TECHNICAL RESEARCH REPORT

Are We Ready for Future Fuels in the Maritime Industry?

Regulation, Technology, Fuel Availability, and Competence:
A Multi-Dimensional Readiness Assessment

Prepared by
Mr. Pawan Kapoor - Founder & Managing Director, ISF Group
Yogyata Kapoor - Director, ISF Group

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1. Executive Summary

The global maritime industry is navigating one of the most complex transitions in its history. Driven by the 2023 IMO GHG Strategy's commitment to net-zero emissions by or around 2050, the sector is simultaneously grappling with unresolved regulation, rapidly developing but not yet mature technology, uncertain fuel supply chains, and a profound gap in the competence of seafarers who will be required to operate these new vessels.

This paper assesses readiness across four interconnected dimensions: the regulatory environment, the technological development underway in the industry, the production and availability of future fuels, and the human capital requirements for safe operation. The central conclusion is that progress is genuine but uneven — and the gap between hardware ambition and operational readiness remains dangerously wide.

REGULATION — Incomplete Framework

The IMO has agreed on an ambitious decarbonization strategy and approved the draft IMO Net-Zero Framework. However, the legal amendments required to implement the framework have not yet been adopted. While the industry's long-term direction is clear, uncertainty remains over the final design of the GHG Fuel Intensity standard, economic measures and implementation mechanisms.

TECHNOLOGY — Developing Rapidly, Not Yet Fully Proven

Engine manufacturers including Wärtsilä, WinGD, and MAN have made significant advances in dual-fuel and alternative fuel engine technology for LNG, methanol, and ammonia. LNG dual-fuel vessels are operating commercially. Methanol vessels are entering service. Ammonia engines have been tested. The technology is advancing — but commercial-scale reliability and standardization remain works in progress.

FUEL AVAILABILITY — The Decisive Variable

LNG has established bunkering infrastructure at major hub ports. Methanol availability is limited and predominantly fossil-derived today. Green ammonia and e-methanol production is nascent and expensive. Hydrogen remains a long-term consideration. Ultimately, fuel availability — not vessel orders — will determine which pathway dominates. Production complexity and feedstock competition make this the least predictable dimension of the transition.

COMPETENCE — The Most Urgent Human Risk

Ships with alternative fuel systems are entering the fleet now. The IGF Code course provides a government-approved foundation, but it covers LNG and general gas fuel principles — it does not adequately address the acute toxicity of ammonia, the invisible-flame hazard of methanol, or the practical demands of multi-fuel bunkering operations. The competence gap is real, significant, and closing too slowly.

2. The Regulatory Landscape: Ambition, Delay, and the Search for Consensus

The international regulatory direction for maritime decarbonization is clear, but the binding measures required to deliver it remain unresolved.

The 2023 IMO Strategy on Reduction of GHG Emissions from Ships significantly increased the level of ambition established under the 2018 Initial Strategy. It sets a pathway toward net-zero greenhouse-gas emissions from international shipping by or around 2050, supported by indicative emission-reduction checkpoints for 2030 and 2040.

However, the Strategy itself does not constitute the complete set of enforceable regulations needed to achieve these ambitions. Its implementation depends on amendments to instruments such as MARPOL Annex VI, together with detailed methodologies, compliance thresholds, pricing arrangements and implementation guidelines.

Progress has therefore occurred in two distinct stages. First, IMO Member States agreed on the strategic destination through the 2023 IMO GHG Strategy. Second, they began negotiating the legal and technical measures needed to translate that ambition into ship-level obligations. It is this second stage that has encountered significant political and technical difficulty.

2.1 The 2023 IMO GHG Strategy: What Has Been Agreed

The revised IMO GHG Strategy was adopted at MEPC 80 in July 2023 through resolution MEPC.377(80). It establishes the following principal levels of ambition:

- 2030 indicative checkpoint: To reduce total annual GHG emissions from international shipping by at least 20%, while striving for 30%, compared with 2008.
- 2040 indicative checkpoint: To reduce total annual GHG emissions from international shipping by at least 70%, while striving for 80%, compared with 2008.
- Net-zero ambition: To reach net-zero GHG emissions from international shipping by or around, meaning close to, 2050, taking into account different national circumstances.
- Uptake of cleaner energy: For zero- or near-zero-GHG-emission technologies, fuels and energy sources to represent at least 5%, while striving for 10%, of the energy used by international shipping by 2030.
- Carbon-intensity ambition: To reduce the carbon intensity of international shipping by at least 40% by 2030, compared with 2008.
- Lifecycle assessment: The levels of ambition and future regulatory measures are to account for emissions on a Well-to-Wake basis. This means that the climate impact of a fuel must be

assessed across its production, processing, transport and use, rather than solely on the emissions released during onboard combustion.

The distinction between total emissions and carbon intensity is important. The 20%–30% and 70%–80% checkpoints relate to total annual GHG emissions from international shipping. They are not GHG-intensity targets. Carbon intensity is addressed separately through the 40% reduction ambition for 2030.

The Strategy also calls for the development of a basket of mid-term GHG-reduction measures comprising:

- a technical element in the form of a goal-based marine fuel standard regulating the lifecycle GHG intensity of energy used on board ships; and
- an economic element in the form of a maritime GHG-emissions pricing mechanism.

These strategic commitments have been agreed. The central regulatory challenge is now the conversion of these commitments into legally binding, technically workable and politically acceptable requirements.

2.2 From Strategy to Regulation: The IMO Net-Zero Framework

At MEPC 83 in April 2025, IMO Member States approved draft amendments to MARPOL Annex VI collectively referred to as the IMO Net-Zero Framework.

The draft framework contains two principal elements:

- a global marine fuel standard intended to progressively reduce the lifecycle GHG intensity of energy used by ships; and
- an economic mechanism under which ships exceeding specified GHG-intensity thresholds would be required to make financial contributions, while qualifying zero- and near-zero-emission fuels could receive financial support or incentives.

Approval at MEPC 83 was an important milestone, but it did not make the framework legally binding. Formal adoption of the MARPOL amendments was scheduled to be considered at the second extraordinary session of the Marine Environment Protection Committee, MEPC ES.2, held from 14 to 17 October 2025.

MEPC ES.2 did not adopt the amendments. The session was adjourned after Member States were unable to reach sufficient agreement on the proposed framework and its implementation.

The unresolved concerns included the level and timing of the GHG fuel-intensity requirements, the design and economic impact of the pricing mechanism, the treatment of different fuels and production pathways, the distribution and use of revenues, and the potential effects on developing countries and geographically remote economies.

The regulatory position is therefore unusual. IMO has agreed on the strategic objective and has approved a draft legal architecture, but the amendments required to bring that architecture into force have not yet been adopted.

2.3 The Role of MEPC 84

MEPC 84 was held from 27 April to 1 May 2026. It was not the session at which the IMO Net-Zero Framework was originally expected to be adopted. Rather, it took place after the adjournment of MEPC ES.2 and focused on restoring momentum, considering Member States' concerns and identifying a pathway back toward consensus.

The Committee agreed that further intersessional negotiations were required before the issue could return for formal consideration. Two additional meetings of the Intersessional Working Group on Reduction of GHG Emissions from Ships were scheduled ahead of MEPC 85: 1–4 September 2026; and 23–27 November 2026.

The purpose of these discussions is not simply to choose between two formally defined regulatory models. The negotiations involve a wider range of proposals, amendments and concerns regarding the structure, stringency, economic consequences and implementation of the draft IMO Net-Zero Framework.

It would therefore be inaccurate to characterize the debate as an official contest between a "Net-Zero Framework" and a separately recognized "Market Readiness Approach" unless that term is tied to a specific Member State submission. A more accurate description is that Member States remain divided over how ambitious, prescriptive and economically redistributive the framework should be, and how rapidly its requirements should take effect in relation to the availability of compliant fuels and technologies.

2.4 What Remains Unresolved

Several commercially significant issues remain under negotiation.

GHG Fuel-Intensity Requirements

The draft framework establishes a mechanism for progressively reducing the lifecycle GHG intensity of marine energy. However, the final thresholds, reduction trajectories, compliance arrangements and implementation details remain subject to further negotiation and adoption.

These decisions will materially affect the relative regulatory attractiveness of LNG, biofuels, methanol, ammonia, synthetic fuels and other energy pathways.

GHG Pricing Mechanism

Although the draft framework includes a global pricing element, important questions remain regarding:

- the price applied to emissions above the relevant thresholds;
- the relationship between different compliance tiers;
- the treatment of ships using zero- or near-zero-emission fuels;
- the collection, administration and distribution of revenues; and
- the extent to which revenues will support fuel deployment, technical cooperation and a just and equitable transition.

The mechanism should not presently be described simply as an agreed global levy. The final economic structure remains subject to negotiation.

Lifecycle Emission Factors

A workable Well-to-Wake framework depends on credible and consistently applied lifecycle emission factors for different fuels and production pathways. Emission values can differ substantially depending on feedstock, electricity source, production technology, methane leakage, carbon-capture performance, transport distance and other supply-chain variables. Continued development and review of default emission factors under the IMO lifecycle-assessment framework will therefore remain central to implementation.

Until relevant emission factors and certification arrangements are sufficiently complete, shipowners may face uncertainty regarding the compliance value ultimately assigned to particular fuel pathways.

Treatment of Developing States

The 2023 IMO GHG Strategy recognizes the need to consider different national circumstances and the potential disproportionate negative impacts of regulatory measures.

Questions remain regarding revenue distribution, technical assistance, capacity building, fuel accessibility, impacts on trade costs and the treatment of States that are geographically remote or highly dependent on maritime transport. These issues are not peripheral. They are central to securing the political consensus necessary for adoption.

Detailed Implementation Guidelines

Even after the principal MARPOL amendments are adopted, a substantial body of supporting guidance will be required. This is likely to include methodologies for lifecycle accounting, fuel certification, emissions measurement, compliance reporting, verification, registry arrangements, remedial units, rewards and fund administration.

Adoption of the framework will therefore be a major regulatory milestone, but not the end of the implementation process.

2.5 The Road to MEPC 85 and the Resumed MEPC ES.2

The immediate regulatory pathway consists of the following stages:

- September and November 2026: Further intersessional negotiations aimed at addressing the concerns that prevented adoption at MEPC ES.2 in October 2025.
- MEPC 85, 30 November–3 December 2026: Consideration of the intersessional work and assessment of whether sufficient consensus exists to proceed with formal adoption.
- Resumed MEPC ES.2: The extraordinary session is expected to be reconvened after MEPC 85, subject to the Committee's decision and the progress achieved during the intersessional negotiations. Formal adoption of the draft MARPOL Annex VI amendments would be considered at the resumed extraordinary session rather than automatically at MEPC 85.
- Post-adoption implementation: If the amendments are adopted, further technical guidelines, administrative systems and national implementation arrangements will still be required before the framework can become fully operational.

The longer-term regulatory process will also include the scheduled review of the 2023 IMO GHG Strategy during the 2027–2028 period. Updated emissions data and the Fifth IMO GHG Study are expected to contribute to this review, which will assess whether the industry remains on a credible trajectory toward its 2030, 2040 and 2050 ambitions.

2.6 Commercial Implications of the Continuing Uncertainty

The absence of a fully adopted framework does not mean that maritime decarbonization has stopped. Vessel orders, engine development, fuel-production projects and port-infrastructure investments are continuing. However, regulatory uncertainty materially affects the allocation and timing of capital.

Shipowners must make vessel and fuel-system decisions without complete certainty regarding future compliance thresholds or the lifecycle-emission values assigned to different fuels. Fuel producers must assess future demand without knowing the final regulatory incentives and penalties. Ports must consider investments in bunkering infrastructure before the dominant fuel pathways have emerged. Financial institutions must evaluate asset and transition risk while the future cost of carbon compliance remains uncertain.

It would be too absolute to state that these stakeholders cannot make decisions. Many are already doing so. The more accurate conclusion is that unresolved regulation raises the risk, cost and complexity of those decisions and may encourage investment in flexible, dual-fuel or fuel-ready designs rather than commitment to a single long-term pathway.

The industry is therefore not operating without regulatory direction. The direction has been established through the 2023 IMO GHG Strategy. What remains incomplete is the binding legal and economic framework that will determine the pace of transition, the relative competitiveness of different fuels and the distribution of its costs and benefits.

3. Industry Response: Moving Ahead Despite Regulatory Uncertainty

Despite the continuing regulatory uncertainty, the maritime industry has not stood still. Shipowners, engine manufacturers, classification societies, and fuel suppliers have collectively concluded that the direction of travel — toward zero-carbon fuels — is sufficiently certain to justify large-scale investment, even in the absence of a finalized regulatory framework. The result is a fleet in active, visible transition.

3.1 The Alternative Fuel Vessel Order Surge

Newbuild orders for Alternative Fuel Vessels (AFVs) — vessels ordered with alternative-fuel propulsion capability — reached a historic peak of **more than 500 vessels in 2024**. According to DNV's Alternative Fuels Insight (AFI), this record ordering activity reflected strong industry investment in lower-emission propulsion technologies amid tightening decarbonization ambitions and growing market demand for more sustainable shipping.

Although the number of alternative-fuel vessel orders declined in 2025 as overall global ship ordering softened, alternative-fuel vessels continued to account for **approximately 38% of total ordered gross tonnage**, indicating that shipowners largely maintained their commitment to lower-emission propulsion technologies despite continuing regulatory uncertainty.

This moderation in ordering activity should not be interpreted as a loss of confidence in maritime decarbonization. Rather, it reflects a combination of broader market conditions and continued uncertainty surrounding the final design of the IMO Net-Zero Framework. Many owners are adopting a measured investment approach while awaiting greater clarity on future regulatory requirements and the long-term commercial competitiveness of different fuel pathways.

3.2 LNG: The Established Pioneer

LNG dual-fuel vessels represent the most mature segment of the alternative fuel fleet. Commercially operating LNG-fueled vessels now number in the hundreds, spanning container ships, tankers, cruise vessels, and bulk carriers. The technology is proven, the major engine manufacturers have well-established dual-fuel product lines, and bunkering infrastructure exists at key hub ports including Rotterdam, Singapore, Busan, and Zeebrugge.

LNG's position as the 'bridge fuel' of the maritime transition is secure in the near term. However, its long-term role is complicated by the Methane Slip challenge (discussed in Section 5 and 6) and the question of whether LNG infrastructure investment will be compatible with a longer-term shift to bio-LNG or other gaseous fuels.

3.3 Methanol: The Emerging Challenger

Methanol dual-fuel vessels are entering service, driven particularly by major container shipping operators who have placed large orders for methanol-capable vessels. The appeal of methanol lies in its liquid handling properties at ambient temperature and pressure — significantly simplifying bunkering infrastructure compared to cryogenic LNG — and the theoretical pathway from fossil methanol (available today) to green/e-methanol (the long-term zero-carbon goal).

However, the methanol transition faces significant challenges: bunkering availability remains limited outside a small number of pioneer ports; the overwhelming majority of methanol currently available is fossil-derived, offering limited GHG benefit; and green methanol production at commercial maritime scale remains years away. The industry's methanol experience base is still being built, and caution is warranted in over-claiming readiness.

3.4 Ammonia: Engine Manufacturers Lead the Way

Ammonia as a marine fuel remains in the pre-commercial phase, but the engine development work is substantially more advanced than many outside the industry appreciate. Wärtsilä, MAN Energy Solutions, and other major manufacturers have conducted extensive testing of ammonia combustion in marine engine configurations. The fundamental combustion challenges — ammonia's low flame speed, high minimum ignition energy, and tendency toward NOx formation — have been identified and engineering solutions are being refined.

MAN Energy Solutions has conducted successful ammonia combustion tests on two-stroke engines. Wärtsilä has demonstrated ammonia-capable four-stroke engine concepts. Pilot fuel injection (using a small proportion of diesel or methanol to stabilize ammonia combustion) is the currently favored approach, though it introduces dual-fuel complexity and reduces the full Well-to-Wake emission benefit.

The industry's confidence in ammonia as a long-term pathway is reflected in the growing number of 'ammonia-ready' vessel designs being ordered — vessels built with structural provisions for ammonia fuel systems to be retrofitted once the commercial and regulatory framework matures.

3.5 Resolution MEPC.410(84): Keeping Regulation Aligned with Technology

One positive regulatory development from MEPC 84 is Resolution MEPC.410(84), which updates the EEDI (Energy Efficiency Design Index) calculation guidelines to redefine 'gas' to encompass liquid alternative fuels — including methanol and ethanol — used in dual-fuel mode. This amendment ensures that vessels ordered with methanol or ethanol dual-fuel capability receive appropriate EEDI credit, removing a regulatory disincentive that had previously placed liquid alternative fuels at a disadvantage relative to LNG.

This is a modest but important example of regulatory adaptation keeping pace with technological reality — a pattern the industry needs to see repeated more broadly and urgently in the unresolved areas of the GFI standard and economic measure.

4. Fuel Production, Availability, and Properties: The Supply-Side Reality

Vessels can be ordered. Engines can be designed. Regulations can be written. But a ship cannot sail on ambition alone — it requires fuel. The ultimate determinant of which alternative fuel pathway dominates the maritime transition is not which technology is most elegant or which regulation is most ambitious, but which fuel can be produced, transported, and delivered at scale, at competitive cost, and with the safety and quality standards that maritime operations demand. This section examines each primary fuel candidate through that lens.

4.1 Liquefied Natural Gas (LNG)

Production

LNG is produced by cooling natural gas (predominantly methane, CH_4) to approximately −162°C at atmospheric pressure, reducing its volume by a factor of approximately 600. Production occurs at liquefaction terminals located predominantly in Qatar, Australia, the United States, Russia, and several other major gas-producing nations. The natural gas feedstock is extracted from both conventional gas fields and associated gas (produced alongside oil), purified to remove contaminants (CO_2, H_2S, water, heavy hydrocarbons), and then liquefied through a cascade refrigeration process using multi-stage heat exchangers.

LNG is transported in purpose-built cryogenic carriers (LNG carriers) and stored at terminals in insulated tanks before transfer to LNG bunkering vessels or fixed bunkering facilities. The global LNG trade is well-established, with long-term supply contracts providing commercial certainty to buyers.

Key Properties

Property	Value / Characteristic
Primary Component	Methane (CH_4) — typically 85–99% by volume
Boiling Point	Approximately −162°C at atmospheric pressure
Energy Density (volumetric)	~22 MJ/litre (approx. 60% of HFO by volume)
GHG Intensity (TtW)	Approximately 15% lower CO_2 than HFO — but subject to Methane Slip
Flammability Range	5–15% in air (Methane) — narrower than diesel vapour
Toxicity	Non-toxic; primary hazard is cryogenic burn and asphyxiation in enclosed spaces
Bunkering Infrastructure	Established at major hub ports globally (Rotterdam, Singapore, Busan, Zeebrugge, etc.)

Availability and Future Trajectory

LNG bunkering availability is the most developed of any alternative marine fuel. Singapore, as the world's largest bunkering port, has multiple MPA-licensed LNG bunkering operators. The practical experience on bunkering companies described — of managing ship-to-ship LNG transfers, ensuring compatibility between vessel and bunker craft connections, and coordinating with port authorities — underscores that commercial LNG bunkering is a functioning reality, not a pilot project.

The critical question for LNG's long-term role is whether existing LNG infrastructure can evolve to handle bio-LNG and synthetic methane (e-LNG) — effectively the same molecule produced from renewable feedstocks rather than fossil natural gas. If so, LNG-capable vessels ordered today retain long-term regulatory relevance. The molecular compatibility suggests they can, subject to fuel quality standard alignment.

4.2 Methanol

Production

Methanol (CH3OH) is produced commercially through the catalytic reforming of synthesis gas (syngas — a mixture of hydrogen and carbon monoxide) at high temperature and pressure. The syngas feedstock is currently produced almost entirely from natural gas via steam methane reforming (SMR), making conventional methanol a fossil-derived product with limited GHG benefit versus HFO on a Well-to-Wake basis.

The decarbonization pathway for methanol requires transitioning feedstocks:

- **Bio-Methanol**: Produced from biomass gasification (agricultural waste, forestry residues, municipal solid waste). Limited by feedstock availability and competition with other bio-energy applications.
- **E-Methanol (Green Methanol)**: Produced by combining green hydrogen (from renewable-powered electrolysis) with captured CO2. Near-zero WtW emissions, but currently expensive and small-scale. Multiple projects announced globally, with meaningful production scale expected by the late 2020s.

Key Properties

Property	Value / Characteristic
Chemical Formula	CH3OH — simplest alcohol
Physical State	Liquid at ambient temperature and pressure — no cryogenic storage required
Flash Point	11°C — flammable liquid; requires adapted fire safety systems

Property	Value / Characteristic
Energy Density (volumetric)	~15.6 MJ/litre (approx. 40% of HFO by volume — significant tank space penalty)
Flame Visibility	Burns with a near-invisible flame — conventional fire detection may not detect a methanol fire
Toxicity	Toxic by ingestion, inhalation, and skin absorption; can cause blindness and death in acute exposure
Bunkering Infrastructure	Limited — available at pioneer ports; growing but not yet broadly established

Availability and Honest Assessment

It must be acknowledged directly: the maritime industry's methanol experience base is still being built. Unlike LNG, where extensive operational data exists, methanol dual-fuel operations at sea are recent and the available data pool is limited. The vessel orders placed by major container lines represent a bet on green methanol availability in the late 2020s that has not yet been validated by supply-side reality. The industry should approach methanol with cautious optimism: the technology pathway is credible, but the supply chain is not yet assured.

4.3 Ammonia

Production

Ammonia (NH_3) is produced through the Haber-Bosch process: the catalytic synthesis of nitrogen (from the atmosphere) and hydrogen at high temperature (400–500°C) and pressure (150–300 bar). Today, approximately 180 million tonnes of ammonia are produced annually worldwide, predominantly for agricultural fertiliser. This existing industrial scale is one of ammonia's key theoretical advantages as a marine fuel — the production infrastructure exists, even if it currently runs almost entirely on fossil natural gas.

The decarbonization of ammonia production is the central challenge:

- **Grey Ammonia**: Produced from hydrogen via conventional SMR without carbon capture. Approximately 1.8 tonnes of CO_2 emitted per tonne of ammonia produced. No net GHG benefit as a marine fuel.
- **Blue Ammonia**: Produced as above, but with carbon capture and storage (CCS) applied to the SMR process. Significant reduction in production emissions, contingent on CCS capture rates and storage permanence.

- **Green / Electro-Ammonia**: Produced using hydrogen from renewable-powered electrolysis. Near-zero Well-to-Wake emissions. Currently expensive and small-scale; dependent on renewable energy cost trajectories and electrolyzer scale-up.

Key Properties

Property	Value / Characteristic
Chemical Formula	NH_3 — Ammonia
Physical State	Gas at ambient conditions; liquid under modest pressure (~10 bar at 25°C) or refrigeration (−33°C at 1 atm)
Energy Density (volumetric)	~12.7 MJ/litre (approx. 33% of HFO — substantial tank space penalty)
Carbon Content	Zero — no CO_2 on combustion (nitrogen and water produced)
Acute Toxicity	IDLH: 300 ppm; LC50 (rat, 1hr): ~7,300 ppm. Severe respiratory, eye, and skin hazard.
Flammability	Flammable range 15–28% in air — narrower than most fuels; requires pilot fuel for stable marine combustion
Bunkering Infrastructure	Nascent — no commercial marine ammonia bunkering operations as of 2025
Material Compatibility	Stress Corrosion Cracking (SCC) risk in high-strength steels; incompatible with copper, brass, zinc alloys

Availability and Reality Check

Green ammonia production at commercial maritime scale does not yet exist. The volumes required to fuel even a modest percentage of the global fleet would require electrolyzer and renewable energy capacity that is currently orders of magnitude beyond what has been installed. The production cost premium of green over grey ammonia remains substantial. Blue ammonia offers a nearer-term bridge, but its GHG credentials depend heavily on CCS performance metrics that are still being established.

These realities do not invalidate ammonia as a long-term pathway — the zero-carbon combustion profile and the existing industrial production base are genuine advantages. But they reinforce the conclusion that commercially available green ammonia as a marine fuel is a 2030s prospect, not a 2020s reality. The work being done now — in engine development (Wärtsilä, MAN), safety protocols (Singapore Maritime Week Ammonia Bunkering Seminar), and pilot operations — is the essential preparation for that eventual commercial deployment.

4.4 Hydrogen

Production and Properties

Hydrogen (H2) is the lightest element and the highest energy-density fuel by mass (~120 MJ/kg, approximately three times that of conventional diesel). However, its energy density by volume is extremely low — even as cryogenic liquid hydrogen (stored at −253°C, just 20 degrees above absolute zero), its volumetric energy density is only approximately 8.5 MJ/litre, making the tank space penalty for marine applications severe.

Green hydrogen — produced via electrolysis powered by renewable electricity — is the decarbonization target. Grey hydrogen (from SMR without CCS) and blue hydrogen (SMR with CCS) represent transitional production pathways. The same hydrogen production challenges that constrain green ammonia also apply to green hydrogen, as ammonia is itself a hydrogen carrier.

Maritime Relevance

Hydrogen's direct application as a marine fuel is currently constrained to short-sea and ferry operations where the energy density penalty is manageable and range requirements are limited. For deep-sea shipping — the sector responsible for the bulk of maritime GHG emissions — hydrogen's storage and handling challenges are severe. Consequently, hydrogen is currently more relevant to the maritime sector as a feedstock for green ammonia and e-methanol production than as a direct fuel. Its inclusion in this analysis is important because the production trajectory of green hydrogen is the single most important variable in the viability timeline of both green ammonia and e-methanol.

4.5 Comparative Fuel Overview

Fuel	Carbon Content	Storage	Maturity (Marine)	Availability Now	Zero-Carbon Potential
LNG	High (fossil)	Cryogenic (−162°C)	Commercial	Good (hub ports)	Via Bio-LNG / e-LNG
Methanol	Present (fossil)	Ambient liquid	Early commercial	Limited	Via e-Methanol
Ammonia	Zero	Pressurised / refrigerated	Pre-commercial	Negligible (marine)	Yes (green pathway)
Hydrogen	Zero	Cryogenic (−253°C)	Pilot / niche	Very limited	Yes (direct use, niche)

5. Operational Experience: What We Know from the Frontline

The operational experience that exists today is deeply unequal across the three primary fuel candidates. LNG has years of commercial operational data. Methanol is building its first body of experience. Ammonia's operational learnings come primarily from controlled pilot programmes and seminar findings. This section presents each fuel's operational reality honestly, drawing on the direct sources consulted in the preparation of this paper.

5.1 LNG —Operational Experience and Industry Observations

The LNG sections of this paper draw on operational experience shared by vessel operators, fuel suppliers, and bunkering specialists. Together, these sources provide a grounded, multi-dimensional picture of LNG in commercial maritime operation.

5.1.1 Dual-Fuel Engine Operations

Observations from operators of LNG dual-fuel vessels in commercial service reveal a technology that is effective but still maturing. Key operational findings include:

- **Fuel Switching Reliability**: Transitions between HFO/VLSFO and LNG fuel modes have become increasingly reliable as software and engine management systems have matured, but early fleet vessels experienced control system instabilities during mode switching that required multiple software iterations to resolve. Crews needed to develop an intuitive understanding of the conditions under which fuel switching is and is not advisable.
- **Methane Slip — The Operational Reality**: Methane Slip (Cslip) — the emission of uncombusted methane through the engine cycle — is most pronounced at low engine loads (below approximately 25% MCR). Vessels on port approach, at anchor, or operating slow-steaming legs generate significantly higher Cslip than design assumptions, which are typically based on laden ocean passage conditions. Industry experience highlights that actual Well-to-Wake GHG performance across a voyage may differ materially from design calculations if the operational load profile is not carefully managed.
- **Maintenance Interval Calibration**: Fuel injection systems, gas admission valves, and cryogenic seals have exhibited wear rates and fouling patterns that differ from HFO baseline experience. OEM maintenance recommendations at time of vessel delivery did not always accurately reflect in-service realities, requiring adaptive maintenance planning by technical departments.
- **Equipment Standardization**: Even sister ships from the same yard have exhibited differences in fuel system configuration, control interfaces, and equipment specifications.

This creates crew familiarization challenges and complicates fleet-wide maintenance planning.

5.1.2 Bunkering Operations in Singapore

Singapore, as one of the world's most active LNG bunkering hubs, provides important practical context for understanding what operational readiness means in practice:

- **Connection Interface Standardization**: Despite international guidelines, real-world LNG bunkering connections are not fully standardized across vessel designs and bunkering craft configurations. Adapter management and pre-arrival interface verification are routine operational requirements that add time and complexity to bunkering calls.
- **Controlled Zone Management**: The establishment and enforcement of Controlled Zones during LNG bunkering — restricting access, maintaining atmospheric monitoring, and coordinating with port operations — is operationally intensive and requires well-trained, experienced personnel on both the receiving vessel and the bunkering craft.
- **Pre-Transfer Planning Depth**: Successful LNG bunkering operations require substantially more pre-transfer planning than conventional fuel oil bunkering. Ship/shore compatibility checks, safety management system alignment between vessels, and communication protocol agreement must all be completed before any transfer commences.
- **Regulatory Environment (Singapore)**: Singapore's MPA regulatory framework for LNG bunkering is among the most developed globally, providing clear licensing requirements, operational standards, and safety guidelines. Industry practitioners noted that this regulatory clarity — which many other ports lack — is a significant enabler of safe and efficient commercial operations.

5.1.3 Supply and Commercial Perspective

Experience and insights shared by fuel suppliers and energy companies provide an important perspective that is often absent from purely operational analyses:

- **Supply Security**: LNG supply for marine bunkering is integrated into the broader global LNG market, which is subject to price volatility and supply competition from the power generation and industrial sectors. While supply security has generally been maintained for marine customers, price spikes (as experienced in 2022 following geopolitical disruptions) create significant operational cost uncertainty for shipowners on spot fuel purchases.
- **The Fossil-to-Green Transition**: Major energy companies are investing in bio-LNG and e-LNG development, but the commercial volumes required for meaningful fleet penetration are years away. The current commercial LNG market is overwhelmingly fossil-derived. Shipowners building a decarbonization strategy around bio-LNG availability must plan carefully for the timeline of that transition.

- **Carbon Intensity of Supply Chain**: The carbon intensity of LNG supply varies significantly by source — Norwegian LNG (piped, low flaring) has a materially lower WtT footprint than LNG from high-flaring production regions. Well-to-Wake accounting under the IMO LCA framework will make this supply-chain carbon intensity a compliance variable, not just an ethical consideration.

5.2 Methanol — An Honest Assessment of Limited Experience

The maritime industry's operational experience with methanol as a marine fuel is recent and limited in scope. Unlike LNG — where years of commercial operation across hundreds of vessels have generated a substantial data pool — methanol dual-fuel vessels are only now entering service in meaningful numbers, and the body of operational data is still being built.

What is known from the early experience of pioneer operators and from engine manufacturer testing:

- **Fuel System Compatibility**: Methanol's solvent properties require careful material selection throughout the fuel system. Compatibility issues with conventional seals, gaskets, and coatings used in HFO/diesel systems have been identified and must be addressed in system design. Ships converted to or ordered with methanol capability have required material upgrades throughout their fuel supply systems.
- **Fire Safety Adaptation**: The invisible-flame characteristic of methanol combustion requires dedicated UV/IR fire detection systems, as conventional thermal imaging will not detect a methanol fire. This is a safety requirement that is well understood in principle but demands specific training and equipment that is not universally available.
- **Operational Flexibility**: Methanol's ambient-temperature liquid handling simplifies bunkering infrastructure compared to cryogenic LNG. However, the lower volumetric energy density (approximately 40% of HFO) imposes a significant tank capacity penalty that affects vessel range and cargo capacity planning.
- **Green Methanol Availability Gap**: Pioneer operators who have ordered methanol-capable vessels have, in most cases, secured initial green methanol supply through bilateral agreements with specific producers. Fleet-wide green methanol availability at commercial scale does not yet exist, and the fossil-methanol alternative undermines the decarbonization rationale.

In honest summary: methanol is a credible medium-term pathway with a clear technology trajectory, but the operational data to speak with authority about its maritime performance across a range of vessel types, trade routes, and operational profiles does not yet exist. This paper acknowledges that gap and will supplement this section as experience accumulates.

5.3 Ammonia — Singapore Maritime Week 2025: Seminar Findings

The ammonia bunkering content in this paper is derived primarily from presentations, discussions, and findings presented during the Ammonia Bunkering Seminar at Singapore Maritime Week 2025. This seminar brought together representatives from vessel operators, engine manufacturers, port authorities, classification societies, and safety specialists to present and discuss the current state of ammonia as a marine fuel. The Pilbara Ship-to-Ship pilot and the operational framework developed from it were among the central case studies presented.

5.3.1 The Pilbara Ship-to-Ship (STS) Ammonia Bunkering Pilot

The Pilbara ship-to-ship (STS) ammonia transfer trial, conducted off the Western Australian coast, represents an important milestone in the industry's efforts to assess the operational feasibility of ammonia as a future marine fuel. The trial brought together vessel operators, port authorities, technical specialists, and other stakeholders to evaluate the practical, safety, and operational considerations associated with ammonia transfer operations under controlled conditions.

Publicly available information from the project indicates that the trial was supported by extensive preparatory work, including risk assessments, mooring studies, atmospheric dispersion modelling, emergency response planning, and operational safety reviews. The transfer operation was conducted within predefined environmental and operational parameters, with continuous monitoring of safety-critical systems and conditions throughout the exercise.

The broader significance of the trial lies not simply in the successful transfer of ammonia between vessels, but in the validation of key safety principles that will underpin future commercial ammonia bunkering operations. These include the importance of detailed planning, stakeholder coordination, emergency preparedness, atmospheric monitoring, personnel protection measures, and clearly defined operational controls.

The findings reported from the trial suggest that ammonia transfer operations can be conducted safely when supported by appropriate engineering safeguards, operational procedures, and risk management measures. At the same time, the exercise highlighted the continuing need for further development of industry standards, crew competence requirements, emergency response capabilities, and supporting bunkering infrastructure before ammonia can be adopted on a wider commercial scale.

As one of the most significant ammonia transfer demonstrations undertaken to date, the Pilbara trial provides valuable practical insights into the opportunities and challenges associated with the future deployment of ammonia as a marine fuel and contributes meaningfully to the industry's growing body of operational experience.

5.3.2 Step-wise Operational Procedure

The discussions and case studies presented during Singapore Maritime Week highlighted several common elements that are likely to be essential for future ammonia ship-to-ship (STS) bunkering operations. These include comprehensive pre-transfer planning and stakeholder coordination, verification of safety systems and emergency response arrangements, continuous monitoring throughout fuel transfer operations, controlled post-transfer activities, and structured operational review processes following completion of bunkering.

The broader industry consensus emerging from these discussions is that ammonia bunkering will require a significantly higher level of planning, monitoring, and risk management than conventional marine fuel transfers. Particular emphasis was placed on personnel protection, atmospheric monitoring, emergency shutdown capability, operational coordination among stakeholders, and the management of concurrent activities within the operational area.

While specific procedures and operational requirements will continue to evolve as commercial ammonia bunkering develops, the experiences shared to date indicate that robust safety management systems, clear communication protocols, and comprehensive emergency preparedness will be fundamental to safe and successful ammonia fuel operations.

5.3.3 Key Seminar Findings on Ammonia Safety Culture

Beyond the operational procedure, there is a broader set of findings that are essential context for understanding ammonia's readiness status:

- **Toxicity-First Culture Required**: A recurring theme throughout the seminar discussions was that ammonia operations require a fundamentally different safety culture from conventional marine fuels. The acute toxicity of ammonia — immediately dangerous to life and health at 300 ppm — means that there is no 'acceptable' leak level, no 'acceptable' delay in response, and no 'acceptable' gap in PPE coverage during transfer operations.
- **SCC — The Unresolved Engineering Challenge**: Stress Corrosion Cracking in high-strength steel components exposed to ammonia was identified as the most significant unresolved material engineering challenge for commercial ammonia fuel systems. Solutions exist for ammonia cargo systems (cargo carriers have managed this for decades), but marine fuel system geometry, pressure cycling, and material specifications differ from cargo

system applications. Commercial-scale solutions specific to fuel systems are still under development.

- **PPE Ergonomics Gap**: Seminar discussions highlighted concerns that current PPE used for ammonia operations may not be optimally suited to the rapid and precise movements required during ship-to-ship fuel transfer activities. The bulk and rigidity of full chemical protection suits impair the fine motor control needed for coupling and decoupling operations.
- **Infrastructure Gap is the Binding Constraint**: The seminar's overall assessment aligned with this paper's finding: ammonia engine technology is advancing, safety protocols are being developed. But the absence of commercial-scale green ammonia production and port bunkering infrastructure means that commercial ammonia bunkering is a 2030s prospect at the earliest.

6. Competence Requirements: Preparing Seafarers for a Multi-Fuel Future

Ships with alternative fuel systems are being delivered now. The LNG dual-fuel fleet is already substantial. Methanol vessels are entering service. Ammonia-capable designs are on order. The question of whether seafarers are competent to operate these vessels safely is not a future concern — it is a present operational reality. And the honest answer, at this point, is that the industry's competence framework has not kept pace with its hardware ambition.

6.1 The IGF Code Course: What It Covers

The International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) provides the primary international safety framework for vessels using low-flashpoint fuels. The associated STCW training requirement — commonly referred to as the 'IGF Code course' — is a government-approved, internationally standardized training programme that represents the current formal foundation for alternative fuel competence among seafarers.

The IGF Code course covers the following core areas:

- **Fuel Properties and Hazards**: General principles of low-flashpoint fuel properties, including flammability, toxicity basics, and cryogenic hazard awareness. Primarily oriented toward LNG and general gaseous fuel principles.
- **Ship Systems**: Overview of IGF Code-compliant vessel design: fuel containment systems, gas detection systems, ventilation requirements, and safety system architecture.
- **Risk and Safety Management**: Introduction to risk assessment principles for low-flashpoint fuel operations. Generic safety management system application.
- **Emergency Procedures**: Basic emergency response procedures: alarm response, mustering, fuel shutdown principles, and coordination with shore-side emergency services.
- **Bunkering Operations**: An introduction to low-flashpoint fuel bunkering procedures, safety checklists, and communication requirements.

The IGF Code course is an important and necessary foundation. It represents genuine progress in establishing a baseline international standard. For seafarers operating LNG dual-fuel vessels in normal commercial operations, with well-trained shore-side bunkering partners and established port infrastructure, the IGF Code course provides a meaningful competence baseline.

6.2 Why the IGF Code Course Is Not Enough: The Competence Gap

The IGF Code course was developed primarily in the context of LNG as a marine fuel. Its scope, depth, and operational specificity do not adequately address the realities of the multi-fuel maritime future now unfolding. The gaps are significant, specific, and safety-critical:

GAP 1 — Ammonia Toxicity Is Not Fully Addressed

Since 2025, IMO has also developed generic interim training guidance for ships using alternative fuels and new technologies. In 2026, fuel-specific interim guidance for ammonia and methyl/ethyl alcohol fuels was approved by MSC 111. These developments represent important progress toward addressing competence gaps. However, the guidance remains interim in nature and has not yet been fully incorporated into harmonized mandatory STCW competence requirements.

GAP 2 — Methanol Fire Detection Is Not Covered

Methanol burns with a near-invisible flame that conventional fire detection systems and thermal imaging cameras cannot reliably detect. The IGF Code course does not address this hazard in sufficient depth or with sufficient specificity to prepare crew for fire response on a methanol-fueled vessel. The practical implications — delay in fire detection, incorrect suppression agent selection, inadequate evacuation decisions — are potentially fatal.

GAP 3 — Practical Bunkering Competence Requires OJT That The Course Cannot Provide

The IGF Code course is primarily a knowledge-based programme. It cannot replicate the physical experience of connecting and disconnecting cryogenic hoses in full PPE, operating gas detection instruments in real conditions, or executing an Emergency Shutdown under time pressure. Industry experts and operational data both confirm that knowledge-based training alone does not produce the reliable, automatic responses required in emergency conditions.

GAP 4 — Stress Corrosion Cracking and Material Integrity Are Not Covered

Understanding SCC — recognizing its precursors, conducting appropriate inspections, and making correct operational decisions when material integrity is in doubt — requires specific engineering knowledge beyond the IGF Code course scope. For ammonia fuel system operators, this gap is not theoretical: it is the difference between identifying an emerging integrity problem and missing it until failure occurs.

GAP 5 — Multi-Fuel Complexity Is Not Addressed

The maritime future is multi-fuel. Vessels may bunker LNG in Rotterdam, methanol in Singapore, and bio-LNG in Zeebrugge across a single trading rotation. The IGF Code course does not prepare seafarers for the cognitive and procedural demands of managing different fuel types across a voyage — each with different hazard profiles, different PPE requirements, different emergency procedures, and different bunkering interfaces.

6.3 The Required Competence Framework: The 4-Tier Hierarchy

A 4-tier framework represents best practice and should be the reference model for any serious competence development program:

Tier	Core Requirements	Assessment Method
1 — Management	Strategic risk management; SMS architecture for alternative fuels; regulatory compliance oversight; emergency authority and incident investigation.	Theoretical examination; regulatory scenario case studies; management simulation exercises.
2 — Operator	Direct bunkering operations; Controlled Zone management; Fire & Gas system operation; PPE donning and use; full bunkering procedure execution.	Simulator-based practical assessment; supervised OJT on actual vessel or bunkering facility; emergency scenario response evaluation.
3 — Support	System maintenance; continuous monitoring; routine inspection; early detection of leaks, corrosion, or system degradation; PPE maintenance.	Practical assessment; equipment handling verification; monitoring system operation; inspection record review.
4 — Emergency	ESD and ERS activation; Toxic Vapor Response (ammonia/methanol); spill containment; coordination with shore emergency services; rescue breathing.	High-fidelity simulation drills; timed ESD/ERS assessment; post-incident debrief regardless of outcome.

6.4 Training Methodology: From Knowledge to Competence

Bridging the gap between the IGF Code course baseline and the competence actually required demands a blended learning approach that moves beyond knowledge testing to verified operational capability:

- **High-Fidelity Simulation**: Emergency scenarios — ESD failure, toxic vapor release, cryogenic exposure, simultaneous fuel release and engine room fire — must be rehearsed in simulator environments that replicate the physical and cognitive demands of the real event, including full PPE operation and time pressure. Single exposure is insufficient; repeated rehearsal to reliable, automatic response is the standard.

- **Supervised On-the-Job Training (OJT)**: Practical experience aboard vessels or at bunkering facilities, with defined competency milestones verified by a qualified assessor. Hours-based OJT requirements are insufficient; milestone-based assessment is the appropriate standard.
- **OEM-Integrated Training**: Manufacturer-specific system documentation must be integrated directly into training, not treated as supplementary reference material. Crew must be able to navigate OEM documentation fluently under operational pressure.
- **Crew Resource Management (CRM)**: The communication and decision-making failures that contribute to maritime incidents are frequently systemic. CRM principles — closed-loop communication, shared mental models, appropriate authority gradients — must be embedded in alternative fuel training programs.

6.5 The Urgency of Action

The competence gap is not a future problem awaiting a future solution. LNG dual-fuel vessels with crews trained only to the IGF Code course baseline are operating today. Methanol vessels are entering service. The gap between what the IGF Code course provides and what safe operation of these vessels requires is real, measurable, and potentially dangerous.

The industry — flag states, training institutions, shipowners, and classification societies — must treat competence development with the same urgency it has applied to hardware ordering. The vessels will be delivered on schedule. The question is whether the people required to operate them safely will be ready when they arrive.

7. Conclusion: An Industry in Transition, Not Yet Ready

The maritime industry's commitment to decarbonization is not in question. The orders are real. The engine development is real. The pilot operations are real. The regulatory ambition is real. What is also real — and what this paper has sought to document honestly — is that the gap between hardware commitment and operational readiness remains wide, and closing it requires urgent, coordinated action across regulation, fuel supply, and human capital development simultaneously.

7.1 Where We Are

- **Regulation**: The IMO Net-Zero Framework has not yet been formally adopted. Although significant progress has been made, further negotiations remain necessary before the regulatory framework becomes legally binding. The subsequent MEPC 85 are the next opportunities for the framework that will unlock committed, long-term investment decisions.
- **Technology**: Advancing, but not yet fully proven at commercial scale. LNG dual-fuel is mature. Methanol is early-commercial. Ammonia is pre-commercial but developing rapidly — driven notably by engine manufacturers including Wärtsilä and MAN who have not waited for regulation to advance their engineering work.
- **Fuel Availability**: The binding constraint for the long-term transition. LNG is available. Fossil methanol is available but delivers limited GHG benefit. Green methanol and green ammonia are not available at commercial maritime scale. The production economics and timeline for scaling green fuel supply are the least predictable variables in the entire transition.
- **Competence**: The most urgent near-term gap. Ships are being delivered now. The IGF Code course is a necessary but deeply insufficient foundation. The competence framework the industry needs — articulated in a 4-tier hierarchy, the protocols emerging from the Singapore Maritime Week ammonia seminar, and the operational lessons of the industry thus far — must be developed, standardized, and deployed at scale.

7.2 Priority Actions

Priority	Action	Who	Indicative Timeline
1 — CRITICAL	Build consensus on the IMO Net-Zero Framework and finalize the GHG Fuel Intensity (GFI) standard and economic measures.	IMO Member States	Prior to formal adoption of the framework
2 — CRITICAL	Complete lifecycle emission factors and certification methodologies for	IMO / GESAMP-LCA Working Group	2026–2028

	alternative fuels and production pathways.		
3 — URGENT	Transition interim alternative-fuel training guidance into harmonized mandatory STCW competence standards.	IMO MSC; Flag States; MET Institutions	2026–2029
4 — URGENT	Accelerate R&D into ergonomics and usability of PPE for alternative-fuel bunkering and emergency response.	Manufacturers; Classification Societies	2026–2028
5 — URGENT	Expand deployment of Engine Load Monitoring (ELM) and Continuous Emission Monitoring Systems (CEMS) to improve methane-slip measurement and emissions verification.	Flag States; Shipowners; Engine Manufacturers; Classification Societies	2026–2029
6 — IMPORTANT	Accelerate coordinated R&D into Stress Corrosion Cracking (SCC), materials compatibility and long-term integrity of ammonia fuel systems.	Shipbuilders; Classification Societies; Research Institutions	2026–2030
7 — STRUCTURAL	Expand high-fidelity alternative-fuel simulator capacity and practical training infrastructure globally, particularly in developing maritime nations.	MET Institutions; Flag States; Industry Associations	2026–2030
8 — STRUCTURAL *(optional)*	Establish globally harmonized fuel certification and chain-of-custody systems for Well-to-Wake compliance.	IMO; Fuel Producers; Classification Societies	2026–2028

7.3 Final Reflection

The conversations with industry experts that informed this paper share a common thread. Every one of these practitioners understands both the scale of the challenge and the genuine progress being made. None of them are complacent. None of them believe the industry is ready. All of them believe it can be — if the urgency is matched to the ambition.

The vessels will be delivered. The fuels will eventually be available. The regulations will, in time, be resolved. The only question that the industry controls entirely, right now, is whether the people on board those vessels will be prepared to operate them safely. That question demands an answer — not a study, not a committee, not a framework. An answer, in the form of trained, assessed, and certified seafarers who can handle what is coming.

8. References and Sources

8.1 Industry Consultations

- The preparation of this report was informed by industry consultations and discussions conducted primarily during Singapore Maritime Week 2025 and through related industry engagements. Organizations consulted included British Petroleum (BP), Fuel LNG, BW Hafnia, and Wärtsilä Corporation, representing perspectives from energy and fuel supply, LNG bunkering, vessel operations, and marine engine technology. These consultations provided practical industry perspectives on LNG supply and bunkering operations, ship-to-ship transfer practices, dual-fuel vessel operations, alternative-fuel engine development, maintenance considerations, methane slip, safety management, and crew familiarization. Insights from these engagements have been consolidated and presented on an aggregated, non-attributable basis and should not be interpreted as statements, endorsements, or positions of any individual organization.

8.2 Conference and Seminar Sources

- **Ammonia Bunkering Seminar, Singapore Maritime Week 2025**: This paper draws upon discussions, presentations, and publicly discussed industry developments presented during Singapore Maritime Week 2025.

8.3 IMO Regulatory Instruments

- **IMO Resolution MEPC.410(84)**: Amendments to EEDI calculation guidelines — redefinition of 'gas' to encompass liquid alternative fuels in dual-fuel mode.
- **IMO Resolution MEPC.414(84)**: 2026 Guidelines for measurement and reporting of CH4 and N2O emissions from ship operations.
- **IMO Resolution MEPC.415(84)**: Guidelines for Engine Load Monitoring (ELM) — framework for quantifying methane slip risk in LNG and bio-methane engine operations.
- **IMO Resolution MEPC.416(84)**: Guidelines for Continuous Emission Monitoring Systems (CEMS) — standards for real-time shipboard exhaust gas monitoring.
- **MEPC.1/Circ.916**: Methodology for submission and review of default emission factors under the IMO LCA Guidelines.
- **2023 IMO GHG Strategy**: Revised Strategy on Reduction of GHG Emissions from Ships, adopted MEPC 80, July 2023.

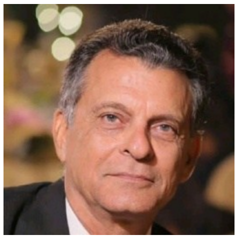
8.4 Technical Standards

- **IGF Code**: International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels — foundational safety standard for LNG and alternative fuel vessel design and operations.
- **IGC Code**: International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk — applied by analogy to ammonia fuel system design.
- **STCW Convention (as amended)**: International Convention on Standards of Training, Certification and Watchkeeping for Seafarers — global legal framework for maritime crew competence, pending amendment for alternative fuel specifics.
- **TR 56:2020**: Technical Reference for Bunkering of LNG Fuelled Vessels, Singapore Standards Council.
- **MARPOL Annex VI**: International Convention for the Prevention of Pollution from Ships — primary regulatory instrument for air pollution from shipping, under amendment via the IMO GHG Strategy framework.

8.5 Forthcoming Key Documents

- **5th IMO GHG Study**: Updated scientific baseline for maritime GHG inventory and projections. Will inform the 2028 strategy review and the regulatory trajectory toward 2040 and 2050.
- **Outputs of the 2026 intersessional GHG working group meetings**: Technical instruments developed inter-sessionally to operationalize the regulatory framework to be agreed at MEPC ES.2.

9. About the Authors



Pawan Kapoor is the Founder and Director of ISF Group, a maritime organization specializing in maritime training, research, consultancy, and digital solutions for the global shipping industry. With more than three decades of experience across ship operations, maritime education, and organizational leadership, he has worked extensively in seafarer competence development, maritime safety, competency-based training, and human capital development.

Over the years, he has led numerous international research initiatives, developed training programmes aligned with IMO and industry standards, and collaborated with shipping companies, maritime administrations, classification societies, and industry associations to advance safety, competence, sustainability, and innovation across the maritime sector.

Yogyata Kapoor is Director at ISF Group, where she leads strategic initiatives in maritime research, digital transformation, software development, and training management. She holds a Master's degree in Mechatronics from Cranfield University, United Kingdom, and combines an engineering background with practical experience in maritime operations, technology, and business management.

Her work focuses on developing digital solutions for the maritime industry, leading international research and benchmarking studies, and designing competency-based learning systems that support the future maritime workforce. She works closely with shipping companies, industry bodies, and global maritime stakeholders on projects involving decarbonization, seafarer competence, maritime technology, and digital innovation. She also serves as a Board Member of WISTA Singapore, contributing to industry collaboration and the advancement of diversity and innovation within the maritime sector.

END OF REPORT

Technical Research Report — Maritime Future Fuels Readiness Assessment