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OF
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IIRE Journal of Maritime Research and Development

Maritime sector has always been influencing the global economy. Shipping facilitates the bulk transportation of raw material, oil and gas products, food and manufactured goods across international borders. Shipping is truly global in nature and it can easily be said that without shipping, the intercontinental trade of commodities would come to a standstill.

Recognizing the importance of research in various aspects of maritime and logistic sector, IIRE through its Journal of Maritime Research and Development (IJMRD) encourages research work and provides a platform for publication of articles, manuscripts, technical notes, papers, *etc.* on a wide range of relevant topics listed below:

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Editorial Board

Editorial

Navigating the Great Maritime Realignment: Systemic Safety, Competence Lags, and Geopolitical Agility

The global maritime industry is experiencing a profound structural transformation that challenges its traditional operating models across multiple vectors simultaneously. The historical stability of trade routes, predictable regulatory timelines, and conventional safety methodologies are giving way to an era of systemic discontinuity. This volume brings together five seminal papers that collectively diagnose these vulnerabilities and offer cohesive, forward-looking frameworks to navigate this high-risk landscape. From the commercial realities of shifting geopolitical maps to the acute technological and human challenges of the future-fuels transition, these authors argue that shipping's next competitive advantage lies not in static compliance, but in dynamic, systems-oriented resilience.

The Architecture of the Realignment

A core thread connecting these works is the recognition that traditional, point-in-time assurance structures are fundamentally inadequate for a volatile, rapidly evolving industry.

- **Geopolitical Agility:** Punit Oza introduces the **A.R.E.A. (Alliances, Relationships, Execution, Assets)** framework, arguing that shipping must move away from static forecasting toward building organizational muscle capable of adapting when chokepoints and sanctions move within a single news cycle. Oza emphasizes that true control over supply chains serves as the ultimate differentiator and client insurance policy in an era defined by geopolitical fragmentation.
- **Operational Accountability:** This paradigm shift from static structures to dynamic verification is mirrored in safety governance. Examining the June 2026 hydrocarbon release involving the LNG vessel *SOHAR* at Alang-Sosiya, Capt. (Dr.) Y. C. Shah demonstrates how facility certification under the Hong Kong Convention is merely a baseline. Shah exposes the dangerous gap between point-in-time certification and real-time operational performance during environmental emergencies, proposing a rigorous post-incident audit protocol to bridge this divide.

The Alternative Fuel Conundrum: Ambition vs. Readiness

The industry's ambitious push toward net-zero emissions by or around 2050 introduces a multi-dimensional readiness crisis where the development of vessel hardware is outpacing regulatory frameworks and human capabilities.

- **The Multi-Dimensional Gap:** Pawan and Yogyata Kapoor provide a comprehensive readiness assessment across regulation, technology, fuel availability, and competence. They highlight an uneven landscape: while dual-fuel hardware advances rapidly under the leadership of major engine manufacturers, commercial-scale availability of green fuels remains restricted, and the human capital gap remains dangerously wide.
- **Training Ahead of the Rulebook:** Focusing intensely on this human risk, Pushkal Kapoor highlights the acute regulatory and competence lag in future-fuel operations. As seafarers face highly hazardous, unfamiliar environments—such as the toxic profile of ammonia or the near-invisible flames of methanol—the mandatory international standard architecture (STCW) is lagging years behind commercial deployment. Pushkal champions immersive technology (**VR/AR**) as a scalable, high-fidelity instrument to build automated, life-saving competencies before crew members encounter real-world shipboard emergencies.

Redefining Safety Science: From Deficit to Context

At the heart of managing both future-fuel hazards and operational discontinuities is a necessary revolution in safety philosophy, moving away from archaic blame cultures.

Dr. (Captain) Suresh Bhardwaj advocates for the integration of **Safety II** and **Resilience Engineering** into maritime operations, shifting the focus from why things go wrong (Safety I) to how systems usually succeed under variable conditions. Bhardwaj critiques traditional investigation tools like SCAT (Systematic Cause Analysis Technique), which rely on deficit-based taxonomies that default to "human error" or procedural failure.

Instead, he introduces the **CLUE (Contextual Learning and Understanding of Events)** taxonomy. Grounded firmly in Human and Organizational Performance (HOP) principles, CLUE utilizes neutral language to analyze how task, workplace, individual, and organizational factors interact. It recognizes that human error is a symptom of contextual vulnerability, not the cause of failure.

Future Horizons: A Cohesive Blueprint

Synthesizing these five pieces reveals a unified mandate for global maritime leadership. The industry cannot afford to treat geopolitics, environmental safety, technology, and crew training as isolated, independent silos.

1. **Dynamic Risk Alignment:** Commercial operations must embed Technical and Legal expertise directly at the point of decision-making, continuously auditing standard-form charterparties against active trade corridors.
2. **Proactive Competence Cultivation:** Training institutions and flag states must accelerate the deployment of milestone-based, high-fidelity simulator training, moving past the rigid boundaries of outdated regulatory rulebooks.
3. **Linguistic and Behavioural Reframing:** Ship operators must transition from punitive, compliance-heavy reporting metrics to context-driven learning taxonomies, sustaining the psychological safety required for transparent incident reporting.

The vessels of the next generation are already hitting the water; the geopolitical maps are already moving. This volume demonstrates that our systems, governance structures, and human safety cultures must evolve with equal velocity if we are to successfully navigate the uncharted waters ahead.

Happy Reading!

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ARE WE READY FOR FUTURE FUELS IN THE MARITIME INDUSTRY?

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

Pawan Kapoor [1] & Yogyata Kapoor [2]

Abstract

The maritime industry is undergoing a critical transition toward low- and zero-carbon fuels in response to global decarbonization objectives and the International Maritime Organization's net-zero ambition. This paper evaluates the readiness of the sector through four interconnected dimensions: regulation, technology, fuel availability, and seafarer competence. The assessment identifies significant progress in alternative fuel vessel development, engine innovation, and regulatory planning; however, operational readiness remains uneven. LNG demonstrates commercial maturity, methanol presents a promising but supply-constrained pathway, and ammonia offers long-term zero-carbon potential while requiring further development in safety systems, infrastructure, and production capacity. The study highlights that fuel availability and human competence are the decisive factors influencing successful adoption of future marine fuels. Existing training frameworks provide a foundation but require expansion to address ammonia toxicity, methanol fire risks, multi-fuel operations, and practical emergency response requirements. The paper concludes that maritime decarbonization is advancing, but achieving safe and effective deployment of future fuels will require coordinated action among regulators, shipowners, fuel producers, technology providers, ports, and training institutions. A balanced transition strategy must therefore align technological advancement with regulatory certainty and workforce preparedness to ensure sustainable maritime operations.

Keywords; *Maritime Decarbonization, Future Marine Fuels, Alternative Fuel Vessels, Zero-Carbon Shipping, LNG, Methanol and Ammonia Fuels, IMO Net-Zero Strategy, Fuel Availability and Infrastructure, Seafarer Competence and Training, Regulatory Readiness, Sustainable Maritime Operations*

1. INTRODUCTION

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

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conclusion is that progress is genuine but uneven — and the gap between hardware ambition and operational readiness remains dangerously wide.

Table 1: Executive Summary Overview by Readiness Dimension

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.

2.4.1 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.

2.4.2 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.

2.4.3 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.

2.4.4 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.

2.4.5 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 dong 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)

4.1.1 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.

4.1.2 Key Properties

Table 2: Key Properties of LNG

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.)

4.1.3 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

4.2.1 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.

4.2.2 Key Properties

Table 3: Key Properties of Methanol

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
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

4.2.3 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

4.3.1 Production

Ammonia (NH3) 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.

4.3.2 Key Properties

Table 4: Key Properties of Ammonia

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

4.3.3 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

4.4.1 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.

4.4.2 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

Table 5: Comparative Overview of Candidate Marine Fuels

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:

Table 6: Competence Gaps in the Current IGF Code Course

Gap	Description
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

Gap	Description
	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:

Table 7: 4-Tier Competence Framework for Alternative Fuel Operations

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	High-fidelity simulation drills; timed ESD/ERS assessment; post-

Tier	Core Requirements	Assessment Method
	containment; coordination with shore emergency services; rescue breathing.	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

Table 8: Priority Actions for Industry Stakeholders

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 alternative fuels and production pathways.	IMO / GESAMP-LCA Working Group	2026–2028
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.

REFERENCES

Ammonia Bunkering Seminar. (2025). *Ammonia bunkering: Discussions, presentations and publicly discussed industry developments* [Conference sessions]. Singapore Maritime Week 2025, Singapore.

International Maritime Organization. (n.d.-a). *IGC Code: International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk*. IMO. (Applied by analogy to ammonia fuel system design.)

International Maritime Organization. (n.d.-b). *IGF Code: International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels*. IMO.

International Maritime Organization. (n.d.-c). *MARPOL Annex VI: International Convention for the Prevention of Pollution from Ships*. IMO.

International Maritime Organization. (n.d.-d). *MEPC.1/Circ.916: Methodology for submission and review of default emission factors under the IMO LCA Guidelines*. IMO.

International Maritime Organization. (n.d.-e). *STCW Convention (as amended): International Convention on Standards of Training, Certification and Watchkeeping for Seafarers*. IMO.

International Maritime Organization. (2023). *2023 IMO strategy on reduction of GHG emissions from ships* (Resolution MEPC.377(80), adopted at MEPC 80). IMO.

International Maritime Organization. (2026a). *Resolution MEPC.410(84): Amendments to the EEDI calculation guidelines — redefinition of "gas" to encompass liquid alternative fuels in dual-fuel mode* (MEPC 84). IMO.

International Maritime Organization. (2026b). *Resolution MEPC.414(84): Guidelines for measurement and reporting of CH4 and N2O emissions from ship operations* (MEPC 84). IMO.

International Maritime Organization. (2026c). *Resolution MEPC.415(84): Guidelines for engine load monitoring (ELM) — framework for quantifying methane slip risk in LNG and bio-methane engine operations* (MEPC 84). IMO.

International Maritime Organization. (2026d). *Resolution MEPC.416(84): Guidelines for continuous emission monitoring systems (CEMS) — standards for real-time shipboard exhaust gas monitoring* (MEPC 84). IMO.

International Maritime Organization. (in press-a). *Fifth IMO GHG study: Updated scientific baseline for maritime GHG inventory and projections*. IMO.

International Maritime Organization. (in press-b). *Outputs of the 2026 intersessional GHG working group meetings*. IMO.

ISF Group. (2025). *Industry consultations conducted during Singapore Maritime Week 2025 and related engagements with British Petroleum (BP), Fuel LNG, BW Hafnia and Wärtsilä Corporation* [Aggregated, non-attributable industry insights]. ISF Group.

Singapore Standards Council. (2020). *TR 56:2020: Technical reference for bunkering of LNG fuelled vessels*. Enterprise Singapore.

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THE A.R.E.A. IMPERATIVE
WHY SHIPPING'S NEXT COMPETITIVE ADVANTAGE IS A CHANGE OF MINDSET, NOT A CHANGE OF MARKET

Punit Oza[1]

Abstract

The maritime and trading industry is entering a period of structural uncertainty driven by geopolitical disruptions, shifting trade corridors, sanctions risks, and evolving customer expectations. This paper introduces the A.R.E.A. framework—Alliances, Relationships, Execution, and Assets—as a strategic approach for shipping organisations seeking resilience and competitive advantage in a rapidly changing environment. The study argues that traditional measures such as freight performance, vessel utilisation, and cost efficiency are no longer sufficient to manage contemporary risks. Instead, companies must develop adaptive alliances, strengthen trust-based relationships, improve operational execution, and secure strategic control over critical maritime assets. The framework highlights that resilience depends not on accurately predicting future disruptions but on building organisational capability to respond effectively when uncertainty arises. By integrating geopolitical awareness with commercial strategy, operational discipline, and asset-based control, maritime organisations can enhance reliability and customer confidence. The paper concludes that future success in shipping will depend on a mindset shift from forecasting market movements to developing flexible, relationship-driven, and execution-focused organisations capable of converting uncertainty into strategic opportunity.

Keywords: Maritime Strategy, Geopolitical Risk, Shipping Resilience, Strategic Alliances, Supply Chain Security, Maritime Operations, Asset Control, Relationship Management, Operational Excellence, Trade, Corridor, Disruption

For most of the last four decades, the shipping and trading world operated on a reasonably stable map. Chokepoints were geography, not geopolitics. Sanctions regimes were the exception, not the operating condition. Alliances were signed once, in liner conferences and P&I clubs, and revisited once a decade. That map is gone. What has replaced it is not simply "volatility" — a word used so often in shipping circles that it has lost its ability to alarm anyone. What has replaced it is a structurally different operating environment, one in which the chokepoint, the sanctions list, and the trade corridor can all move within a single news cycle.

The Strait of Hormuz crisis of 2026 has made this concrete rather than theoretical. Toll regimes have been proposed and contested. War-risk premiums have swung by the week. Charterparties drafted for a calmer age — CONWARTIME clauses, force majeure language, sanctions warranties — have been tested in real time, sometimes found wanting. And underneath all of it, a quieter but equally important shift has been under way: the buyers of freight, of storage,

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of maritime connectivity, are no longer simply asking "what is your rate." They are asking "can you actually deliver, and can I trust you when the map moves again."

> ***The companies that will profit from this age are not the ones with the best forecast. They are the ones with the right mindset.***

That is the argument of this piece. Not a prediction about where the next chokepoint closes, or which sanctions list expands next — no one can offer that with any honesty. Instead, a framework for where organisational attention must now go if a company intends to manage this age well, and more ambitiously, to profit from it. I call it A.R.E.A.: Alliances, Relationships, Execution, Assets. Four areas of focus, one underlying mindset shift.

1. WHY A NEW FRAMEWORK, AND WHY NOW

It would be easy to dismiss another four-letter acronym as consultancy shorthand. I would ask for patience on that point, because A.R.E.A. is not descriptive — it is not simply naming four things that already matter in shipping. It is prescriptive: it names four things that matter differently now, in a way that requires a genuine reallocation of leadership attention, and in some cases capital, away from where it has traditionally sat.

Consider where senior attention in a typical shipping or trading organisation has historically concentrated: freight rates, vessel utilisation, cost control, and increasingly, digital transformation. All of these remain necessary. None of them, on their own, addresses the central risk of this era, which is not operational inefficiency but geopolitical discontinuity — the chokepoint that closes without warning, the counterparty that becomes sanctioned overnight, the trade corridor that simply ceases to exist for a period of months. A.R.E.A. is an attempt to name what leadership attention must add, not replace.

2. A — ALLIANCES: FROM STATIC CONTRACTS TO LIVING COALITIONS

For a generation, the word "alliance" in shipping meant something specific and slow-moving: a liner consortium, a P&I club membership, a class society relationship. These structures were built for stability and they served that purpose well. They were not built for speed, and speed is now the defining requirement.

The alliances that matter in this new age are dynamic by design. They include flag-state relationships that can flex as sanctions designations expand or contract. They include coalitions of insurers, financiers, and P&I correspondents who are prepared to move together — quickly, and with shared risk appetite — when a strait tightens or a toll regime is proposed. They include counterparties chosen not purely for cargo fit or freight competitiveness, but for geopolitical alignment: a charterer, a bank, or a terminal operator whose interests and exposures run in a broadly compatible direction to your own when the map shifts.

2.1 What this means in practice

- Treat alliance-building as a continuous discipline, not a contract signed once and filed away — review key relationships against the current geopolitical map, not the map that existed when the contract was signed.
- Build genuine redundancy into critical alliances — insurers, flag administrations, correspondent banks — so that a single relationship going dark does not strand an operation.
- Extend alliance thinking beyond the traditional shipping fraternity into adjacent domains — cyber, satellite connectivity, trade finance — where the next point of fragility is as likely to appear as in the hull itself.

The organisations moving fastest here are the ones that have stopped treating alliance management as a legal or compliance function and started treating it as a strategic one, sitting close to the top table rather than several layers below it.

3. R — RELATIONSHIPS: TRUST AS THE FASTEST FORM OF DUE DILIGENCE

Trade flows are being redrawn in real time. New buyers of crude have emerged where sanctioned cargo once moved. New corridors for grain, fertiliser, and dry bulk have opened as traditional routes have become contested or uneconomic. None of this redrawing happens through a tender portal or a standard freight index. It happens through relationships — the ones already banked over years of dealing, and critically, the new ones being built right now with counterparties in markets that barely registered five years ago and matter enormously today.

> ***In this environment, trust is not a soft virtue. It is the fastest form of due diligence you have.***

This is a genuinely uncomfortable point for organisations that have spent the last decade professionalising and systematising counterparty risk — building scorecards, compliance checklists, and automated screening. Those tools remain essential and are not being argued away here. But when a new corridor opens and a decision is needed within days, not months, it is the relationship — the years of dealing, the personal credibility of the broker or the trader on the other end of the call — that allows a company to move while competitors are still completing their onboarding forms.

3.1 What this means in practice

- Invest deliberately in relationship-building in the markets that are gaining relevance, not only the markets where your book has traditionally been concentrated.
- Give commercial teams genuine latitude to move on relationship-based judgement within clear risk parameters, rather than requiring every new counterparty decision to clear the same process built for a calmer age.
- Recognise that relationships are now a balance-sheet asset in all but name — protect and cultivate them with the same seriousness applied to any other strategic resource.

4. E — EXECUTION: THE MICRO HAS BECOME THE STRATEGY

There is a temptation, in a period defined by macro shocks, to focus leadership attention almost entirely at the macro level — the geopolitical briefing, the scenario plan, the board presentation on chokepoint risk. All of that has its place. But in a volatile macro environment, it is very often the micro that determines who actually profits and who is exposed when the shock arrives.

A war-risk clause drafted a shade too loosely. A sanctions warranty not updated to the latest designation list. A voyage instruction issued an hour later than it should have been. A charterparty that references BIMCO Sanctions 2020 language without having been tested against the specific corridor in question. These are not glamorous failures. They rarely make the geopolitical briefing. But they are, overwhelmingly, where the financial exposure actually crystallises.

> ***This is not the age for generalists managing by exception. It is the age for deep operational expertise, embedded in every fixture, every clause, every routing decision.***

4.1 What this means in practice

- Push technical and legal expertise — clause drafting, sanctions screening, war-risk assessment — closer to the point of decision, rather than leaving it as a back-office review function that operates after commitments are already made.
- Audit standard-form clauses regularly against the corridors currently in use, not the corridors that were relevant when the template was last updated.
- Treat execution excellence as a source of competitive advantage and client trust, not merely a cost of doing business — customers increasingly select counterparties on the strength of this capability.

5. A — ASSETS: CONTROL AS THE PRODUCT CUSTOMERS ARE ACTUALLY BUYING

When the map keeps moving, the most durable hedge available to any organisation is control. Owning — or securing long-term, contractually robust rights to — the assets that move and store cargo provides a degree of certainty that no amount of forecasting, however sophisticated, can replicate. Vessels. Terminal capacity. Storage. Positions in the corridors most likely to matter over the coming decade rather than the coming quarter.

This is, in a sense, the most traditional of the four areas — shipping has always been a capital-intensive, asset-owning business. What has changed is the reason asset control matters. It is no longer simply about capturing freight upside in a strong market. It is about being able to look a customer in the eye and say, credibly, that the supply chain will function regardless of what the geopolitical map does next.

> ***What the customer is really buying today is not a rate. It is the certainty that comes from a counterparty who controls its own supply chain.***

5.1 What this means in practice

- Weigh asset ownership and long-term control decisions explicitly against geopolitical resilience, not only against freight-market cyclicality.
- Consider strategic positions in chokepoint-adjacent infrastructure — storage, terminal capacity, alternative-corridor assets — as a form of insurance as much as a form of investment.
- Communicate asset control to customers as a commercial differentiator, not merely a balance-sheet fact buried in an annual report.

6. THE MINDSET BEHIND THE FRAMEWORK

It would be a misreading of this argument to treat Alliances, Relationships, Execution, and Assets as four independent workstreams to be assigned to four different departments. The point of A.R.E.A. is that these four areas now reinforce one another in ways they did not need to a generation ago. An alliance is only as strong as the relationship underpinning it. A relationship is only as valuable as the execution that honours it under pressure. And execution, in turn, is only credible when it is backed by genuine asset control — the ability to actually deliver, not merely to promise.

This is, at heart, a call for a different kind of leadership attention: less time spent refining the forecast, more time spent building the organisational muscle — in alliances, in relationships, in execution discipline, in asset control — that allows a company to respond well regardless of which forecast turns out to be right. The companies that make this shift will not have predicted the next closure of the Strait of Hormuz, or the next sanctions designation, or the next corridor to open. They will simply be the ones best placed to profit when it happens.

7. CLOSING THOUGHT

The geopolitical map of trade and shipping will keep moving. That is not a temporary condition to be endured until stability returns — it is very likely the operating condition of this decade and the next. The organisations that treat A.R.E.A. as a genuine mindset shift, rather than a slogan for a slide, will be the ones writing the next chapter of this industry rather than simply reacting to it.

REFERENCES

BIMCO. (2020). *BIMCO sanctions clause for time charter parties 2020*. Baltic and International Maritime Council.

Christopher, M. (2016). *Logistics & supply chain management* (5th ed.). Pearson Education.

Notteboom, T., Pallis, A. A., & Rodrigue, J.-P. (2022). *Port economics, management and policy*. Routledge.

Stopford, M. (2009). *Maritime economics* (3rd ed.). Routledge.

UNCTAD. (2023). *Review of maritime transport 2023*. United Nations Conference on Trade and Development.

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TRAINING AHEAD OF THE RULEBOOK: VIRTUAL AND AUGMENTED REALITY AS INSTRUMENTS FOR FUTURE-FUEL FIREFIGHTING AND EMERGENCY-RESPONSE COMPETENCE AT SEA

Pushkal Kapoor[1]

Abstract

Shipping is committing capital to methanol-, ammonia- and hydrogen-capable tonnage faster than it is building the training estate required to crew it. The mandatory competence architecture has not caught up: the International Maritime Organization (IMO) governs alternative-fuel safety through a set of interim circulars, has issued its first training guidance for alternative fuels only in non-mandatory form between June 2025 and May 2026, and has adjourned adoption of its Net-Zero Framework to a resumed session in December 2026. This paper argues that the resulting interval, in which ships are capable, rules incomplete and sea berths for gaining experience scarce, is precisely the condition under which virtual and augmented reality (VR/AR) deliver disproportionate value, and that the industry's hesitation is therefore mistimed rather than unreasonable. Drawing on regulatory instruments, agency studies and the peer-reviewed literature on immersive training, the paper examines why future-fuel fire and toxic-release scenarios resist conventional live-fire pedagogy, weighs the evidence for and against extended reality (XR), and identifies the barriers that explain delayed adoption: cost, an instructor workforce that is itself unprepared for the technology and for the fuels, the absence of any requalification pathway for trainers, missing assessment equivalence and a regulatory "causality dilemma". It closes with a four-tier adoption model designed so that investment made before the rules mature remains auditable once they do.

Keywords: *maritime education and training; alternative fuels; ammonia; methanol; virtual reality; augmented reality; firefighting; STCW; IMO*

1. INTRODUCTION

The maritime energy transition is usually discussed as an engineering and commercial problem. It is at least as much a competence problem. Ammonia is acutely toxic. Methanol burns with a flame that is difficult to see and cannot be extinguished with ordinary foam. Hydrogen is buoyant, wide-ranging in its flammability and prone to ignition from very low energy inputs. None of these behave like the residual fuel oil around which a century of shipboard fire training was designed, and none of them can be introduced into a conventional live-fire training ground for casual practice.

The scale of the requirement is not speculative. Research conducted for the Maritime Just Transition Task Force, a body convened at COP 26 by the IMO Secretariat together with the International Chamber of Shipping, the International Transport Workers' Federation, the

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International Labour Organization and the UN Global Compact, indicated that as many as 800,000 seafarers could require additional training by the mid-2030s to work safely with alternative fuels and new propulsion technologies (Maritime Just Transition Task Force, 2022). Meanwhile the fleet continues to change: DNV's Alternative Fuels Insight platform recorded 275 orders for alternative-fuelled vessels in 2025, and although that was a 47 per cent reduction on an exceptional 2024, alternative fuels still accounted for roughly 38 per cent of ordered gross tonnage (DNV, 2026).

The argument advanced here is straightforward. The competence requirement is arriving before the mandatory standard that will define it, and before there are enough alternative-fuelled ships to train people on board. In that gap, immersive technologies are not a luxury or a marketing device. They are the only scalable way to give a seafarer repeated, structured exposure to an ammonia release or a methanol bilge fire before the first one happens in front of them.

2. THE REGULATORY POSITION: GUIDANCE RUNNING AHEAD OF MANDATE

IMO's safety framework for alternative fuels is presently a patchwork of interim guidelines rather than a code. The Organization's own future-fuels portal lists interim guidelines for ships using methyl/ethyl alcohol as fuel (MSC.1/Circ.1621), LPG fuels (MSC.1/Circ.1666), fuel cell power installations (MSC.1/Circ.1647), ammonia as fuel (MSC.1/Circ.1687), hydrogen as fuel (MSC.1/Circ.1701) and ammonia cargo used as fuel (MSC.1/Circ.1702), alongside the mandatory IGF Code, which in practice was written around gas (IMO, n.d.).

On the human side the position is newer still. The Maritime Safety Committee approved Generic interim guidelines on training for seafarers on ships using alternative fuels and new technologies (STCW.7/Circ.25) at its 110th session in June 2025, noting that fuel-specific guidance remained in development and referring the European Maritime Safety Agency's competence study to its correspondence group (IMO, 2025a). Fuel-specific training guidance followed only in May 2026, when MSC 111 approved interim guidelines on training for seafarers on ships using methyl/ethyl alcohol as fuel (STCW.7/Circ.26) and on ships using ammonia as fuel (STCW.7/Circ.27) (IMO, 2026b, 2026c).

Three features of that timeline matter for training providers. First, every one of these instruments is non-mandatory. Second, the underlying convention is still being rebuilt: MSC 110 noted the completion of phase 1 of the comprehensive review of the 1978 STCW Convention and Code, which identified gaps, and endorsed a revised roadmap for phase 2, the drafting of amendments (IMO, 2025a). Mandatory competence standards for future fuels are therefore several years away from entry into force. Third, the commercial driver is itself unsettled: the second extraordinary session of the Marine Environment Protection Committee adjourned in October 2025 without adopting the IMO Net-Zero Framework and is scheduled to resume on 4 December 2026, subject to confirmation (IMO, 2025b, 2026a).

MSC 110 also considered a correspondence group report analysing 51 regulatory gaps and barriers capable of impeding the uptake of alternative fuels, with 32 recommendations to address them (IMO, 2025a). Safety expectations for future fuels are, in short, being assembled in public and in stages while ships are already being ordered against them.

3. WHY FUTURE-FUEL FIREFIGHTING IS A DIFFERENT TRAINING PROBLEM

Fuel-specific hazard profiles, not general fire theory, make this a distinct pedagogical challenge. Methanol has a flashpoint of approximately 12 °C, an auto-ignition temperature of about 470 °C and a wide explosive range of roughly 6.7 to 36 per cent by volume; it is fully miscible with water, so conventional foam breaks down and alcohol-resistant foam is required (Ismail et al., 2025). In a study coding 30 methanol accident investigation reports, Ismail et al. (2025) found that physical hazards accounted for 81 per cent of identified risks, that tank explosions represented 38 per cent of coded events, and that those explosions were associated with 15 of the 19 recorded fatalities. Their gap analysis against MSC.1/Circ.1621 identified deficiencies bearing directly on training design: guidance does not specify alcohol-resistant foam mixing ratios, application rates or coverage times; detection provisions do not address methanol's near-invisible flame; and PPE requirements are stated only in general terms. Methanol is also acutely toxic, with an odour threshold above concentrations already hazardous to health, so the crew's own senses are an unreliable alarm.

Ammonia inverts the usual emphasis. Its dominant risk is toxicity rather than flammability. In a structured expert elicitation using SWOT analysis and the best–worst method with 17 maritime experts, Hazar and Seyhan (2025) found that weaknesses carried the second-highest overall weight after opportunities, and that higher toxicity relative to other marine fuels was ranked the single most critical weakness, with regulatory gaps also identified as a significant weakness. Reviews of ammonia's suitability as a marine fuel reach a similar conclusion about the shift in emphasis from combustion control to release control (Machaj et al., 2022). Operationally this means the competence being trained is not primarily hose handling; it is boundary setting, vapour-cloud behaviour, water-spray suppression and its consequences, respiratory protection discipline, casualty extraction and medical response.

The consequence for the training estate is uncomfortable. STCW's advanced firefighting standard and the associated model courses assume realistic exposure to hydrocarbon fire in a controlled environment. No training centre can responsibly release ammonia vapour or ignite methanol pools for a cohort of cadets at the frequency skill acquisition requires, and the

European Maritime Safety Agency's TRAINALTER study notes the further constraint of scarce berths on alternative-fuelled ships on which to accumulate real experience (EMSA, 2024). Some part of this competence must therefore be developed synthetically, or it will not be developed at all.

4. WHAT THE EVIDENCE SAYS ABOUT IMMERSIVE TRAINING

The case for XR in this niche does not rest on novelty. It rests on a reasonably mature evidence base, which is best read as encouraging but qualified.

The most cited quantitative synthesis is the meta-analysis by Kaplan et al. (2021), which found that training conducted in extended reality did not produce outcomes different from training conducted in non-simulated control conditions. In other words, XR proved as effective as conventional training, and therefore especially attractive wherever conventional training is dangerous or prohibitively expensive. That framing fits future-fuel emergency response almost exactly.

Domain reviews agree. Renganayagalu et al. (2021), reviewing 60 studies of head-mounted display training across three decades, found evidence of effectiveness for procedural memory, spatial knowledge and psychomotor skill, with firefighting and safety preparedness among the principal application domains; they also cautioned that many studies used small student samples and weak assessment instruments, and flagged content cost, hardware ergonomics and cybersickness as practical limits. Stefan et al. (2023), reviewing 136 studies published between 2016 and August 2021, found that evaluations concentrated on the learning (72.06 per cent) and reaction (66.18 per cent) levels of Kirkpatrick's model, with very few studies measuring behaviour change at work or organisational results. For a safety-critical application that is the crucial gap: the literature demonstrates that people learn in VR far more convincingly than it demonstrates that fewer people are hurt afterwards.

Firefighting-specific findings are nevertheless encouraging. Lovreglio et al. (2021) compared VR and video training in fire-extinguisher use and found that VR trainees outperformed video trainees on knowledge acquisition and retention, and, notably for a competence that decays with time, that the VR group's self-efficacy was unchanged three to four weeks later while the video group's had fallen significantly. Narciso et al. (2024) compared a firefighting exercise across virtual and real environments and found comparable self-reported stress and fatigue, with heart-rate variability indicating a stronger physiological stress response in the real setting, making the virtual exercise a reasonable analogue rather than an identical one. Work on virtual environments for shipboard firefighting dates to the late 1990s (Tate et al., 1997); what has changed since is that headset cost and content tooling have fallen far enough to make fleet-scale deployment plausible.

Two maritime studies speak to assessment and acceptance. Hjellvik and Mallam (2024), working with 15 marine engineering students and 8 expert marine engineers on an oil separator task, found no significant difference between head-mounted and desktop VR in predicting real-world performance, and reported that VR assessment scores predicted performance on the physical equipment with adjusted R^2 of 0.436, rising to R^2 of 0.740 when motivation was included as a moderator. For anyone hoping to use XR for assessment rather than familiarisation alone, the signal is real but entangled with candidate motivation. Bačnar et al. (2025), applying the Technology Acceptance Model to 84 maritime engineering students trialling an immersive VR engine-room simulator, found perceived usefulness to be the dominant determinant of behavioural intention ($\beta = 0.694$), with perceived ease of use acting almost entirely through it. The practical implication is that adoption resistance is rarely about the headset being awkward; it is about whether the learner believes the exercise is relevant to the job.

5. WHY ADOPTION HAS BEEN SLOW

Six barriers account for most of the hesitation, and they are worth naming precisely because most of them are not technological at all.

A regulatory causality dilemma. TRAINALTER describes the deadlock directly: training providers wait for regulators to define requirements, while regulators wait for providers to indicate what curricula are feasible, which makes it hard for shipping companies to justify investing in tailored programmes and specialised training centres (EMSA, 2024). With only interim, non-mandatory guidance in circulation before mid-2026, nobody wants to build to a standard that then moves.

Capital and content economics. The headset is not the expense. Bačnar et al. (2025) identify substantial initial investment in bespoke immersive content, a continuing need for technical support, and the absence of standardised instructional frameworks aligned to maritime education requirements. Renganayagalu et al. (2021) make the same point about the cost and time of content development. A high-fidelity ammonia bunkering scenario is a software product with a maintenance liability, not a one-off purchase, and it must be revised each time IMO guidance is revised.

Instructor capability, not merely instructor numbers. TRAINALTER identifies a shortage of qualified instructors for alternative fuels and proposes dedicated train-the-trainer provision

(EMSA, 2024). The deeper issue is what the existing instructor body is equipped to teach. Sharma and Nazir (2021), surveying 62 European and UK maritime instructors with a mean age of 43 using a validated technology self-assessment scale, found generally sound confidence with established digital tools but markedly lower scores for collaborative and emerging technologies, and singled out teaching with emerging technology as the principal area for improvement. If that is the position in the best-resourced training systems, the position in the large crew-supply nations is unlikely to be stronger. Practitioner experience in India suggests an instructor cadre that is older, drawn largely from senior sea-going ranks, comfortable with the classroom and the full-mission simulator but not with headset-based delivery, and inclined to treat immersive tools as a distraction rather than as an instrument of assessment. That impression is not yet supported by published survey data for the region, and the absence of such data is itself part of the problem. An immersive scenario without a competent debrief is an experience rather than training, and the binding constraint is frequently the person in the room rather than the equipment in it.

No requalification pathway for the trainers themselves. STCW sets qualification requirements for those who conduct training and assessment in section A-I/6, and requires seafarers to revalidate their certificates of competency at intervals not exceeding five years under regulation I/11 (IMO, 2026d). No equivalent periodic requalification applies to instructor and assessor competence. National train-the-trainer awards follow the same pattern: in India the Vertical Integration Course for Trainers, formerly the Training of Trainers and Assessors, is in practice a once-only qualification. A trainer certified a decade ago therefore holds the same standing as one certified last year, with no structured obligation to refresh either pedagogy for a younger and more digitally native cohort of cadets or familiarity with the tools now available. Upgrading is left to individual appetite rather than to any framework, and appetite is an unreliable basis on which to plan a fleet-wide competence programme.

Teaching staff without alternative-fuel sea time. A related and largely unspoken constraint is that most of the people teaching future-fuel subjects today have never sailed on a ship that uses these fuels. The berth scarcity that TRAINALTER identifies for trainees (EMSA, 2024) applies first and most acutely to faculty, who left sea service before dual-fuel and alternative-fuel tonnage entered the trades in any number. The technical specialists who do understand ammonia or methanol systems in depth generally come from the fuel, engine or process industries rather than from ships, and lack the shipboard operational context in which the competence has to be exercised. Immersive content, developed jointly by the two groups, is one of the few practical ways to give an instructor credible command of a system on which neither party alone can claim complete authority.

No assessment equivalence. STCW recognises simulator-based training and assessment through established provisions on simulator use, but there is no settled pathway by which an immersive VR exercise is accepted as equivalent evidence of competence for a fuel-specific endorsement. TRAINALTER's expert panel was explicit that VR only approximates real conditions, that hand controllers do not reproduce the tactile reality of operating equipment, that multi-user VR depends on low-latency connectivity, and that VR should always be combined with other methods (EMSA, 2024). Combined with the behaviour-level evidence gap identified by Stefan et al. (2023), this leaves administrations with a reasonable basis for caution.

Commercial signal noise. Ordering data reinforce hesitancy. The 47 per cent fall in alternative-fuelled orders in 2025, driven by regulatory uncertainty and cost sensitivity in the bulk and tanker segments (DNV, 2026), makes it easy to defer training investment for another budget cycle, even though the vessels already on order will need competent crews on delivery.

6. A STAGED ADOPTION MODEL

The barriers above suggest that the useful question is not whether to adopt XR but how to sequence it so that money spent before the rules mature survives contact with them. Four tiers, applied in order, address that.

Tier 1: AR for familiarisation and in-service support. Augmented overlays on fuel-supply systems, double-walled piping, gas detection points, nitrogen purging arrangements, emergency shutdown devices and PPE stowage orient both cadets and serving crew on systems most have never seen. Because AR content is anchored to a physical arrangement rather than a regulatory competence table, it dates slowly and can be produced from existing class-approved drawings.

Tier 2: VR for procedural rehearsal and hazard recognition. Bunkering sequences, leak detection, boundary cooling decisions and initial-response drills are procedural and spatial tasks, precisely the skill classes for which the evidence is strongest (Renganayagalu et al., 2021). Repetition is effectively free once content exists, which is what breaks the scarcity-of-experience constraint.

Tier 3: deliberate hybridisation with physical training. XR should take the scenarios that cannot be run live: toxic ammonia vapour dispersion, a methanol fire with a barely visible flame, a fuel-cell alarm cascade, decision-making under conflicting indications. Physical training grounds should retain what XR cannot yet deliver: heat, weight, breathing-apparatus discipline, hose reaction and genuine sensory overload. The division follows TRAINALTER's recommendation that immersive methods always be combined with others (EMSA, 2024), and it is defensible to an auditor because each competence sits with the medium that can actually evidence it.

Tier 4: instructor capability and evidence capture. Investment should be weighted towards instructor qualification and towards the assessment data an immersive system can generate, such as time to isolate, sequence errors, boundary decisions and search behaviour, all recorded against the competence tables in STCW.7/Circ.25, 26 and 27. Two things follow. Providers accumulate exactly the behaviour-level evidence the literature is missing (Stefan et al., 2023), and when the comprehensive STCW review converts today's interim guidance into mandatory standards, the existing training record can be mapped to it rather than rebuilt. Administrations could reinforce this cheaply by attaching a periodic requalification interval to instructor and assessor approvals, mirroring the five-yearly revalidation already required of seafarers.

Governance should assume the rules will tighten. Content with competences tagged at module level, and fuel-specific hazard data held separately from the scenario engine, can be revised when a circular is superseded. Content built as a monolithic film cannot.

7. LIMITATIONS

This paper is a synthesis of regulatory instruments, agency studies and published research rather than an empirical study, and inherits the limitations of that base. Much of the immersive-training evidence relies on small student samples rather than serving seafarers (Renganayagalu et al., 2021), and almost none measures whether immersive preparation reduces harm during real shipboard emergencies; no published trial yet compares XR-trained and conventionally trained crews on an ammonia or methanol casualty, because the operational population remains small. Cost figures for immersive content are commercially sensitive and were unavailable in verifiable form, so the economic argument is directional rather than quantified. The observations offered on instructor demographics and technology resistance in South Asia rest on the author's professional experience rather than on published survey evidence, since no equivalent to the Sharma and Nazir (2021) European sample appears to exist for the region; establishing that evidence base would be a useful piece of work in its own right. The regulatory position described is current as at August 2026 and will move. Finally, the four-tier model is a structured practitioner proposal informed by the cited evidence; it has not itself been validated experimentally.

8. CONCLUSION

The industry's caution about virtual and augmented reality has been rational in the wrong direction. Providers and owners have hesitated because the mandatory standard is not yet written, when the absence of that standard, combined with hazardous fuels and too few berths on which to gain experience, is the strongest argument for building synthetic capability now. That interval, between non-mandatory guidance and enforceable competence, is where the gap opens.

The evidence supports a specific, bounded claim rather than an enthusiastic one. Extended reality performs about as well as conventional training in general, performs particularly well for procedural and spatial skills, retains self-efficacy better than passive instruction, and can generate assessment data with a demonstrable relation to real performance. It remains, however, a poor substitute for the tactile and physiological demands of live firefighting, and it still lacks behaviour-level validation. Read together, that profile matches the future-fuel problem well: XR is strongest exactly where live training is impossible, and weakest exactly where live training remains available.

The practical recommendation is to treat immersive training as infrastructure rather than a procurement item, to build it in tiers, to invest first in instructors and evidence capture rather than hardware volume, and to tag every module to the interim competence tables so the work converts into compliance when the rulebook catches up. Fleets that do so will have crews who have faced an invisible methanol flame and an ammonia release many times before meeting one. Fleets that wait for the regulation will begin that learning on a ship.

REFERENCES

Bačnar, D., Barić, D., & Ogrizović, D. (2025). Charting the future of maritime education and training: A technology-acceptance-model-based pilot study on students' behavioural intention to use a fully immersive VR engine room simulator. *Applied System Innovation, 8*(3), 84. https://doi.org/10.3390/asi8030084

DNV. (2026, January 8). *LNG-fuelled container ships sustain alternative fuel share of global orderbook amid industry slowdown*. https://www.dnv.com/news/2026/lng-fuelled-container-ships-sustain-alternative-fuel-share-of-global-orderbook-amid-industry-slowdown/

European Maritime Safety Agency. (2024). *TRAINALTER: Study on the identification of specific competences for seafarers on ships using alternative fuels and energy systems*. EMSA. https://www.emsa.europa.eu/publications/item/5377-train-alter-report.html

Hazar, C., & Seyhan, A. (2025). Investigating ammonia as an alternative marine fuel: A SWOT analysis using the best–worst method. *Sustainability, 17*(20), 9314. https://doi.org/10.3390/su17209314

Hjellvik, S., & Mallam, S. (2024). Training transfer validity of virtual reality simulator assessment. *Virtual Reality, 28*(4), Article 165. https://doi.org/10.1007/s10055-024-01058-0

International Maritime Organization. (n.d.). *Safety guidelines: IMO alternative fuel and technology safety guidelines*. Future Fuels and Technology. https://futurefuels.imo.org/safety-guidelines/

International Maritime Organization. (2025a). *Maritime Safety Committee – 110th session (MSC 110), 18–27 June 2025* [Meeting summary]. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MSC-110th-session.aspx

International Maritime Organization. (2025b, October 17). *IMO net-zero shipping talks to resume in 2026* [Press briefing]. https://www.imo.org/en/MediaCentre/PressBriefings/Pages/imo-net-zero-shipping-talks-to-resume-in-2026.aspx

International Maritime Organization. (2026a, May 1). *IMO progresses work on ship emissions, pollution and ocean protection* [Press briefing]. https://www.imo.org/en/MediaCentre/PressBriefings/Pages/imo-progresses-work-on-ship-emissions-pollution-and-ocean-protection.aspx

International Maritime Organization. (2026b). *MSC 111th session – highlights*. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/temporary-msc-111.aspx

International Maritime Organization. (2026c, August 11). *Preparing seafarers in the Caribbean for the fuel transition*. https://www.imo.org/en/MediaCentre/Pages/WhatsNew-2480.aspx

International Maritime Organization. (2026d). *STCW Convention and Code* (consolidated ed.). IMO Publishing. https://doi.org/10.62454/ke938e

Ismail, A. M., Metwalli, M. M. A., & Alamoush, A. S. (2025). Towards safe maritime decarbonization: Safety barriers of methanol fuel. *Sustainability, 17*(11), 4896. https://doi.org/10.3390/su17114896

Kaplan, A. D., Cruit, J., Endsley, M., Beers, S. M., Sawyer, B. D., & Hancock, P. A. (2021). The effects of virtual reality, augmented reality, and mixed reality as training enhancement methods: A meta-analysis. *Human Factors, 63*(4), 706–726. https://doi.org/10.1177/0018720820904229

Lovreglio, R., Duan, X., Rahouti, A., Phipps, R., & Nilsson, D. (2021). Comparing the effectiveness of fire extinguisher virtual reality and video training. *Virtual Reality, 25*(1), 133–145. https://doi.org/10.1007/s10055-020-00447-5

Machaj, K., Kupecki, J., Malecha, Z., Morawski, A. W., Skrzypkiewicz, M., Stanclik, M., & Chorowski, M. (2022). Ammonia as a potential marine fuel: A review. *Energy Strategy Reviews, 44*, 100926. https://doi.org/10.1016/j.esr.2022.100926

Maritime Just Transition Task Force. (2022). *Mapping a maritime just transition for seafarers* [Position paper]. International Maritime Organization. https://www.imo.org/en/OurWork/HumanElement/Pages/Maritime-Just-Transition.aspx

Narciso, D., Melo, M., Rodrigues, S., Dias, D., Cunha, J., Vasconcelos-Raposo, J., & Bessa, M. (2024). Assessing the perceptual equivalence of a firefighting training exercise across virtual and real environments. *Virtual Reality, 28*(1), Article 14. https://doi.org/10.1007/s10055-023-00917-6

Renganayagalu, S. K., Mallam, S. C., & Nazir, S. (2021). Effectiveness of VR head mounted displays in professional training: A systematic review. *Technology, Knowledge and Learning, 26*(4), 999–1041. https://doi.org/10.1007/s10758-020-09489-9

Sharma, A., & Nazir, S. (2021). Assessing the technology self-efficacy of maritime instructors: An explorative study. *Education Sciences, 11*(7), 342. https://doi.org/10.3390/educsci11070342

Stefan, H., Mortimer, M., & Horan, B. (2023). Evaluating the effectiveness of virtual reality for safety-relevant training: A systematic review. *Virtual Reality, 27*(4), 2839–2869. https://doi.org/10.1007/s10055-023-00843-7

Tate, D. L., Sibert, L., & King, T. (1997). Virtual environments for shipboard firefighting training. In *Proceedings of the IEEE 1997 Virtual Reality Annual International Symposium* (pp. 61–68). IEEE. https://doi.org/10.1109/VRAIS.1997.583045

UN Global Compact, International Chamber of Shipping, & International Transport Workers' Federation. (2024). *Consideration of training aspects for seafarers on ships powered by ammonia, methanol and hydrogen*. Maritime Just Transition Task Force. https://www.imo.org/en/OurWork/HumanElement/Pages/Maritime-Just-Transition.aspx

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Through his work, Pushkal focuses on bridging the gap between practical maritime experience and innovative technology solutions to create more effective, accessible, and industry-relevant.

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FROM CERTIFICATION TO INCIDENT ACCOUNTABILITY: A CRITICAL CASE STUDY OF THE SOHAR HYDROCARBON RELEASE AT ALANG-SOSIYA

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Abstract

The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships entered into force on 26 June 2025, making facility certification central to ship recycling governance. Certification, however, is a point-in-time assurance mechanism and does not by itself demonstrate how a recycling facility performs during an environmental incident. This paper examines the reported hydrocarbon release involving the LNG vessel SOHAR at Priya Blue's Alang-Sosiya facility in June 2026. It uses a qualitative documentary single-case study design based on triangulation of company communication, civil-society reporting, legal instruments and regulatory materials. The case is not used to determine legal liability or accident causation. Instead, it examines how post-certification evidence should be structured when a material incident occurs at an authorised yard. The analysis identifies six assurance gaps: incident disclosure, hydrocarbon mass balance, vessel-stage and tank-status verification, emergency-response evidence, worker/contractor protection and independent post-incident review. The paper proposes a post-certification environmental incident audit protocol aligned with the Hong Kong Convention, India's Recycling of Ships Act, 2019 and comparable high-assurance requirements under the EU Ship Recycling Regulation. The study contributes a practical governance tool for moving from static certification to evidence-based operational accountability.

Keywords: *ship recycling; Hong Kong Convention; Alang-Sosiya; environmental incident; certification; post-certification audit*

1. INTRODUCTION

Ship recycling recovers steel and equipment from end-of-life vessels, but it also creates environmental and occupational risks when hazardous materials, oils, sludges, gases and contaminated wastes are not properly controlled. The regulatory problem is therefore one of assurance: how can authorities and stakeholders verify that a certified recycling facility performs safely under actual operating conditions?

Recent scholarship supports this framing. Systematic reviews describe ship recycling as a resource-recovery sector with connected environmental, social, economic, law/policy, technology and management challenges (Dey et al., 2021), and identify continuous

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environmental monitoring and human factors as continuing research needs (Moussa et al., 2024). Indian legal studies stress that the Recycling of Ships Act's long-term environmental value depends on implementation, detailed rules and monitoring (Ahmad, 2022; Mathew, 2024). Governance scholarship on sustainable ship recycling notes the central role of public-private certification under the HKC and EU Ship Recycling Regulation (Glinski, 2022). Reviews of open-beach shipbreaking and recent global governance assessments also underline continuing concerns about hazardous materials, worker safety, pollution control and enforcement gaps (Barua et al., 2018; Xu et al., 2025). A recent ICS/ECSA gap analysis further shows that the HKC and EU Ship Recycling Regulation remain distinct governance frameworks whose divergences require careful implementation attention (European Community Shipowners' Associations [ECSA] & International Chamber of Shipping [ICS], 2026).

The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, 2009 entered into force on 26 June 2025. The Convention addresses ship preparation for recycling, operation of ship recycling facilities, and enforcement mechanisms including survey, certification and reporting requirements (International Maritime Organization [IMO], n.d., 2025). India is a key jurisdiction because Alang-Sosiya in Gujarat is one of the world's major ship recycling regions, and India has implemented a domestic framework through the Recycling of Ships Act, 2019 (Government of India, 2019).

This paper examines a recent incident in that implementation context: the reported hydrocarbon release involving the LNG vessel SOHAR at Priya Blue's Alang-Sosiya facility in June 2026. Priya Blue publicly stated that the incident occurred on 13 June 2026 when strong tidal currents during a spring high tide caused excessive vessel movement, contact with a nearby barge crane structure, localised damage to a fuel oil tank and release of hydrocarbons into the intertidal area (Priya Blue, 2026). Civil-society reporting by the NGO Shipbreaking Platform attributed the incident to Priya Blue plot V1/V2, identified the vessel as SOHAR, IMO 9210816, and raised concerns regarding containment, worker protection, transparency and certification reliability (NGO Shipbreaking Platform, 2026).

The research question is: How can post-certification incident auditing strengthen environmental and worker-safety assurance in Hong Kong Convention-compliant ship recycling yards? The paper does not function as an accident investigation and does not determine statutory violation. Its contribution is a structured audit protocol that identifies what evidence should be preserved, disclosed and independently reviewed after a material environmental incident at a certified or authorised recycling facility.

2. CONCEPTUAL AND REGULATORY FRAMING

2.1 Certificate-based and incident-based assurance

Certification is a necessary assurance mechanism, but it is not the same as demonstrated performance. Institutional literature on decoupling shows that formal structures may diverge from actual practice where monitoring and accountability do not connect commitments with operations (Bromley & Powell, 2012; Meyer & Rowan, 1977). In ship recycling, this risk is sharpened by reliance on facility authorisation, recognised organisations, third-party inspection and documentary proof (Glinski, 2022). Power's account of audit as a ritual of verification is relevant because audit can strengthen accountability only when it examines operational evidence rather than merely confirming auditable documents (Power, 1997).

For ship recycling, this distinction is practical. Certificate-based assurance confirms that a facility has been authorised or certified against defined requirements. Incident-based assurance asks whether the facility can show, through auditable evidence, how its systems performed during an abnormal event. The SOHAR incident is analytically useful because it tests the boundary between these two forms of assurance.

2.2 Indian statutory context

India's Recycling of Ships Act, 2019 provides the legal setting for this analysis. Section 12 requires a Ship Recycler seeking authorisation to prepare a ship recycling facility management plan and submit it to the Competent Authority. It also provides for enquiry, approval and periodic audit linked to authorisation (Government of India, 2019). Section 13 empowers enquiry, inspection and suspension or cancellation of authorisation where statutory requirements are breached. Section 14 requires emergency preparedness and response. Section 15 addresses worker safety, health, training and welfare (Government of India, 2019).

Sections 21 and 22 are most directly relevant to environmental incidents. Section 21 requires every Ship Recycler to ensure safe and environmentally sound removal and management of hazardous materials and to comply with requirements for infrastructure, waste disposal and hazardous-material management. Section 22 requires measures to protect the environment, including action where oil spill occurs, and provides a basis for remedial directions, environmental damages and compensation for cleanup where contravention is established

(Government of India, 2019). These provisions support a post-incident audit as an operational method for verifying statutory compliance.

2.3 Comparative benchmark

The EU Ship Recycling Regulation is used only as a comparator, not as governing law for Indian yards. It links facility approval with prevention of adverse effects on human health and the environment, containment, impermeable handling areas, effective drainage, waste documentation and emergency preparedness (European Union, 2013). The European Commission's enforcement notice on Inventory of Hazardous Materials obligations further illustrates how documentation and inspection guidance support practical enforcement of EU-SRR requirements (European Commission, 2020). Recent classification-society guidance also illustrates how HKC and EU-SRR requirements are operationalised through IHM certification, survey regimes and recycling-related certification processes for shipowners and yards (ClassNK, n.d.; DNV, 2025). These requirements provide a useful benchmark for high-assurance recycling governance and support the need for evidence-based incident verification.

3. METHODOLOGY

The study uses a qualitative documentary single-case study design. The case is bounded by event, place, vessel, period and institutional context. The event is the reported hydrocarbon release from a vessel under recycling. The place is Priya Blue plot V1/V2, Alang-Sosiya, Gujarat, as identified in civil-society reporting. The vessel is the LNG vessel SOHAR, IMO 9210816. The period begins with the reported incident on 13 June 2026 and extends through the public reporting and response period that followed. The institutional context is HKC implementation under Indian regulation and international scrutiny.

The unit of analysis is the post-certification incident-accountability process. This includes incident notification, emergency response, containment, recovery, vessel-stage and tank-status verification, worker and contractor protection, public disclosure, regulatory oversight, evidence preservation and corrective action.

The documentary corpus consists of four source categories: company communication from Priya Blue; civil-society reporting by the NGO Shipbreaking Platform; legal and regulatory materials including the Hong Kong Convention framework, the Recycling of Ships Act, 2019 and the EU Ship Recycling Regulation; and secondary media or industry reports used only for context.

The case is treated as a critical case, not a statistically representative case. Critical case logic is appropriate where one case tests a proposition under conditions where the proposition should be expected to hold (Flyvbjerg, 2006). Here, the proposition is that certification and modern compliance systems should provide credible assurance of environmental control and worker protection. If serious post-incident questions arise at a high-profile certified facility, then the governance model requires stronger verification.

The analysis proceeded in three steps. First, public material was classified as confirmed facts, source-attributed claims or contested claims. Second, claims were grouped under six assurance domains: disclosure, hydrocarbon mass balance, vessel-stage and tank-status verification, emergency response, worker/contractor protection and independent review. Third, those domains were converted into an audit protocol for material environmental incidents at authorised ship recycling facilities.

Discrepancies between sources were handled through attribution, not forced reconciliation. Company statements were used as evidence of the company's account and reported response. Civil-society material was used as evidence of counter-claims, public-interest concerns and requests for disclosure. Legal texts were used only to identify duties, powers and benchmarks. The study does not determine legal liability, negligence, final environmental damage or accident causation.

4. CASE EVIDENCE AND CHRONOLOGY

The evidence base is mixed and must be read according to source function. Table 1 summarises what each source type can and cannot support.

Table 1. Evidence provenance used in the case analysis

Source type	What it can support	Main limitation
Company public statement	Company account of incident sequence, response actions, authority notification, recovery figures and corrective intent.	Does not independently verify environmental spread, worker exposure or completeness of disclosure.
Civil-society reporting	Allegations, counter-evidence, stakeholder concerns, satellite-imagery claims, community concerns and requests for disclosure.	May reflect advocacy position; requires triangulation and careful attribution.
Legal/regulatory texts	Formal duties, powers, authorisation conditions and governance benchmarks.	Cannot prove how implementation worked in the incident.
Media/industry reports	Context, public concern and reported developments.	May depend on secondary reporting and requires corroboration.

Priya Blue reported that an environmental incident occurred at its Alang facility on 13 June 2026 involving a vessel under recycling. The company attributed the immediate trigger to strong tidal currents during a spring high tide, excessive surge and yaw movement, contact with a nearby barge crane structure, localised fuel-tank damage and hydrocarbon release into the surrounding intertidal area (Priya Blue, 2026). It stated that its Emergency Response Plan and Oil Spill Contingency Plan were activated, operations nearby were suspended, containment and recovery measures were deployed, and contaminated waste, sand and sludge were collected for authorised treatment and disposal (Priya Blue, 2026).

The company reported no injuries, no fatalities, no fire and no explosion. It also stated that the Gujarat Pollution Control Board, Gujarat Maritime Board and other relevant authorities were informed, and that an independent third-party marine surveyor was engaged to assess vessel damage. Priya Blue reported approximately 63 tonnes of fuel oil affected and approximately 32 tonnes directly recovered through containment and transfer operations (Priya Blue, 2026).

The NGO Shipbreaking Platform reported the incident in more critical terms. It stated that the spill occurred at Priya Blue plot V1/V2, involved the LNG vessel SOHAR, IMO 9210816, and that the vessel had been beached only a few days earlier (NGO Shipbreaking Platform, 2026). The Platform alleged worker-protection concerns, pollution spread beyond the immediate plot and oil sightings along the coastline. It also questioned why the vessel reportedly carried about 1,800 tonnes of fuel and requested a detailed incident timeline, hydrocarbon mass balance, waste documentation, survey information, tank identification and damage photographs (NGO Shipbreaking Platform, 2026).

The public record therefore establishes a material hydrocarbon-release incident and divergent accounts of response adequacy. It does not establish, on the currently available evidence, the affected tank's exact operational status: whether the fuel was retained for arrival/beaching support, remained during early post-beaching preparation, or was present despite cleaning, gas-freeing or safe-for-hot-work certification. This missing fact is central to the legal and technical assessment.

5. FINDINGS

5.1 Certification requires post-incident verification

The case shows that certification cannot substitute for post-incident verification. Priya Blue reported activation of emergency procedures and recovery of a substantial quantity of affected fuel oil (Priya Blue, 2026). The NGO account questioned containment, worker protection and disclosure (NGO Shipbreaking Platform, 2026). The finding is not that certification failed. The finding is that certification must be supported by a mechanism capable of testing how certified systems performed during the actual incident. Recent sectoral analysis comparing HKC and EU-SRR requirements similarly shows that the details of certification, survey, authorisation and implementation guidance matter for the credibility of the ship recycling governance regime (ECSA & ICS, 2026).

5.2 Hydrocarbon mass balance is central to accountability

The difference between approximately 63 tonnes of fuel oil affected and approximately 32 tonnes directly recovered requires a documented mass balance (Priya Blue, 2026). A credible post-incident record should reconcile tank contents, quantity released, quantity recovered as oil, quantity transferred, quantity absorbed, quantity collected as contaminated waste, quantity disposed, quantity dispersed and quantity uncertain. Without that reconciliation, public discussion remains dependent on competing narratives rather than shared evidence.

5.3 Vessel-stage and tank-status verification is decisive

The compliance significance of the release depends on the vessel's stage and the affected tank's status. A recycling-bound ship may legitimately retain limited operational fuel for final voyage, manoeuvring, generators, pumps and beaching support. A spill during approach or initial beaching does not automatically prove breach of Section 21; the relevant questions are whether the fuel was necessary, declared, controlled and covered by emergency preparedness.

The position changes after beaching if the affected tank or space has undergone fuel removal, cleaning, gas-freeing, safe-for-entry or safe-for-hot-work certification. In that situation, a later hydrocarbon release from the same tank or space would raise a serious compliance question under Sections 21 and 22, requiring determination by the competent authority on the basis of tank records, certificates, response logs, environmental evidence and the applicable statutory provisions (Government of India, 2019; Ministry of Ports, Shipping and Waterways, 2026).

For the SOHAR case, the currently available public evidence does not establish the affected tank's cleaning, gas-free or safe-for-hot-work status. This is therefore not a peripheral factual gap. It is the decisive compliance question that a post-incident audit must answer.

5.4 Worker and contractor protection must be verifiable

Worker protection during emergency response requires evidence, not only procedure. Priya Blue stated that trained personnel wearing full personal protective equipment were mobilised (Priya Blue, 2026). The NGO alleged that workers were seen cleaning oil without adequate protective equipment (NGO Shipbreaking Platform, 2026). The important governance issue is contractor control. Facility certification should extend to contractors, sub-contractors and emergency clean-up personnel when they enter contaminated areas. An audit should verify who entered the area, what PPE was required, what PPE was issued, what PPE was worn, who supervised the work and whether health follow-up was provided.

5.5 Disclosure should follow a minimum evidence template

Voluntary narrative disclosure is insufficient for material environmental incidents. A standard record should include incident date and time, vessel name and IMO number, affected tank/space, material released, estimated quantity involved, quantity recovered, first containment action, authority notification, worker-safety measures, environmental sampling locations, waste-disposal pathway and corrective actions. This protects both responsible facilities and affected communities by reducing reliance on unsupported claims.

5.6 Intertidal risk requires scenario testing

Both accounts identify tidal conditions as relevant. Priya Blue referred to spring high tide and strong tidal currents (Priya Blue, 2026). The NGO argued that tidal flows in beaching conditions complicate containment (NGO Shipbreaking Platform, 2026). The audit question is therefore not whether oil-spill equipment exists. It is whether the facility has demonstrated that its response can function during spring tide, monsoon conditions, vessel movement, difficult access and shoreline exposure.

6. PROPOSED POST-CERTIFICATION ENVIRONMENTAL INCIDENT AUDIT PROTOCOL

The findings support a practical protocol for material environmental incidents at certified ship recycling facilities. The protocol is intended for hydrocarbon releases, hazardous-material releases, fires, explosions, uncontrolled worker exposure, vessel movement causing damage, pollution beyond a facility boundary or events requiring regulatory intervention.

The proposed protocol operationalises existing duties rather than creating a separate legal regime. Sections 12 to 15 of the Recycling of Ships Act support authorisation, audit, inspection, emergency preparedness and worker safety. Sections 21 and 22 support hazardous-material management, environmental protection, remedial action and cleanup accountability where contravention is established (Government of India, 2019). Table 2 sets out the audit components, required evidence and purpose.

Table 2. Proposed post-certification environmental incident audit protocol

Audit component	Minimum evidence required	Purpose
Trigger and notification	Time of incident, time of detection, authorities notified, time of notification and statutory notice status.	Establish whether notification and regulatory response were prompt.
Event timeline	Sequence from first indication to source control, containment, recovery, sampling, clean-up and demobilisation.	Reconstruct response performance.
Vessel-stage and tank-status verification	Arrival/beaching status, recycling stage, tank/space status, cleaning records, gas-free/safe-for-entry/safe-for-hot-work certificates and adjacent-space controls.	Determine whether hydrocarbons were legitimate operational fuel, residual fuel not yet removed, or inconsistent with declared status.
Source and quantity	Tank identification, contents, sounding records, estimated release quantity and uncertainty range.	Establish what was released.
Hydrocarbon mass balance	Released, recovered, transferred, absorbed, disposed, dispersed and uncertain quantities.	Reconcile environmental accountability.
Worker and contractor protection	Personnel list, contractor details, PPE requirement, PPE evidence, supervision and medical follow-up.	Verify occupational safety and contractor control.
Environmental sampling	Sampling locations, dates, parameters, laboratory records and results.	Verify pollution extent and clean-up.
Waste disposal	Waste quantity, category, transporter, treatment/disposal facility and manifests.	Track contaminated material.
Third-party review	Survey report, damage photographs, structural findings and corrective actions.	Reduce reliance on self-reporting.
Corrective action	Preventive measures, responsible persons, deadlines and verification method.	Ensure learning and non-recurrence.

The protocol can be incorporated into domestic authorisation conditions, pollution-control-board requirements, recognised-organisation audits, facility certification procedures, class-based assurance programmes or shipowner due-diligence clauses.

7. IMPLEMENTATION PATHWAYS

Four implementation pathways are available. First, Indian authorities can incorporate the protocol into authorisation, annual audit, inspection and post-incident reporting conditions for ship recycling facilities. The Directorate General of Shipping, National Authority, Competent

Authority, Gujarat Maritime Board and Gujarat Pollution Control Board are the most relevant actors.

Second, IMO could develop the protocol as guidance, a circular or a best-practice annex for competent authorities implementing the Hong Kong Convention. This would not require amendment of the Convention. Existing IMO guidance on survey, certification and authorisation, together with current classification-society materials on HKC/EU-SRR compliance, shows that such technical guidance already shapes state and industry practice (ClassNK, n.d.; DNV, 2025; IMO, n.d.). Third, recognised organisations and classification societies could include incident-history review, contractor-control verification and post-incident corrective action in facility assurance processes. Fourth, shipowners, cash buyers, insurers and financiers could require the protocol as part of responsible recycling due diligence.

8. DISCUSSION

The case supports a shift from certification as documentary status to certification as continuing assurance. Facility plans and certificates remain necessary, but they must be tested against abnormal events. The SOHAR incident shows that the credibility of certified recycling depends on the availability of an auditable post-incident record.

The main theoretical contribution is the distinction between certificate-based and incident-based assurance in ship recycling governance. The main practical contribution is the audit protocol. The protocol addresses the evidence needed to evaluate release quantity, tank status, worker protection, environmental spread, waste disposal and corrective action.

The case also shows why legal and technical analysis must be stage-sensitive. If fuel was retained for arrival or initial beaching, the focus is preparedness and response. If the affected tank had already been cleaned, gas-freed or certified safe for work, the same release would carry a much stronger implication of non-compliance. Public evidence does not yet resolve that question; the audit protocol identifies how it should be resolved.

For India, the protocol would strengthen the credibility of HKC implementation by showing that authorised recycling includes operational accountability and not only facility certification. For shipowners, it provides a due-diligence tool for selecting and monitoring recycling facilities.

9. LIMITATIONS

The study relies on publicly available documents. It does not include site inspection, interviews, sampling, original satellite-image analysis or access to complete official investigation records. It does not independently verify shoreline contamination claims, worker-exposure allegations or the reported 1,800-tonne fuel figure. It does not determine legal liability, negligence, final environmental damage or statutory breach. The case is analytically informative but not statistically representative of all ship recycling yards.

These limits define the paper's claim. The study does not prove the full environmental impact of the incident. It demonstrates that a material incident at a certified facility requires a structured post-certification audit mechanism.

10. CONCLUSION

The Hong Kong Convention has moved ship recycling governance into a formal compliance phase. Certification and facility authorisation are necessary, but they do not by themselves establish operational performance during environmental incidents.

The reported SOHAR hydrocarbon release at Alang-Sosiya is a useful critical case because it produced divergent public accounts about containment, recovery, worker protection, tank status and transparency. The public record confirms a material incident but does not establish the affected tank's cleaning, gas-free or safe-for-work status. That missing fact is central to compliance assessment.

The paper recommends a post-certification environmental incident audit protocol for Hong Kong Convention-compliant ship recycling facilities. The protocol would require incident timelines, vessel-stage and tank-status verification, hydrocarbon mass balance, worker/contractor evidence, environmental sampling, waste-disposal records and independent corrective-action review. This would help regulators, shipowners and facilities move from certificate-based compliance to operational accountability.

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REFERENCES

Ahmad, M. (2022). Ship recycling in India: Environmental stock taking. *Indian Law Review, 6*(3), 465–478. https://doi.org/10.1080/24730580.2022.2082100

Barua, S., Rahman, I. M. M., Hossain, M. M., Begum, Z. A., Alam, I., Sawai, H., Maki, T., & Hasegawa, H. (2018). Environmental hazards associated with open-beach breaking of end-of-life ships: A review. *Environmental Science and Pollution Research, 25*(31), 30880–30893. https://doi.org/10.1007/s11356-018-3159-8

Bromley, P., & Powell, W. W. (2012). From smoke and mirrors to walking the talk: Decoupling in the contemporary world. *Academy of Management Annals, 6*(1), 483–530. https://doi.org/10.1080/19416520.2012.684462

ClassNK. (n.d.). *Ship Recycling Convention (the Hong Kong Convention): Statutory guidance and related information*. Retrieved August 19, 2026, from https://www.classnk.or.jp/HP/en/activities/statutory/shiprecycle/index.html

Dey, A., Ejohwomu, O. A., & Chan, P. W. (2021). Sustainability challenges and enablers in resource recovery industries: A systematic review of the ship-recycling studies and future directions. *Journal of Cleaner Production, 329*, 129787. https://doi.org/10.1016/j.jclepro.2021.129787

DNV. (2025, June 20). *Hong Kong Convention and how to obtain IHM certification for ship recycling*. https://www.dnv.com/news/2025/hong-kong-convention-and-how-to-obtain-ihm-certification-for-ship-recycling

European Commission. (2020). Commission notice: Guidelines on the enforcement of obligations under the EU Ship Recycling Regulation relating to the Inventory of Hazardous Materials of vessels operating in European waters (2020/C 349/01). *Official Journal of the European Union, C 349*, 1–3. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020XC1020(01)

European Community Shipowners' Associations, & International Chamber of Shipping. (2026). *Assessing global standards for ship recycling: Gap analysis of the Hong Kong Convention and EU Ship Recycling Regulation*. https://www.ics-shipping.org/resource/assessing-global-standards-for-ship-recycling-gap-analysis-of-the-hong-kong-convention-and-eu-ship-recycling-regulation/

European Union. (2013). Regulation (EU) No 1257/2013 of the European Parliament and of the Council of 20 November 2013 on ship recycling and amending Regulation (EC) No 1013/2006 and Directive 2009/16/EC. *Official Journal of the European Union, L 330*, 1–20. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013R1257

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry, 12*(2), 219–245. https://doi.org/10.1177/1077800405284363

Glinski, C. (2022). The public–private governance regime on sustainable ship recycling: An in-depth analysis. *Review of European, Comparative & International Environmental Law, 31*(2), 268–281. https://doi.org/10.1111/reel.12449

Government of India. (2019). *The Recycling of Ships Act, 2019* (Act No. 49 of 2019). Gazette of India Extraordinary. https://www.indiacode.nic.in/handle/123456789/15690

International Maritime Organization. (n.d.). *The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships*. Retrieved August 19, 2026, from https://www.imo.org/en/about/conventions/pages/the-hong-kong-international-convention-for-the-safe-and-environmentally-sound-recycling-of-ships.aspx

International Maritime Organization. (2025, June 26). *New era for ship recycling as Hong Kong Convention enters into force* [Press briefing]. https://www.imo.org/en/mediacentre/pressbriefings/pages/hong-kong-convention-entry-into-force.aspx

Mathew, E. (2024). Recycling of Ships Act 2019: Challenges and opportunities for ship recycling industry in India. *Journal of the Indian Ocean Region, 20*(1), 37–53. https://doi.org/10.1080/19480881.2024.2373515

Meyer, J. W., & Rowan, B. (1977). Institutionalized organizations: Formal structure as myth and ceremony. *American Journal of Sociology, 83*(2), 340–363. https://doi.org/10.1086/226550

Ministry of Ports, Shipping and Waterways (National Authority), Government of India. (2026, January 2). *Recycling of Ships Regulations, 2026* (G.S.R. 19(E)). Gazette of India Extraordinary. https://egazette.gov.in/WriteReadData/2026/269345.pdf

Moussa, A. A., Farag, Y. B. A., Gunbeyaz, S. A., Fahim, N. S., & Kurt, R. E. (2024). Development and research directions in ship recycling: A systematic literature review with bibliometric analysis. *Marine Pollution Bulletin, 201*, 116247. https://doi.org/10.1016/j.marpolbul.2024.116247

NGO Shipbreaking Platform. (2026, July 2). *Massive oil spill at India's 'best shipbreaking yard' raises serious concerns over Hong Kong Convention certification* [Press release]. https://shipbreakingplatform.org/massive-oil-spill-at-indias-best-shipbreaking-yard-raises-serious-concerns-over-hong-kong-convention-certification/

Power, M. (1997). *The audit society: Rituals of verification*. Oxford University Press.

Priya Blue. (2026). *Priya Blue's response to the environmental incident: Transparency, action and continuous improvement* [Company statement]. https://www.priyablue.com/post/priyablues-response-to-the-environmental-incident-transparency-action-and-continuous-improvement

Xu, J., Chen, J., & She, S. (2025). Green governance of global shipbreaking: Key problems and reform pathways. *Journal of Cleaner Production, 533*, 146995. https://doi.org/10.1016/j.jclepro.2025.146995

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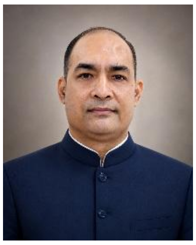
AUTHOR



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KEEPING PACE WITH CONTEMPORARY SAFETY SCIENCE

Dr (Captain) Suresh Bhardwaj[1]

Abstract

The maritime industry operates within a highly complex and safety-critical environment where human performance, organizational systems, technology, and operational conditions continuously interact. This paper examines the evolution of maritime safety management from traditional Safety-I approaches, focused primarily on identifying failures and assigning causes, toward contemporary Safety-II and resilience-based approaches that emphasize how systems succeed under variable conditions. The study highlights the importance of Human and Organizational Performance (HOP), Performance Shaping Factors, and human-centered system design in understanding operational outcomes. It explores the limitations of conventional incident investigation methods based on deficit-oriented classifications and presents the CLUE (Contextual Learning and Understanding of Events) taxonomy as a system-oriented alternative that promotes learning from both successful and adverse events. By adopting neutral language, contextual analysis, and simplified contributing-factor classification, CLUE supports improved organizational learning, psychological safety, and continuous improvement. The paper concludes that future maritime safety excellence will depend on integrating safety science principles, digital technologies, human factors, and resilient organizational practices to create adaptive systems capable of managing uncertainty and complexity.

Keywords: *Maritime Safety, Safety-II, Human and Organizational Performance, Resilience Engineering, Human Factors, Performance Shaping Factors, CLUE Taxonomy, Incident Investigation, Safety Management Systems, Organizational Learning*

Maritime industry is probably the worst-case scenario among the globalised industries. Safety regulations are mandated by International Maritime Organization, however, these regulations are brought into effect by individual countries. And the ship owner has the liberty to register in any country and fly its flag. So, the safety standards vary.

It has been observed that the best pressure for safety standards in the maritime industry is the customer pressure.

Oil companies International Marine Forum - as the biggest customer for energy transportation has mandated higher safety standards that align with Safety II and Resilience Engineering. They have moved on from person-centric causation of incidents to "systems thinking" & Human and Organizational Performance (HOP) as conceptual foundation.

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While Safety I asks why things go wrong, Safety II focuses on how things usually go right and how systems adapt under variable conditions (Hollnagel et al., 2015).

Accordingly, HOP tries to capture performance variability and adaptations (e.g., workarounds), rather than only deviations. This dual perspective supports learning from both failure and success, which is fundamental to building resilience.

It is pertinent to recall the SHELL model, in the complex work environment of today - the (L) liveware interacts with (H)hardware, (S) software and the working (E)environment - which all influence the performance of the liveware. And it is the mismatch between the components of liveware & hardware, or the liveware and software - or for that matter the environment which includes the company culture, that influence the performance of the human element (Miller and Holley, 2017).

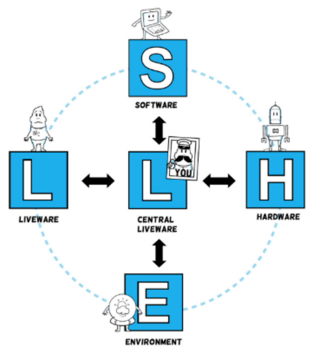

Figure 1: The SHELL Model

"Human Factors is really about - making it easy for people to do things right, and hard to do things wrong". We need to fit the task, equipment, environment to the capabilities and limitations of person. Not try to adapt or fit the person to the task.

Human error is not random. It is systematically connected to features of people's tools, tasks, and operating environment. (SHELL Model).

Human error is not a cause of failure. It is the effect, or symptom, of deeper trouble.

Human error is not the conclusion of an investigation. It is the starting point (Dekker, 2014)

1. PERFORMANCE INFLUENCING FACTORS

Therefore, it is the context that drives human behaviours – what we call as Performance Shaping Factors - be it stress or lack of HMI or Ergonomics, could be time constraints, or complexity of task.

Which brings us to a moot point – these Performance shipping factors or influencing factors can <u>either positively or negatively</u> influence the performance.

And this view completely aligns with Safety II and Resilience Engineering.

So, Safety can be described as an emergent property of the interactions between human, organizational and technical elements - that together create robust, resilient systems that <u>are capable of continuous improvement.</u>

2. INDUSTRY 5.0

If one looks at the popular global macroeconomic concept of Industry 5.0, this also shifts the focus from pure automation (which was Industry 4.0) - to human-centric, sustainable and resilient systems, aligning safety management which had become more data driven. Cyber-physical integration, real time sensing, predictive analytics did enable better safety monitoring, planning, training and risk prediction.

However in the milieu - it overlooked workers subjective experiences <u>and contributions</u>.

Industry 5.0 in this way - is more consistent with Safety-II. It emphasizes worker well-being, adaptive performance, as well as resilience and sustainability in Safety Management systems.

And it seeks to promote more adaptive systems in which human factors are treated as core elements of workflow design.

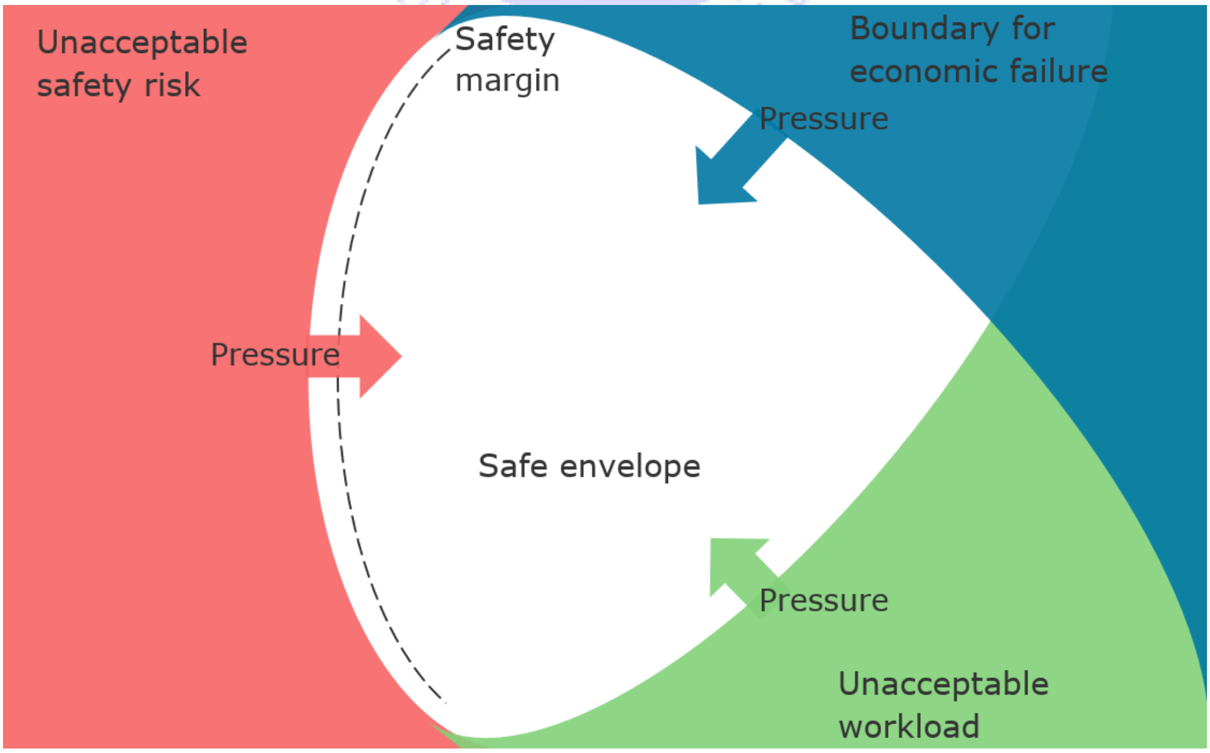

Figure 2: Dynamic Safety Model – Drift into Failure

So this image illustrates the dynamic safety model - focusing on the concept of drift into failure within a maritime operation context.

The diagram visualizes how a system - which is symbolized by the ship in the center - maneuvers under everyday pressure - within the three hard operational boundaries of economic failure, unacceptable workload and unacceptable safety risk. So you can see how - in a safety critical environment of shipping, the Human & Organizational Performance plays the most critical part (Rasmussen, 1997).

3. FROM SCAT TO CLUE

While the aim is good – there is a need to help companies and leadership teams recognize and control the conditions and systems that influence human actions and decisions,

The challenge is: Instruments like SCAT (systematic cause analysis technique) which is one of most popular tools used in the shipping industry for incident investigation – has traditionally had Deficit-based taxonomies ……*failure to follow procedure, lack of competence, or incorrect action.*

Taxonomies actively structure the lens through which incidents are interpreted.

Any incident reporting typically has four broadly comparable stages - Description of incident narrative, - consequence assessment, - classification of contributing factors – typically the causes, - and specification of corrective actions.

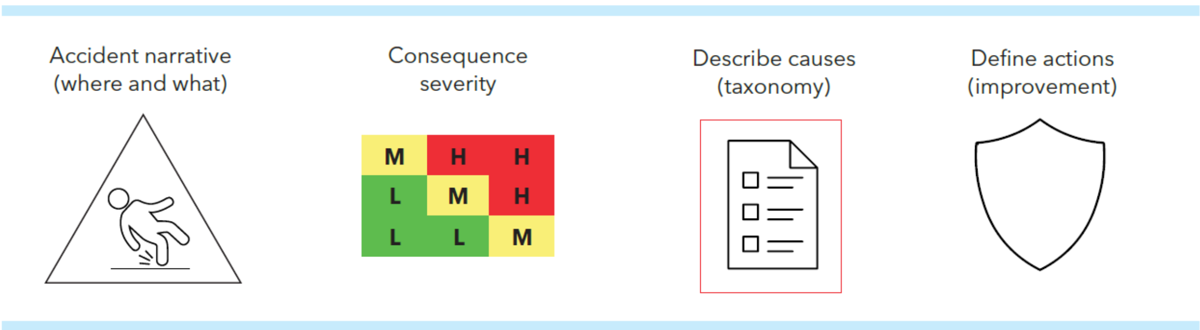

Figure 3: Stages of Incident Reporting

It is the 3rd stage - classification of the causes or contributory codes is the referred taxonomy. These categories translate the narrative into structured data, trend analysis, and safety KPI's.

Research across cognitive psychology and communication science demonstrates that language and framing profoundly shape human reasoning. In this way, linguistic framing becomes an early—and often invisible—driver of organisational learning.

Negatively framed taxonomies have limited applicability beyond failure analysis.

They are poorly suited for documenting successful performance or learning from normal work, (Safety II) - where descriptive, neutral terminology is essential for capturing the conditions that enable safe, effective outcomes.

Replacing the notion of "cause" with words such as factors, conditions, or contributors represents more than a semantic adjustment.

It reflects a shift toward systemic thinking, acknowledging that incidents emerge from interactions among multiple elements rather than from discrete, isolatable causal agents.

Hence - The CLUE taxonomy – Appropriately abbreviated for "Contextual Learning and Understanding of Events."

A contemporary, - system-oriented approach - to learning from events, designed to strengthen organizational learning - by reframing - how incidents and other events are registered, assessed, and communicated, using neutral language.

The four categories of contributing factors are :-

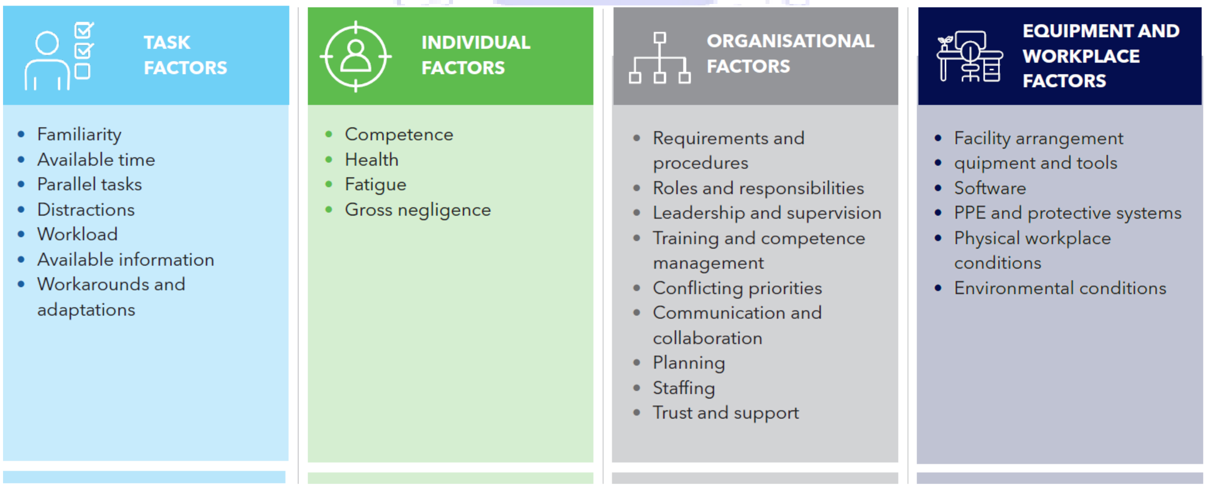

Figure 4: Four Categories of Contributing Factors (CLUE Taxonomy)

Task factors – covering cognitive and procedural aspects of the work itself (e.g., workload, time pressure, task complexity, familiarity, etc.).

Workplace and equipment factors – addressing tangible conditions and resources that shape performance (e.g., tool availability, equipment design, layout, housekeeping, and environmental influences such as wind, weather, and currents, etc.)

Individual factors refers to personal characteristics that can influence their performance and safety. It has four categories - competence, health, fatigue, and gross negligence.

Although 'gross negligence' is not considered a performance shaping factor, it is included as an exceptional category to address rare cases of reckless lack of concern and extreme carelessness. The purpose is to capture exceptional behaviors that fall outside the normal humor error patterns, while maintaining the taxonomy's emphasis on systemic conditions and learning oriented language.

& Organizational factors - This taxonomy does not distinguish between immediate that is direct causes and basic that is underlying causes. It however does target more latent conditions within an organization.

CLUE differs in three key ways.

First, the use of more neutral language reduces hindsight bias and normative judgements. This, in turn, decreases implicit blame and supports a more system-oriented approach to learning. The result is more constructive conversations, higher-quality data for analysis, and ultimately more effective strategies for risk reduction.

Second, the taxonomy includes fewer factors, not needing any specialist training, making it usable for a wider population.

Third, CLUE simplifies analysis by applying a single causal layer – meaning no "immediate" cause and then a "basic cause". Furthermore it replaces the term *cause* with *contributing factor*.

The CLUE taxonomy thus consists of JUST 26 contributing factors - grouped under four main categories.

Such a taxonomy better supports systemic inquiry, enables learning from both success and failure, and aligns incident reporting practices with contemporary understandings of human performance and organizational resilience.

Why? Because it is perfectly grounded in the 5 HOP principles -

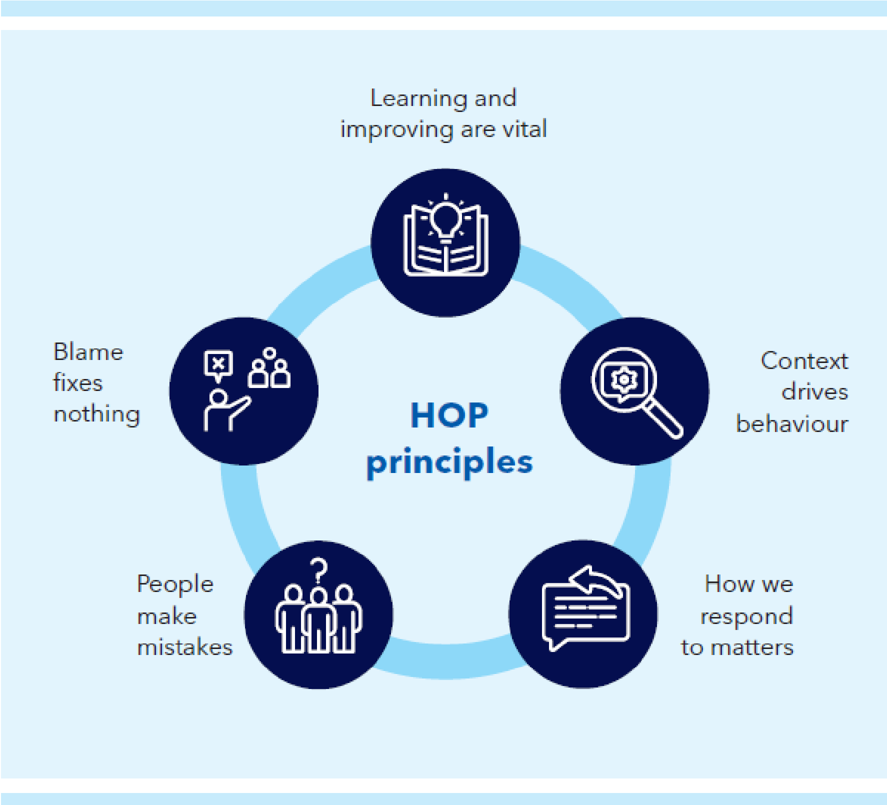

Figure 5: The Five HOP Principles

Principle 1 - People make mistakes - codes treat error as a signal of system vulnerability and a pointer to conditions (e.g., goal conflicts, workload spikes, information quality) rather than to personal deficiency.

Principle 2 - Blame fixes nothing - Person focused categories suppress reporting and bias analysis; whereas descriptive, neutral wording sustains psychological safety and learning.

Principle 3 - Content drives behaviour - Actions make sense locally given time pressure, tools, signals, and incentives; a taxonomy must help render these conditions visible and analysable.

Principle 4 - Learning and improving are vital - The same categories should support analyses of success, normal work, near misses, and adverse events—consistent with Safety II's focus on how work usually goes right.

Principle 5 - How they respond to matters - A classification scheme that centres conditions rather than culprits, promotes just culture responses, thereby increasing transparency and data richness over time.

4. TRANSITIONING TO CLUE

Transitioning from traditional, root-cause-based incident taxonomies to a PSF-model such as CLUE reshapes how organizations describe events, - how analysts interpret contributing conditions, - and how leaders identify opportunities for improvement.

It greatly helps in Designing effective follow-up actions

With a PSF-based taxonomy (CLUE), the purpose of actions shifts from correcting people to modifying the conditions of work—task demands, tools and interfaces, information flows, coordination mechanisms, and organizational controls that shape performance. This reorientation reflects contemporary safety science: humans are the adaptors in systems, and error is a signal of contextual vulnerability, not a moral or competence deficit.

And lastly, not to forget the Advantages of Simplification.

Simplified taxonomies are generally more accessible to nonexpert users, reducing the (cognitive) workload, enhances user performance and improve data quality.

So also it is well-suited for integration with automated systems and machine learning models, LLMs and machine learning will play a vital role in the next generation of reporting systems.

REFERENCES

Conklin, T. (2019). *5 principles of human performance: A contemporary update of the building blocks of human performance*. Pre-Accident Investigation Media.

Dekker, S. (2014). *The field guide to understanding "human error"* (3rd ed.). Taylor & Francis.

DNV. (2026). *Contextual learning & understanding of events* [Report].

U.S. Department of Energy. (2009). *Human performance handbook: Volume 2: Human performance tools for individuals, work teams, and management* (DOE-HDBK-1028-2009). U.S. Department of Energy. https://www.standards.doe.gov/files/doe-hdbk-1028-2009-human-performance-tools-for-individuals-work-teams-and-management

Hollnagel, E., Wears, R. L., & Braithwaite, J. (2015). *From Safety-I to Safety-II: A white paper*. The Resilient Health Care Net. https://www.england.nhs.uk/signuptosafety/wp-content/uploads/sites/16/2015/10/safety-1-safety-2-whte-papr.pdf

Miller, M. D., & Holley, S. (2018). SHELL revisited: Cognitive loading and effects of digitized flight deck automation. In D. D. Schmorrow & C. M. Fidopiastis (Eds.), *Advances in neuroergonomics and cognitive engineering* (pp. 91–101). Springer. https://doi.org/10.1007/978-3-319-60642-2_9

Rasmussen, J. (1997). Risk management in a dynamic society: A modelling problem. *Safety Science, 27*(2–3), 183–213. https://doi.org/10.1016/S0925-7535(97)00052-0

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Dr. Captain Suresh Bhardwaj's expertise in safety science centres on the critical intersection of human factors, technological introduction, and regulatory compliance in safety-critical maritime environments. As a veteran Master Mariner and academic researcher, his work approaches safety science not merely as a set of rules, but as an evolving system where technology must safely interface with human operations.

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