-of-the-art of alternative marine fuels: A viable approach to zero-carbon shipping, Cleaner Logistics and Supply Chain, 16 (2025), 100232, doi
[25] Global Maritime Forum, Zero-emission shipping fuels: A guide to methanol and ammonia, August 2025, link
[26] Britannia P&I club, Alternative Fuels Update – April 2025, link
[27] I. Carlsson, World's first commercial-scale e-methanol plant opens in Denmark, Reuters, May 2025, link
[28] German Environment Agency (Umwelt Bundesamt), In-depth analysis 3: Lifecycle emissions of future fuels, June 2023, link
[29] Korean Register Presentations, KR Technical Seminar in Greece, 24 September 2025, Athens.

2.5. IMO Net-Zero Fund

A central and integral component of the NZF is the IMO Net-Zero Fund. The Fund would collect revenues from the purchase of Remedial Units (RUs), intended to underpin the framework's economic logic by financing rewards, support mechanisms, and mitigation measures, which has been challenged by some Member States as an "unsanctioned global tax regime" and an institutional overreach, i.e., extending IMO action beyond technical regulation into revenue-raising and redistribution[30]. Regardless, its design and calibration – particularly with respect to the effectiveness of reward mechanisms – have also emerged as a source of concern. The Fund's proceeds would be allocated to several key objectives: rewarding ships that utilize zero or near-zero (ZNZ) greenhouse gas technologies, supporting innovation, research, and infrastructure in developing countries, funding training and technology transfer, and mitigating negative impacts on vulnerable states such as Small Island Developing States and Least Developed Countries[17,18]. The criteria for rewards and the allocation of funds is not defined under the IMO NZF text, subject to guidelines under development, with periodic reviews to align with evolving industry needs and technological advancements.

The methodology for determining these rewards, as well as the percentage of the Fund allocated to them, were also to be specified under guidelines developed by 2027 and reviewed every five years. All the above are depicted in Figure 1, by the Global Centre for Maritime Decarbonisation, and presented in Table 2.

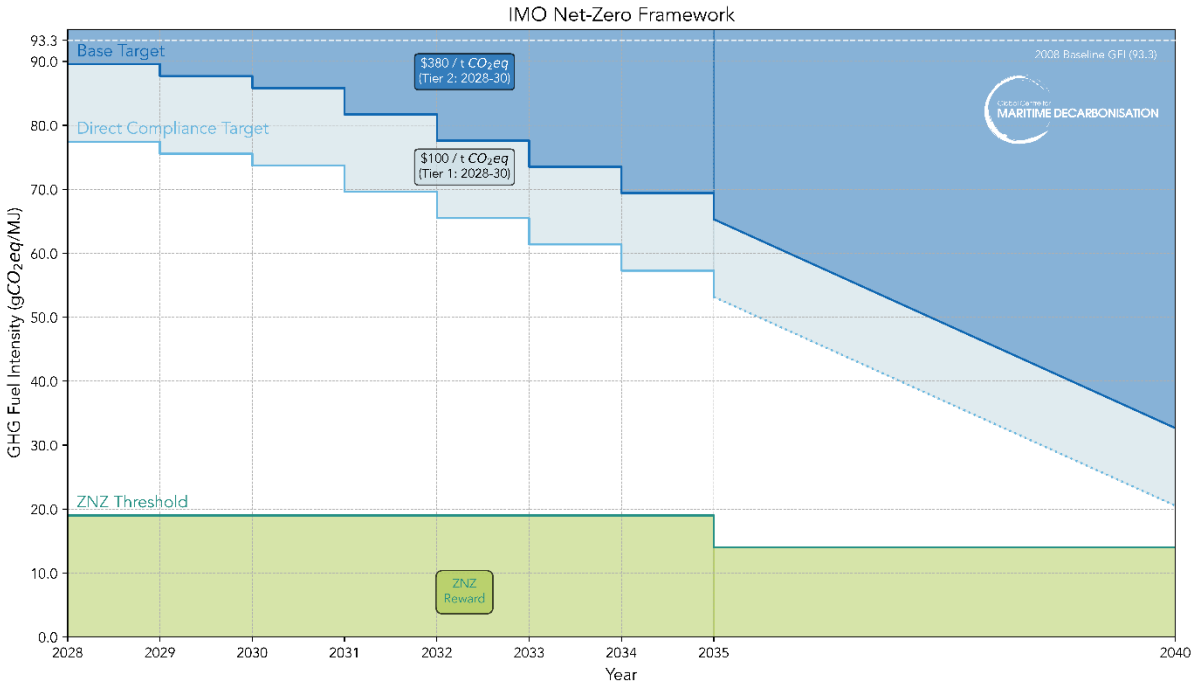


Figure 1: Graphical Representation of the IMO Two Tier Target GFI Mechanism (Source: Global Centre for Maritime Decarbonisation)[31]

[30] Ifchor Galbraiths, Net-Zero Framework adoption postponed: what next? (28/02/2026), link

[31] Global Centre for Maritime Decarbonisation, IMO MEPC 83 - Two-tier GFI-linked pricing system - Cost and compliance calculator, link

2.5.1. Reward Mechanism Design

UMAS provides a detailed analysis of alternative reward structures (e.g., based on abatement cost or total cost of ownership, TCO, spreads) and their implications for the competitiveness of e-fuels, biofuels, and other options. The report **highlights the risk that, unless rewards are carefully calibrated and sufficiently funded, the NZF may not provide a strong enough signal for long-term investment in scalable, sustainable fuels** [21].

Table 2: GFI Compliance Targets 2028-2035

Reference Value: 93.300 g CO_2eq/MJ				
Year	**Reduction Percentage (%)**		**Actual Value (g CO_2eq/MJ)**	
	Base Target	Direct Target	**Base Target**	**Direct Target**
2028	4.0	17.0	**89.568**	**77.439**
2029	6.0	19.0	**87.702**	**75.573**
2030	8.0	21.0	**85.836**	**73.707**
2031	12.4	25.4	**81.731**	**69.602**
2032	16.8	29.8	**77.626**	**65.497**
2033	21.2	34.2	**73.520**	**61.391**
2034	25.6	38.6	**69.415**	**57.286**
2035	30.0	43.0	**65.310**	**53.181**

2.6. Data Collection, Verification, and Certification

Data collection, verification, and certification processes are integral to the effective implementation of the NZF. Ships will be required to report their attained GFI and compliance balance annually, with verification conducted by independent entities such as classification societies. The IMO GFI Registry will serve as the central repository for all compliance data and transactions. The reporting and verification cycle is strictly defined: data must be reported by 31 March, verified by 30 June, compliance actions executed by 31 July, account statements issued by 31 August, and Statements of Compliance provided by 30 September.

The GFI and sustainability attributes of fuels must be certified by a Sustainable Fuels Certification Scheme (SFCS) recognized by the IMO, also subject to guidelines being developed. Certification is documented on a Fuel Lifecycle Label (FLL), which accompanies the Bunker Delivery Note. The SFCS must be approved by the IMO's Marine Environment Protection Committee (MEPC), and a list of recognized schemes will be published and updated regularly. The certification process is designed to ensure transparency, traceability, and environmental integrity, aligning with international standards such as the EU Renewable Energy Directive [18,19].

2.7. Responsibilities and the Polluter Pays Principle

Responsibility for compliance and monetary contributions lies with the ISM company, which may be the ship manager or bareboat charterer[19,32]. The NZF does not prejudge on contractual allocation of compliance costs to the party exercising operational control, such as the time charterer. This is in spirit intended equivalent with the polluter-pays principle as enshrined in EU regulations and EU Member State law. However, the framework does not establish an explicit or enforceable mechanism for cost recovery, nor does it impose an obligation on States or counterparties to ensure reimbursement, in contrast to the more prescriptive approach adopted under the EU ETS. As a result, the practical allocation of NZF-related costs is expected to give rise to contractual complexity and potential disputes, particularly where operational control and regulatory responsibility are not aligned. **This arrangement is expected to have significant implications for charterparties, management agreements, and fuel procurement contracts**, necessitating the development of new contractual clauses to allocate compliance costs and manage financial risks effectively[32].

The NZF's approach to responsibility and cost allocation intended to ensure that those who have operational control over fuel procurement, cargo, routing, and speed bear the associated compliance costs. This principle is consistent with EU law and intended to promote fairness and accountability throughout the maritime value chain [19].

2.7.1. Enforcement and Sanctions

Enforcement of the NZF will be primarily the responsibility of flag States, which issue Statements of Compliance. Port States may verify compliance, but again the specific enforcement powers and sanctions are to be clarified in future guidelines [19]. **The NZF does not currently specify detailed sanctions for non-compliance, and it was anticipated that these would be addressed in the implementation phase and through flag State enforcement**. While it is reasonable to assume that non-compliance with NZF requirements could result in withdrawal or suspension of the relevant compliance statement or other enforcement actions under MARPOL Annex VI and port State control (PSC) procedures once implemented, such outcomes will ultimately depend on how States incorporate and enforce NZF obligations in their national legislation and PSC frameworks. The framework's reliance on annual verification and certification processes, together with the central role of the IMO GFI Registry, intended to ensure a high level of compliance and transparency.

In practice, effective enforcement under IMO instruments is closely linked to the degree of Member State consensus and the consistency of domestic implementation. For a regulation of this scale, any material divergence in interpretation, resourcing, or political support can translate into uneven enforcement across flag and port States, which would risk regulatory fragmentation and, ultimately, erosion of the IMO's credibility as a uniform global standard-

[32] Business implications of the IMO Net-Zero Framework, link

setter. Accordingly, addressing the substantive concerns raised during deliberations and working toward broad consensus on both the regulatory text and implementing guidelines is critical to safeguarding enforceability and compliance integrity.

2.8. Remaining Work and Review

From the above, it can be seen that there is significant work to develop and agree on the necessary guidelines and operational details, subject to framework amendments before adoption and eventual entry into force[18,20]. Key areas currently requiring further development include the detailed methodology for GFI calculation (including the treatment of wind propulsion, electricity, and carbon capture), default emission factors for various fuels, certification requirements for sustainable fuels, LCA Guidelines, Guidelines for governing provisions of the IMO Net-Zero Fund, Crew Training guidelines and requirements, determining RU prices, and the methodology for rewarding the use of zero or near-zero GHG technologies. The NZF would be subject to periodic review every five years, with the possibility of amending reduction factors, thresholds for zero and near-zero technologies, and the scope of application to include smaller vessels (down to 400 GT).

In addition to technical finalization, achieving broad Member State consensus on the design and calibration of key elements will be important to support consistent flag-State and port-State enforcement and to reduce the risk of uneven application.

2.8.1. Uncertainties and Sensitivities

The UMAS report highlights that **many key details such as the final structure of ZNZ rewards, future RU/SU prices, and the precise definition of qualifying fuels/technologies, remain unresolved and will only be finalized in guidelines over the next few years**[21]. The report also notes that national/regional policies (e.g., EU ETS, FuelEU Maritime) may interact with or even compete against the IMO NZF, affecting global market dynamics.

2.9. Business and Contractual Implications

The NZF, if in force, is expected to have **far-reaching business and contractual implications for the shipping industry**. Compliance will increase operational, administrative, and financial costs, particularly in relation to the procurement of low-GHG fuels, investment in new technologies, and the management of compliance balances[21,32]. Shipping companies will need to develop data management systems, ensure continuous data verification, and establish clear contractual arrangements with charterers, managers, and fuel suppliers.

Commercial arrangements between shipowners, ISM companies, and charterers will need to address the allocation of compliance costs, the sharing of emissions data, and the settlement of compliance balances[32]. The inclusion of NZF-related clauses in charterparties, management

agreements, and fuel procurement contracts will be essential to manage financial risks and ensure clarity of responsibilities. The NZF's emphasis on reliable, third-party verified data and robust data-sharing architectures will be critical for both regulatory compliance and commercial settlements.

2.10. Evolution of the NZF Timeline and Geopolitical Implications[33]

The NZF was introduced as a new Chapter 5 under MARPOL Annex VI, receiving provisional approval at the IMO's Marine Environment Protection Committee (MEPC) in April 2025, with a formal adoption originally planned for October 2025. The framework was intended to enter into force in March 2027, with the first reporting period beginning in 2028. Alongside this, a suite of guidelines and technical provisions were being developed, following a schedule for adoption and revision.

Notwithstanding this procedural roadmap, the development and prospective adoption of the NZF have highlighted not only technical and economic challenges, but also broader governance and policy sensitivities associated with global maritime decarbonization. During the IMO deliberations preceding the scheduled adoption, several Member States expressed reservations concerning, inter alia, the governance and calibration of the Net-Zero Fund, the maturity and robustness of lifecycle assessment methodologies, the treatment of transitional fuels, and the availability of zero- or near-zero-emission fuels at commercial scale. Against this background, the decision to adjourn formal adoption reflected a broader lack of consensus regarding both the design and the timing of the framework, rather than opposition to the underlying objective of emissions reduction.

2.10.1. Risk of Unilateral Countermeasures, Loss of Consensus and Regulatory Fragmentation

A central risk arising from the NZF process is not limited to the possibility of unilateral retaliation. Rather, it is the potential damage to the IMO's credibility as a global standard-setter if adoption is pursued under a framework whose operational definition remains incomplete and whose effectiveness and distributional impacts remain contested. It has been already highlighted that key technical and governance components are still to be finalized through future guidelines (including elements of GFI calculation, default emission factors, certification and LCA-related provisions, Net-Zero Fund governance rules, and mechanisms influencing RU pricing and ZNZ rewards). In a regime of this scale, attempting to lock in binding obligations while material parameters remain unsettled increases the likelihood of divergent interpretation, uneven national implementation, and inconsistent enforcement across flag

[33] Eirik Nyhus, From expectations to delay: Updates on the work around IMO's Net-Zero Framework, DNV Maritime Impact – series 10, episode 1, link

and port States – outcomes that directly undermine the enforceability and compliance integrity of IMO instruments and increase the probability of regulatory fragmentation.

In that context, the position articulated by the United States should be treated as a significant credibility stress-test for the NZF rather than a peripheral geopolitical footnote. The U.S. administration has indicated that, should the NZF be ratified in its current or a similar form, it may consider unilateral countermeasures affecting maritime trade and compliance obligations for States supporting the framework[34,35,36]. These have been presented as potential responses rather than codified enforcement actions and include measures such as differentiated port treatment, additional port-related charges, changes to maritime crew visa requirements, commercial restrictions linked to U.S. government contracts and infrastructure projects, and broader trade-related actions[37,38,39,40,41]. Even if selectively applied, the mere prospect of such measures materially increases uncertainty and incentivises a patchwork of defensive national responses—precisely the opposite of the uniform global approach that IMO regulation is intended to deliver.

For major shipping nations such as Greece, whose fleets operate extensively across U.S., EU, and third-country trades, the combination of an NZF architecture still reliant on unresolved guidelines and contested calibration, along with the credible prospects of external countermeasures, raises the risk of regulatory fragmentation, increased compliance complexity, and heightened exposure to overlapping or potentially conflicting regulatory regimes. This environment of uncertainty may have material implications for voyage planning, charterparty risk allocation, crewing arrangements, and long-term investment decisions. All the above have been reflected in the procedural posture of key IMO Member States with major flag/ownership interests (including Greece and Cyprus), reinforcing the lack of consensus and the case for framework adjustment and definitional finalisation prior to adoption consideration[42].

[34] Ship&Bunker, US Warns of Visa Restrictions and Sanctions for Countries Backing IMO 2028 Deal, October 2025, link (14/12/2025)
[35] Reuters, US tells countries to reject UN ship fuel emissions deal or face tariffs, sources say, September 2025, link (14/12/2025)
[36] US Department of State, Taking Action to Defend America from the UN's First Global Carbon Tax – the International Maritime Organization's (IMO) "Net-Zero Framework" (NZF), October 10, 2025, link (14/12/2025)
[37] Reuters, US threatens visa restrictions, sanctions against UN members that back IMO emissions plan, October 2025, link (14/12/2025)
[38] Safety4Sea, US threatens sanctions as EU backs IMO Net-Zero Framework, October 2025, link (14/12/2025)
[39] Safety4Sea, U.S. threatens retaliation over IMO NZF ahead of key October vote, September 2025, link (14/12/2025)
[40] World Cargo News, US warns of retaliation against nations supporting IMO carbon tax, October 2025, link (14/12/2025)
[41] M. Hand, US threatens raft of penalties against states supporting IMO NZF, Seatrade Maritime, 10/2025, link (14/12/2025)
[42] D. Bush, IMO to delay Net-Zero Framework vote for one year, Lloyd's List, 17/10/25, link (18/1/2026).

2.11. Further Reading

Rystad Energy, IMO Net-Zero Framework, Consequences study on the adoption of the IMO's latest maritime regulation, Q3 2025 (18/01/2026).

Rystad Energy study of the IMO Net-Zero Framework's (NZF) design, modelling fuel transition trajectories and the implied flows of "surplus units/remedial units" and fund revenues under different scenarios. It highlights structural risks (notably fuel-supply and incentive adequacy gaps) and assesses whether NZF rewards can bridge the cost differential between synthetic fuels and conventional fuels over time.

Vinson & Elkins, IMO Postpones Adoption of Net Zero Framework, 24/10/2025.

Legal/practice update explaining that MEPC adjourned for one year without adopting the NZF, citing intensified political pressure. It outlines the NZF's core compliance architecture (fuel-intensity targets plus credits/contributions to a Net-Zero Fund) and flags ongoing uncertainty for shipowners, financiers, and fuel suppliers while technical guideline work continues.

DNV, Decision on the IMO Net-Zero Framework delayed for one year, 15/12/2025.

Short regulatory-news brief stating MEPC/ES.2 voted to adjourn the session for one year, so the NZF amendments (and a separate North-East Atlantic ECA amendment) were not adopted and will be taken up again in October 2026. It notes the earliest potential entry into force would shift to 1 March 2028 (at the earliest) and that guideline-development work is expected to continue.

T. Ewing, IMO Delays Net Zero Framework Vote, The Waterways Journal Weekly, 24/10/2025.

Trade-press article describing the October 14–17, 2025 MEPC meeting and the 57–49 vote to delay the NZF decision by one year, emphasizing the political dynamics (including U.S. and Saudi influence) and controversy over an effective "carbon tax"/fee concept. It also explains why inland waterways could still be indirectly affected via downstream fuel/bunkering infrastructure changes even if the rule formally targets international ocean-going ships.

M. Ruth, Opponents Seek to Weaken Net-Zero Framework Vote Rules at IMO, Maritime Context News, 15/10/2025.

News analysis focused on procedural maneuvering ahead of the NZF vote, arguing opponents sought to change voting thresholds/procedural guardrails to make the framework harder to adopt or enter into force. It summarizes the stakes and contrasts proponents' warnings about fragmentation with opponents' concerns about fuel availability, cost pass-through, and capacity constraints.

T. Ballerini, The United States halted the adoption of the Net-Zero Framework, Renewable Matters, 25/10/2025.

News piece asserting U.S.-led pressure contributed to postponing NZF adoption for one year. It explains the tacit vs explicit acceptance distinction and frames the outcome as both geopolitical and consequential for regulatory certainty and investment signals.

Wikborg Rein, IMO's "Net-Zero Framework" postponed following failed vote, 22/10/2025.

Law-firm update summarizing that IMO member states postponed NZF adoption for 12 months after the October 2025 session, and outlining key proposed mechanics.

CIMAC, Extraordinary IMO MEPC meeting fails to adopt Net-Zero Framework, 3/11/2025.

Industry association summary stating that the MEPC meeting did not adopt the MARPOL Annex VI amendments that would establish the NZF and that the vote was adjourned to October 2026 after a divided and politicized debate. It recaps the framework's two main instruments and describes ongoing intersessional technical work.

Beveridge & Diamond, Net-Zero Framework for International Shipping Postponed for One Year: International Maritime Organization Bows to U.S. Opposition, 22/10/2025.

Client alert arguing that the MEPC deferred making the NZF legally binding until October 2026 amid U.S. opposition, and listing practical implications for supply-chain stakeholders. It provides a relatively detailed plain-language description of the NZF architecture and notes EU/regional measures remain relevant in the interim.

3. NZF Reward Eligible Fuels

The IMO NZF restricts rewards to fuels that achieve near-zero lifecycle emissions on a well-to-wake (WtW) basis. At present, the range is limited to green synthetic fuels – namely, green ammonia, methane and methanol, or green hydrogen (See Annex A for a description of fuel colors). While a WtW performance-based approach is, in principle, agnostic, the existence of demanding thresholds in conjunction with steep GFI trajectories, renders available fuels with known emissions reduction capacity invalid, and therefore the framework **not technology-neutral**. Furthermore, its practical implementation faces significant constraints. The WtW methodology inherently carries substantial complexity, requiring harmonized global standards for upstream emissions accounting – standards that are still incomplete or inconsistent across regions.

A critical technical challenge is that current Sustainable Fuel Certification Schemes (SFCS) differ widely in their treatment of indirect land-use change (ILUC), electricity grid factors, and fugitive methane emissions. Without unified and representative emission factors – still under development – ships operating on identical fuels could refer to materially different GFI scores depending on certification source. This undermines regulatory predictability and risks distorting fuel markets until a consolidated IMO methodology is adopted.

3.1. Availability Status

The availability gap for green fuels remains the most significant barrier to NZF readiness. As shown by ClassNK data (Figure 2 and Figure 3), current global output of synthetic/renewable marine fuels is on the order of **1% or less of the energy-equivalent quantities** that would be required if shipping were to substitute conventional marine fuels with any single green alternative. This is not a transient shortfall but a structural deficit, rooted in limited electrolyzer deployment, insufficient renewable energy capacity, and immature supply chains for hydrogen derivatives.

Moreover, green fuel projects face permitting delays, high capital costs, and supply chain bottlenecks for critical minerals. Large-scale facilities (>1 GW) typically exhibit multi-year development cycles (from final investment decision to commercial output). Thus, even if aggressive investment begins in 2025–2027, many fuel plants will not contribute meaningfully to global supply before the mid-2030s, mainly due to permitting lead times, electrolyzer and critical-material supply limits, and the long build schedules of utility-scale renewables. Additional evidence is provided in Annex B.

A practical illustration of scale is ammonia: current global ammonia production (from all sources) is ~200 Mtpa, developed over more than a

Numbers

Global production of synthetic fuels amounts to equivalent **1% or less** of the quantities required for shipping alone.

Large-scale green-fuel production is capital- and time-intensive; many projects **announced in 2024–2027** will not materially relieve global fuel shortages until the **mid- to late-2030s**.

Regulatory friction or supply-chain bottlenecks **can add 2–4 years (or more) per project**.

Bureau Veritas: By 2028, **no fossil fuel will be compliant with the IMO's Net-Zero Framework**, including low-methane slip LNG.

century[43]. The energy-equivalent volumes implied for an ammonia-based pathway to fully displace shipping fuel demand would require **more than doubling today's ammonia production capacity** (with multiple more energy input capacity required, once upstream electricity and conversion efficiencies for synthetic ammonia are accounted for).

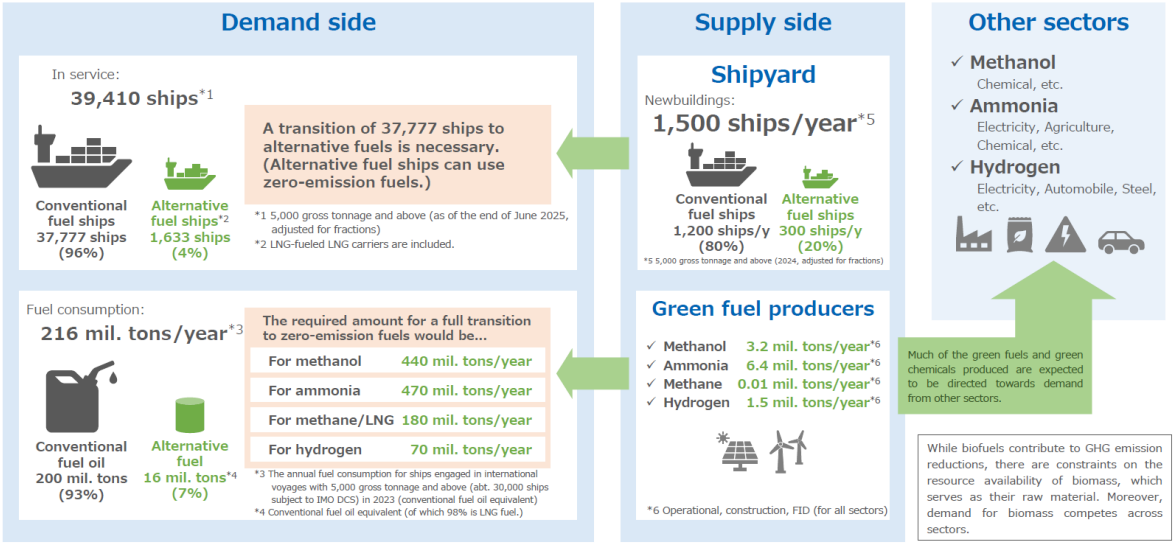


Figure 2: A snapshot of the current state of energy transition in International Shipping[44] (Source: ClassNK Presentation, 07/2025)

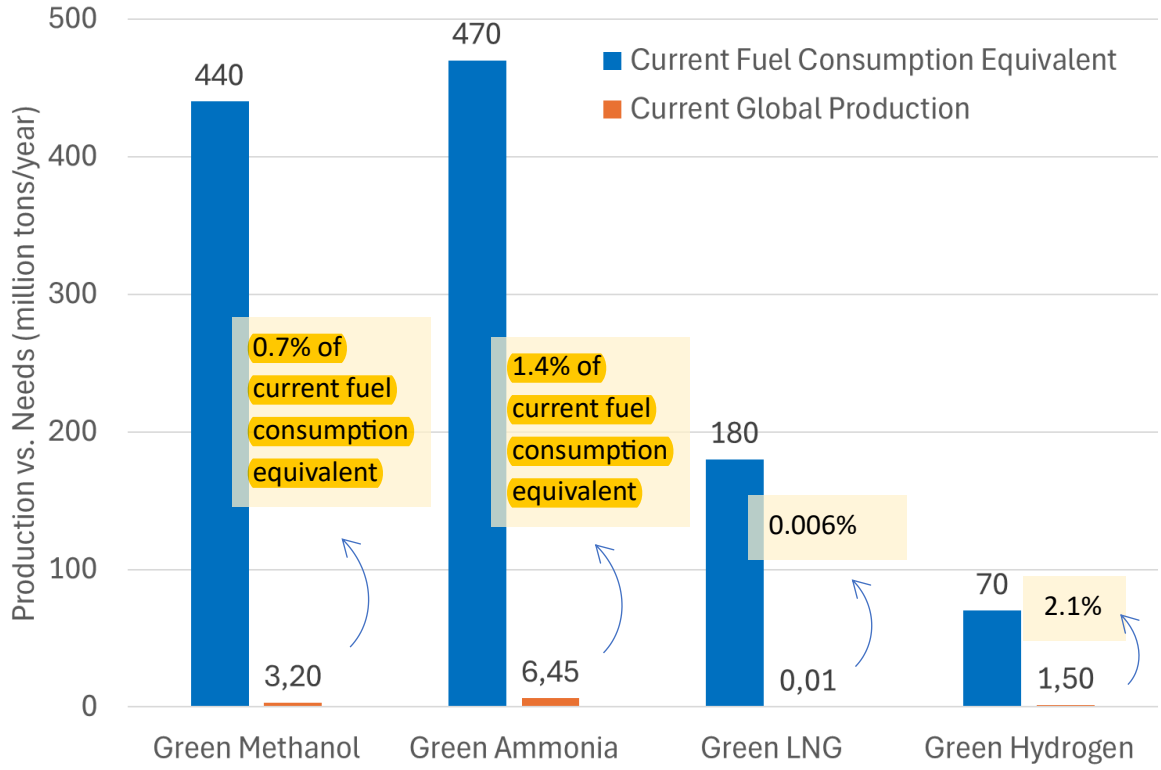


Figure 3: Production Shortfall of Green Fuels needed for Global Shipping (Source: ClassNK Presentation, July 2025)

[43] International Fertilizer Association (IFA), Short-term Fertilizer Outlook 2024-2025, Public Summary, link
[44] ClassNK Alternative Fuels Insight, Version 3.1, July 2025, link

In addition, under conditions of limited early supply, the system-wide abatement impact of green ammonia may be higher when used to displace existing grey ammonia production (a high-emissions baseline) rather than being allocated to shipping, where it would displace a smaller mass of conventional fuel per ton of ammonia due to energy-density differences.

Overall, these considerations underscore one of the main conclusions of this report: The NZF begins imposing steep GFI reduction requirements from 2030 onward, creating a regulatory ambition misaligned with industrial reality. While the NZF may be directionally correct, the timeline does not currently reflect feasible market conversion rates.

3.2. Production Costs[45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60]

Green fuels today remain **3–7 times more expensive** than conventional bunkers on an energy-equivalent basis (Figure 4). Even with continued declining cost of renewable energy, electrolyzers, and CO_2 capture, synthetic fuel costs are unlikely to reach cost parity before the late 2030s. Current estimates indicate:

- Green ammonia: 800–1,200 USD/ton (may fall to 400–600 USD/ton by 2040)
- Green methanol: 1,100–1,600 USD/ton

[45] Ship & Bunker, High Cost of Ammonia May Keep It Out of Reach for Most Shipowners: DNV. September 2025, link
[46] Wartsila, Sustainable fuels for shipping by 2050 – the 3 key elements of success: A report on future fuels in the marine industry, 2024, link
[47] Wartsila, Sustainable shipping fuels can reach cost parity with fossil fuels by 2035 with decisive policy, says new Wärtsilä report, March 2024, link
[48] Odenweller, A., Ueckerdt, F. The green hydrogen ambition and implementation gap. Nat Energy 10, 110–123 (2025). doi
[49] European Biogas Association (EBA), Mapping e-methane plants and technologies: The role of e-methane in the total energy mix, September 2024.link
[50] G. MOLNAR, E-methane: a new gas for a net-zero future?, International Energy Agency (IEA), 2024. link
[51] International Renewable energy Association (IRENA), Making the Breakthrough: green Hydrogen policies and technology costs, 2021, link
[52] J. Verschuur et al, Optimal fuel supply of green ammonia to decarbonise global shipping, 2024, Environ. Res.: Infrastruct. Sustain. 4 015001, doi
[53] Z. Cesaro, M. Ives, R. Nayak-Luke, M. Mason, R. Bañares-Alcántara, Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants, Applied Energy, 282, Part A, 2021, 116009, doi
[54] C. Pistolesi, A. Giaconia, C. Bassano, M. De Falco, Flexible Green Ammonia Production: Impact of Process Design on the Levelized Cost of Ammonia, Fuels 2025, 6(2), 39; doi: doi
[55] T. Galimova, M. Fasihi, D. Bogdanov, C. Breyer, Feasibility of green ammonia trading via pipelines and shipping: Cases of Europe, North Africa, and South America, Journal of Cleaner Production, 427, 2023, 139212, doi
[56] J. Rechreche, Why does green ammonia struggle to kick-off, & what can we do about it?, Proton Ventures, May 2025, link
[57] International Energy Agency (IEA), Global Hydrogen Review 2021: Executive Summary, link
[58] S. Revinova, I. Lazanyuk, S. Ratner, K. Gomonov, Forecasting Development of Green Hydrogen Production Technologies Using Component-Based Learning Curves, Energies, 2023, 16(11), 4338; doi
[59] Alessandro Franco, Green Hydrogen and the Energy Transition: Hopes, Challenges, and Realistic Opportunities, Hydrogen 2025, 6(2), 28, doi: doi
[60] Bunker Prices, https://www.bunkerindex.com/

- E-LNG (synthetic methane): 2,500–3,500 USD/ton
- Green hydrogen: 4–6 USD/kg (with production costs alone at ~3 USD/kg in best-case regions)

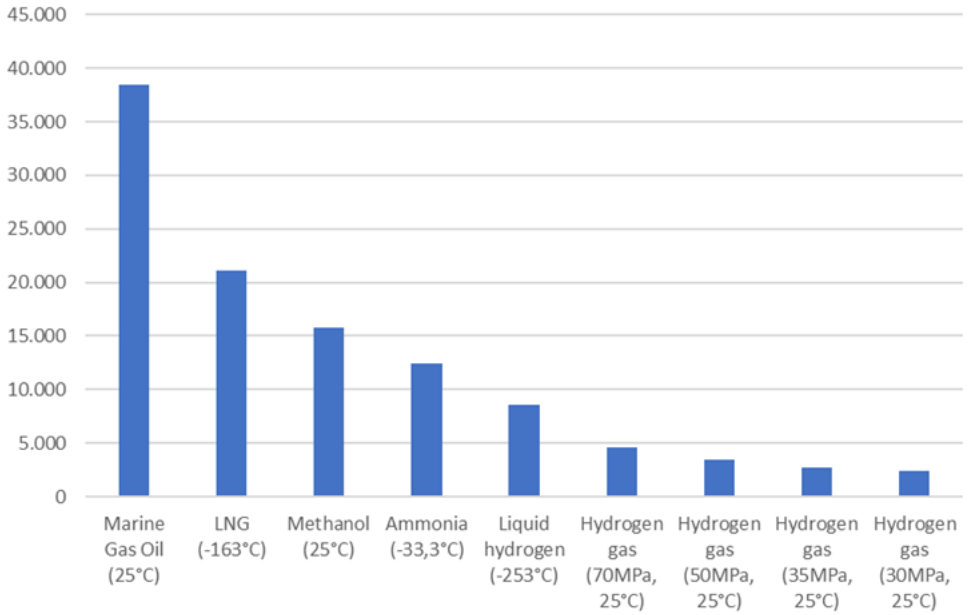


Figure 4: Energy Density (in MJ/m³) for various Shipping Fuel Options

These cost premiums are reflected directly in GFI scores and indirectly in RU purchases. **Ships running on transitional fuels such as LNG or biofuels will face increasing exposure to Tier 2 RU penalties as GFI requirements tighten**. Analyses from UMAS/UCL show that even optimistic cost-reduction scenarios cannot offset NZF-imposed financial pressures without a parallel expansion of reward mechanisms—which remains undefined in the draft framework.

Each fuel provides a certain amount of energy when combusting a certain quantity. The amount of energy per unit of weight is called the lower heating value (LHV), in MJ/kg. By multiplying LHV with density, in kg/m³, we get the Energy Density, measured in MJ/m³.

The energy density determines the storage volume needed on a ship to get the amount of energy required to propel the vessel.

Prices per equivalent MDO ton:

Green ammonia (NH_3): ~1,840–2,750 USD/MDO-eq ton (may fall to ~920–1,380 USD/MDO-eq ton by 2040)

Green methanol: ~2,360–3,430 USD/MDO-eq ton

E-LNG / synthetic methane: ~2,135–2,990 USD/MDO-eq ton

Green hydrogen: ~1,420–2,135 USD/MDO-eq ton
Production cost alone at ~1,070 USD/MDO-eq ton

3.2.1. Energy cost

The transition toward zero-carbon marine fuels is fundamentally an energy-conversion challenge. E-fuels such as green hydrogen, green ammonia, e-methanol, and e-LNG are not primary energy sources; they are **energy carriers** produced through processes that require large amounts of **renewable electricity**. The cost and feasibility of scaling these fuels therefore depend overwhelmingly on the cost and availability of green energy.

Table 3 [Korean Register] shows the **process energy demand**—the amount of green electricity required to produce one ton of each e-fuel—compared with the **usable energy that each ton of fuel can deliver** on board a ship:

Table 3: Green Energy Demands for the Production of Zero Carbon Fuels vs. the Energy they Generate. ***The alternative fuels consume more renewable energy in production than they ultimately yield***[61]

E-Fuel Type	Process Energy Demand	Energy Generated
e-Hydrogen	50 - 55 MWh/t	33 MWh/t
e-Ammonia	10 - 13 MWh/t	5 MWh/t
e-Methanol	12 - 15 MWh/t	5.6 MWh/t
e-LNG	14 - 20 MWh/t	13.89 MWh/t

This large energy requirement is a natural consequence of electrolytic hydrogen production, synthesis reactions (Haber–Bosch, methanation, Fischer–Tropsch), liquefaction, and storage. Taking green ammonia (currently one of the most discussed zero-carbon shipping fuels) as an example, the annual energy requirement to replace today's fossil fuels for ships above 5,000 tons corresponds to approximately **470 million tons of NH_3 per year**. Considering that **10–13 MWh of green electricity** is required **per ton** of NH_3, this implies a need for:

$$5,170\ TWh/year$$

of new, dedicated renewable electricity — *for international shipping alone*. For comparison, **all wind and solar generation worldwide in 2024 totaled:**

$$\approx 4,625\ TWh$$

(from ~ 3,969 *TWh* in 2023) meaning the maritime sector would require **more than the entire current global output** of these renewables[62]. Annex B presents detailed calculations supporting the statement that the construction of the solar and wind capacity required to generate green electricity required for the existing merchant fleet exceeding 5,000 GT, would entail an investment of approximately **USD 1.5 to 10.4 trillion**, based on a full-range, worst-to-best scenario comparison; **USD 1.2 to 3.7 trillion** with a more conservative estimate.

The renewable energy parks themselves are expected to last **20–25 years**, after which substantial reinvestment or replacement will be necessary. These capital expenses are only one piece of the transition: additional significant costs include building and operating the industrial plants that convert electricity into alternative marine fuels, installing the shore-side and on-

Numbers

The maritime sector alone would require **an additional 5,170 TWh/year** of clean electricity.

Building this capacity would demand **1.5–10.4 trillion USD** of new renewable-energy infrastructure every 20–25 years.

Due to conversion losses, e-fuels deliver only **one-half to one-third** of the energy required for their manufacture.

Fewer than 15 ports worldwide have pilot scale (Port Readiness Level 6+) ammonia bunkering readiness.

23 ports can provide methanol refueling services for ships.

[61] Korean Register, Economic Feasibility Study & Alternative Fuel Review, for Newbuilding Vessels, September 2025, KR Technical Seminar in Greece

[62] Rinnovabili Editorial Team, Global electricity production: 41% now carbon-free, but heat waves boost fossil fuel use, April 2025, link

board infrastructure for fuel supply and bunkering, and the associated logistics and ongoing operating expenditures for factories and supply chains.

The discrepancy between the green fuels/energy required and that available highlights a substantial **supply gap** and raises concerns about the feasibility of near-term compliance.

3.3. Logistics and Infrastructure

A global transition to green fuels requires a complete overhaul of bunkering infrastructure, not only in terms of **availability** but also **scale**. On an energy-equivalent basis, lower volumetric energy density fuels such as methanol and ammonia imply materially higher physical fuel volumes and throughput than today's HFO/MGO supply chain, which in practice translates into larger port-side storage, higher transfer capacity, and more demanding bunkering logistics (e.g., tankage footprint and bunkering frequency). Ammonia additionally introduces a higher-consequence safety case (toxicity and release management, see also Chapter 4 of the report), which typically drives tighter operational controls, enhanced detection/mitigation systems, and more conservative procedures. However, as of 2025, readiness remains limited:

- Fewer than **15 ports worldwide** have pilot-scale (Port Readiness Level 6+) ammonia bunkering readiness.
- Only 23 ports can provide methanol refueling services for ships[63,64].
- Hydrogen bunkering is at a demonstrator stage and unsuitable for deep-sea shipping.
- As of mid-2025, there is no publicly reported major port that offers routinely available commercial-scale bunkering of *green* (bio/renewable) LNG; the infrastructure remains at early/pilot stage.

This presents a systemic risk: ships compliant on paper may be unable to access compliant fuels in practice. Without synchronized global port deployment, the NZF risks creating an uneven regulatory landscape where access to compliance depends on geography rather than technical readiness. Finally, these port and bunkering constraints are inseparable from upstream constraints: the scale of renewable electricity, hydrogen production, and fuel conversion capacity required to supply these volumes is substantial, and conversion losses amplify the primary energy requirement.

3.4. Contribution of Energy Efficiency Technologies and Operational Measures

In addition to fuel transition pathways, a wide range of technical and operational measures can contribute to the reduction of greenhouse-gas emissions from shipping. These include

[63] European Maritime Finance (EMF), Worldwide ammonia rollout continues apace, August 2025, link
[64] Safety4Sea, New report highlights key developments on green shipping, October 2025, link

energy-efficiency technologies such as improved hull forms and coatings, propulsion and power-train optimisation, energy-saving devices (e.g. ducts, fins, air-lubrication systems), waste-heat recovery, wind-assisted propulsion, and digital performance monitoring, as well as operational measures such as speed optimisation, weather routing, voyage planning, trim optimisation, and improved maintenance practices[65,66].

Current literature[67] and empirical evidence from fleet-level implementation indicate that, depending on ship type, age, and operational profile, combined technical and operational measures can deliver emissions reductions in the order of at least 10–30% relative to baseline performance. These measures are generally deployable in the near term, often require lower capital investment than fuel conversion, and can reduce overall fuel consumption irrespective of fuel type, thereby mitigating both emissions and compliance costs under the NZF.

Observed historical performance also suggests that a meaningful portion of efficiency gains has already been realized relative to the 2008 reference year. The Fourth IMO GHG Study[68] indicates that by 2018, the carbon intensity of international shipping was approximately ~21–29% lower than in 2008 (on voyage-based allocation), with improvements varying by ship type. This is consistent with the view that post-2008 operational adjustments (notably speed management and related optimisation) delivered substantial early gains, while subsequent reductions have been more gradual as operational and technical measures approach practical limits.

Looking forward, additional efficiency contributions remain available (through continued speed/power management, voyage and port-call optimization, hull/propeller performance management, and selected retrofits, including wind-assist and air lubrication where technically and operationally suitable). Recent modelling by the World Bank[69] suggests that technical and operational energy-efficiency measures could reduce shipping emissions by 23–39% in 2030 compared to 2008, with speed reduction identified as the most immediately impactful lever and with a large share of the savings projected to be cost-effective (i.e., fuel savings that can offset implementation costs). However, these gains are expected to be incremental at fleet level and **unevenly accessible** across segments: liner networks typically have greater centralized control over schedules, speed and operational standardization, whereas tramp operations face higher variability (routing, utilisation and charterparty constraints), which can limit the consistent capture of operational savings[68].

Nevertheless, while energy-efficiency and operational measures can make a material contribution to emissions reduction and should be considered a necessary first step in any

[65] IMO, Improving the Energy Efficiency of Ships, link (14/12/2025)
[66] Southampton Marine and Maritime Institute, The impact of shipping's energy efficiency measures on reduction of underwater radiated noise, and opportunities for co-benefit, link
[67] AG Elkafas, M Shouman, Assessment of Energy Efficiency and Ship Emissions from Speed Reduction Measures on a Medium Sized Container Ship, TRANS RINA, 163, A3, INTL J MARITIME ENG, JUL-SEP 2021, doi
[68] Fourth IMO Greenhouse Gas Study, 2020, link
[69] World Bank Group, Keys to Energy Efficient Shipping, 2025, link (18/1/2026)

decarbonization strategy, their potential is inherently limited. Efficiency improvements are inconsequential toward meeting GFI thresholds, hence the reductions envisaged under the NZF should be consistent with the contribution from efficiency improvements in meeting absolute emissions reduction indicative checkpoints per IMO Strategy. Indeed, their role is complementary rather than substitutive, helping however to moderate overall costs and fuel transition requirements, without eliminating the need for low- and zero-carbon fuels in the medium to long term.

3.5. Emerging and Bridging Technologies: OCCS and Nuclear Options

Beyond alternative fuels, several emerging technologies have been proposed as potential contributors to maritime decarbonization, most notably onboard carbon capture and storage (OCCS)[70,71] and nuclear propulsion concepts. These technologies are at an early stage of development and face significant technical, regulatory, and infrastructural barriers, but they merit consideration in the context of longer-term transition pathways.

OCCS systems aim to capture CO_2 emissions directly from ship exhausts and store them onboard for subsequent discharge to shore-based transport and permanent storage facilities. In principle, OCCS could function as pathway enhancing solution by coupling conventional, transition or synthetic fuels with carbon content, reducing net emissions. In practice, however, widespread deployment remains constrained by unresolved regulatory questions, including accounting treatment under IMO frameworks, acceptance under port state control, and liability for captured CO_2. In addition, OCCS requires the parallel development of shore-side logistics, transport networks, and certified storage infrastructure, which should not be expected to be available at scale before the mid-2030s. Current regulatory discussions suggest that a comprehensive framework for OCCS will not be finalized before the end of 2028, limiting its relevance for early NZF compliance periods[72].

Nuclear propulsion, including small modular reactor concepts, represents an emerging yet long-term option[73]. While nuclear power offers the theoretical advantage of near-zero operational emissions, its application in commercial shipping faces substantial technological, regulatory, safety, liability, and public-acceptance challenges. Existing international maritime conventions provide only limited and outdated provisions for nuclear-powered ships, and the development of a modern regulatory framework would require extensive international coordination and time. Consequently, nuclear propulsion is best regarded as a potential long-term solution beyond the NZF's initial time horizon, rather than a practical compliance option under the framework's early or mid-term phases.

[70] IMO, Onboard Carbon Capture and Storage highlighted as possible climate technology solution, link (14/12/2025)
[71] Ship Universe, Onboard Carbon Capture Systems Made Simple: 2026 Update, link (14/12/2025)
[72] Lloyd's Register, Concept study to offload onboard captured CO_2, link (14/12/2025)
[73] S Lee, Marine Nuclear Applications of Small Modular Reactors, Korean Register Presentation.

3.6. Overall

Taken together, the analysis in this chapter indicates that the principal challenge facing the NZF lies not in the absence of technological options, but in the sequencing and scalability of those options relative to the framework's tightening emissions requirements. Energy-efficiency technologies and operational measures can deliver meaningful near-term reductions in energy use per ton-mile (and, where demand does not fully rebound, in absolute emissions) by lowering fuel consumption; however, they do not reduce the lifecycle GHG intensity of the fuel per MJ that underpins the NZF's GFI metric, and therefore cannot achieve the progressively stringent GFI thresholds envisaged under the NZF. Similarly, emerging solutions such as onboard carbon capture and storage may offer a potential bridging role by enabling partial emissions mitigation while alternative fuel supply chains develop, but their deployment remains constrained by unresolved regulatory treatment, energy penalties, and the absence of mature shore-side CO_2 logistics and storage infrastructure.

In the absence of sufficient availability and cost convergence of low- and zero-carbon fuels at scale, these limitations risk shifting near-term compliance behaviour toward remedial mechanisms rather than accelerating structural fuel transition. An effective NZF implementation will therefore depend on aligning regulatory ambition with the realistic deployment trajectories of efficiency measures, bridging technologies, and fuel pathways, ensuring that incentives initially support deployable solutions while enabling zero- and near-zero-emission options to emerge and scale gradually over time.

4. Environmental Assessment

As has been assessed above, the NZF compliant alternative fuels are not presently available in required quantities. It was also noted that production of alternative fuels requires more renewable energy than what they ultimately yield, being inherently inefficient. This raises the consideration of prioritizing emerging renewable power and associated synthetic fuels use to sectors yielding higher carbon reduction. This part provides a technical evaluation of the environmental impacts associated with the NZF.

4.1. Comparative CO_2 Reduction Potential of Renewable Electricity Use

The diagram[74] below presents the distribution of the global energy mix throughout the years. It can be seen that, although there is an increasing trend, renewable electricity expansion remains limited (4,625 TWh produced in 2024 from wind and solar energy[75]). Thus, sub-optimal allocation will significantly reduce net climate benefit.

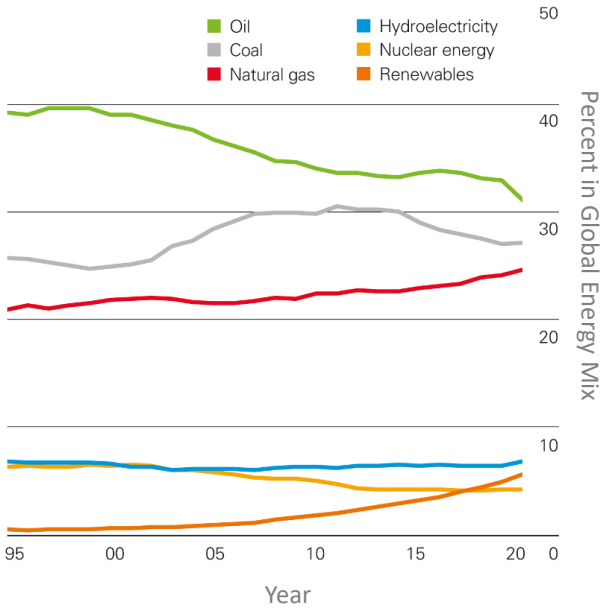


Figure 5: Distribution of the Global Energy Mix, 1995-2020

The following diagram shows the distribution of global CO_2 emissions by sector in 2023[76]. The transportation sector contributed approximately 21% of total emissions, with shipping (both domestic and international) accounting for about 11% of transportation emissions[77]. Overall, shipping represents roughly **2.5–3% of global CO_2 emissions**. Importantly, this relatively modest share reflects the intrinsic energy efficiency of maritime transport: on a ton-kilometre basis, ocean shipping is already among the most carbon-efficient freight modes, typically

[74] BP Statistical Review of World Energy, 2021, link
[75] Rinnovabili Editorial Team, Global electricity production: 41% now carbon-free, but heat waves boost fossil fuel use, April 2025, link
[76] https://www.statista.com/statistics/276480/world-carbon-dioxide-emissions-by-sector/
[77] https://www.statista.com/statistics/1185535/transport-carbon-dioxide-emissions-breakdown/

emitting an order of magnitude less CO_2 than road freight and up to two orders of magnitude less than air freight. As a result, redirecting large fractions of global renewable output into a relatively small emissions sector imposes a substantial systemic opportunity cost.

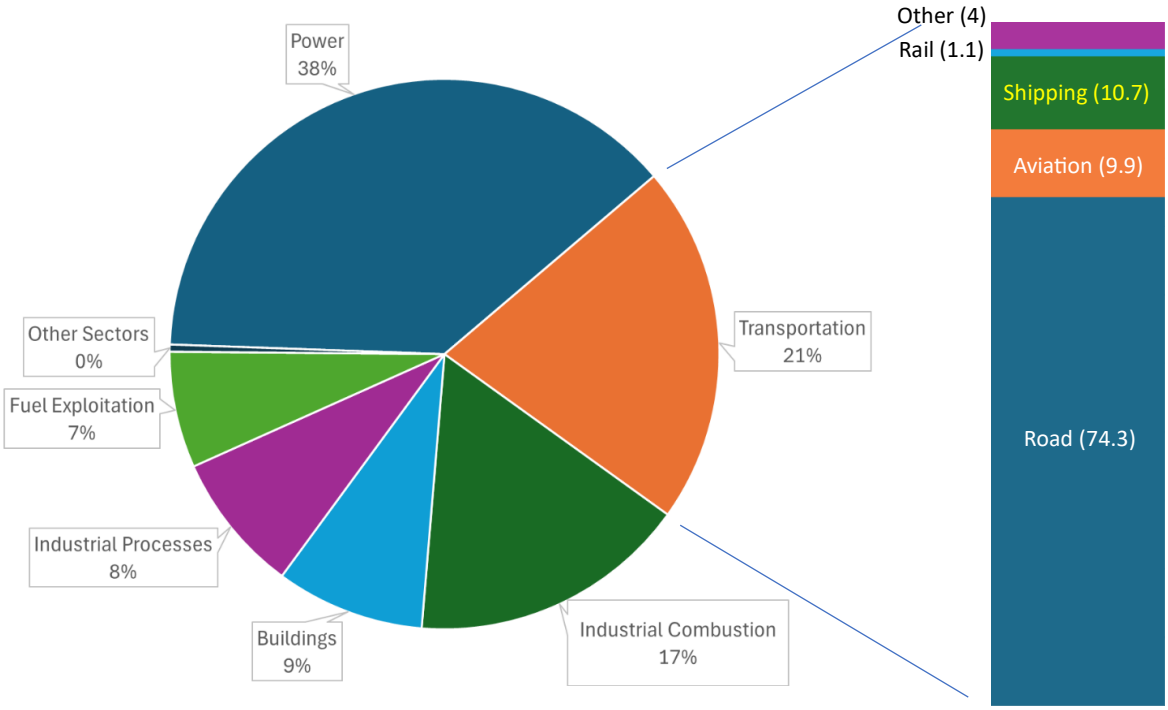


Figure 6: Global CO_2 emissions, by sector (2023) – Percent Distribution of CO_2 emissions produced by the transportation sector (2024): Shipping accounts for 2-3% of global CO_2 emissions (Source: Statista)

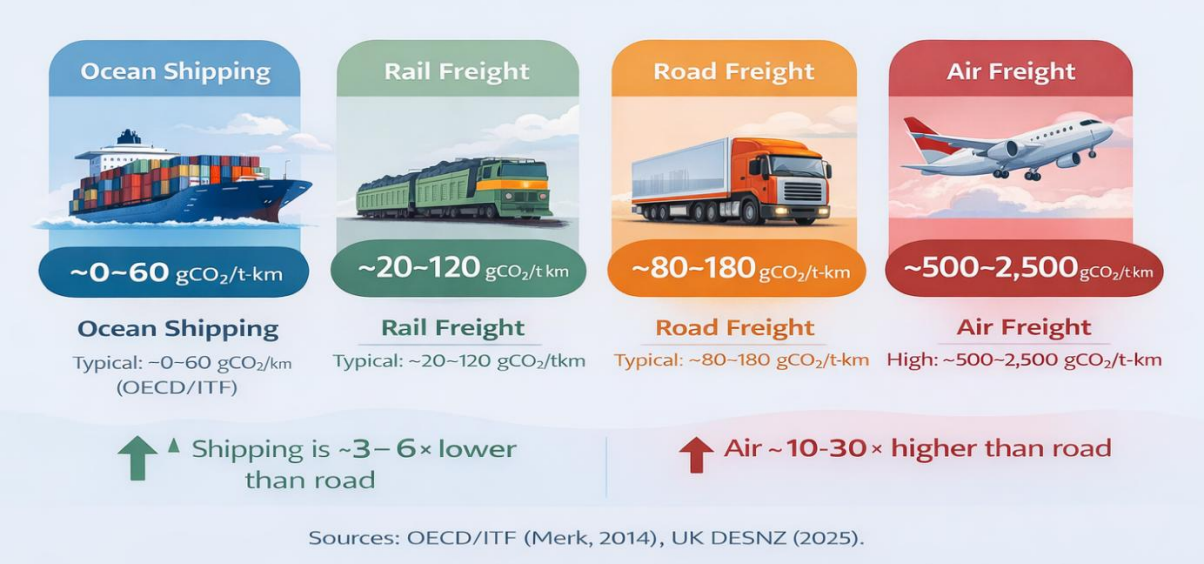


Figure 7: Ocean Shipping is already among the most carbon-efficient freight modes on a ton-kilometre basis: typical estimates place ships at ~0–60 gCO_2/t-km versus ~80–180 gCO_2/t-km for road freight, while air freight is orders of magnitude higher (~500–2,500 gCO_2/t-km)[78,79]

[78] O. Merk, Shipping Emissions in Ports, OECD International Transport Forum Discussion Papers 2014/20, link
[79] UK Department for Energy Security and Net Zero, 2025 Government Greenhouse Gas Conversion Factors for Company Reporting, link

Figure 8[80] depicts the CO_2 reduction potential of different pathways for renewable electricity. The reduction potential of renewable electricity from producing ammonia for deep sea shipping is given a factor of 1.

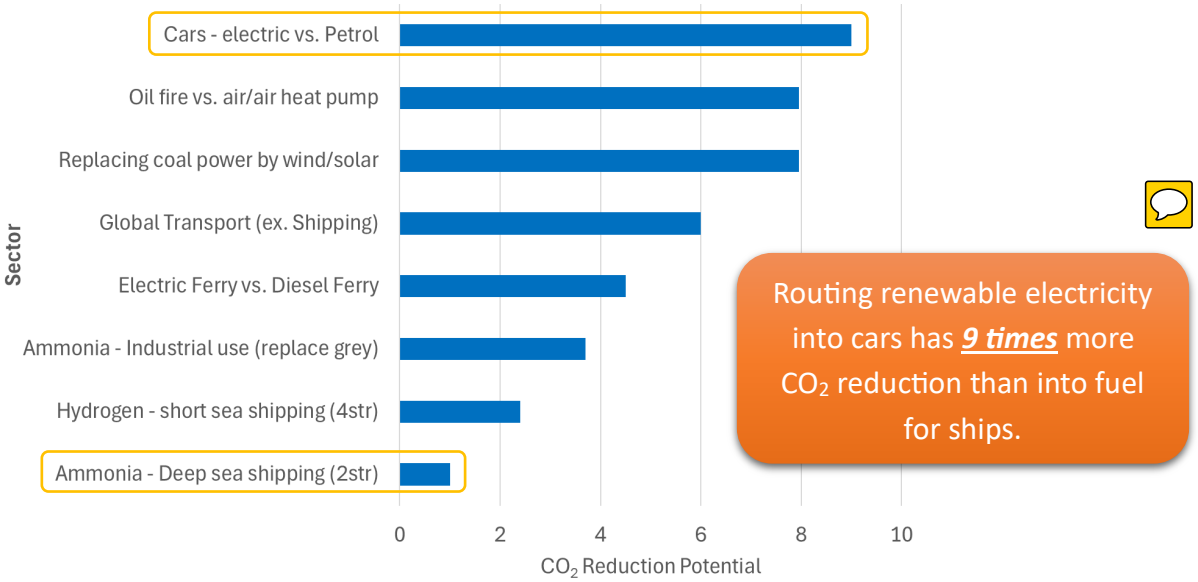


Figure 8: CO_2 reduction potential per kWh renewable electricity input for different pathways (Source: Odfjell): If the CO_2 reduction potential of renewable electricity from producing fuel for shipping is given a factor of 1, the same amount of electricity can achieve 9 times more reductions if it is routed into electrification of cars.

The figure shows that directing the same amount of renewable electricity towards electric-vehicle charging yields a significantly higher impact – approximately nine times the reduction potential. This is because shipping constitutes a 10–20% efficient fuel chain (Figure 9). Synthetic marine fuels – including ammonia, methane, methanol, and other hydrogen-derived carriers – require multistep conversion processes.

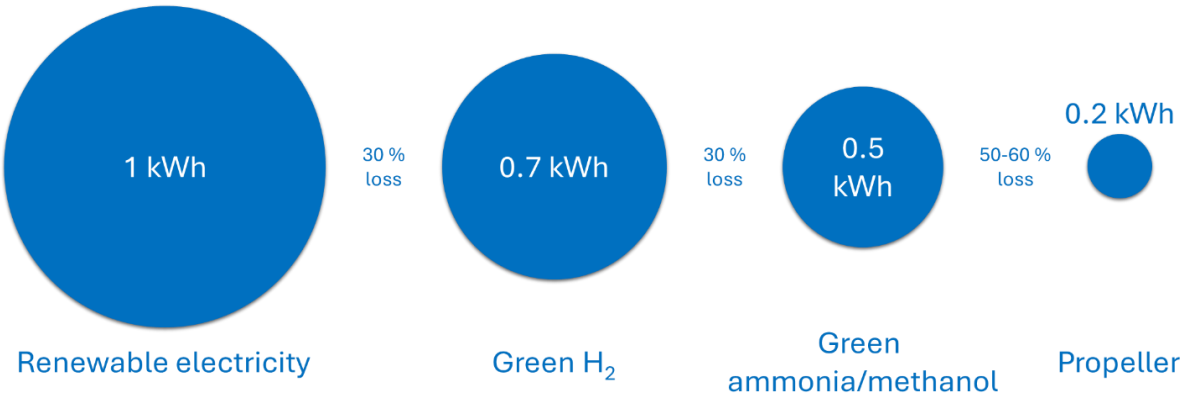


Figure 9: Energy loss in the green fuels production process.[80] In an ideal scenario, renewable electricity would be stored directly in a battery, but this is not feasible for deep-sea shipping. Instead, the energy must first be converted into hydrogen, which results in an energy loss of about 30%. Because hydrogen is also impractical for deep-sea vessels, it must then be further converted into green ammonia or green methanol, leading to an additional energy loss of roughly 30%. Finally, when these fuels are combusted in the engine, another 50–60% of the remaining energy is lost.

[80] Erik Hjortland, Towards zero Emission-Odfjell's perspective on Decarbonization of deep-sea shipping, presentation at the Singapore Norway Innovation Conference (SNIC) in November 2022, link

Literature indicates the following efficiencies, although real-world values vary a lot by technology, scale, and operating point:

1. **Electrolysis**: approx. 60–80% efficiency.[81,82,83,84]
2. **Synthesis or liquefaction:** 50–70% efficiency depending on pathway.[85,86,87,88,89]
3. **Storage, distribution, and conditioning losses:** 5–20%.[90,91, 88,92]
4. **Onboard conversion via combustion or fuel cells:** 20–60%[93,94,95,96].

Multiple studies[97,98,99,100,101,102,103] show that when renewable electricity is routed through hydrogen and synthetic fuel production chains, the overall electricity-to-movement efficiency is several times lower than for direct electrification. Electric transport is typically about 3–8 times more energy-efficient than hydrogen-based options, implying end-to-end efficiencies

[81] MH Bhuiyan, Z Siddique, Hydrogen as an alternative fuel: A comprehensive review of challenges and opportunities in production, storage, and transportation, International Journal of Hydrogen Energy, 102, 2025, pp. 1026-1044, doi

[82] A. Berrada, M.J. Sanjari, R. El Mrabet, Techno-economic assessment of hydrogen production: Comparative analysis of electrolyzer technologies in a hybrid PV/wind system, International Journal of Hydrogen Energy, 141, 2025, pp. 193-211, doi

[83] M. Nasser, T.F Megahed, S. Ookawara, H. Hassan, A review of water electrolysis–based systems for hydrogen production using hybrid/solar/wind energy systems, Environ Sci Pollut Res Int. 2022,25;29(58):86994–87018. doi

[84] IEA Greenhouse Gas R&D Programme, Comparative analysis of electrolytic hydrogen production technologies with low-carbon (CCS-abated) hydrogen pathways. Technical Report 2024-08, link

[85] C. Zauner, D. Leibetseder, Techno-Economic Analysis of Renewable Methanol Production at Gigawatt Scale – Utilizing Green Hydrogen for Direct CO_2 Hydrogenation, Hy2Market Project, link

[86] International Renewable Energy Agency (IRENA), Innovation Outlook: Renewable Methanol, 2021, link

[87] European Association for Storage of Energy (EASE), Power to Ammonia - Gasoline synthesis from H2 and N2 by using water electrolysis and Air Separation, 2018, link

[88] R. Edwards, et al, Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, 2014, link

[89] T. Brown, Round-trip Efficiency of Ammonia as a Renewable Energy Transportation Media, Ammonia Energy Association (AEA), 2017, link

[90] IEA-ETSAP, Hydrogen Production and Distribution, Technology Brief P12, 2014, link

[91] Storelectric, Hydrogen Storage: Supporting the race to net zero, link

[92] GENH2, Hydrogen Loss Mitigation with Active Refrigeration, 2024, link

[93] Soop+soop, Hydrogen Fuel Cells vs Hydrogen Combustion Engines, 2023, link

[94] R. Campe, Hydrogen co-combustion in ICE, ICCT ZEV Workshop, San Francisco, July 2019, link

[95] T. Hountalas, The Effect of Residual and Distillate Fuel on Camshaft & Electronically Controlled Marine Diesel Engines Combustion and Performance, Diploma Thesis, NTUA, 2016, link

[96] DNV GL AS Maritime, Comparison of Alternative Marine Fuels, 2019, link

[97] T.J. Wallington, M. Woody, G.M. Lewis, G.A. Keoleian, E.J. Adler, J. Martins, M.D. Collette, Green hydrogen pathways, energy efficiencies, and intensities for ground, air, and marine transportation, Joule, 8 (8), 2024, pp. 2190-2207, doi

[98] Uddin, M.N.; Wang, F. Fuelling a Clean Future: A Systematic Review of Techno-Economic and Life Cycle Assessments in E-Fuel Development. *Appl. Sci.* 2024, *14*, 7321. doi

[99] Stephanie Searle, E-fuels won't save the internal combustion engine, International Council on Clean Transportation (ICCT), 2020, link

[100] Brynolf, S., Fridell, E., & Andersson, K. (2014). Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of Cleaner Production, 74*, 86–95. doi

[101] Krantz G, et al. Assessing the environmental impact of eight alternative fuels in international shipping: A comparison of marginal vs. average emissions. Environments 2023, 10, 155, doi.

[102] H. Wang, et al, Life cycle analysis of ammonia fuelled ship – case ship studies for marine vessels, Journal of Cleaner Production, 520, 2025, Pp. 146105, doi

[103] International Energy Agency (IEA), Global Hydrogen Review 2025, link

for many e-fuel pathways on the order of a few tens of percent at best, once electrolysis, synthesis, storage, and conversion losses are included.

Decarbonization of steel, cement, chemicals, heavy industry, and national grid electricity systems provides CO_2 avoidance on a multi-gigaton scale[104]. These sectors require high-efficiency electrification to meet the <2°C and <1.5°C carbon targets. Directing renewable electricity to low-efficiency maritime fuel synthesis displaces mitigation opportunities in sectors where marginal abatement potential is significantly higher.

Allocating renewable electricity to e-fuel production before the underlying technology is mature risks carbon lock-in, whereby energy systems become dependent on inefficient pathways, delaying optimal electrification strategies and prolonging fossil fuel use in other sectors.[105,106,107]

Policy Note

Policy alignment and system boundary effects are also material. If shipping-specific carbon costs and fuel mandates move materially ahead of decarbonization requirements in the industrial value chains that shipping serves, trade patterns may be re-optimized on the basis of delivered regulatory cost rather than life-cycle emissions. This can create trade diversion and carbon leakage outcomes, such as shifting procurement toward geographically closer but more carbon-intensive sources or production routes, which may increase net global emissions even if regulated shipping emissions decline.

Accordingly, maritime decarbonization policy should be designed and sequenced in coordination with decarbonization pathways for steel, cement, chemicals, and power systems, using consistent life-cycle GHG accounting to minimize unintended system-wide outcomes.

Shipping must decarbonize with the global economy and its value chains, not ahead of them in isolation.

4.2. Environmental and Human Safety

Certain NZF compliant green fuels, i.e. green ammonia, green methanol and green hydrogen, exhibit intrinsic toxicological, chemical, and operational hazards that introduce substantial risks to crew, port personnel, surrounding communities, and marine ecosystems. These risks differ qualitatively from those associated with conventional petroleum fuels and require a detailed assessment of human-health impacts, environmental toxicity, and accident potential across the entire fuel lifecycle.

It is well established[108,109,110] that **ammonia** is a highly toxic, corrosive, and volatile compound classified as Immediately Dangerous to Life or Health (IDLH) at relatively low airborne concentrations. Even short-term exposure

[104] IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the IPCC. Cambridge University Press. link Chapter 6: Energy Systems, link, Chapter 11: Industry, link

[105] Ueckerdt, F., Bauer, C., Dirnaichner, A. *et al.* Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nat. Clim. Chang.* 11, 384–393 (2021). doi

[106] Transport & Environment (2022). A drop of e-fuel in an ocean of oil: Why carbon neutral fuels will not significantly decarbonise the existing car stock. link

[107] European Parliament (2023). Assessment of the potential of sustainable fuels in transport. Policy Department for Structural and Cohesion Policies, PE 733.103. link

[108] G. Hrenov, K. Reinhold, M. Järvis, P. Tint, G. Prause, Managing the Hazards of Ammonia in Seaports as a Potential Alternative Fuel for Green Shipping, 33rd European Safety and Reliability Conference (ESREL2023): The Future of Safety in a Reconnected World, Southampton, UK, 3-8 September 2023, doi

[109] International Maritime Organization (IMO), Maritime Safety Committee, 2025, Development of a Safety Regulatory Framework to support the Reduction of GHG Emissions from Ships using New Technologies and Alternative Fuels: The potential environmental impact of ammonia spills on the marine environment, link

[110] International Tanker Owners Pollution Federation (ITOPF), Consequences of an ammonia spill in the marine environment, March 2025, link

can cause severe respiratory distress, ocular damage, and chemical burns, while larger releases posing mass-casualty risks (Table 4). Ammonia is also acutely toxic to aquatic organisms, and accidental spills can result in extensive ecological damage due to rapid pH shifts and the formation of ammonium in water bodies. [111,112,113]

Beyond acute toxicity, large-scale adoption of ammonia as an energy carrier would constitute an expansion of anthropogenic reactive nitrogen throughput, with potential implications for the global nitrogen cycle[114]. Industrial nitrogen fixation via Haber–Bosch already represents a major perturbation of natural nitrogen flows, and additional production, storage, and distribution for maritime fuel would increase the importance of minimizing losses (e.g., ammonia slip, venting, and spill pathways) that can contribute to eutrophication, acidification, and broader ecological impacts[115,116].

Table 4: Impact of Ammonia leakage to humans[117]

Ammonia Content (ppm)	Impact to Humans
5-10	Odor-based detection
20-50	Mild discomfort
50-100 ppm for 2h	Annoyance and inconvenience
140 ppm for 2h	Some irritation
200-300	Effects on throat and eyes
300-500	Bearable for 20-60 min
2500-5000	Rapidly fatal (around 30 min)
5000-10000	Promptly lethal

In addition, the climate performance of ammonia-fuelled propulsion is sensitive to nitrogen-species byproducts. Nitrous oxide (N_2O)—a potential byproduct under certain combustion and aftertreatment regimes and also via indirect environmental pathways—is a particularly

[111] Yarandi, M.S., Mahdinia, M., Barazandeh, J., Soltanzadeh, A. Evaluation of the toxic effects of ammonia dispersion: consequence analysis of ammonia leakage in an industrial slaughterhouse, Medical Gas Research, 11(1), p 24-29, Jan–Mar 2021, doi

[112] Danish Centre for Environment and Energy (DCE), Assessment of the potential environmental impacts of a major ammonia spill from a Power-to-X plant and from shipping of ammonia in Greenland, Report 487, 2022, link

[113] Wärtsilä, Ammonia as marine fuel? Benefits, challenges, and smart adoption, July 2025, link

[114] Wolfram, P., Kyle, P., Zhang, X. *et al.* Using ammonia as a shipping fuel could disturb the nitrogen cycle. *Nat Energy* **7**, 1112–1114 (2022). link

[115] Fowler D et al. 2013 The global nitrogen cycle in the twenty-first century. Phil Trans R Soc B 368: 20130164. link

[116] EU Directorate-General for Environment, Shipping ammonia fuel could reduce the sector's greenhouse gas emissions, but air pollution controls would be needed to limit health impacts, News Article, 24/2/2025, link (6/1/26)

[117] D. Tsiourva, Ammonia in Shipping: From Molecule to Mainstream, Presentation in the International Conference on Marine Engineering and Renewable Energy, September 2025, Hangzhou, China

high-impact greenhouse gas (see also Chapter 5 of this report). Given this leverage, the uncertainty around N_2O formation and control effectiveness should be explicitly recognized and addressed through appropriate lifecycle accounting assumptions, robust emissions measurement/verification, and clear requirements for NOx/N_2O and ammonia-slip mitigation[118].

Methanol, though less acutely toxic than ammonia, is still a high-risk substance, particularly due to its systemic toxicity, flammability, and water solubility (Table 5)[119,120,121] . Methanol exposure through inhalation, ingestion, or skin absorption can cause metabolic acidosis, neurological damage, and irreversible blindness at relatively low doses. A methanol spill is less severe than an oil spill[122]. However, as a fully miscible liquid, methanol can spread rapidly in marine environments, and its biodegradation exerts high biochemical oxygen demand, potentially leading to oxygen depletion and secondary ecological harm.

Table 5: Physicochemical and Toxicological Properties of Methanol[123]

Property	Value
Flash Point	9.7 °C
Autoignition Temperature	455 °C
Solubility	Miscible with water
LD_{50} (oral)	1187 – 2769 mg/kg (Rat)
LD_{50} (dermal)	17100 mg/kg (Rabbit)
LD_{50} (inhalation)	128.2 mg/L (Rat) 4 h
Ecotoxicity	
Freshwater Fish	Pimephales promelas: LC50 > 10000 mg/L 96h
Microtox	EC_{50} = 39000 mg/L 25 min EC_{50} = 40000 mg/L 15 min EC_{50} = 43000 mg/L 5 min
Water Flea	EC_{50} > 10000 mg/L 24h

Facts

Methanol exposure can cause **metabolic acidosis, neurological damage, and irreversible blindness at relatively low doses.**

As a fully miscible liquid, methanol can **spread rapidly in marine environments**.

From a combustion stoichiometry perspective, methanol produces **~25% more CO_2 per unit energy than methane** on an LHV basis (see also Table 7), which is relevant for avoiding simplistic comparisons that treat methanol as inherently "lower-carbon" than methane **absent a lifecycle accounting framework**.

Hydrogen presents a different but equally critical set of hazards. As the smallest and most diffusive molecule, hydrogen has extremely low ignition energy, wide flammability range, and near-invisible flame, creating high explosion risk in confined or partially ventilated spaces

[118] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS), Managing Emissions from Ammonia-Fueled Vessels, 2023, link
[119] www.lr.org
[120] GATE Energy, Methanol In Produced Water Discharge, link
[121] Environmental Protection Agency (EPA), Methanol, link
[122] International Tanker Owners Pollution Federation Limited (ITOPF), Fate, Behaviour and Potential Damage and Liabilities Arising from a Spill of Methanol into the Marine Environment, May 2024, link
[123] Safety Data Sheet, Thermo Fisher Scientific, 2021, link

(Table 6)[124,125,126,127]. Leaks can migrate rapidly through micro-fissures or structural joints, complicating detection and containment. When stored cryogenically (e.g., as LH_2 at –253 °C), hydrogen introduces additional cold-burn, material embrittlement, and structural integrity risks. Repeated cryogenic cycling can degrade metals and seals, increasing the probability of catastrophic failure unless specialist materials and rigorous inspection regimes are employed.

Table 6: Comparison of the characteristics of hydrogen and natural gas[128]

Characteristic	Hydrogen (H_2)	Natural gas (methane)	Hydrogen
Molar mass [g/mol]	2.02	16.04	is markedly lighter
Density (20 °C; 1,013 bar) [kg/m3]	0.08375	0.72	is markedly lighter
Buoyancy in air	14 times lighter	4 times lighter	is markedly lighter
Diffusion coefficient in air NTP [cm^2/s]	0.61	0.16	Mixes with air faster
Melting or freezing point [°C]	-259	-182	-
Boiling point [°C]	-253	-162	-
Minimum ignition energy in air [mJ]	0.017	0.3	is markedly more flammable
Laminar burning rate [m/s]	2.7	0.4	is considerably more reactive
Self-ignition point [°C]	560	650	-
Flammable range, concentration in air [vol%]	4-75	5-17	has a significantly wider flammable range
Hazard classification	very highly flammable gas	very highly flammable gas	the hazard classification is the same as that of natural gas
Explosion range [% vol.]	18-59	6-14	has a significantly wider explosion range
Lower heating value [MJ/kg]	120	49	has a higher calorific value
Detonation ignition energy [g TNT]	1	1,000	is much more sensitive to detonation
Physical form	colourless, odourless gas	colourless, odourless gas	is less noticeable
Other properties	colourless, poorly visible flame	visible flame, usually bluish	is less noticeable
Hajustus	no fragrances	strong, added fragrance	is less noticeable

All three fuels require high-integrity containment, advanced leak-detection technologies, robust ventilation systems, and extensive crew training. However, unlike conventional marine fuels, global operational experience at the scale envisioned for maritime adoption remains limited. The absence of mature bunkering standards, emergency-response protocols, and shipboard safety systems introduces an additional layer of uncertainty. Before large-scale

[124] Calabrese, M.; Portarapillo, M.; Di Nardo, A.; Venezia, V.; Turco, M.; Luciani, G.; Di Benedetto, A. Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. *Energies* **2024**, *17*, 1350. doi

[125] Stargate Hydrogen, Liquid Hydrogen: A choice for Efficient Energy Storage and Transport, 2024, link

[126] European Industrial Gases Association (EIGA), Safety in Storage, Handling and Distribution of Liquid Hydrogen, Doc 06/19, 2019, link

[127] arXiv:2308.16048, doi

[128] Sun, B., Lu, W., Gault, B. *et al.* Chemical heterogeneity enhances hydrogen resistance in high-strength steels. *Nat. Mater.* **20**, 1629–1634 (2021). link

regulatory adoption, a complete hazard assessment – including toxicological profiles, explosion modelling, cryogenic behavior, environmental persistence, and consequence analysis – is essential to ensure that possible emissions reductions do not come at the expense of elevated human-health risks or new environmental liabilities.

4.3. Absence of completed Life Cycle Assessments under NZF

A full, multi-impact Life Cycle Assessment (LCA) covering the full basket of IMO Net-Zero Framework (NZF) fuel pathways has not yet been completed or adopted. ISO 14040 and ISO 14044 define LCA as a cradle-to-grave framework that must include inventory, impact assessment and interpretation across multiple environmental areas of protection (ecosystems, human health, resources)[129,130]. Recent reviews find that existing LCAs for maritime fuels are fragmented: a 2024 systematic review of 43 studies on maritime fuel LCAs reports that only 19% provide a complete life-cycle inventory and that methodological inconsistencies and limited transparency prevent clear guidance on the environmental impacts of emerging fuels[23].

The 2024 IMO Life Cycle GHG Guidelines[131], which form the LCA basis under IMO NZF, are expressly limited to calculating well-to-wake GHG emission factors (CO_2, CH_4, N_2O) for marine fuels and are still under development for future revisions at MEPC 84 and MEPC 87[132,133]. This means that, although they refer to ISO 14040/44, the adopted NZF LCA framework currently covers only climate-related indicators (lifecycle GHG intensity) and not a full ISO-style multi-impact LCA. Missing assessments are discussed in the following paragraphs.

4.3.1. Well-to-wake GHG accounting, including upstream electricity generation mix.

IMO's own description of the LCA Guidelines stresses that they are designed to assess life-cycle GHG intensity "from primary production to carriage of the fuel in a ship's tank" (well-to-tank) and from tank-to-exhaust (tank-to-wake) (Figure 10), and that upstream emissions are critical for evaluating the GHG performance of candidate fuels in the NZF[132,133].

Recent LCAs for alternative marine fuels (e.g. ammonia and methanol for a VLCC) show that fossil-based production pathways offer little or no well-to-wake GHG benefit, while pathways powered by low-carbon electricity (solar, wind, batteries) can drastically change the overall GHG balance, though the magnitude of improvement depends strongly on feedstock and

[129] *ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework.* International Organization for Standardization. link
[130] *ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines.* International Organization for Standardization. link
[131] R. Miyake, IMO Guidelines on Life Cycle GHG Intensity of Marine Fuels, ClassNK, link
[132] International Maritime Organization (IMO). "IMO's work to cut GHG emissions from ships" – section on LCA Guidelines on life cycle GHG intensity of marine fuels. link
[133] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. "How the IMO LCA guidelines work in the Net-Zero Framework." *SAFETY4SEA* column, 1 Oct 2025. link

electricity mix[134]. A 2025 global assessment of well-to-tank carbon intensity for marine fuels similarly finds that upstream extraction and refining account for the majority of well-to-tank GHG emissions and vary widely by country and supply chain, underscoring the need to model upstream electricity and fuel production explicitly[23,135].

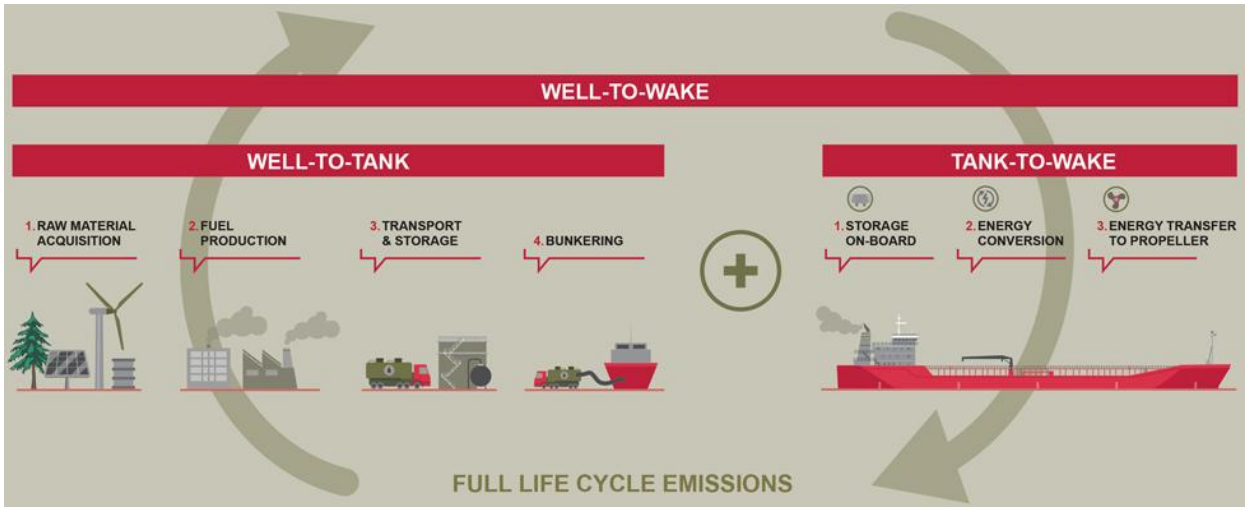


Figure 10: "Well-to-wake" refers to the entire process from fuel production, and delivery to use onboard ships, and all emissions produced therein.[136]

4.3.2. Toxicity, eutrophication, and ecosystem impacts of fuel production

Multi-impact LCAs of biofuels and marine fuels repeatedly show that climate benefits can come at the cost of other environmental impacts. Roux et al. review[23] of biofuels LCAs concludes that GHG reductions are often achieved at the expense of higher acidification, eutrophication, water footprint and biodiversity loss. For marine shipping, a Baltic Sea damage-cost study[138] finds that marine eutrophication and ecotoxicity damage costs are of similar magnitude to those from climate change and reduced air quality, and warns that policy can become biased if only some impact categories are considered. Several LCAs of alternative marine fuels likewise report substantial trade-offs in eutrophication and ecotoxicity when production routes, feedstocks and electricity mixes are varied.

4.3.3. Human health impact analysis (acute and chronic exposure)

ISO-based LCA frameworks explicitly include human health as a core area of protection in the impact assessment phase[130,137]. Empirical work on shipping shows that health-related impacts

[134] Huang, J.; Fan, H.; Xu, X.; Liu, Z. Life Cycle Greenhouse Gas Emission Assessment for Using Alternative Marine Fuels: A Very Large Crude Carrier (VLCC) Case Study. J. Mar. Sci. Eng. 2022, 10, 1969. doi
[135] Wang, Y.; Xiao, X.; Ji, Y. A Review of LCA Studies on Marine Alternative Fuels: Fuels, Methodology, Case Studies, and Recommendations. *J. Mar. Sci. Eng.* **2025**, *13*, 196. doi
[136] Bureau Veritas, What well-to-wake decarbonization means for ship owners, link
[137] Asia-Pacific Economic Cooperation (APEC), Life Cycle Assessment: Best Practices of ISO 14040 Series, 2004,link

are non-trivial: Ytreberg et al.[138] quantify damage costs from ship emissions and find that health impacts from air pollution are comparable to those from climate change, while marine eutrophication and ecotoxicity also impose large societal costs. Marine biofuel LCAs likewise report increased human toxicity indicators even when climate impacts improve[130]. However, the IMO NZF and its LCA Guidelines currently only regulate lifecycle GHG intensity, and do not yet incorporate human-health-related mid-point or end-point indicators in the regulatory metric.

4.3.4. Infrastructure-embedded emissions

State-of-the-art LCAs of fossil-free propulsion concepts show that embedded impacts from energy infrastructure can dominate non-climate categories. For example, a life-cycle assessment of the HyMethShip concept[139] (electro-methanol with onboard carbon capture) finds lower climate change, acidification, eutrophication and particulate-matter impacts than conventional options, but higher toxicity impacts driven largely by metal demand in wind power plants supplying renewable electricity. A 2022 life-cycle assessment and costing study of fossil-free shipping solutions similarly reports that promising electro-fuels and fuel-cell systems exhibit trade-offs in human toxicity and freshwater ecotoxicity linked to wind-power infrastructure used to generate electricity for hydrogen and e-fuel production[130]. These results illustrate that ignoring infrastructure-embedded emissions (renewable power plants, electrolyzers, batteries, storage and distribution assets) can under- or mis-estimate real environmental burdens.

4.3.5. Regulatory risk

As shown previously, the NZF is structured around well-to-wake (WtW) GHG fuel intensity, which is conceptually appropriate for avoiding a narrow tank-to-wake focus. However, implementation risk remains material because the underlying LCA inputs (default emission factors, pathway definitions, methane-slip assumptions, and certification/verification data) are still evolving and, for several emerging/synthetic pathways, necessarily rely on limited empirical operational data. In this context, the regulatory signal can become inadvertently **technology-skewed** (penalizing incremental abatement options in existing value chains and engine platforms that require material capex and commercial scale to mature), while over-rewarding pathways whose **WtW performance is not yet fully established**. In parallel, because the NZF metric is GHG-focused, it still carries a burden-shifting risk: fuel pathways that improve WtW GHG intensity may increase non-GHG impacts (e.g., toxicity,

[138] Ytreberg, E., Åström, S., Fridell, E. Valuating environmental impacts from ship emissions – The marine perspective. *Marine Pollution Bulletin* 171 (2021) 112–127. doi

[139] E. Malmgren, S. Brynolf, E. Fridell, M. Grahn, K. Andersson. The environmental performance of a fossil-free ship propulsion system with onboard carbon capture-a life cycle assessment of the HyMethShip concept, Sustain Energy Fuels, 5 (2021), pp. 2753-2770, doi

eutrophication, land/water pressures), implying the need for ISO-consistent LCA discipline and transparent, regularly updated default values and verification rules.

4.4. Infrastructure, Resource, and Land-Use Implications

Meeting the renewable-energy requirements for large-scale production of green fuels for maritime transport would necessitate an unprecedented expansion of global clean-energy infrastructure. The International Energy Agency[140] reports that tripling renewable-electricity capacity by 2030 could require up to 600,000 km² – an area the size of France – and 2 million km² by 2050, highlighting the scale of land transformation required for solar, wind, and associated grid systems. Producing green ammonia for even 10% of global shipping demand[141] would require electricity volumes[142] on the order of the annual consumption of major industrialized economies, alongside electrolyzer deployment far exceeding today's global manufacturing capacity, which the IEA notes[143] remains orders of magnitude below what hydrogen-based fuels would require under net-zero scenarios. Infrastructure expansion also brings significant ecological pressures: utility-scale solar photovoltaic installations demand large surface areas often located in biodiversity-sensitive regions; onshore and offshore wind farms can cause habitat fragmentation, avian mortality, and noise impacts; and large-scale battery and hydrogen-storage systems depend on intensive extraction of lithium, cobalt, nickel, and rare earth elements, each linked to water pollution, land degradation, and social impacts in mining regions[144,145]. Concentration of these resource-intensive infrastructures in coastal zones to support maritime fuel production risks amplifying cumulative ecological burdens, particularly where sensitive marine and shoreline ecosystems coincide with industrial activity.

4.5. Fleet Turnover and Embedded Emissions

Modern oceangoing vessels are engineered for long service lives, often 25 to 30 years or more[146,147,148], which means that premature retirement driven by net-zero-fuel (NZF) policy pressures can generate unintended environmental consequences. Early scrapping leads to

[140] International Energy Agency (IEA). (2025). Land-Use Competition between Biodiversity and Net-Zero Goals. link
[141] Getting to Zero Coalition & Global Maritime Forum. (2022). Maritime Decarbonization Strategy 2022. link
[142] Saygin, D. (2023). *Ammonia Production from Clean Hydrogen and the Potential for Green Ammonia Trade*. *Sustainability, 15*(2), 1623. doi
[143] International Energy Agency (IEA). (2021). Global Hydrogen Review 2021. link
[144] Huber, S. T., Steininger, K.W. (2022). Critical sustainability issues in the production of wind and solar electricity generation as well as storage facilities and possible solutions. Journal of Cleaner Production, 339, 130720. doi
[145] OECD & International Energy Agency (IEA). (2021). The Role of Critical Minerals in Clean Energy Transitions, link
[146] Safety4Sea, Do you know what happens to a ship when it's too old to sail anymore?, 2020, link
[147] Maritime Page, Lifespan of Cargo Ships: Inside the Global Maritime Trade, January 2025, link
[148] Thai Subsea Services, What happens to a ship when it's no longer safe to sail?, 2021, link

significant embodied CO_2 emissions associated with steel recovery, re-processing, and re-manufacturing, since steel makes up 75–85% of a ship's weight[149] and its production for shipbuilding generated 72.2 million tonnes of CO_2 equivalent in 2021–2022[150]. Scrapping also contributes to substantial industrial waste from ship-breaking activities, much of which occurs in low-regulation environments such as South Asia, where over 85% of global ship recycling takes place[151]. These practices have been criticized for toxic pollution, unsafe working conditions, and ecosystem damage[146].

Available lifecycle studies show that steel production dominates the construction-phase carbon footprint of ships–with steel alone accounting for up to 90% of hull-related emissions–and that producing virgin steel generates several tons of CO_2 per ton of material[152]. As a result, replacing vessels ineffectively can add substantial embodied emissions that may significantly offset the operational emissions reductions achieved by early fleet renewal[153]. Conversely, accelerating the construction of NZF-compliant newbuilds before key technologies and fuel systems have matured risks locking the sector into sub-optimal fuel architectures for decades[154], given uncertainties in alternative fuel supply chains and regulatory frameworks. Such premature technological commitment can prolong systemic inefficiencies, constrain future decarbonization pathways, and elevate lifecycle emissions across the global fleet.

4.6. Shipyard and Retrofit Capacity Constraints

An additional and often under-appreciated constraint on NZF implementation relates to the availability and capacity of shipyards capable of executing fuel conversions, retrofits, and major energy-efficiency upgrades. Recent assessments indicate that global retrofit capacity is geographically concentrated and already under significant pressure from competing regulatory and commercial demands, including ballast water treatment system retrofits, scrubber installations, LNG and methanol readiness conversions, and life-extension works for existing fleets.

The *ABS Sustainability Outlook 2025*[155] highlights that retrofit demand is expected to grow sharply in the period leading up to 2030, while effective yard capacity expands at a much slower pace, creating a structural bottleneck. The analysis shows that limited berth availability, skilled labor shortages, long lead times for specialized equipment, and the complexity of

[149] International Council on Clean Transportation (ICCT), Tracing the steel supply chain of the shipbuilding industry, 2024, ID 174, link
[150] Edwin Lampert, Shipping targets hidden steel emissions with new regulatory framework, riviera, 2025, link
[151] D. Gupta, P. Schröder, Towards a just and circular shipbreaking industry in South Asia, Circular Economy.Earth, January 2025, link
[152] Önal, M., Neşer, G., & Gürsel, K. T. (2020). Environmental impacts of steel ship hulls building and recycling by life cycle assessment (LCA). Ships and Offshore Structures, 16(10), 1061–1066. doi
[153] Lloyd's Register, Steel's embedded emissions boost shipping's GHG, 2023, link
[154] McKenney T., The Impact of Maritime Decarbonization on Ship Design: State-of-the-Art Report, Proceedings of 15th International Marine Design Conference (IMDC-2024) June 2-6, 2024, Amsterdam, the Netherlands, doi
[155] ABS, Vision meets Reality, Sustainability Outlook 2025, link

alternative-fuel retrofits constrain the rate at which the existing fleet can realistically be converted (Figure 11).

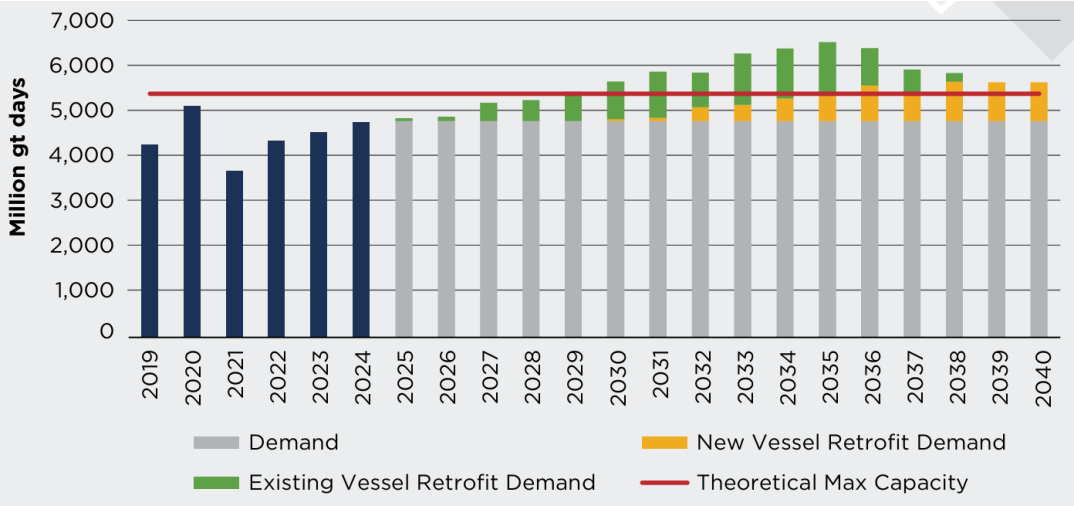


Figure 11: Retrofit Projection (ABS Sustainability Outlook 2025)

These capacity constraints have direct implications for NZF compliance. Even where fuel pathways or retrofit solutions are technically viable and economically justified, physical limitations in shipyard availability may delay implementation beyond regulatory timelines. This increases the likelihood that shipowners will rely on interim compliance mechanisms, such as the purchase of Remedial Units, not solely due to cost considerations but due to practical infeasibility of executing retrofits within required timeframes. As a result, shipyard capacity emerges as a critical, non-fuel bottleneck in the transition, reinforcing the broader conclusion that NZF ambition must be assessed against not only fuel availability and cost, but also industrial execution capacity.

4.7. Conclusions

The production of green fuels for shipping is associated with comparatively low system-level CO_2 abatement efficiency, as achieving meaningful emissions reductions in the maritime sector would require very large quantities of renewable electricity for a relatively modest contribution to global emissions reduction (Shipping represents roughly 2.5–3% of global CO_2 emissions). In contrast, several other sectors exhibit significantly higher marginal CO_2 reduction potential per unit of renewable electricity deployed, with direct electrification of road transport offering faster and more efficient emissions abatement (9 times the CO_2 reduction potential per kWh versus ammonia for deep-sea shipping).

Given the technical challenges associated with alternative marine fuels, together with considerations related to toxicity, handling, and safety, their large-scale deployment in shipping warrants a cautious and phased approach until scalability, safety, and sustainability are more firmly established.

Comprehensive feasibility studies and full life-cycle assessments are still required to evaluate the environmental footprint, safety risks, and potential human-health impacts associated with these fuels across their entire value chains.

In addition, large-scale scrapping of efficient vessels and accelerated fleet replacement would itself entail substantial embedded emissions and environmental impacts, while the extensive renewable generation, storage, and supporting infrastructure required to produce and handle synthetic fuels risks compounding land-use and ecological pressures. Critically, even where retrofit solutions are technically viable and economically justified, the limited global capacity of shipyards to execute fuel conversions and major modifications—together with skilled-labour constraints, equipment lead times and competing retrofit demands—creates a practical bottleneck that may delay fleet transition relative to regulatory timelines.

From a system-optimization perspective, a sustainable allocation framework for renewable electricity should therefore prioritise sectors based on marginal CO_2 abatement per kilowatt-hour, technological readiness levels of conversion pathways, cumulative infrastructure impacts, and safety and human-health risk profiles, within which marine synthetic fuels tend to rank unfavourably relative to direct electrification and certain forms of industrial decarbonization.

5. Economic Impact of NZF

According to Class NK's Alternative Fuels Insight (July 2025)[44], the global fleet of ships above 5,000 GT includes 39,410 vessels, of which 37,777 ships (96%) are conventional-fuel ships and only 1,633 ships (4%) are equipped for any form of alternative fuel. Of these, just 869 ships (2.2%) are alternative-fuel capable in actual operation, with LNG-fuelled ships representing 659 vessels, or approximately 1.7% of the fleet, while methanol-, LPG-, ammonia- and hydrogen-fuelled ships collectively represent far less than 1% of the fleet.

Fuel consumption data for 2023 show a similar pattern: ships above 5,000 GT consumed 216 million tonnes of fuel (HFO-equivalent), of which 93% was conventional fuel oil, while only 7% was alternative fuel, almost entirely LNG (98% of the alternative-fuel share)[156].

Taken together, these figures indicate that over 95% of the fleet has no ability to use alternative fuels beyond drop-in biofuel blends, and therefore nearly all ships face limited compliance pathways other than continuing to burn conventional fuels and bearing regulatory costs under emerging frameworks such as the IMO mid-term measures and the Net-Zero Fund. An important distinction relates to the LNG pathway: while LNG-fuelled vessels remain a small share of the fleet, LNG already accounts for the vast majority of alternative-fuel use and can, in principle, provide a scalable transition vector via liquefied biomethane (bio-LNG) and, later, synthetic methane (e-LNG), leveraging existing storage, bunkering infrastructure, and end-user continuity across industries—provided that robust lifecycle accounting and chain-of-custody certification frameworks are in place. In this context, regulatory approaches that effectively "target" LNG without recognizing fossil LNG immediate potential and scope for improvement also from certified renewable/synthetic methane (and without accounting for methane-emissions controls) risk slowing near-term emissions abatement and weakening an infrastructure bridge that could enable faster scaling of low-carbon methane fuels.[157,158]

5.1. GFI Calculation

As previously mentioned (Paragraph 2.2), the NZF methodology is based on the Greenhouse Gas Fuel Intensity (GFI), expressed in g CO_2eq/MJ on a well-to-wake basis. For a given ship and reporting period, the attained GFI is calculated as the ratio of total lifecycle greenhouse-gas emissions associated with the energy used to the total energy delivered:

$$GFI_{attained} = \frac{\sum_i (E_i \cdot GFI_i)}{\sum_i E_i} \quad (1)$$

[156] IMO MEPC, Energy Efficiency of Ships: Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2023), MEPC 82/6/38, 2024, link
[157] DNV, Net-zero shipping: Key findings from the latest Maritime Forecast, 10 October 2025, link (1/2026)
[158] DNV, Fleet readiness surges ahead of fuel supply - green transition at a tipping point, 11 Sep 2025, link (1/2026)

In Equation (1), E_i is the energy consumed from fuel i (MJ), derived from fuel mass using the lower heating value (LHV):

$$E_i = m_i \cdot LHV_i \tag{2}$$

with m_i in kg and LHV_i in MJ/kg.

GFI_i is the fuel-specific well-to-wake greenhouse gas fuel intensity (in g CO_2eq/MJ), calculated by converting the lifecycle GHG emissions of fuel i into CO_2-equivalent and dividing by the energy delivered by that fuel.

$$GFI_i = \frac{\sum_g \left(CF_{i,g}^{WTW} \cdot GWP_g \right)}{LHV_i} \tag{3}$$

where:

$CF_{i,g}^{WTW}$ is the **well-to-wake emission factor** of greenhouse gas g for fuel i, expressed as $\mathrm{kg}_g/\mathrm{kg}$ of fuel, including both upstream ("well-to-tank") and onboard ("tank-to-wake") contributions;

GWP_g is the **global warming potential** for gas g (dimensionless) over 100 years lifecycle.

LHV_i is the **lower heating value** of fuel i, expressed as MJ/kg.

Default Well-to-Tank (WtT) values of CO_2 emissions are referred as per the FuelEU Maritime Regulation (2023/1805)[159], largely unspecified under IMO. These factors sit within the broader IMO life cycle (Well-to-Wake) GHG intensity framework adopted in the 2024 IMO LCA Guidelines on Life Cycle GHG Intensity of Marine Fuels, Annex 10[160], which provides Tank-to-Wake (TtW) CO_2 and CO_2-equivalent emission factor guidance. Ongoing technical refinement and implementation support for the IMO LCA framework is being undertaken under GESAMP's Working Group on Life Cycle GHG Intensity of Marine Fuels (WG 46)[161].

The Tank-to-Wake (TtW) values of CO_2 and CO_2 equivalent emissions given by the IMO 2024 Guidelines take into account the following Global Warming Potential (GWP) for a 100 years life span:

$$GWP_{CO_2}(100\ years) = 1$$

$$GWP_{CH_4}(100\ years) = 28$$

$$GWP_{N_2O}(100\ years) = 265$$

Thus, the GFI for various options is presented in Table 7, next page.

[159] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC, link
[160] IMO MEPC 81/16/Add.1, Annex 10, 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels, link
[161] GESAMP, Working Group on Life Cycle GHG Intensity of Marine Fuels (GESAMP-LCA WG), link (1/2026)

Table 7: Indicative Well-to-Wake (WtW) GHG intensities (GWP100, IPCC AR5) compiled using the IMO 2024 LCA Guidelines (Resolution MEPC.391(81)

Fuel	LCV (MJ/ g fuel)	WtT	TtW					WtW		
		CO_2eq (gCO_2/MJ)	CfCO_2 (gCO_2 / gfuel)	CfCH_4 (gCH_4/ g fuel)	CfN_2O (gN_2O/g fuel)	Cf CO_2 eq (g CO_2eq / g fuel)	CO_2eq (gCO_2eq/MJ)	Total CO_2eq (gCO_2eq/MJ)	Total CO_2eq (t CO_2/ t fuel)	Total CO_2eq (t CO_2/ t FOeq)[a]
HFO (VLSFO)	0.0402	16.8	3.114	0.00005	0.00018	3.163	78.68	95.48	3.84	3.84
LFO	0.0412	13.2	3.151	0.00005	0.00018	3.200	77.67	90.87	3.74	3.65
MDO	0.0427	14.4	3.206	0.00005	0.00018	3.255	76.23	93.93	4.01	3.78
LNG	0.0480	18.5	2.750	0	0.00011	2.779	57.90	76.40	3.67	3.07
LPG§	0.0463	7.8	3.000	0.00005	0.00018	3.000	65.86	73.66	3.41	2.96
Hydrogen‡	0.12	132	0	0	"–" for N_2O, interpreted as zero	0	0	132.0	15.84	5.31
Ammonia‡	0.0186	121	0	N/A	TBM	-	-	121.0**	2.25**	4.86
Methanol†	0.0199	31.3	1.375	TBM	TBM	-	69.10**	100.40**	2.00**	4.04
e-LNG§§	0.0491	§§	2.750	0	0.00011	2.779	56.60	WtT + 56.60	—	—
Biodiesel‡‡	0.0372	20.8	2.834	TBM	TBM	-	76.18**	96.98**	3.61**	3.90

* LCV values obtained from the IMO MEPC 81/16/Add.1, Annex 10, 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels, link. Where IMO default Well-to-Tank (WtT) factors are not yet established for a given pathway, default factors obtained from the EU Regulation 2023/1805[159]. N/A stands for not applicable, TBM stands for "to be measured". **Methane slip is not accounted for in the LNG calculations (see Note 2).**

[a] Values are reported primarily as gCO_2eq/MJ (LCV) consistent with the IMO 2024 LCA Guidelines. For reader convenience, values are also expressed as tCO_2eq per tonne fuel-oil-equivalent (t FOeq), where 1 t FOeq is defined on an energy basis using as reference the lower calorific value for HFO stated in the table. Conversion equation:

$$t\,CO_{2\,eq}/t\,FO_{eq} = \frac{g\,CO_{2\,eq}/MJ \times LCV_{FOeq}(MJ/t\,FOeq)}{10^6}$$

§ fossil

‡ Fossil; natural gas pathway.

** CO_2 only. The EU Regulation flags CH_4 and/or N_2O as TBM, so the above figures are the minimum emissions from the fixed CO_2 factor alone.

† Fossil; natural gas pathway.

§§ Renewable Fuel of Non-Biological Origin (RFNBO). Synthetic fuel produced using renewable electricity and non-biogenic feedstocks, whose lifecycle greenhouse-gas intensity must be determined on the basis of certified production pathways rather than fixed default values. Thus EU Regulation does not provide WtT emission factor.

‡‡ WtT obtained from IMO MEPC 81/16/Add.1, Annex 10. Also, certain biofuels pathways are certified separately, so respective WtW values are not determinable from defaults. **See also Note 3**.

Notes on Table 7

1. The IMO 2024 LCA Guidelines include procedures and templates for establishing default emission factors and explicitly anticipate updates as further pathways are reviewed. Several submissions—explicitly including **default emission factors and slip values for LNG and ammonia**—have been referred into the **GESAMP-LCA Working Group** process[162], and values under consideration differ materially across submissions and methodological choices. Consequently, any point estimates shown here for LNG and ammonia should be treated as **indicative** pending IMO/GESAMP conclusions; FuelEU defaults can be used as a pragmatic benchmark in the interim for comparability across fossil pathways.
2. In the IMO 2024 LCA Guidelines, LNG tank-to-wake default emission factors include an explicit methane slip term (Cslip, mass % of fuel) that depends on engine concept. The default Cslip values for LNG are: 0.15% for LNG Diesel (dual-fuel, slow-speed), 1.7% for LNG Otto (dual-fuel, slow-speed), and 3.5% for LNG Otto (dual-fuel, medium-speed) engines (with additional defaults for other types of engines). Incorporating this factor into the calculations above, changes the LNG WtW totals as shown below:

Fuel / engine	WtW Total CO_2eq (gCO_2eq/MJ)	WtW Total CO_2eq (t CO_2/t fuel)	Total CO_2eq (t CO_2/t FOeq)
LNG Diesel (dual fuel, slow speed)	77.19	3.71	3.10
LNG Otto (dual fuel, slow speed)	85.33	4.10	3.43
LNG Otto (dual fuel, medium speed)	94.79	4.55	3.81

B30 GFI Calculation removing the biogenic CO_2 portion

Under FuelEU, the biodiesel WtT value, adjusted to remove the CO2 combustion content, would be:

$$WtT_{FAME} = WtT - \frac{Cf_{CO_2}}{LCV} = 20.8 - \frac{2.834}{0.0372} = -55.38\ gCO_2eq/MJ$$

Considering emission factors as per HFO since biofuel-specific onboard factors are not yet established/verified, the non-CO2 emission factor for the combustion of biodiesel will be:

$$Cf_{nonCO_2eq} = (0.00005 \times 28) + (0.00018 \times 265) = 0.0491\ gCO_2eq/g$$

The TtW value for biodiesel must include both CO_2 and non-CO_2 combustion spieces, thus:

$$TtW_{FAME} = \frac{Cf_{CO_2} + Cf_{nonCO_2eq}}{LCV} = \frac{2.834 + 0.0491}{0.0372} = 77.50\ gCO_2eq/MJ$$

And the WtW value of biodiesel, adjusted to remove biogenic CO_2 combustion content, will be:

$$WtW_{FAME} = WtT_{FAME} + TtW_{FAME} = 22.12\ gCO_2eq/MJ$$

Assuming that B30 is 70% HFO and 30% Biodiesel (FAME) by mass, the weighted energy share of biodiesel calculates as:

$$x_{FAME} = \frac{0.3 \times LCV_{FAME}}{0.7 \times LCV_{HFO} + 0.3 \times LCV_{FAME}} = 0.2840$$

And:

$$WtW_{B30} = (1 - x_{FAME}) \times WtW_{HFO} + x_{FAME} \times WtW_{FAME} \Rightarrow$$

$$WtW_{B30} = 72.29\ gCO_2eq/MJ$$

3. The biodiesel (FAME) WtT value reported under the IMO LCA framework can also create an interpretational mismatch with FuelEU Maritime conventions. Because biofuels contain biogenic carbon, FuelEU-type accounting often presents results by removing the "biogenic CO_2" portion from the life-cycle total (to avoid counting biogenic CO_2 as a net addition to the atmosphere), while still retaining non-CO_2 combustion species (CH_4, N_2O) as climate-relevant. Thus, the WtW value, adjusted to remove the biogenic CO_2 combustion content, would be $22.12\ gCO_2eq/MJ$ for FAME. Accordingly, for a B30 blend defined on a 70/30 mass basis, the IMO-required energy-weighted blend WtW value is $72.29\ gCO_2eq/MJ$ (see also the note in the side bar for the relevant calculations).

[162] IMO, Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 17), 23-27 September 2024, link (1/2026)

4. **Hydrogen leakage (not captured in current IMO LCA scope):** While hydrogen is not a direct GHG, literature[163] indicates that **fugitive H_2 emissions can create indirect warming effects** and could be material depending on leakage rates; this remains uncertain and is not included in the current IMO LCA scope (CO_2/CH_4/N_2O).

As demonstrated by these values and the progressively tightening NZF targets, compliance with the Direct target in particular, **presupposes the large-scale availability and deployment of alternative fuels whose production pathways, supply chains, and bunkering infrastructure are not yet established at commercial scale**.

This **implicit reliance on early adoption of alternative fuels despite limited physical availability and significant cost and infrastructure constraints, will increase the likelihood that compliance will be achieved through remedial mechanisms rather than through fuel switching in the initial phases of implementation**. Moreover, for several existing fuel options (particularly ZNZs and biofuels) the processes and criteria governing lifecycle emissions accounting, sustainability thresholds, and fuel accreditation remain under development, with key parameters dependent on future certification methodologies rather than fixed default values. This creates **uncertainty regarding the environmental integrity, comparability, and verifiability of claimed GFI performance, complicating both compliance planning and investment decision-making**.

Against this background, the following sub-chapter sets out the calculation methodology used to assess NZF penalties across different fuel options, based on attained GFI, applicable targets, and the associated remedial unit structure.

5.2. NZF Compliance Calculation Methodology

Under the NZF, compliance is assessed by comparing a ship's attained greenhouse-gas fuel intensity, $GFI_{attained}$, with the applicable regulatory targets for each reporting year y. Two targets apply: the **Base Compliance Target**, T_y^{Base}, and the more stringent **Direct Compliance Target**, T_y^{Direct}, both expressed in g CO_2eq/MJ. Depending on the relative position of $GFI_{attained}$ with respect to these targets, a ship may generate either a compliance deficit, requiring the purchase of Remedial Units (RUs), or a compliance surplus, generating Surplus Units (SUs). When the $GFI_{attained}$ exceeds the Base Target, the portion of the deficit **between the Direct target and the Base target** is charged at the **Direct RU** rate, while only the incremental deficit **above the Base target** is charged at the **Base RU** rate.

For a given reporting period, the intensity exceedance relative to each target is defined as:

[163] Warwick N, et al. Atmospheric implications of increased Hydrogen use, 2022, link.

$$\Delta_y^{Base} = GFI_{attained} - T_y^{Base}$$

$$\Delta_y^{Direct} = GFI_{attained} - T_y^{Direct}$$

These intensity differences are converted into emissions quantities by scaling with total energy consumption, in MJ:

$$E_{tot} = \sum_i E_i$$

as derived in the GFI calculation section. When Δ_y^{Base} and/or Δ_y^{Direct} are greater than zero, they represent compliance deficits, expressed in tonnes of CO_2-equivalent:

$$D_y^{Base} = \max\left(0, \Delta_y^{Base}\right) \cdot \frac{E_{tot}}{10^6}$$

$$D_y^{Direct} = \max\left(0, \Delta_y^{Direct}\right) \cdot \frac{E_{tot}}{10^6}$$

The total annual compliance cost is then calculated as:

$$C_y = P_{Base} \cdot D_y^{Base} + P_{Direct} \cdot \left(D_y^{Direct} - D_y^{Base}\right)$$

where P_{Direct} and P_{Base} denote the prices of Tier-1 (Direct band) and Tier-2 (above Base) Remedial Units, respectively.

Conversely, when the $GFI_{attained}$ is below T_y^{Direct}, a surplus is generated, expressed in tonnes of CO_2-equivalent:

$$S_y = \max\left[0, \left(T_y^{Direct} - GFI_{attained}\right)\right] \cdot \frac{E_{tot}}{10^6}$$

Fuels whose attained GFI fall below the Direct Compliance Target incur no penalty, instead they generate Surplus Units:

$$SU = P_S \cdot S_y$$

where P_S denotes the price of the Surplus Units.

By construction, $S_y > 0 \Rightarrow D_y^{Direct} = D_y^{Base} = 0$, and $D_y^{Direct} > 0 \Rightarrow S_y = 0$.

The following sub-section presents a calculation of NZF compliance costs for three fuel options, taking as an example a Capesize bulk carrier consuming 18,000 tons of fuel per year.

5.3. NZF Compliance Cost Calculations and Fuel Cost Sensitivities

This subsection presents the calculation of NZF compliance costs for a representative ship with an annual energy demand equivalent to the consumption of 18,000 tons of HFO, and compares compliance outcomes for conventional fuel use, LNG, and biofuel blending (B30). All calculations are based on fuel-specific GFI values derived from IMO lifecycle guidelines and

FuelEU referencing of WtT, the NZF Base and Direct targets for the period 2028–2035, and the two-tier remedial structure comprising Tier-1 Remedial Units (RUs) priced at USD 100/t CO_2eq and Tier-2 RUs priced at USD 380/t CO_2eq. Surplus Units (SUs), where generated, are valued at USD 350/t CO_2eq.

To ensure comparability across fuels, energy demand is held constant and fuel consumption is adjusted on an energy-equivalent basis using lower heating values. Compliance deficits and surpluses are calculated by converting GFI exceedances or shortfalls relative to the applicable NZF targets into tons of CO_2-equivalent, which are then monetized using the relevant RU or SU prices. The resulting annual compliance costs are presented in Table 8.

It must be noted that these quantitative results are intended as **indicative** estimates of the order-of-magnitude. Life cycle (WtT/WtW) emission factors – particularly for pathways such as LNG and ammonia – remain subject to **material variation across studies and assumptions** and are also the subject of ongoing refinement under the IMO LCA workstream. Accordingly, Table 8 should be read as a **scenario illustration** rather than a definitive compliance cost calculation; results are best interpreted in terms of **directionality and relative sensitivity**. This uncertainty is itself a drawback of the NZF architecture, because it weakens investment predictability and can create **volatile or inconsistent incentives** across fuels depending on how default factors evolve.

5.3.1. Energy basis and equivalent annual fuel consumption

Energy demand from 18,000 tons/year HFO (LHV 0.0402 MJ/g = 40.2 MJ/kg):

$$E_{tot} = 18{,}000{,}000\ kg \times 40.2 \frac{MJ}{kg} = 723{,}600{,}00 \frac{MJ}{year}$$

Thus, the Energy-equivalent annual fuel masses will be for LNG:

$$\frac{723{,}600{,}00\ MJ/year}{48\ MJ/kg} = 15{,}075\ tons/year$$

while for the B30 blend, assuming a LHV value of $0.7 \times 40.2 + 0.3 \times 37.2 = 39.3\ MJ/kg$[29], the Energy-equivalent annual fuel masses will be:

$$\frac{723{,}600{,}00\ MJ/year}{39.3\ MJ/kg} = 18{,}412\ tons/year$$

5.3.2. Compliance Cost Calculations

Table 8 does not account for **fuel price premiums**, which represent a material and immediate economic consideration for shipowners. Using conservative market assumptions, both LNG and B30 are associated with incremental fuel costs of approximately USD 2.5 to 4 million per vessel per year on an energy-equivalent basis, relative to HFO. These premiums are of

comparable magnitude to, and in some cases exceed, the calculated NZF compliance benefit over HFO in the early years of implementation. A sensitivity analysis applying a ±25% variation in fuel prices indicates that fuel-cost uncertainty can materially alter the relative attractiveness of compliance pathways, reinforcing the importance of fuel market volatility in investment decisions.

*Table 8: IMO NZF Compliance Cost Comparison of a Ship Consuming HFO 18,000 tons/year – FIGURES **DO NOT INCLUDE** FUEL PRICE PREMIUMS OR METHANE SLIP – Negative values imply compliance deficits*

	HFO	LNG	B30*
GFI (g CO_2eq/MJ)	92.18	76.40	72.29
Year	**Compliance cost (USD)**		
2028	-1,595,871	263,137	1,304,036
2029	-2,108,961	-59,842	831,453
2030	-2,622,051	-194,865	358,869
2031	-3,750,850	-491,918	-194,518
2032	-4,879,649	-788,970	-491,570
2033	-6,008,447	-1,669,452	-788,623
2034	-7,137,246	-2,798,251	-1,668,132
2035	-8,266,045	-3,927,050	-2,796,931
Total	**-36,369,120**	**-9,667,211**	**-3,445,417**

* The B30 greenhouse-gas fuel intensity is calculated as an energy-weighted (MJ, LCV basis) blend of HFO and FAME, consistent with the IMO LCA blending rule. For comparability with the biofuel treatment discussed under Table 7, the FAME component is reported on a carbon-source-consistent basis, i.e., biogenic CO_2 from combustion is excluded from the WtW total, while non-CO_2 combustion species (CH_4 and N_2O) are retained. Using Table 7 LCVs (HFO: 40.2 MJ/kg; FAME: 37.2 MJ/kg), a nominal 70/30 mass blend corresponds to energy shares of 0.716/0.284, yielding GFI_{B30} = 72.29 gCO_2eq/MJ under this convention.

For LNG, additional uncertainty arises from **methane slip**, which **is not included in the GFI values used** but remains highly dependent on engine technology, operating profile, and control measures. High methane slip would materially increase the attained GFI, reduce or eliminate any early-year compliance advantage, and raise Tier-2 penalty exposure under the NZF. This sensitivity further weakens the case for LNG as a long-term compliance solution under increasingly stringent targets, despite its potential role as a transitional fuel.

Moreover, the additional capital expenditure required for an LNG-fuelled Capesize bulk carrier – estimated at **USD 18–20 million** – cannot be recovered under NZF conditions, as the penalty differential between LNG and VLSFO is too small, producing a payback period of **15–18 years**. Thus, the NZF regulation renders LNG non-viable as a transition fuel, a conclusion inconsistent

with the fact that LNG is responsible for **98% of all alternative-fuel use** in the 2023 IMO DCS dataset, yet provides no compliance advantage under the NZF structure.

Concerning B30, as mentioned, even during periods of nominal regulatory compliance, biofuel blending does not necessarily offer an economically superior pathway. This outcome is compounded by structural supply limitations. Global biodiesel supply data[164] confirm that production reached approximately **46 million tonnes in 2024** and is projected to increase to around **57 million tonnes by 2035**, whereas the maritime sector alone consumes approximately **216 million tonnes of fuel annually**. Even under optimistic supply scenarios, B30 would therefore be capable of supplying only about **26% of the sector's total fuel demand by 2035**, confirming that biodiesel cannot support fleet-wide NZF compliance and must remain a niche or transitional option rather than a systemic solution.

Taken together, the results demonstrate that, under the proposed NZF design, compliance costs are dominated by Tier-2 penalties as the Base target tightens, while fuel-switching strategies entail substantial upfront capital expenditure, fuel price risk, and uncertainty regarding long-term availability and certification. These factors explain why, for a significant portion of the existing fleet, short- to medium-term compliance through remedial payments may appear economically preferable to immediate retrofitting or fuel conversion.

Similar penalty structures and cost dynamics apply across all major ship types, as can easily be shown. Based on the calculations presented, cumulative NZF penalties over the period from 2030 to 2050 are projected to reach levels that, for many vessel categories, exceed their capital cost by a substantial margin. For large bulk carriers, container vessels, and LNG carriers alike, the cumulative compliance burden is expected to be multiple times higher than the initial investment cost of the vessel itself.

Even for modern or newly built ships, including LNG carriers and vessels incorporating advanced energy-saving technologies, the overall penalty trajectory is only marginally altered. While such measures may reduce fuel consumption or operational emissions, they do not materially lower the attained GFI to a level that would avoid sustained Remedial Unit obligations under the NZF. As a result, long-term compliance costs remain structurally high.

Moreover, NZF-related costs are additive to obligations arising under other regulatory regimes, notably the EU ETS and FuelEU Maritime. The combined effect of overlapping regulatory frameworks significantly amplifies total cost exposure over the vessel's lifetime. Comparable patterns are observed across shipping segments, indicating that, under the current NZF design, cumulative regulatory costs frequently approach or exceed vessel capital values, with material implications for asset economics, investment decisions, and fleet renewal strategies.

[164] IndexBox report: World-Biodiesel-Market Analysis, Forecast, Size, Trends And Insights, update of 1st Nov. 2025.

Table 9 depicts calculations based on the NZF, showing what the penalties of the existing global fleet would be considering the present activities and fuel consumption. The total projected annual penalties could surpass the gross domestic product of smaller national economies, highlighting the disproportionate magnitude of the regulatory burden (Figure 12).

Table 9: Potential Total Penalties Collectable by the IMO Net-Zero Fund. Assumption: Most ships continue operating business-as-usual and comply by purchasing RUs. Estimated annual marine fuel consumption for the global fleet - HFO: 90,710,000 tons - VLSFO: 102,050,000 tons – LSMGO: 34,020,000 tons.

	Tier 2 (USD)	Tier 1 (USD)	Total Penalties (USD)
2028	$ 16,074,994,677	$ 11,160,627,917	$ 27,235,622,594
2029	$ 22,599,669,460	$ 11,160,627,917	$ 33,760,297,377
2030	$ 29,124,344,242	$ 11,160,627,917	$ 40,284,972,159
2031	$ 43,478,628,764	$ 11,160,627,917	$ 54,639,256,681
2032	$ 57,832,913,285	$ 11,160,627,917	$ 68,993,541,202
2033	$ 72,187,197,807	$ 11,160,627,917	$ 83,347,825,724
2034	$ 86,541,482,328	$ 11,160,627,917	$ 97,702,110,245
2035	$ 100,895,766,850	$ 11,160,627,917	$ 112,056,394,767
2036	$ 123,732,128,588	$ 11,160,627,917	$ 134,892,756,505
2037	$ 146,568,490,327	$ 11,160,627,917	$ 157,729,118,244
2038	$ 169,404,852,066	$ 11,160,627,917	$ 180,565,479,983
2039	$ 192,241,213,804	$ 11,160,627,917	$ 203,401,841,721
2040	$ 215,077,575,543	$ 11,160,627,917	$ 226,238,203,460
2041	$ 226,495,756,412	$ 11,160,627,917	$ 237,656,384,329
2042	$ 237,913,937,282	$ 11,160,627,917	$ 249,074,565,199
2043	$ 249,332,118,151	$ 11,160,627,917	$ 260,492,746,068
2044	$ 260,750,299,020	$ 11,160,627,917	$ 271,910,926,937
2045	$ 272,168,479,890	$ 11,160,627,917	$ 283,329,107,807
2046	$ 283,586,660,759	$ 11,160,627,917	$ 294,747,288,676
2047	$ 295,004,841,628	$ 9,014,353,318	$ 304,019,194,946
2048	$ 306,423,022,498	$ 6,009,568,879	$ 312,432,591,377
2049	$ 317,841,203,367	$ 3,004,784,439	$ 320,845,987,806
2050	$ 329,259,384,236	$ -	$ 329,259,384,236
Total	**$ 4,054,534,960,984**	**$ 230,080,637,059**	**$ 4,284,615,598,043**

When these regulatory cost projections are viewed alongside the aforementioned fleet-composition and fuel-consumption data, a consistent conclusion emerges. **The global fleet scarcely possesses the technical capability to use NZF-compliant fuels**. The fuels that are technically available (LNG, biofuels), demonstrating lower well-to-wake environmental footprints, are penalized by the NZF during the early phase of the GFI trajectories, despite their measurable reductions in CO_2, NO_x, SO_x, and particulate emissions relative to conventional marine fuels. In practical terms, even the most technologically and commercially advanced lower-carbon fuels available today are treated as non-compliant under the NZF methodology, resulting in immediate and unavoidable penalty exposure irrespective of their environmental advantages.

On the other hand, fuels that would satisfy NZF GFI thresholds (green ammonia, green methanol, e-fuels, hydrogen) do not exist at a commercial scale. As a result, ships have virtually no feasible alternative-fuel compliance pathway and are therefore structurally bound to NZF penalties. The NZF thus functions less as an emissions-reduction mechanism via fuel transition and more as a global carbon-pricing system applied to the deep-sea fleet.

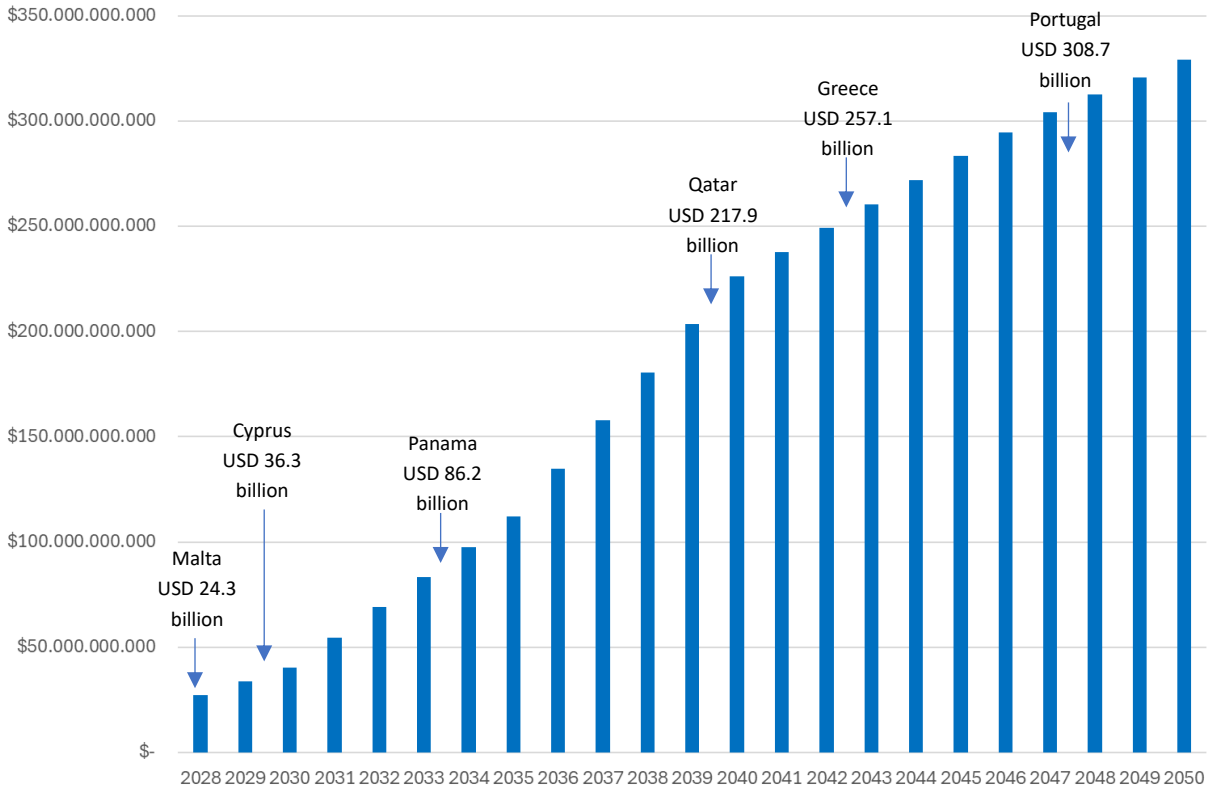


Figure 12: Projected Annual IMO NZF Penalties 2028-2050[165]

From an institutional-governance perspective, assigning the International Maritime Organization (an intergovernmental body whose mandate is regulatory standard-setting rather than financial administration) the responsibility for managing a fund of about USD 4 trillion is operationally impracticable and structurally misaligned with its core competencies. Reliance on such a mechanism would risk transforming the IMO NZF from an environmental-performance instrument into a de facto revenue-collection framework, thereby undermining its stated objective of reducing the environmental footprint of international shipping and failing to deliver the decarbonization outcomes for which it was conceived.

5.3.3. Key takeaways

As shown in Table 7, the well-to-wake emission intensities of conventional fossil marine fuels such as HFO, LFO, and MGO exceed the NZF Base Compliance Target from the outset of

[165] https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

implementation and, over time, also exceed the more stringent Direct Compliance Target. As a result, the use of these fuels gives rise to sustained remedial obligations under the NZF, initially dominated by Tier-1 charges and progressively shifting toward Tier-2 penalties as the targets tighten. Even in the early years of the framework, these obligations translate into a material surcharge per unit of fuel consumed, reflecting the high lifecycle carbon intensity of conventional fuels.

As the NZF targets are progressively tightened in subsequent years, the cost exposure associated with fossil fuels escalates sharply. The increasing gap between attained GFI values and the regulatory targets causes a growing share of emissions to fall under the higher-priced Tier-2 remedial structure, substantially increasing the effective carbon cost embedded in fuel use. Under this tightening regime, LNG – despite its lower lifecycle GHG intensity relative to oil-based fuels – also becomes subject to NZF penalties once its attained GFI no longer remains below the applicable thresholds.

By the mid-2030s, when both the Base and Direct Compliance Targets have declined significantly, no fossil marine fuel remains below the NZF thresholds. All fossil fuels are therefore subject predominantly to Tier-2 remedial charges, resulting in an effective surcharge per tonne of fuel that is of the same order of magnitude as the underlying market fuel price. Under these conditions, the NZF compliance cost alone materially increases the total cost of fossil-fuel use, in some cases approaching or exceeding the fuel's purchase price, thereby fundamentally altering the economics of continued reliance on conventional marine fuels.

5.4. Impact on the Greek-owned and Greek-operated fleet

The economic implications of the NZF for the Greek-owned and Greek-operated fleet are expected to mirror those observed at the global level. Analytical calculations presented in the following pages demonstrate that, irrespective of whether vessels continue operating on fossil marine fuels or transition to green fuels, total fuel-related expenditure increases by more than 300%, even before accounting for the substantial capital investments required for retrofitting or replacing conventional propulsion systems.

Beyond the global-level cost escalation, the incidence of the NZF on Greek-controlled shipping is likely to be **structurally shaped by fleet composition and trading patterns**. The following analysis indicates that the Greek-controlled energy and fuel footprint is concentrated in **bulk carriers and tankers**, with a smaller share in **containerships**. This matters, because bulk and tanker segments predominantly operate in **tramp markets**, with variable routes, heterogeneous charterers, and limited ability to commit to fixed corridors or guaranteed bunkering volumes. In practice, early supplies of NZF-compliant "ZNZ" fuels are likely to be **scarce, geographically concentrated, and allocated through multi-year offtake arrangements and chain-of-custody structures**, conditions that are operationally easier for large liner operators to satisfy due to network stability and demand aggregation. Under this asymmetry,

the NZF's tightening GFI trajectory risks rendering tramp-heavy fleets (Greek-controlled in particular) disproportionately reliant on **Remedial Unit (RU) purchases** as the marginal compliance mechanism. This would imply that a significant share of Greek-owned compliance spend delivers limited direct decarbonization within the tramp segment, while effectively transferring value toward actors best positioned to secure scarce low-carbon fuels and monetize compliance flexibility, with cost pass-through dynamics that are structurally more available to liner supply chains than to tramp shipping.

Table 10 summarizes global fuel consumption by ship type and by fuel category. To derive the corresponding consumption for the Greek-controlled fleet, the analysis applies the global deadweight tonnage (DWT) distribution per ship type together with the share of Greek-controlled DWT within each segment, as shown in Table 11.

Table 10: Global Fuel Consumption of Marine Fuels, by Ship Type (Source: IMO)[166]

Global Consumption (t/year)					
Type of ship	**Diesel/Gas Oil (ton)**	**Heavy Fuel Oil (HFO) (ton)**	**Light Fuel Oil (LFO) (ton)**	**Liquefied Natural Gas (LNG) (ton)**	**Liquefied Petroleum Gas (LPG) – Propane (ton)**
Bulk carriers (all sizes)	3,933,563	36,888,628	14,035,409	66,123	4,896
Containerships	4,858,186	43,113,643	10,182,858	468,540	3,990
Tankers	6,984,682	27,696,693	7,637,017	207,668	187
LNG carriers	1,063,442	1,822,407	1,015,466	11,530,785	22,346
Gas Carrier	640,003	3,523,942	1,276,417	76,887	160,986
LNG+Gas Carries	1,703,445	5,346,349	2,291,883	11,607,672	183,332
Ro-ro cargo ships (vehicle carrier)	699,028	3,008,399	2,535,193	39,547	0
Total (for the above types)	**18,178,904**	**116,053,712**	**36,682,360**	**12,389,550**	**192,405**

Table 11: Global DWT per Ship Type and the DWT Share of Greek-controlled fleet[167,6]

Type of ship	Global DWT (values for 2020)	% of total global DWT	Greek DWT (%of global DWT)
Bulk carriers (all sizes)	810,000,000	41.5	24.9
Containerships	260,000,000	13.4	8.1
Tankers oil	490,000,000	25.1	29.2
Tankers chemicals+others	110,430,000	5.6	15.4
Tankers total	600,430,000		
LNG carriers + Gas Carriers	65,000,000	3.3	13.4[168]
Ro-ro cargo ships (vehicle carrier)	6,400,000	0.3	8.2

[166] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Reporting year 2023.pdf
[167] https://ghgsmart.imo.org/wp-content/uploads/2023/05/Fourth-IMO-GHG-Study-2020-Full-report-and-annexes_compressed.pdf
[168] https://maritimes.gr/wp-content/uploads/2024/03/Greek-Controlled-Shipping-Statistics-2024.pdf

The fuel consumption attributable to the Greek-controlled fleet was then calculated by multiplying the total fuel consumption for each ship type by the Greek share of world DWT for that ship type. The resulting estimates, disaggregated by ship type and fuel type, are presented in Table 12.

Table 12: Greek Fleet Consumption calculations

Type of ship	Greek DWT/global DWT	Diesel/Gas Oil (ton)	Heavy Fuel Oil (HFO) (ton)	Light Fuel Oil (LFO) (ton)	Liquefied Natural Gas (LNG) (ton)	Liquefied Petroleum Gas (LPG) – Propane (ton)
Bulk carriers (all sizes)	0.249	979,457	9,185,268	3,494,817	16,465	1,219
Containerships	0.081	393,513	3,492,205	824,811	37,952	323
Tankers	0.267	1,862,251	7,384,473	2,036,176	55,368	50
LNG+Gas Carries	0.134	228,262	716,411	307,112	1,555,428	24,566
Ro-ro cargo ships (vehicle carrier)	0.082	57,320	246,689	207,886	3,243	0
Total		**3,520,803**	**21,025,046**	**6,870,803**	**1,668,456**	**26,159**

The total annual fuel cost for each fuel type is calculated in Table 13, under both low-price and high-price scenarios. **These figures represent commodity fuel expenditure only (and exclude CAPEX) and should be treated as the baseline cost to which regulatory costs must be added.** In practice, the total cost of operating under the decarbonization policy environment equals fuel cost plus compliance-related charges and/or credits arising from FuelEU Maritime, the EU ETS and the IMO Net-Zero Framework (NZF), the latter being quantified in the relevant sections of this report. Accordingly, Table 13 should not be interpreted as a "total cost" comparison across fuels, but as the **underlying fuel-spend component onto which the regulatory compliance impacts are applied**.

Table 13: Calculations of Total Annual Fuel costs for Greek-controlled ships[169]

Fuel	Consumption (ton/year)	Price ($/ton)		Total Cost ($)	
		Low	High	Low price scenario	High price scenario
Diesel (MGO)	3,520,803	720	886	2,534,978,255	3,119,431,574
Heavy Fuel Oil (HFO)	21,025,046	330	480	6,938,265,031	10,092,021,863
Light Fuel Oil (LFO)	6,870,803	415	666	2,851,383,051	4,575,954,487
Liquefied Natural Gas (LNG)	1,668,456	745	850	1,242,999,395	1,418,187,229
Liquefied Petroleum Gas (LPG) - Propane	26,159	534	673	13,968,714	17,604,765
Total				**13,581,594,445**	**19,223,199,919**

[169] https://integr8fuels.com/bunker-types/lsmgo-prices/ (Accessed 22/11/2025)

In parallel, the lower heating value (LHV) of each fuel, obtained from the IMO 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels, Annex 10[160], was used to calculate the total energy output associated with each fuel type.

Table 14: Total Energy Produced from the Fuels used annually by the Greek-controlled fleet

Fuel	ton/year	Energy produced from 1 Kg of fuel (MJ)[170]	Energy produced (MJ)	ton FOeq
Diesel (MDO)	3,520,803	42.7	150,338,293,706	3,739,759
Heavy Fuel Oil (HFO)	21,025,046	40.2	845,206,831,046	21,025,046
Light Fuel Oil (LFO)	6,870,803	41.2	283,077,064,381	7,041,718
Liquefied Natural Gas (LNG)	1,668,456	48.0	80,085,867,053	1,992,186
Liquefied Petroleum Gas (LPG) - Propane	26,159	46.3	1,211,145,023	30,128
Total			**1,359,919,201,209**	**33,828,836**

The energy values derived in Table 14 form the basis for estimating the quantities of respective key ZNZ fuels that would be required to meet the entire energy demand of the Greek-controlled fleet, hence achieving near zero. The resulting fuel-quantity requirements, presented in

Table 15, indicate that the cost of operating exclusively on any of key ZNZ fuels increases by a factor of four or more. Fuel prices from Paragraph 3.2 of the present report were used.

Table 15: Fuel Cost for ZNZ fuels needed to meet Greek-controlled fleet energy demand

ZNZ Fuel	Energy produced by 1 Kg of fuel (MJ)	Quantity of ZNZ fuel (ton) to produce total required energy*	Low price ($/ton)	High price ($/ton)	Low price scenario ($)	High price scenario ($)
Hydrogen	120	11,332,660	4000	6000	45,330,640,040	67,995,960,060
Ammonia	18.6	73,113,936	800	1200	58,491,148,439	87,736,722,659
Methanol	19.9	68,337,648	1100	1600	75,171,413,132	109,340,237,283
e-LNG	49.1	27,696,929	2500	3500	69,242,321,854	96,939,250,595

** The column calculates the quantity that would be required if each of the presented ZNZ fuels would be used alone to produce the total required energy of 1,359,919,201,209 MJ*

Overall, irrespective of whether vessels transition to green fuels or continue operating on fossil fuels while bearing NZF penalties, total fuel costs increase by a great extent. These

[170] IMO MEPC 81/16/Add.1, Annex 10, 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels, link

estimates do not account for the substantial capital expenditure required to retrofit existing vessels or replace conventional propulsion systems, which further amplifies the financial burden. When the extremely limited availability of green hydrogen, ammonia, methanol, and LNG is considered – an availability constraint that is expected to persist for several years until large-scale production facilities become operational – the NZF framework appears to create a near-term compliance impasse. Moreover, the NZF penalizes even the most readily available lower-emission transitional fuels, such as LNG and biofuel blends, during the early phase of the GFI trajectory, despite their demonstrably reduced environmental footprint relative to conventional fuels.

5.5. Greece-Specific Exposure and External Countermeasure Risks

5.5.1. Structural exposure of Greek-controlled shipping to NZF cost escalation

As demonstrated in the preceding sections, the NZF's cost effects are disproportionately material for Greece due to the scale and composition of the Greek-controlled fleet and its concentration in segments with high energy use and high exposure to global regulatory measures, with limited capacity for leveraging scarce ZNZ options. Greece controls the world's largest merchant fleet by deadweight tonnage and maintains particularly strong positions in tankers, LNG carriers, and bulk carriers, meaning that a large share of global fuel consumption and compliance liabilities will be borne by entities managed and financed from Greece, irrespective of flag[1].

As demonstrated in the above calculations, total fuel-related expenditure rises sharply under all modelled pathways, and this increase is amplified when regulatory compliance costs (RUs/SUs and overlapping EU measures where applicable) and capital costs for conversion or fleet renewal are incorporated. The combination of (i) limited commercial availability of fuels that meet stringent GFI thresholds at scale and (ii) high projected price levels for e-fuels increases the likelihood that, for a substantial portion of the existing Greek-controlled fleet, near-term compliance will be optimized through unit purchases and operational measures rather than rapid fuel switching.

5.5.2. Second-order impacts on Greek economic value creation and maritime cluster activity

Because Greek shipping constitutes a major contributor to Greek value added, employment, and foreign exchange inflows, NZF-driven cost escalation and compliance uncertainty can transmit beyond ship operating companies into the wider maritime cluster (broking, technical management, legal services, insurance, finance, bunkering, port services, and maritime consultancy). The report already quantifies shipping's significance for Greece's GDP/GVA and its employment footprint, implying that sustained margin compression or reduced

competitiveness could have second-order impacts on domestic economic activity even when vessels trade globally.

In practice, the economic incidence will depend on pass-through: where markets permit, compliance costs are transferred via freight rates and charter hire; where they do not, owners absorb a larger share through reduced earnings. This may be particularly relevant in weaker cycles for dry bulk and certain tanker sub-markets, where chartering dynamics and voyage competition constrain full cost pass-through.

5.5.3. Exposure to U.S. countermeasures: operational, commercial, and contractual pathways

A material Greece-specific risk arises from the United States' stated position that it may consider unilateral countermeasures against States supporting the NZF if it is ratified in its current or similar form. The U.S. State Department has publicly outlined possible measures, and Reuters reporting indicates that U.S. officials delivered warnings to at least some governments (including the Netherlands) that support for the NZF could entail economic consequences[35,36,171].

For Greek shipping, the relevance of these measures is not limited to Greek-flagged tonnage; Greek-controlled groups operate multi-flag fleets and frequently trade into U.S. ports across tankers, bulk carriers, LNG carriers, and containerized supply chains. Consequently, even a targeted regime based on flag, ownership, or operator nationality could create operational disruption and incremental costs in specific trades. The principal exposure channels are set out below:

Port access restrictions and differentiated port treatment: U.S. statements have referenced potential investigations and measures that could include blocking vessels registered under supporting nations from U.S. ports or otherwise imposing differentiated port treatment. Even if applied selectively, such restrictions would create immediate operational disruption (diversion, re-routing, discharge at alternative ports, demurrage claims) and could reduce the effective liquidity and tradability of affected tonnage in U.S.-linked chartering markets.

Additional port fees or port levies: The announced "reciprocal measures" include port levies/fees. For Greece, the impact mechanism is direct: increased call costs translate into higher voyage costs on U.S. routes and can alter chartering decisions (e.g., selection of alternative tonnage or reallocation of trades). This may also intensify disputes over cost allocation under charter parties, particularly where "operational control" and "financial responsibility" are separated.

Crew visa restrictions (C-1/D) and crew-change friction: The U.S. has indicated the possibility of visa restrictions for maritime crew members, including increased fees and processing

[171] E. Tunagur, UN shipping emissions deal to pit US against EU-led bloc, October 2025, link (14/12/2025)

burdens, mandatory re-interviews, and quota revisions for C-1/D visas. For Greek shipping companies that rely on multinational crewing and on U.S.-linked crew-change pathways (including relief crew rotations during U.S. calls), this would create operational friction, increased crewing costs, and potential schedule disruption.

Commercial penalties involving U.S. government contracts, LNG terminals, and infrastructure: U.S. statements include potential "commercial penalties" linked to U.S. government contracts and maritime infrastructure projects, with explicit reference to LNG terminals and related infrastructure. Greek-controlled owners are material participants in global tanker and LNG shipping, and the report itself highlights the strategic role of Greek-owned tonnage in energy transport, implying that any restriction affecting LNG-linked commercial opportunities could create outsized strategic consequences for Greek shipping interests and for European energy logistics.

Tariffs and broader trade penalties: Reuters has reported U.S. warnings referencing tariffs and related trade actions as potential responses to support for the NZF. While tariffs are not shipping-specific measures, they can reduce cargo flows, alter trade patterns, and affect demand for tonnage in the relevant routes—thereby indirectly impacting Greek-controlled fleet earnings in U.S.-linked commodity and container trades.

5.5.4. Implications for Greek shipping strategy and risk management

If ratification of the NZF proceeds while U.S. countermeasures remain a credible risk, Greek shipping companies are likely to face a dual-layer challenge. This challenge arises not only from the underlying compliance economics of the NZF—characterised by tightening GFI targets, limited availability of compliant fuels, and escalating remedial costs—but also from increased exposure to geopolitical and regulatory fragmentation across key trade lanes. The interaction of these factors introduces additional uncertainty into commercial decision-making and heightens the importance of proactive risk management.

In response, Greek-controlled operators are expected to place greater emphasis on contractual structuring and claims management. This includes the accelerated incorporation of NZF-specific and reciprocal-measure clauses into time charters, contracts of affreightment, and fuel procurement agreements, with explicit provisions addressing the allocation of remedial and surplus unit costs, potential port levies, rerouting rights, and the treatment of delay or detention arising from regulatory or geopolitical disruptions. Such contractual adjustments will be critical to managing disputes and preserving commercial certainty in an evolving regulatory environment.

At the operational level, maintaining trade and routing optionality is likely to become an increasingly important strategic consideration. Operators may seek to preserve the flexibility to redeploy tonnage away from routes that become exposed to disproportionate regulatory or political risk, particularly where cost impacts become non-linear or unpredictable. This

flexibility, however, must be balanced against reputational considerations and the expectations of long-standing chartering counterparties.

Greek shipping groups are also expected to adopt a more cautious approach to flag selection and corporate structuring. As potential countermeasures may be triggered by a range of criteria—such as flag state, ownership, operational control, or perceived political alignment—it will be essential for operators to monitor how such measures are defined and enforced, and to ensure that governance and ownership structures do not inadvertently increase exposure for fleets managed from Greece.

In parallel, compliance itself is likely to evolve into a distinct area of portfolio management. Given the persistence of high fuel-price differentials and the limited availability of zero- or near-zero-emission fuels in the early years of the NZF, operators may need to develop internal capabilities for managing remedial and surplus unit positions, including optimisation, pooling strategies, and registry interaction, in order to reduce cost volatility and compliance risk over time.

Finally, financing and investment decisions are expected to reflect the combined impact of regulatory stringency and fragmentation risk. For both newbuildings and retrofits, hurdle rates and payback assumptions will need to incorporate uncertainty surrounding future fuel availability, regulatory overlap, and potential countermeasures. Evidence presented by classification societies and shipbuilders indicates that e-fuels remain structurally expensive even after accounting for NZF penalties, and that payback periods for certain dual-fuel configurations may be commercially unattractive. This reinforces the need for disciplined investment sequencing and cautious timing, particularly for capital-intensive projects with long economic lives.

6. Conclusions

The analysis undertaken in this report leads to a set of interrelated conclusions concerning the technical feasibility, environmental efficiency, distributional effects, and economic consequences of the proposed IMO Net-Zero Framework (NZF).

Under the current regulatory design, only green synthetic fuels—specifically green ammonia, methane, methanol, or green hydrogen—may leverage compliance with ZNZ thresholds, albeit under substantial uncertainty. These fuels introduce material risk exposure under significant uncertainty on effectiveness. They exhibit significantly lower gravimetric and volumetric energy density than conventional marine fuels, requiring more than double the infrastructure and onboard storage volumes to deliver equivalent propulsion energy. This characteristic has direct implications for vessel design, cargo capacity, and operational efficiency.

At present, global production of these fuels is negligible relative to the needs of international shipping, amounting to well below one percent of annual demand. Scaling production to levels sufficient for shipping alone would require renewable electricity volumes exceeding current global wind and solar generation, highlighting a fundamental resource constraint. The production pathways for these fuels consume more renewable energy than they ultimately deliver as usable propulsion energy, resulting in low overall system efficiency.

Meeting the estimated annual renewable electricity demand of the existing merchant fleet would necessitate investments in wind and solar capacity on the order of trillions of U.S. dollars, with asset lifetimes limited to approximately two decades. These investments represent only one component of total system cost, which also includes electrofuel production plants, port and bunkering infrastructure, onboard retrofits or newbuild premiums, and the logistics required to sustain global fuel supply chains.

From a climate-mitigation perspective, the opportunity cost of allocating scarce renewable electricity to marine synthetic fuels is substantial. The same renewable energy, if applied directly to land-based electrification, yields up to 9 times the CO_2 reduction achieved compared to maritime fuel substitution. This raises concerns regarding the environmental efficiency of the NZF as a global decarbonization instrument.

Economically, the framework creates strong incentives for vessel operators to rely on compliance payments rather than physical fuel transition, particularly given high fuel prices, limited availability, and unresolved certification and lifecycle accounting methodologies. For several ship types, cumulative NZF penalties over time are projected to exceed vessel asset values by wide margins, reaching $300bn annually by 2035 for the global fleet. The resulting cost pressures are expected to distort freight markets, elevate transport costs, and transmit inflationary effects through global supply chains, with disproportionate impacts on small and medium-sized operators lacking access to green finance.

In addition to the aggregate cost impacts, the NZF is expected to generate material sectoral discrepancies driven by differences in operating model and fuel-procurement capability. Access to early volumes of NZF-compliant "ZNZ" fuels is certain to be scarce, geographically concentrated, and allocated through multi-year offtake structures and chain-of-custody arrangements. These conditions are structurally easier to satisfy for large liner operators with stable networks, predictable port rotations, and the ability to aggregate demand across fleets and routes. By contrast, tramp shipping—characterized by variable routes, heterogeneous charterers, and limited ability to commit to fixed corridors or guaranteed bunkering volumes—faces significantly higher barriers to securing constrained ZNZ fuel supply at scale. This implies that the NZF's tightening GFI trajectory may be formally fuel-neutral while functionally advantaging networked liner models and disadvantaging tramp sectors that lack similar procurement leverage.

These sectoral asymmetries are particularly relevant for the Greek-owned and Greek-operated fleet due to its composition. The Greek-controlled fuel and energy footprint is heavily concentrated in bulk carriers and tankers, with a comparatively smaller share in containerships. Because bulk and tanker segments predominantly operate in tramp markets, Greek-controlled tonnage is more likely to face a practical constraint in accessing niche ZNZ fuels in the early and mid-phases of implementation. As a consequence, Greek-controlled operators may be disproportionately pushed toward Remedial Unit (RU) purchases as the marginal compliance pathway, amounting to $20-50bn annually post mid-2030s, not because of technological unwillingness but due to structural barriers to fuel access and deployment. This outcome raises a distributional concern: a material share of compliance expenditures for tramp-heavy fleets may deliver limited direct decarbonization within those segments, while effectively transferring value toward actors best positioned to secure scarce low-carbon fuels and monetize compliance flexibility, with cost pass-through dynamics more available to liner supply chains than to tramp shipping.

The IMO Net-Zero Fund, while central to the framework's architecture, remains insufficiently defined in terms of governance, transparency, and allocation mechanisms. Without clear rules, the fund risks becoming a large-scale financial intermediary with limited accountability, while failing to deliver timely and effective emissions reductions and while amplifying the distributional issues noted above.

Finally, the framework's emphasis on an end-state fuel transition, without adequate recognition of transition fuels, energy-efficiency technologies, and incremental emissions reductions, limits its practical effectiveness. A more robust approach would prioritise near-term emissions abatement through all available means—including transition fuels and efficiency measures—while allowing alternative fuels to scale in line with demonstrable industrial and energy-system readiness. In parallel, addressing sectoral disparities explicitly (e.g., through compliance flexibility mechanisms that reflect tramp operating realities and avoid penalising limited-access segments) would improve both environmental effectiveness and economic fairness.

Taken together, these conclusions indicate that the NZF, in its current form, is misaligned with physical energy constraints, industrial development timelines, and economic realities, and it risks creating uneven sectoral burdens—especially for tramp-heavy fleets such as the Greek-controlled fleet. A recalibrated, phased, and technology-inclusive framework would better serve both climate objectives and the stability of global maritime trade, while reducing the likelihood that compliance is achieved primarily through financial transfers rather than real-world emissions abatement.

7. Annex A - The colors of fuels

In discussions about the energy transition, a wide range of "market colors" and labels, such as green, blue, grey, and others, are often used to describe different types of hydrogen and alternative fuels. These terms are not formal regulatory classifications, nor are they always technically precise, but they have become common shorthand. They help policymakers, industry stakeholders, and the public communicate more easily about production pathways, carbon footprints, and technological approaches, even if the underlying realities are more complex than the labels suggest.

7.1. Hydrogen[172]

Hydrogen is the most abundant element on Earth, and it typically needs to be extracted from water or organic compounds, like petroleum products or natural gas. It is also produced via renewable sources such as solar, wind or biogas without the need to use fossil fuels (Figure 13).

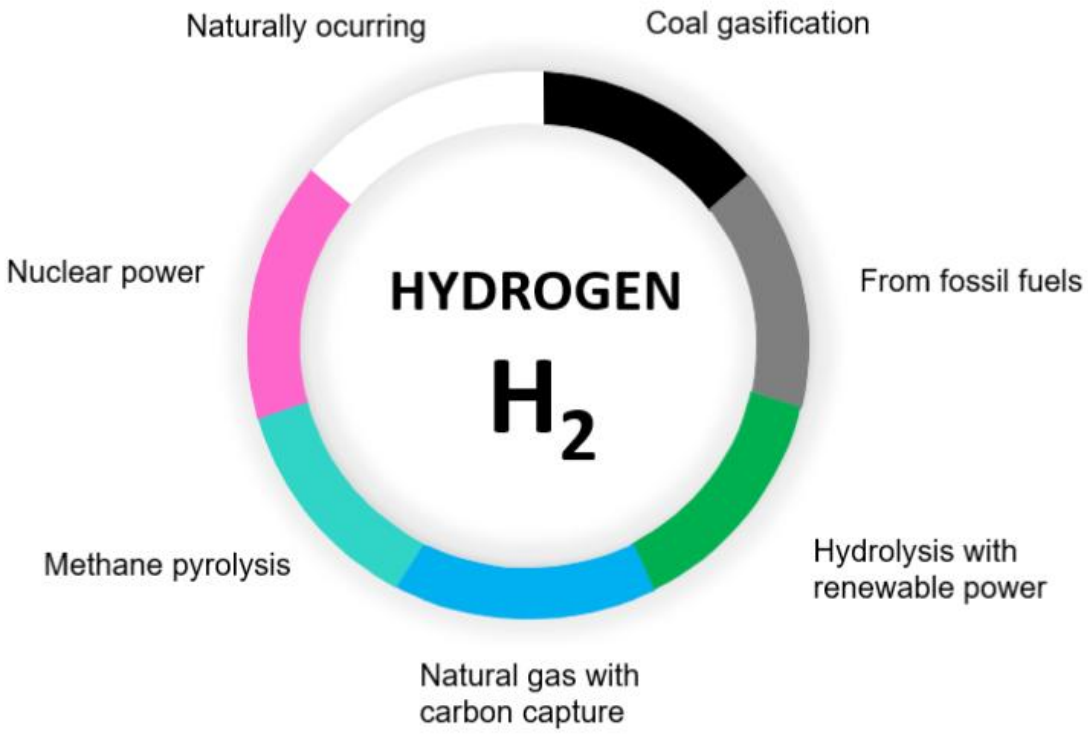


Figure 13: The "colors" of hydrogen[173]

7.1.1. Green Hydrogen

Green hydrogen is mainly produced by splitting water (i.e., water electrolysis) using electricity generated from renewable energy sources (RES). The reason it is called green is that there is

[172] Hydrogen Europe, The colors of hydrogen, link
[173] S. Sen, M. Bansal, S. Razavi, A.S. Khan, The Color Palette of the Colorless Hydrogen, The way ahead, 2022 link

no CO2 emission associated with the hydrogen production nor with its usage. When used in a fuel cell, the only by-product of its use is the pure water that was originally used in its production. Renewable hydrogen is generally more expensive than blue hydrogen, though prices are becoming more competitive. Although “green” hydrogen often refers to electrolytic hydrogen produced using electricity generated from renewable energy sources, it can also refer to hydrogen produced via different methods using other renewable sources such as biogas, biomethane, bio-waste and other renewable sources, these methods are less common than water electrolysis but also result in either very low or zero emissions.

7.1.2. Blue Hydrogen

Blue hydrogen refers to hydrogen derived from natural gas, which is a fossil fuel, however, most (albeit not all) the CO2 emitted during the process would be captured and stored underground (carbon sequestration) or bound in a solid product (such as bricks) and utilized. This is called carbon capture, utilization and storage (CCUS).

One process for achieving this is called steam methane reforming (SMR). This mixes natural gas with very hot steam, in the presence of a catalyst, where a chemical reaction creates hydrogen and carbon dioxide and carbon monoxide. An improvement of this process, auto-thermal reforming (ATR) combines the steam reforming reaction and fuel oxidation into a single unit. This process is more efficient and is able to capture more of the CO_2 emitted in course of production. When considering the CO_2 emission reduction potential of “blue” hydrogen, it is important to acknowledge the importance of tackling methane leakage upstream of the hydrogen production plant. This should be done by applying a strict life-cycle assessment when determining the CO2 emissions associated with its production.

Due to the differences in CO_2 emissions that can occur in the production of “blue” hydrogen (depending on upstream methane emissions and the production technology used), the term itself can be considered too broad. Instead, when referring to hydrogen produced from natural gas, it is more accurate to refer to it using the actual GHG footprint associated with its production.

7.1.3. Turquoise

Extracted by using the thermal splitting of methane via methane pyrolysis, this process (though at the experimental stage) removes carbon in a solid form instead of CO_2 gas.

7.1.4. White

White hydrogen refers to naturally occurring hydrogen in its most natural state.

7.1.5. Red

Red hydrogen is produced through the high-temperature catalytic splitting of water using nuclear power thermal as an energy source.

7.1.6. Pink

Pink hydrogen is generated through electrolysis of water by using electricity from a nuclear power plant.

7.1.7. Purple

Purple hydrogen is made though using nuclear power and heat through combined chemo-thermal electrolysis splitting of water.

7.1.8. Grey

Grey hydrogen is produced from fossil fuel and commonly uses the SMR method. During this process, CO_2 is produced and eventually released into the atmosphere.

$$2CH_4 + 2H_2O \rightleftharpoons 2CO + 3H_2 \quad \Delta H +206 \text{ kJ/mol}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H -41 \text{ kJ/mol [Water-gas shift reaction (exothermic)]}$$

7.1.9. Black / Brown

Produced from coal, the black and brown colours refer to the type of bituminous (black) and lignite (brown) coal. The gasification of coal is a method used to produce hydrogen. However, it is a very polluting process, and CO_2 and carbon monoxide are produced as by-products and released into the atmosphere.

$$3C + O_2 + H_2O \rightleftharpoons 3\ CO + H_2$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H -41 \text{ kJ/mol [Water-gas shift reaction (exothermic)]}$$

7.2. Ammonia[174]

Figure 14 presents the various colors for ammonia.

[174] The colors of Ammonia, ACS Energy Lett. 2024, 9, 2920−2921, link

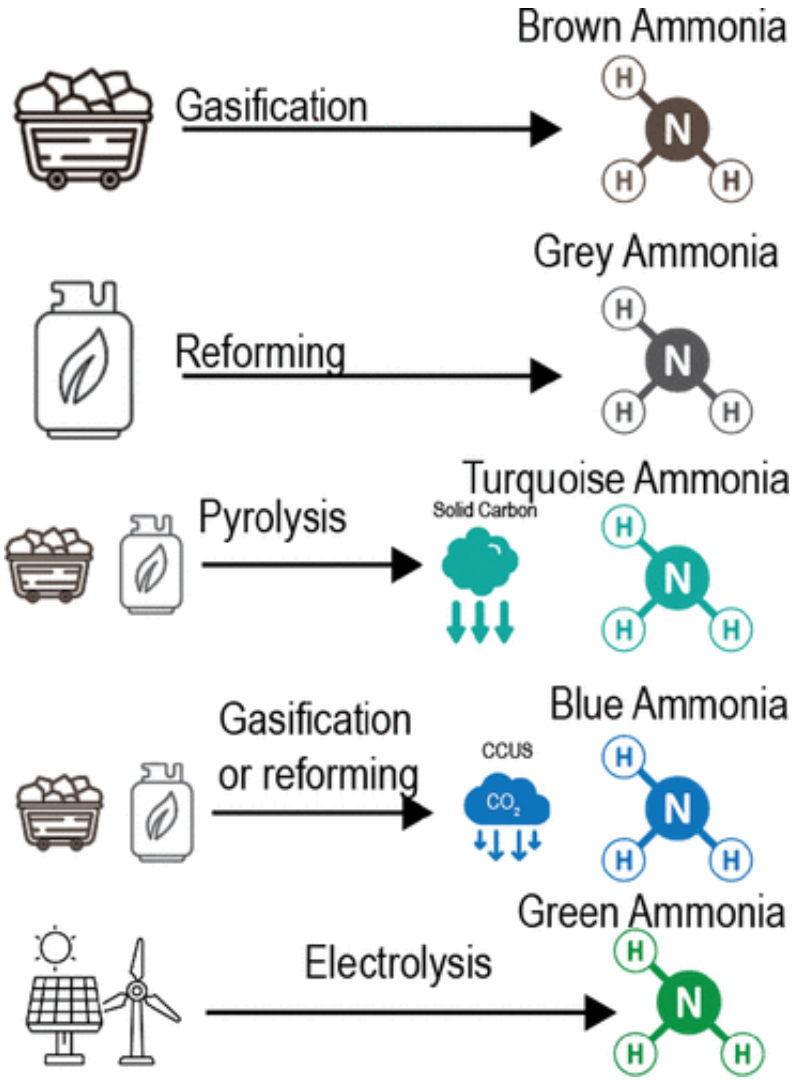


Figure 14: Colors of Ammonia

7.2.1. Brown Ammonia

Brown Ammonia often refers to ammonia produced from fossil fuel-derived hydrogen. However, more specifically, brown ammonia refers to systems that rely on coal gasification for hydrogen production. The Haber−Bosch process combines nitrogen with hydrogen in a thermo-catalytic process and is responsible for the production of more than 400 $MtCO_{2,eq}$ per year (~2.4 tCO_2/tNH_3). Most of the carbon emissions are associated with the production of hydrogen. Today, about 30% of ammonia comes from coal-derived hydrogen, with much of this produced in China. Brown ammonia has an emissions intensity between 2.4 and 3.2 tCO_2/tNH_3.

7.2.2. Grey Ammonia

"Grey Ammonia" refers to ammonia produced from methane-derived hydrogen. Traditionally, this hydrogen is generated through steam-methane reforming. About 70% of ammonia produced today is derived from natural gas-derived hydrogen. The emissions intensity of grey ammonia ranges from 1.6 to 1.8 tCO_2/tNH_3. The Paris Agreement on climate change and the growing concern for global carbon emissions have largely driven interest in innovations that allow for ammonia to move beyond "Brown" and "Grey".

7.2.3. Turquoise Ammonia

One approach being employed to lower the carbon emissions at ammonia manufacturing sites is carbon capture and storage/utilization. If carbon is captured and stored as a solid, the ammonia is termed "Turquoise Ammonia".

7.2.4. Blue Ammonia

If carbon is captured and utilized, the ammonia is termed "Blue Ammonia". Carbon capture can increase the energy consumption of an ammonia production plant by 0.7 GJ/tNH_3; however, the use of carbon capture can reduce the emission intensity of ammonia to 0.1–0.2 tCO_2/tNH_3. It should be noted that carbon capture and utilization occur today at several ammonia plants, with 130 $MtCO_2$/year captured for the production of urea.

7.2.5. Green Ammonia

The most recent innovations in the manufacture of carbon-free ammonia have focused on "Green Ammonia". Like green hydrogen, green ammonia refers to ammonia where hydrogen is produced using only renewable electricity (e.g., wind, solar, hydro, etc.). It is estimated that 36 GJ of renewable electricity is needed per ton of ammonia. Green ammonia, if feasible, would allow for the emission intensity of ammonia to drop theoretically toward 0 tCO_2/tNH_3. However, if the electrolysis is connected to the grid, the emission intensity of the grid would need to drop substantially.

7.3. Methanol[175]

The colors for methanol are presented in Figure 15, below.

[175] Wärtsilä, Methanol as marine fuel – is it the solution you are looking for?, link

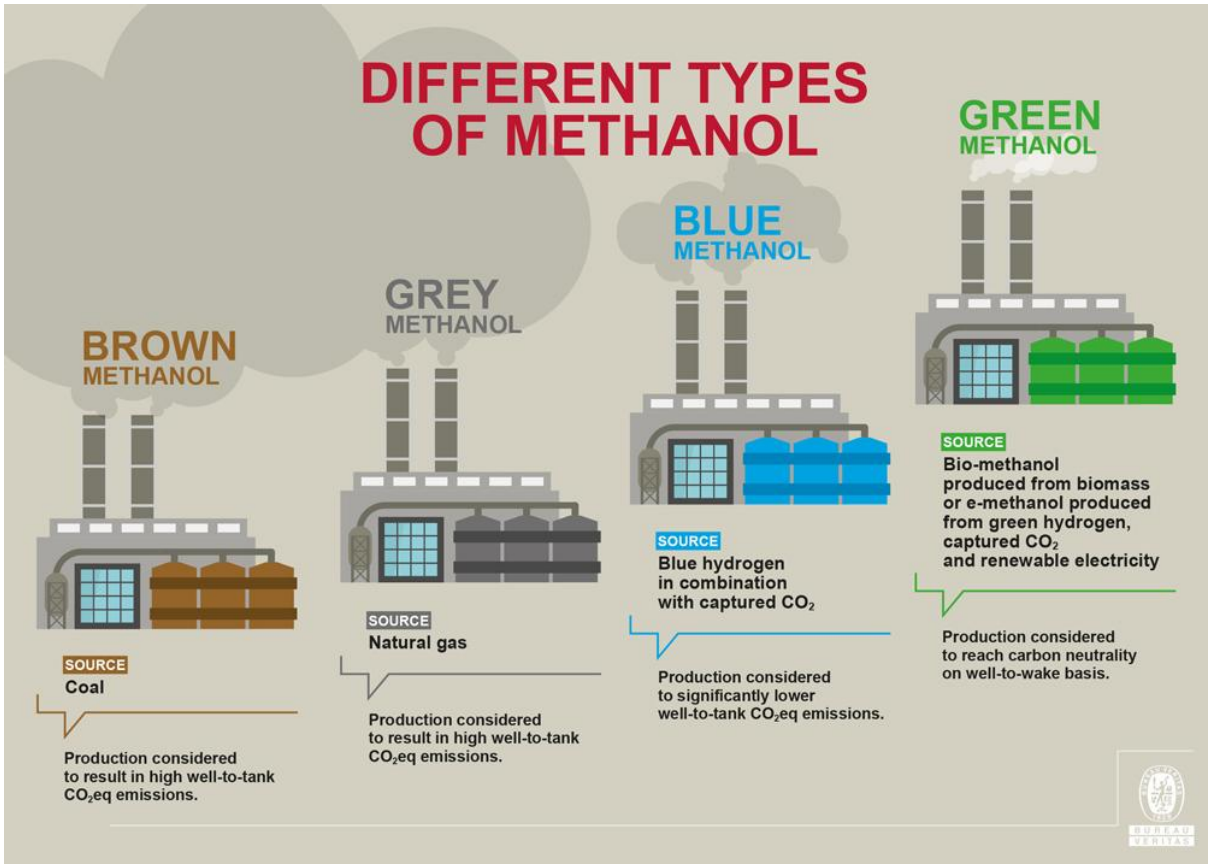


Figure 15: Colors of methanol[176]

Green methanol is made from biomass or captured CO_2 and green hydrogen. It is the most environmentally sustainable type of methanol. **Blue methanol** is made using blue hydrogen in combination with carbon capture technology. It still significantly reduces well-to-tank CO_2 emissions compared to fossil fuels like diesel. However, one of the biggest challenges for maritime decarbonization is that most methanol today is either grey or brown. **Grey methanol** is produced using natural gas, while **Brown methanol** is produced using coal. All types of methanol could lead to a tank-to-wake CO_2 reduction of about 7% compared to diesel. However, if we take the well-to-wake approach (from production to utilisation), the CO_2 impact of grey and brown methanol is worse than that of diesel. This is why green and blue methanol are the only real alternatives when targeting well-to-tank GHG reduction.

7.4. Types of LNG

Liquified Natural Gas does not have colors, but it is also characterized by the production path (Figure 16)

[176] link

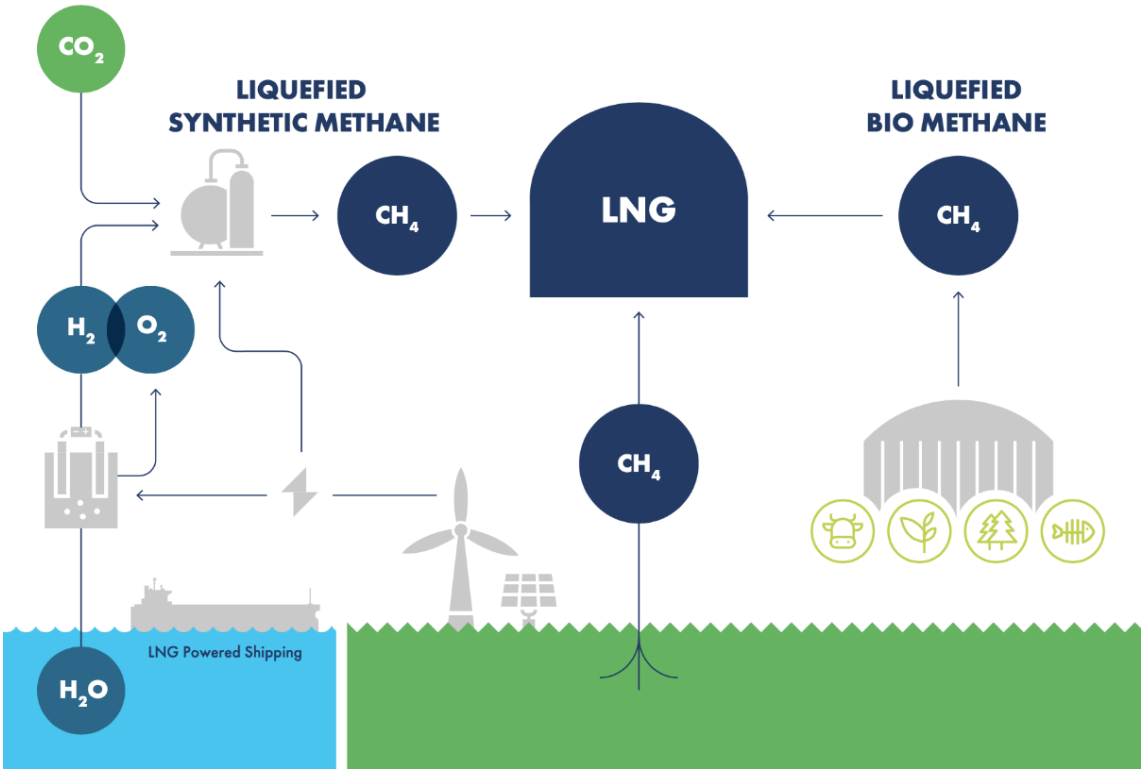


Figure 16: Production paths for LNG[177]

7.4.1. Bio-LNG[178]

Bio-LNG is liquefied biomethane and is chemically identical to LNG. In North America biomethane is sometimes also known as renewable natural gas (RNG); and in Europe as synthetic natural gas (SNG). Biomethane is mainly produced from anaerobic digestion of agricultural and human waste streams e.g. animal manure, silage, wastewater and landfill. It can also be produced through gasification of cellulosic waste, such as sawmill and forest harvest residues. This is a less mature technology. Biomethane is produced from sustainable biomass feedstocks, which are nationally, or regionally defined, for example by the EU (RED II) in Europe and the EPA (Renewable Fuel Standards) in the USA. This means that it does not compete with the production of food, fibre or fodder.

7.4.2. e-LNG[179]

Liquefied e-methane, also known as e-LNG, is chemically identical to LNG (liquefied natural gas). It is an electro-fuel, or e-fuel, so called because it is produced from renewable electricity. It is also known as liquefied synthetic methane, or natural gas. Liquefied e-methane is produced by combining hydrogen and carbon dioxide. For liquefied e-methane to be considered a zero-emission fuel, hydrogen has to stem from electrolysis, using water and

[177] link
[178] link
[179] link

renewable electricity as inputs; the carbon dioxide has to be obtained from biogenic sources, or captured from the atmosphere. Liquefied e-methane is one of a family of electro-fuels including e-methanol and e-ammonia which are being discussed for use in maritime. These fuels are all derived from the same renewable hydrogen feedstock. Liquefied e-methane and e-methanol are produced by combining hydrogen with carbon dioxide; ammonia is produced by combining hydrogen with nitrogen.

8. Annex B – Development Cycles for NZF Compliant Fuels

8.1. Green Hydrogen

Large electrolyzer-based hydrogen plants typically require **3–6 years** from final investment decision (FID) to commissioning under favorable permitting regimes, while first-of-a-kind or export-scale (>1 GW) projects frequently extend into the **6–10-year** range. Analyses from the International Energy Agency (IEA, 2024; 2025) show that global hydrogen project pipelines suffer from permitting delays, limited availability of critical minerals (notably iridium and platinum for PEM systems), and manufacturing bottlenecks for high-capacity electrolyzers. These constraints often cause slippage of planned commissioning timelines by **2–4 years** compared with initial project schedules.

Further, large hydrogen projects require coordinated deployment of renewable-energy capacity, grid connections, water treatment/desalination infrastructure, and in some cases CO_2 transport or storage infrastructure (for blue-hydrogen variants). Each of these components introduces additional approval steps and supply-chain dependencies, amplifying overall project duration. Industry surveys (Ramboll, 2024; BCG, 2024) emphasize that procurement of long-lead components—such as stacks, rectifiers, compressors, and high-capacity transformers—frequently becomes the critical path of project delivery. As a result, many hydrogen projects announced in the 2025–2027 period will not reach full commercial operation before the **mid-2030s**, mirroring the development trajectory observed for green ammonia and PtM facilities.

APA Sources: International Energy Agency. (2024). *Global Hydrogen Review*. OECD Publishing. International Energy Agency. (2025). *Hydrogen Projects and Outlook*. OECD Publishing. Ramboll. (2024). *The Material Risk of Green Hydrogen*. Ramboll Group. Boston Consulting Group. (2024). *Hydrogen Supply Chain Outlook*. BCG Research.

8.2. Green ammonia

Green ammonia plant projects typically consist of three major phases: (1) development & permitting, (2) procurement & construction (including electrolyzer and Haber–Bosch synthesis train installation), and (3) commissioning and ramp-up. For large, first-of-a-kind facilities the aggregate lead time from final investment decision (FID) to commercial operation commonly spans **several years** and often reaches the **mid-single digits to low double digits** of years in practice. This range reflects variability in project scale, permitting regimes, grid/renewable supply arrangements, and whether CO_2 transport/CCUS is required for low-carbon variants. The IEA's ammonia technology analysis and national hydrogen/ammonia roadmaps show that, while "mature" projects with streamlined permitting can be delivered in roughly **3–6 years** from FID, complex export-scale projects and integrated PtX hubs regularly take **6–9+ years**, especially where new electrolyzer factories, dedicated renewables and port/export infrastructure are required.

Permitting and consenting are commonly cited binding constraints: environmental impact assessments, grid-connection agreements, desalination/water permits (where needed), and export-licences for carrier fuels (e.g., ammonia) can add multiple years before construction can legally begin. Large projects thus face long pre-construction lead times that are frequently as long as — or longer than — the physical construction phase.

Supply-chain constraints materially lengthen schedules and increase capex risk. Electrolyzers, power-electronics, and certain catalyst and membrane materials (for PEM electrolyzers) have concentrated production footprints and are subject to order-book backlogs; procurement lead times for critical supply-chain items can be 12–36 months or longer. The dependency on rare or constrained commodities (e.g., iridium/platinum group metals in some electrolyzer designs, and specialised steels/catalysts for Haber–Bosch) creates additional schedule risk and cost volatility. These bottlenecks, together with long lead times for large renewables plants, mean that even rapid investment commitments in 2025–2027 often do not translate into commercial green-ammonia output at scale until the **mid-2030s** in many regions.

A practical illustration is provided by announced large projects: integrated green-hydrogen/ammonia complexes targeted to reach commercial operations toward the **late 2020s to 2030** (several of the largest projects publicly reported plan on 2028–2032 start dates), highlighting that multi-year construction and commissioning schedules are the norm at scale. This supports a conservative planning assumption that >1 GW-equivalent PtX hubs (or export-scale ammonia plants) will generally need **6–9 years** after FID to deliver sustained commercial volumes.

8.3. Synthetic methane / power-to-methane (PtM)

Power-to-methane (PtM) projects combine electrolysis (green H_2) with a downstream methanation step ($CO_2 + H_2 \rightarrow CH_4$). Compared with ammonia, PtM can be attractive where existing CO_2 point-sources or DAC (direct air capture) are available; however, PtM projects face the same fundamental constraints as hydrogen/ammonia projects: electrolyzer availability, renewable-power availability and permitting for plant and CO_2 handling. Historical and recent compendia of PtM projects show that many demonstration and early commercial PtM plants require **4–8 years** from project inception to commercial operation, with larger commercial plants often stretching to the mid-2030s for significant volumes.

Table 16: Typical Lead Times for NZF Compliant Fuel Projects

Project Type	Scale	Typical Total Timeline (Development → COD)	Key Bottlenecks
Green Ammonia (NH_3)	200–500 MW	4–7 years	Permitting, electrolyzer supply, renewable PPA, port infrastructure
Green Ammonia (1–2 GW export hub)	>1 GW	6–9+ years	Large renewables build-out, Haber–Bosch equipment procurement, water/desalination permits, transmission expansion
Power-to-Methane (PtM)	50–150 MW	4–6 years	CO_2 sourcing, methanation system integration, electrolyzer supply
Power-to-Methane (large commercial)	>300 MW	6–8 years	DAC or CO_2 capture capacity, grid access, multi-step permitting
Green Methanol (e-methanol)	100–300 MW	5–7 years	CO_2 sourcing (biogenic or DAC), electrolyzer supply, methanol synthesis equipment
Green Hydrogen (electrolysis)	200–500 MW	3–6 years	Permitting, electrolyzer manufacturing bottlenecks, grid/renewables integration
Green Hydrogen (1 GW+ export-scale)	>1 GW	6–10 years	Renewable build-out, desalination, transmission, critical-mineral constraints, long-lead equipment

Sources: ClassNK (2025); UMAS & UCL Energy Institute (2025); DNV Maritime Forecast (2024–2025); CE Delft Alternative Fuels Outlook (2023); IEA Global Hydrogen Review (2024).

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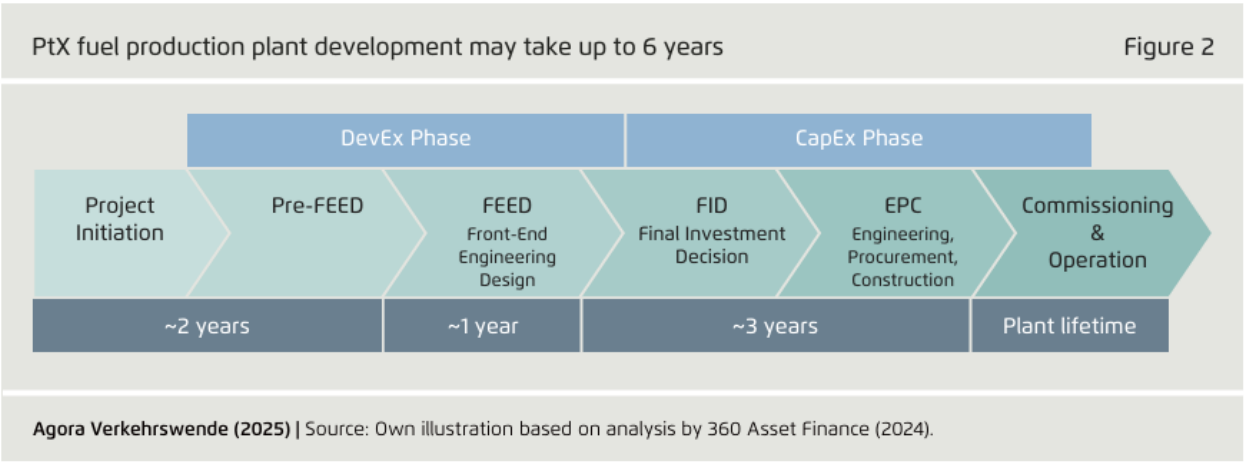


Figure 17: PtX Fuel Production Plant Development (source: International PtX Hub, Scaling Power-to-X Fuels in Transport, https://ptx-hub.org/publication/scaling-power-to-x-fuels-in-transport/)

9. Annex C – Calculation of Renewable-Energy Requirements and Capital Costs incurred for the Production of Green Ammonia

This Annex provides the calculations to quantify the renewable electricity to produce green ammonia, and the associated capital expenditure (CAPEX) based on current wind and solar construction costs. All numerical values are based on the energy-demand ranges provided in the main report and on renewable-energy cost data supplied below:

Table 17: Construction and Operational Cost for Solar Parks

CONSTRUCTION COST	OPERATIONAL COST (yearly)	COMMENTS
0.89-1.01 mUSD/MW	-	Solar Market Insight Report 2021 Q4, source
1.20 mUSD/MW	-	Average data from various countries, source
0.98 mUSD/MW	-	Land acquisition costs NOT included, source
2.28 mUSD/MW	0.043 mUSD/MW	APV Type Energy Storage Cost Included, source

Table 18: Construction and Operational Cost for Wind Parks (exchange rate: 1 EUR = 1.1583 USD)

CONSTRUCTION COST	OPERATIONAL COST (yearly)	TYPE	SOURCE
1.00-1.3 mEUR/MW	0.05 EUR/MW	ONSHORE - Factor: 37.5%	Link
2.00-2.50 mEUR/MW	-	ONSHORE - Factor: 37.5%	Link
≈2.30 mEUR/MW	-	OFFSHORE - Factor: 52.5%	Link
0.90 mEUR/MW	0.088 mEUR/MW	OFFSHORE - Factor: 52.5%	Link

Considering the following Capacity Factors (CF)[180]:

- Solar Park: 13–20%
- Onshore wind park: 30–45%
- Offshore wind park: 45–60%

And an average energy demand for NH_3 synthesis of:

$$E_{NH_3} = 11\ MWh/tonne\ (midpoint\ of\ 10-13)$$

The total electricity demand to fully replace fossil fuels by Green Ammonia in International shipping above 5,000 GT will be:

[180] The Capacity Factor of a Solar or Wind Park is the ratio of its actual energy production over a period to the energy it could have produced if it operated at its maximum rated power continuously

$$E_{\text{total}} = M_{\text{NH}_3} \times E_{\text{NH}_3}$$

$$E_{\text{total}} = 470{,}000{,}000\ \text{t/yr} \times 11\ \text{MWh/t}$$

$$\boxed{E_{\text{total}} = 5{,}170{,}000{,}000\ \text{MWh/yr} = 5{,}170\ \text{TWh/yr}}$$

9.1. Installed Capacity Required

General formula:

$$P_{\text{inst}} = \frac{E_{\text{total}}}{CF \times 8{,}760}$$

where:

P_{inst} = Installed capacity (MW)
E_{total} = Annual energy demand (MWh/yr)
CF = Capacity factor
$8{,}760$ = total hours in one year

Using the best and worst case capacity factors, the Installed Capacity Required for each case is presented below:

Table 19: Installed Capacity Required for best and worst case Capacity Factors

Capacity Factor (best and worst case)	Installed Capacity Required
Onshore wind parks	
0.45 (best case)	$P = \frac{5.17 \times 10^9}{0.45 \times 8{,}760} = 1{,}311{,}517\ \text{MW}$
0.30 (worst case)	$P = 1{,}967{,}275\ \text{MW}$
Offshore wind parks	
0.60	$P = 983{,}638\ \text{MW}$
0.45	$P = 1{,}311{,}517\ \text{MW}$
Solar Parks	
0.20	$P = 2{,}950{,}913\ \text{MW}$
0.13	$P = 4{,}539{,}867\ \text{MW}$

9.2. CAPEX Calculation

The general formula for CAPEX calculation is:

$$CAPEX_{total} = P_{inst} \times CAPEX_{per\ MW}$$

Following this equation, the CAPEX for best- and worst-case scenarios can be found in the Table below:

Table 20: CAPEX required for best- and worst-case senarios

Best and worst case	CAPEX (trillion USD)*
Onshore wind parks	
Best case (CF = 45%, CAPEX = 1.158 MUSD/MW)	$1{,}311{,}517 \times 1.158 = 1{,}519{,}130\ MUSD = 1.52$
Worst case (CF = 30%, CAPEX = 2.896 MUSD/MW)	5.70
Offshore wind parks	
Best case (CF = 60%)	2.62
Worst case (CF = 45%)	3.49
Solar Parks	
Best case (CF = 20%, CAPEX = 0.89 MUSD/MW)	**2.63**
Worst case (CF = 13%, CAPEX = 2.28 MUSD/MW)	10.35
* Using exchange rate of 1 EUR=1.1583 USD	

It must be noted however that the table above presents a full-range, worst-to-best comparison. A more realistic approach would exclude the largest construction costs combined with low Capacity factors. In that case, the respective calculations would indicate 1.5 – 3.7 trillion USD of CAPEX.

9.3. Important Notes

1. These values represent only the **electricity generation CAPEX**.
2. Electrolyzers, ammonia/methanol synthesis units, storage, transport infrastructure, and bunkering facilities are **not included.**
3. O&M expenditures (typically 0.04–0.10 MUSD/MW·yr) are also excluded from the totals.
4. The calculated renewable-energy requirement (5,170 TWh/year) exceeds all current global wind and solar generation.