TRUSTEE

FUTURE PROOF EFFICIENT AND SUSTAINABLE DEPLOYMENT OF ZEWT

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Abstract

This deliverable provides a comprehensive readiness-based assessment of technologies shaping the future of sustainable maritime transport, applying Technology Readiness Level (TRL), Commercial Readiness Level (CRL) and Societal Readiness Level (SRL) frameworks to a wide portfolio of solutions. The analysis spans alternative fuels, energy converters and onboard power-generation systems, and energy-efficiency devices and technologies, addressing both retrofit applications for the existing fleet and solutions suited to newbuild vessels.

The report identifies maturity gradients across technology families, highlighting those already deployable at scale in the near term and those requiring further development, infrastructure build-up or regulatory consolidation before wide uptake. TRL evaluations capture differences in technological robustness and shipboard integration, from well-established efficiency devices and dual-fuel engines to emerging fuel-supply chains and next-generation energy converters. CRL analysis compares investment attractiveness, supply-chain maturity and exposure to evolving regulatory cost drivers, outlining where strong business cases already exist and where uncertainty related to fuel availability, infrastructure rollout or capital intensity remains a barrier. SRL assessment complements the techno-economic perspective by examining regulatory alignment, stakeholder acceptance and human-factor implications, including crew training needs and port-side impacts. Beyond individual technology assessments, the deliverable conducts a cross-technology comparison in terms of readiness, costs and environmental benefits, and explores interdependencies and integration pathways among fuels, propulsion systems and efficiency measures.

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Overall, the deliverable supports evidence-based decision-making for policymakers, shipowners, technology developers and financiers by clarifying which solutions are already commercially and socially deployable, which are approaching market readiness, and which remain longer-term options within Europe's transition towards climate-neutral shipping.

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TABLE OF CONTENTS

Funded by
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List of Tables

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TRUSTEE Project GA n° 101192328

LIST OF FIGURES

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LIST OF ACRONYMS

ABS	American Bureau of Shipping
AD&A	Alternative Design and Arrangements
AEGL	Acute Exposure Guideline Levels
ALS	Air Lubrication System
BIMCO	Baltic and International Maritime Council
BLEVE	Boiling Liquid Evaporating Vapour Explosion
BMS	Battery Management System
BOG	Boil-Off Gas
BTL	Biomass-to-Liquid
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
CoC	Chain of Custody
CRL	Commercial Readiness Level
DCS	Data Collection System
DNV	Det Norske Veritas
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EMA	Energy Market Authority
EMSA	European Maritime Safety Agency
EPA	Environmental Protection Agency
ESD	Emergency Shutdown
ESPO	European Sea Ports Organisation
ETS	Emissions Trading System
FAME	Fatty Acid Methyl Esters
FC	Fuel Cell
FOGs	Fats, Oils, and Greases
FT	Fischer-Tropsch
GFR	Gas-cooled Fast Reactor
GHG	Greenhouse Gas
HDRD	Hydrogenation Derived Renewable Diesel
HTL	Hydrothermal Liquefaction
HVO	Hydrotreated Vegetable Oil
IACS	International Association of Classification Societies
IAEA	International Atomic Energy Agency
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LFP	Lithium Iron Phosphate
LFR	Lead-cooled Fast Reactor
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LTO	Lithium Titanate Oxide
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MPA	Maritime and Port Authority
MSC	Maritime Safety Committee
MSR	Molten Salt Reactor
MTF	Maritime Technologies Forum
NEA	Nuclear Energy Agency

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NFPA	National Fire Protection Association
NZF	Net-Zero Framework
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
OPS	Onshore Power Supply
OSV	Offshore Support Vessel
PBCF	Propeller Boss Cap Fins
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
PPE	Personal Protective Equipment
PtX	Power-to-X
PV	Photovoltaic
QRA	Quantitative Risk Assessment
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
RINA	Registro Italiano Navale
SAF	Sustainable Aviation Fuel
SCC	Stress Corrosion Cracking
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
SMS	Safety Management System
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea
SRL	Societal Readiness Level
STCW	Standards of Training, Certification and Watchkeeping for Seafarers
STS	Ship-to-Ship
T-TS	Truck-to-Ship
TRL	Technology Readiness Level
TTS	Terminal-to-Ship (or Shore-to-Ship)
TTW	Tank-to-Wake
UCO	Used Cooking Oil
VHTR	Very High Temperature Reactor
VLSFO	Very Low Sulphur Fuel Oil
VRFB	Vanadium Redox Flow Batteries
WAPS	Wind Assisted Propulsion Systems
WPT	Well-Practised Training
WTW	Well-to-Wake
ZEWT	Zero Emission Waterborne Transport

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1. Introduction

This report presents the activities and results of Task 1.2. The report describes the development paths and factors influencing technological solutions that will shape future zero emission waterborne transport (ZEWT) scenarios, emphasising a systematic review of emerging concepts and technologies aimed at reducing emissions. It encompasses aspects such as vessel engineering, powertrain systems, future fuels, and digital services through an evidence-based technology readiness assessment to determine their potential deployment and interdependencies within specified time horizons.

2. Overview of Zero-Emission Waterborne Transport Technologies

2.1. Review of technologies

The technologies examined in this deliverable have been selected on the basis of their relevance to the current international regulatory debate on maritime decarbonisation and their alignment with the framework discussed within the International Maritime Organization. The review focuses on technological pathways that are already under active consideration by regulators, classification societies, industry stakeholders, and research institutions, and that are expected to play a decisive role in enabling the transition towards zero- and near-zero-emission waterborne transport. The scope therefore encompasses alternative fuels such as hydrogen, ammonia, methanol, biofuels and synthetic e-fuels, advanced energy conversion and generation systems including fuel cells, batteries and hybrid powertrains, as well as energy-efficiency devices and technologies aimed at reducing overall energy demand. These solutions were selected not only for their potential to significantly reduce greenhouse gas emissions across the vessel lifecycle, but also because they raise critical safety, operability, and regulatory challenges that are currently being addressed at IMO level. In particular, the use of low-flashpoint and toxic fuels introduces new risk profiles related to onboard storage, bunkering operations, material compatibility, crew exposure and emergency response, making them central to ongoing IMO Maritime Safety Committee (MSC) discussions. By grounding the technology selection in the official IMO framework, this review ensures consistency with internationally recognised safety and regulatory priorities, while avoiding speculative or immature concepts that lack institutional validation. At the same time, the chosen technologies reflect a balanced portfolio that captures both short- to medium-term solutions with higher deployment potential (such as biofuels, methanol and hybrid systems) and longer-term, transformative options (like hydrogen and ammonia, which are expected to become increasingly relevant as regulatory clarity, infrastructure and supply chains evolve). This approach establishes a coherent and policy-aligned baseline for the subsequent Technology Readiness Level assessment, enabling a structured comparison of technologies that are not only technically promising, but also credible within the current and emerging international maritime governance landscape.

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2.2. Readiness of Technical Choices from the Backlog of Order Perspective

From a quantitative standpoint, the backlog comprises 1,012 vessels across multiple market segments, with container ships representing the largest share, followed by bulk carriers and tankers. What is particularly relevant from a technical readiness perspective is the distribution of propulsion concepts and compliance strategies embedded in these orders. Approximately 38.5% of the backlog specifies an explicit alternative fuel or fuel-readiness solution, while an additional 18.0% adopts scrubber-based compliance, either as a standalone choice or in combination with fuel-readiness notations. The remaining 38.5% of vessels do not explicitly declare alternative fuel or scrubber solutions at the order stage, which should not be interpreted as a lack of environmental consideration, but rather as a reflection of conservative design choices, late-stage option selection, or segment-specific operational uncertainty.

Within this framework, LNG-related solutions emerge as the most mature and widely adopted technical pathway in the backlog. A total of roughly 27% of all orders include LNG in their specification, either as full dual-fuel capability, LNG-ready notation, or LNG-dedicated vessel type such as bunkering units or gas carriers. This confirms LNG’s role as the primary transitional fuel currently available at scale, supported by established engine technology, classification rules, and an expanding bunkering infrastructure. From a technical design perspective, the prevalence of LNG implies early integration of fuel containment systems, fuel gas supply systems, ventilation and safety arrangements, and spatial reservations that significantly influence hull layout and machinery space configuration already at the basic design stage.

Methanol-related solutions represent the second most significant group, appearing in around 17.5% of the backlog. These orders include both methanol-fuelled and methanol-ready configurations, often combined with other readiness notations or hybrid solutions. The technical attractiveness of methanol is reflected in its relatively simpler storage requirements compared to cryogenic fuels and its compatibility with future low-carbon production pathways. From a readiness standpoint, methanol-ready designs typically involve early structural provisions for fuel tanks, material compatibility assessments, and machinery arrangements that allow for later conversion with limited disruption to the vessel’s overall architecture.

Ammonia readiness, while less widespread, is nevertheless a clear emerging signal within the backlog. Approximately 7.5% of orders include ammonia-ready or ammonia-combined readiness notations. Although ammonia is not yet commercially deployed as a mainstream marine fuel, its presence in the backlog indicates that owners and designers are already addressing long-term zero-carbon scenarios by incorporating space reservation, segregation concepts, and safety zoning into the initial design. Technically, this reflects a forward-looking approach in which hull form, tank location, and system separation are defined to avoid future structural constraints, even in the absence of fully mature propulsion systems.

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Within the same RINA-controlled 2025 backlog, hybrid and battery-assisted architectures already form a recognisable, though still numerically limited, cluster of solutions. Around 6.5% of all recorded orders carry a battery-hybrid or battery-equipped notation, or an explicit hybrid qualifier in the alternative-fuel field. This share is strongly segment-dependent. In specialised service and offshore roles, hybridisation is essentially becoming the default: most MSV, CSOV, RoPax, stone-dump/fallpipe and small passenger ferry orders in the backlog adopt hybrid configurations, while a very high proportion of cable layers and a significant fraction of small passenger catamarans integrate batteries. General cargo ships show substantial penetration, whereas deep-sea segments such as container vessels and chemical/oil tankers are only marginally affected, with hybrid notation present in a small percentage of the orders in those classes. From a propulsion-system standpoint, a large part of the hybrid group consists of "pure" battery-hybrid or battery-equipped designs without an explicitly declared alternative fuel, pointing to architectures primarily aimed at peak-shaving, hotel-load optimisation, dynamic positioning efficiency and port-area zero-emission operation rather than a full fuel transition. A further subset combines methanol-ready or methanol-fuelled configurations with batteries, evidencing a composite design logic where alternative fuels and energy storage are co-optimised to manage transient loads and improve overall energy efficiency. The remaining hybrid vessels couple batteries with ammonia, hydrogen or LNG, typically in highly specialised roles, including support and bunkering units. Technically, these patterns suggest that hybrid architectures are being deployed first where operational profiles (frequent port calls, high hotel loads, DP operations) maximise the benefit of energy storage and where regulatory and societal pressure for local emission reduction is strongest, while their limited presence in large deep-sea series indicates that, at this stage, hybridisation is perceived more as an enabling technology for niche or short-sea applications and as a complement to alternative fuels, rather than as a stand-alone mainstream solution for the core oceangoing fleet.

Scrubber-based compliance remains a relevant technical solution, appearing in approximately 18.0% of the backlog. This is particularly evident in tanker and bulk carrier segments, where operational profiles and fuel price dynamics can still justify exhaust gas cleaning systems. From a technical readiness perspective, scrubbers are often integrated alongside alternative fuel readiness, indicating that near-term regulatory compliance and longer-term transition strategies are not mutually exclusive. This coexistence highlights a layered compliance philosophy, where vessels are designed to remain competitive under current regulations while preserving the ability to adapt to stricter future requirements.

The temporal distribution of deliveries reinforces the strategic nature of these technical choices. The majority of vessels in the backlog are scheduled for delivery between 2027 and 2028, a timeframe that coincides with the full implementation of EU ETS maritime obligations and the progressive tightening of FuelEU Maritime requirements. Consequently, the technical specifications observed in the backlog must be interpreted as solutions intended to remain viable under evolving regulatory frameworks, including expanded greenhouse-gas accounting and increased emphasis on well-to-wake performance. This timing effect strongly supports the observed shift toward flexible, readiness-oriented designs rather than single-fuel optimisation.

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2.3. Methodological framework for readiness assessment

The decarbonisation of the maritime sector represents one of the major challenges of the global energy transition. Achieving this goal requires not only the identification of alternative fuels with lower emission potential, but also a systematic assessment of their actual maturity for large-scale deployment. The shift to new energy carriers is inherently complex due to the multifaceted nature of the decision-making process: technological maturity must be complemented by economic, infrastructural, regulatory, and social considerations, all of which are essential for the practical implementation of any solution.

Within this framework, the methodology applied in the TRUSTEE project is based on an integrated assessment approach. It combines the structure of Lloyd's Register's Zero Carbon Fuel Monitor (ZCFM) [1] with internationally recognised standards for evaluating technological maturity, particularly ISO 16290:2013, which defines the Technology Readiness Levels (TRL) scale. This integration enables the development of a robust and widely acknowledged methodology capable of assessing the readiness of alternative fuels and technologies for efficiency across the entire supply chain.

The readiness analysis presented in this deliverable is based on a structured, three-pillar framework that evaluates the maturity of alternative fuels, energy conversion systems, and energy-efficiency technologies across **technological**, **commercial**, and **societal** dimensions. This holistic approach ensures that the assessment captures not only the technical feasibility of the solutions, but also their industrial deployability and the socio-regulatory conditions influencing large-scale adoption in the maritime sector.

Technology Readiness Level (TRL)

The TRL dimension examines the state of technological development of each solution, with a focus on its applicability in real maritime contexts. For alternative fuels, the TRL assessment considers upstream availability of feedstocks, robustness of production processes, and the maturity of bunkering, storage, and onboard handling technologies, including safety aspects and material compatibility.

For energy converters and generation systems—such as dual-fuel engines, fuel cells, batteries, and electrolyzers—the TRL evaluation focuses on technical reliability, onshore development status, efficiency, marinization under representative operating conditions, and integration with the vessel's electrical and energy management systems.

For energy-efficiency devices—including wind-assisted propulsion, air-lubrication systems, optimized propellers and rudders, and waste-heat recovery—the analysis considers structural robustness, operational behaviour in varying weather conditions, and theoretical efficiency indicators (EEDI/EEXI impacts).

In all cases, TRL assessment emphasizes **marinization**, safety on board, and compatibility with ship constraints such as weight, volume, vibration, and stability.

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Commercial Readiness Level (CRL)

The CRL evaluation assesses the level of market maturity and industrial scalability associated with each solution.
For all three technology families, a key criterion is the **robustness of the industrial supply chain**, including the availability of manufacturers, suppliers, and supporting infrastructure (e.g., bunkering systems, technical servicing networks, and logistics chains).
Economic viability is examined through **bankability**, availability of investors, and access to public–private financing instruments, together with considerations of CAPEX and OPEX, including fuel and emissions-related costs under mechanisms such as FuelEU Maritime, CII, and the ETS.
For fuels, CRL includes **feedstock availability and competition** with other sectors (aviation, industry), as well as the feasibility of chain-of-custody models for scaling production.
For energy converters and decarbonisation devices, CRL also accounts for **logistics dependency**, especially when shore-based infrastructure or CO_2-handling chains are required.**Societal Readiness Level (SRL).**

The SRL dimension captures the socio-regulatory maturity of each technology, recognizing that deployment is strongly influenced by acceptance, policy alignment, and safety-related considerations.
All technologies are evaluated against the status of **international regulations** (IMO codes, IACS class rules) and **European policy instruments** (FuelEU Maritime, EU ETS, RED III), which may support or constrain adoption.
Stakeholder acceptance—including shipowners, ports, authorities, crews, and industry actors—is assessed to identify potential barriers arising from perceived risks or operational complexity.
The SRL analysis also includes **social and territorial impacts**, such as effects on communities close to ports, and the **need for crew training**, standardised operational guidelines, and familiarisation with novel technologies.

By combining TRL, CRL and SRL, the methodology provides a **multidimensional readiness profile** that reflects the real deployment landscape for decarbonisation technologies in the maritime sector. A technology may be advanced from a technical perspective but limited commercially (e.g., insufficient supply chain scalability) or socially (e.g., lack of regulatory clarity or low stakeholder acceptance).
This integrated framework enables the identification of **deployment bottlenecks**, **cross-cutting risks**, and **priority areas for further R&I**, ensuring that the subsequent readiness analyses are coherent, comparable, and aligned with EU maritime decarbonisation objectives.

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Unified Evaluation Method for TRL, CRL and SRL

The assessment of TRL, CRL, and SRL follows a common structure divided into three maturity clusters:

Levels 1–3: Concept Definition and Foundational Assessment

- **TRL:** scientific exploration of fundamental principles; laboratory-scale validation of fuel behaviour or energy-conversion mechanisms; no direct maritime applicability.
- **CRL:** preliminary market exploration; early identification of potential supply-chain actors; no established business models or cost benchmarks.
- **SRL:** emerging policy interest; initial regulatory discussions; limited stakeholder awareness; no operational guidelines or training pathways defined.

At this stage, technologies exist mainly as theoretical concepts, early prototypes, or preliminary design studies.

Levels 4–6: Development, Validation, and Pre-deployment Readiness

- **TRL:** component and subsystem validation in **relevant environments**, including conditions simulating maritime operations (vibrations, salinity, humidity, dynamic loads).
  Prototypes of fuel production systems, storage units, bunkering equipment, fuel cells, batteries, or efficiency devices are tested through pilot-scale demonstrators.
- **CRL:** emergence of early supply chains; identification of key industrial partners; preliminary CAPEX/OPEX models; first commercial pilots or demonstration investments.
  Business models are tested at limited scale and initial financing pathways start to appear.
- **SRL:** development of draft regulations and class rules; structured stakeholder engagement; first safety guidelines; early training requirements and operational procedures.

This intermediate phase bridges laboratory feasibility with real-world applicability and early pre-commercial deployment.

Levels 7–9: Demonstration, Operational Validation, and Full Deployment

- **TRL:** large-scale demonstrators installed **on board ships or in port facilities**; integration with vessel energy systems; complete safety validation and maritime certification.
  TRL 9 corresponds to a fully operational, certified, and commercially deployable system.
- **CRL:** mature industrial supply chain; stable cost structures; availability of commercial products and services; established financing mechanisms; inclusion in procurement strategies.
  CRL 9 indicates full market competitiveness and commercial scalability.

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- **SRL:** fully developed international regulations; stable compliance frameworks (IMO, IACS, EU policy); broad stakeholder acceptance; standardised training and operational procedures.
  SRL 9 indicates complete socio-regulatory readiness and absence of structural deployment barriers.

The tables below provide a structured overview of the criteria adopted for assessing Technology Readiness Level (TRL), Commercial Readiness Level (CRL), and Societal Readiness Level (SRL) across the different technological pathways considered in the project, serving as the basis for the subsequent readiness analyses.

Table 1 - overview of the criteria adopted for assessing TRL, CRL and SRL (Alternative Fuels)

	Technology Readiness level	*Commercial Readiness Level*	*Societal Readiness Level*
Alternative fuels (Biofuels, LNG, Methanol,Nuclear, Ammonia, Hydrogen)	**Resource Availability and Production**: availability and sustainability of the feedstock and energy required for the fuel production (e.g. Biowaste, Synthesis). Robustness of the fuel production processes (efficiency, stability, scalability)	**Robustness of the industrial supply chain and Scalability**: availability of manufacturers, suppliers, and supporting infrastructure for the bunkering at most called ports. the capacity of the fuel production systems to reach volumes suitable for the maritime sector.	**International regulation and Consistency with European policies**: status of IMO regulations and safety codes, FuelEU Maritime, EU ETS and IACS class rules
	Bunkering and Storage on board: transport, distribution, storage, and refuelling infrastructure within port environments.	**Bankability**: availability of funding schemes, investors, and public–private financing instruments.	**Stakeholder acceptance**: shipowners, ports, maritime authorities, crews, and industry actors (perception of risk).
	Safety on Board: handling of low flash point and toxic fuels taking into account the commercial operations of the ship,	**CAPEX and OPEX:** Capital Expenditure, refers to the funds spent to buy, upgrade, or refit a vessel and its equipment. Operating Expenses or Operating Costs, which are the day-to-day costs associated with running and maintaining a ship.Fuel and Emissions Costs (e.g. CII, FuelEU, ETS)	**Social and Territorial aspects**: impacts on local communities (e.g. citizens leaving close to ports) and public acceptance (e.g. social network, newspapers).

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	Marinization: Energy Density, Maintenance and Weight/Volume Impact on ship considering the related energy-conversion technologies, such as dual fuel engines, turbines, fuel cells, and their associated support systems.	**Chain of Custody Models:** Feasibility of using flexible models like Mass Balancing to utilize existing infrastructure and reduce CAPEX.	**Crew Safety & Training:** Assessment of safety guidelines, classification guidance (covering installation, safety, operation, materials), and the need for standardized WPT training curriculum for seafarers. familiarization and preparedness of the crew personnel
	Material Compatibility: Compatibility of conventional steels and coating for piping and ship tanks construction , with alternative fuels with corrosion/permeability hazards resulting in degradation or leakage.	**Feedstock Availability & Competition:** Availability and sustainability of feedstocks and competition for these resources from aviation, trucking, and industrial sectors.	

Table 2 - overview of the criteria adopted for assessing TRL, CRL and SRL (Energy converters and generation systems)

	Technology Readiness level	*Commercial Readiness Level*	*Societal Readiness Level*
Energy converters and generation systems (Fuel Cell, Battery)	**Maturity and Reliability of the Technology**: state of technical development onshore technical lifetime, forecast of maintenance intervals	**Robustness of the industrial supply chain and Scalability**: availability of manufacturers, suppliers, and supporting infrastructure for the delivery and prime service of the technology. the capacity of the technolgy production systems to reach sizes and volumes suitable for the maritime sector.	**International regulation and Consistency with European policies**: status of IMO regulations and safety codes, FuelEU Maritime, EU ETS and IACS class rules

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TRUSTEE Project GA n° 101192328

	Marinization: Testing under operating conditions representative of the maritime sector (vibrations, saline atmosphere, humidity, thermal shocks). Compatibility with ship layout, weight, volume, vibrations, and stability requirements. Assessment of specific risks.	**Bankability**: availability of funding schemes, investors, and public–private financing instruments.	**Stakeholder acceptance**: shipowners, ports, maritime authorities, crews, and industry actors (perception of risk).
	Energy Efficiency: Theoretical / Design technology efficiency index related to possible EEDI, EEXI impact, the relationship between the total energy contained in the fuel, and the amount of energy used to perform useful work.	**CAPEX and OPEX:** Capital Expenditure, refers to the funds spent to buy, upgrade, or refit a vessel and its equipment. Operating Expenses or Operating Costs, which are the day-to-day costs associated with running and maintaining a ship.Fuel and Emissions Costs (e.g. CII, FuelEU, ETS)	**Social and Territorial aspects**: impacts on local communities (e.g. citizens leaving close to ports) and public acceptance (e.g. social network, newspapers).
	Safety on Board: handling of novel technologies taking into account the commercial operations of the ship. Ability of the system to be integrated with the vessel's grid and Energy Management System (EMS) with optimization of engine performance despite fluctuating energy input.	**Logistics Dependency:** Economic viability determined by onshore infrastructure, particularly for shore power (OPS) and the logistics chain for carbon sequestration from OCC.	**Crew Safety & Training:** Assessment of safety guidelines, classification guidance (covering installation, safety, operation, materials), and the need for standardized WPT training curriculum for seafarers. familiarization and preparedness of the crew personnel

Table 3 - overview of the criteria adopted for assessing TRL, CRL and SRL (Energy efficiency devices and technologies)

	Technology Readiness level	*Commercial Readiness Level*	*Societal Readiness Level*

Energy efficiency devices and technologies (Wind Assisted Propulsion System, Air Lubricaiton System, Propeller Optimization, Bulbous Optimization)	**Maturity and Reliability of the Technology**: state of technical development onshore, technical lifetime, forecast of maintenance intervals	**Robustness of the industrial supply chain and Scalability**: availability of manufacturers, suppliers, and supporting infrastructure for the delivery and prime service of the technology. the capacity of the technolgy production systems to reach sizes and volumes suitable for the maritime sector.	**International regulation and Consistency with European policies**: status of IMO regulations and safety codes, FuelEU Maritime, EU ETS and IACS class rules
	Marinization: Testing under operating conditions representative of the maritime sector (vibrations, saline atmosphere, humidity, thermal shocks). Compatibility with ship layout, weight, volume, vibrations, and stability requirements. Assessment of specific risks.	**Bankability**: availability of funding schemes, investors, and public–private financing instruments.	**Stakeholder acceptance**: shipowners, ports, maritime authorities, crews, and industry actors (perception of risk).
	Energy Efficiency: Theoretical / Design technology efficiency index related to possible EEDI, EEXI impact, the relationship between the total energy contained in the fuel, and the amount of energy used to perform useful work.	**CAPEX and OPEX:** Capital Expenditure, refers to the funds spent to buy, upgrade, or refit a vessel and its equipment. Operating Expenses or Operating Costs, which are the day-to-day costs associated with running and maintaining a ship.Fuel and Emissions Costs (e.g. CII, FuelEU, ETS)	**Social and Territorial aspects**: impacts on local communities (e.g. citizens living close to ports) and public acceptance (e.g. social network, newspapers).

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	Safety on Board: handling of novel technologies taking into account the commercial operations of the ship. Ability of the system to be integrated with the vessel's grid and Energy Management System (EMS) with optimization of engine performance despite fluctuating energy input.	**Logistics Dependency:** Economic viability determined by onshore infrastructure (port), the logistics chain for CO2 disposal from Carbon Capture .	**Crew Safety & Training:** Assessment of safety guidelines, classification guidance (covering installation, safety, operation, materials), and the need for standardized WPT training curriculum for seafarers. familiarization and preparedness of the crew personnel

3. ALTERNATIVE FUELS

This section analyses the maturity of alternative fuels considered most relevant for zero-emission waterborne transport. Hydrogen and ammonia are often regarded as long-term solutions due to their potential for complete decarbonisation, yet they face significant challenges in terms of storage, safety, and bunkering infrastructure. Methanol and biofuels are closer to commercial readiness, benefiting from existing supply chains and compatibility with internal combustion engines, but their full environmental benefit depends on sustainable production pathways. Synthetic e-fuels present an attractive option for long-term scalability but remain at low TRL due to high costs and limited availability. The TRL assessment highlights the trade-off between immediate deployability (biofuels, methanol) and long-term transformative potential (hydrogen, ammonia, e-fuels), while also considering lifecycle emissions and regulatory frameworks.

3.1. AMMONIA

TECHNOLOGY READINESS LEVEL

Resource Availability and Production

To make ammonia, hydrogen and nitrogen are reacted with a catalyst at high temperature (about 500 °C) and high pressure (20 to 40 MPa) via an industrial process developed by the German chemists Fritz Haber and Carl Bosch more than a century ago.

All told, the Haber-Bosch process accounts for 1.8 percent, or half a billion metric tons, of human-caused global CO2 emissions each year, but the production of hydrogen accounts for around 90% of the carbon emissions in the synthesis of ammonia. If ammonia is to play a part in reducing maritime emissions, the fuel must be made in a cleaner way [2].

The various methods of producing ammonia are differentiated using the following terms:

- Brown ammonia
  Higher carbon ammonia made using a fossil fuel as the feedstock
- Grey ammonia
  Medium-carbon ammonia: ammonia produced from methane-derived hydrogen
- Blue ammonia
  Low-carbon ammonia: brown ammonia but with carbon capture and storage technology applied to the manufacturing processes
- Green ammonia
  Zero-carbon ammonia, made using sustainable electricity, water and air

The ammonia produced is the same, it is the carbon emissions from the processes that are different [3].

Reducing the amount of carbon dioxide produced during the manufacturing process is dependent primarily on the source of hydrogen, using low-carbon energy for the process and system integration to produce the most efficient overall process. Green hydrogen may be produced from several sources. Of particular importance are the following four options:

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- Electrolysis: Renewable energy (e.g. solar, wind, hydro) can be used to provide the energy to obtain hydrogen by splitting water in an electrolyser such as an alkaline electrolyser, a proton-exchange-membrane (PEM) electrolyser, or a solid oxide electrolyser.
- Photocatalysis/photoelectrochemical conversion: Light irradiation (e.g. from a solar source) is used to produce hydrogen through water splitting over a semiconductor (e.g. TiO2).
- Thermochemical water splitting: High-temperature heat (e.g. from a concentrated solar collector) is employed to thermochemically split water within a temperature range of 500 to 2000 °C.
- Biomass conversion: Biomass may be converted into biogas through anaerobic digestion which can then be reformed to hydrogen and other components. Alternatively, biomass may be gasified to produce syngas which contains hydrogen [4].

The main challenges are cost, of which about 85% is electricity, which in most parts of the world is still significantly more expensive than natural gas. The International Energy Agency estimate that electrolysis is cost competitive with steam methane reforming with carbon capture at electricity prices between 1.5 to 5.0 USD cents/kWh.

The cost of electricity in areas with abundant renewable potential has decreased dramatically over the past decade. Auction prices for utility scale solar installations in Marocco, Chile and Saudi Arabia respectively, indicate that water electrolysis may already be cost competitive with steam methane reforming with carbon capture and storage in areas with optimal renewable energy conditions. Taking advantage of such low electricity costs also requires transporting hydrogen affordably on a massive scale. Ammonia, with its existing high degree of technological readiness, is positioned to play a key role in this supply chain.

Figure 1 shows that the lowest current costs of green ammonia production are already competitive with blue ammonia. However, the Figure also reflects how the present costs of ammonia production vary widely across different regions due to variations in fuel and feedstock costs. This is especially evident for production via electrolysis where the cost of electricity is a major factor; the lowest electrolysis costs are from locations where renewable electricity costs are the lowest, which, globally, is solar, from areas of high global horizontal irradiance and onshore wind. In 2019, the UK strike price for future offshore wind dropped to around 4.0 GBP pence/kWh (5.2 USD cents/kWh) [5].

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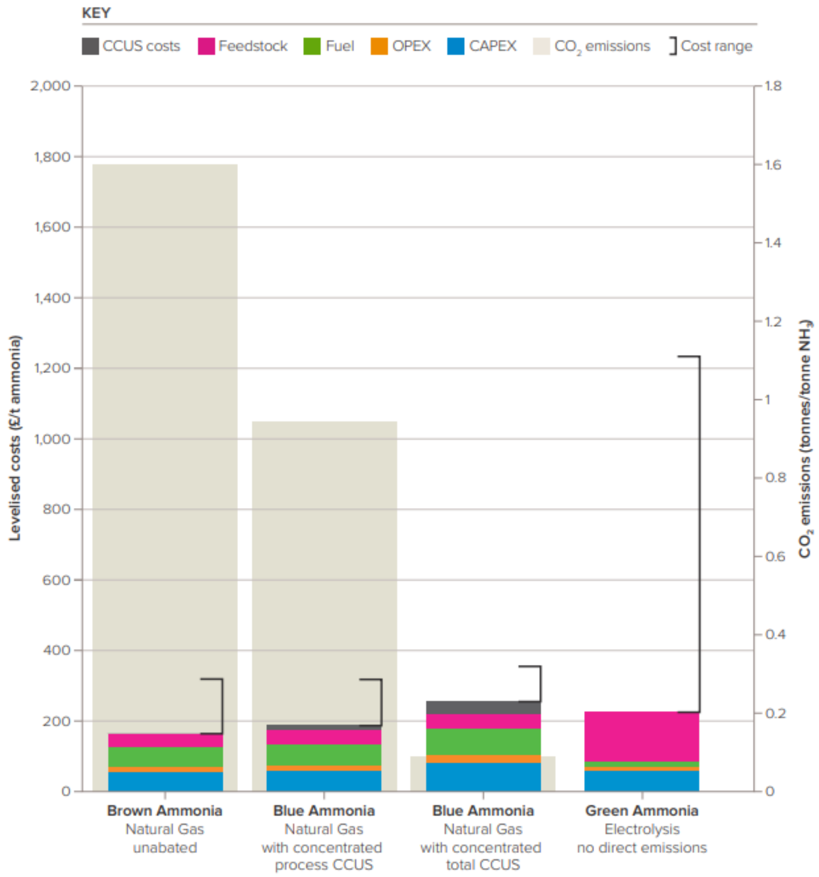

Note: Range refers to the range of total levelised costs across regions, the lower end of the range is disaggregated into cost categories. Electrolysis is assumed to be powered by 100% renewable electricity; the 'feedstock cost' is the electricity for the electrolyser, and 'fuel cost' is additional electricity for the air separation unit, synthesis loop etc. CCUS costs include capture, transport and storage of carbon dioxide; process CCUS is only process emissions; total is process and energy related emissions. % carbon dioxide reduction is relative to unabated production with natural gas (1.6 tonnes/tonne NH_3).

Figure 1 - Cost comparison of ammonia production via different methods

Bunkering and Storage on board

Anhydrous ammonia has been widely stored and transported by pipelines, rail, ships and trucks for many years. The storage and transport of ammonia is mainly in liquid state. This can be achieved either by increasing the pressure (pressurised tanks) or reducing the temperature (insulated tanks). As reference, at room temperature (circa 25°C), ammonia becomes liquid at a pressure of approximately 8.5 bar. The fraction of ammonia liquid and vapour depends directly on pressure and temperature conditions [6].

There is a high level of maturity in many aspects of ammonia storage and transport infrastructure because of its widespread use as a feedstock for inorganic fertilisers. Indeed, an established worldwide ammonia infrastructure already exists with significant ammonia maritime trading. International shipping routes are well-established and there is a comprehensive network of ports worldwide that handle ammonia at large scale. This

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existing port and shipping infrastructure could enable the early accelerated adoption of large-scale transportation of ammonia as an energy vector and fuel [5].

Table 4 - Comparison of ammonia tank types

Characteristics	*Type A/B*	*Membrane*	*Type C*	*Skid-mounted*
Retrofit suitability	✗	✗	✓	✓
Pressurized storage	✗	✗	✓	✓
Secondary containment required	✓	✓	✗	✗
Space utilization	Good	Excellent	Moderate	Poor
Capacity >1000 m³	✓	✓	✓ (modular)	✗
Retrofit installation cost	High (~€900/m³)	Very high (~€1200/m³)	Medium (~€150–250/m³)	Low (~€100–150/m³)
Newbuild installation cost	High (~€700–900/m³)	Very high (~€1000+/m³)	Medium (~€500–700/m³)	Medium (~€400 - 600/m³)

There are several safety related factors to consider when choosing the type of fuel tank:

- Venting of tank vapours should be prevented at all times. This implies that tanks for ammonia will need a boil-off gas (BOG) management system unless they are designed for the full vapour pressure of ammonia at ambient temperatures (18 bar).
- For tanks requiring secondary barriers, management of leakage scenarios and the subsequent emergency venting of fuel gases must be specially considered.
- The choice of fuel tank may also impact flexibility with regard to compatibility with bunkering facilities with respect to pressure and temperature.

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Ammonia bunkering, similar to that of alternative fuels such as LNG, LPG, and hydrogen, can be categorized into three main types: ship-to-ship (STS), terminal-to-ship (TTS), truck-to-ship (T-TS). The suitable ammonia bunkering method is selected after considering the amount of ammonia bunkering required, operational circumstances, and time constraints.

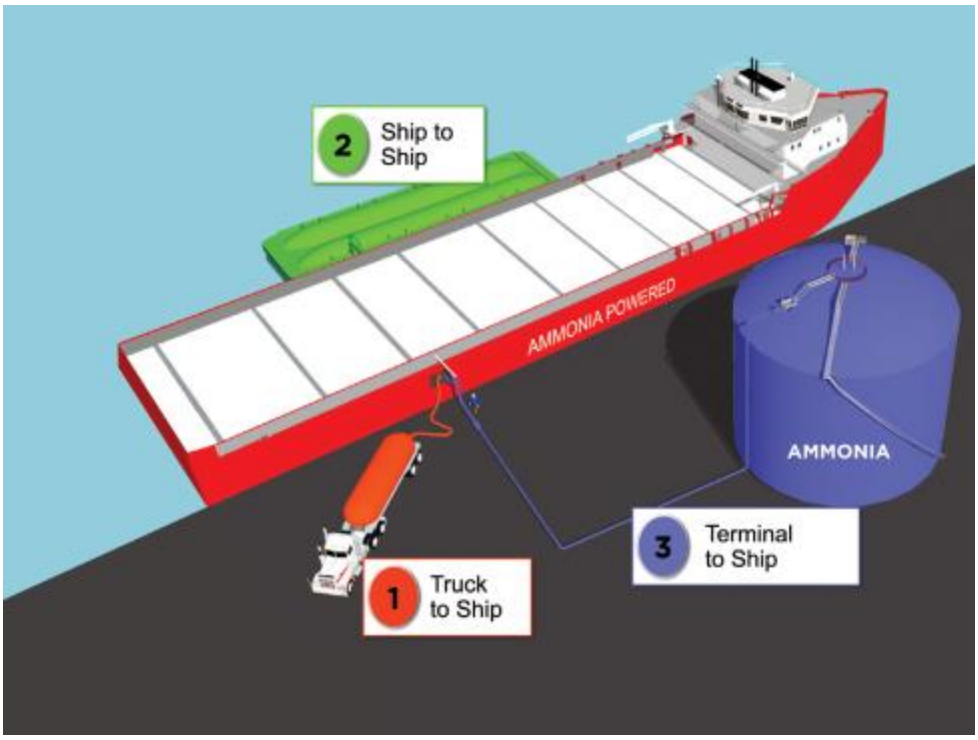

Figure 2 - Ammonia bunkering types (ABS)

1. Ship to Ship (STS)
   Fuel is transferred from one vessel to another, with ammonia in refrigerated or pressurized form. This method offers high flexibility in terms of volume, transfer rate, and location (either at sea or in port). However, it involves operational risks such as wind, currents, and potential collisions, and requires additional infrastructure to refuel the bunkering vessels.
2. Truck to Ship (T-TS)
   Ammonia is delivered from trucks at the dock and pumped aboard the ship. Trucks can only carry non-refrigerated (pressurized) ammonia and are suitable for small fuel volumes. This method is flexible and convenient for initial or small-scale operations but is limited by truck capacity and low transfer rates, making it unsuitable for large volumes.
3. Terminal to Ship (TTS)
   Bunkering is done through a pipeline connecting the terminal's shore storage directly to the vessel. It can operate at different temperatures but is typically pressurized. TTS allows for large volumes and high transfer rates, but it lacks location flexibility because the infrastructure is fixed [7].

Safety on Board

Health and safety

Although the health and safety issues associated with the use of ammonia in electricity/power generation are minimal when compared to transportation, as we can see in table 1, several considerations need to be taken into account.

Table 5 - Comparison between ammonia in transportation and electricity/power generation

	Transportation	**Electricity generation**
Safety	Very Critical	Not as critical
Cracking	Cracking reactor heavy/expensive	Easly done
Storage tank weight	Critical	Not an issue
Storage tank robustness	Need to be “indestructible”	Existing storage tanks are suitable
Distribution	Complicate	Relatively simple
Start up	Problematic	Not many start ups
Operational	Pumps operated by non-professionals	Delivered/handled by professionals

The National Fire Protection Association (NFPA), USA, has classified ammonia as a toxic substance, thus making it a chemical of high risk for health. However, due to its low reactivity, the hazards it presents from accidental combustion or explosions are much lower than other fuel gases and liquids. Human exposure limits of ammonia depend on the legislation and exposure time. The limit is set between 25 and 50 ppm with dangerous consequences for exposure to concentrations above 300 ppm.

A further set of recommendations for industrial interests is given by the Environmental Protection Agency (EPA), USA, and is known as Acute Exposure Guideline Levels (AEGL), which is used for ammonia. There are 3 categories:

- AEGL-1 is the airborne concentration above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic, non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

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- AEGL-2 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL-3 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death [8].

Explosion and fire

Ammonia is non-explosive and not highly flammable. The minimum ignition energy level is 680 MJ - approximately 10,000 times larger than for hydrogen. Ammonia flames are very transparent and show low flame speed. An atmospheric boiling ammonia pool fire cannot sustain itself, as the heat of flames radiated into the pool is insufficient to sustain ignition. Only when external factors heat the pool, sufficient ammonia will be able to evaporate to maintain the fire. The probability of a fire or explosion could almost exclusively arise in poorly ventilated spaces [8].

The flammability limits of ammonia at standard atmospheric conditions range from 15.0% (lower flammability limit, LFL) to 28.0% (upper flammability limit, UFL). This implies that 15%– 28% of ammonia mixed with air in the atmosphere can lead to potential fire and explosion hazards depending on the presence or absence of an ignition source. In addition, a phenomenon called BLEVE (boiling liquid evaporating vapour explosion) can occur, in which fatal accidents such as fires and explosions are triggered by the storage tank rupture and its associated gas released because the cylinder cannot maintain its structural integrity. It is caused by the rising internal pressure due to the boiling of the saturated liquid inside the storage container when heat is applied from the outside.

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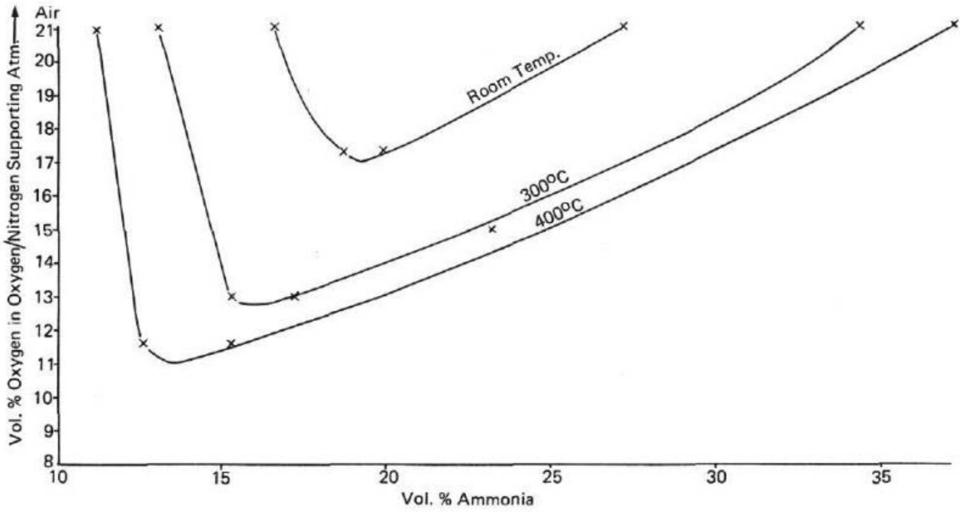

Figure 3 - Ammonia lower flammability limits

On the other hand, ammonia has a significantly higher flash point and auto-ignition temperature compared to other alternative energy sources. In addition, the reaction of the fuel is slow, and the minimum ignition energy is 8.0 MJ, which is much higher than that of LNG 0.28 MJ, methanol 0.14 MJ, and hydrogen 0.011 MJ. Further, in comparison to other fuels such as LPG (0.43 m/s), LNG (0.37 m/s), methanol (0.36 m/s), and hydrogen (3.51 m/s), ammonia has a relatively low laminar burning velocity of 0.07 m/s. This indicates that ammonia is relatively difficult to ignite compared to other fuels, and the above-mentioned fire and explosion potential and severity are somewhat mitigated due to these fuel characteristics [9].

Marinization

Because of its high-octane rating, ammonia (120 compared to gasoline which typically ranges from 86 to 93), it can be used in internal combustion engines with small modifications and can also be used directly in fuel cells.

The figure below shows the technical feasibility of multiple ways of onshore ammonia power generation

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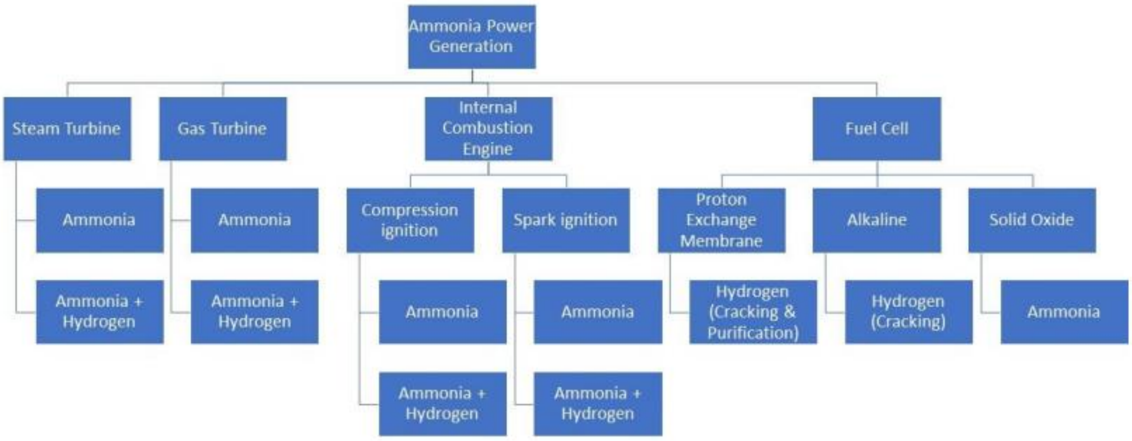

Figure 4 - Ammonia power generation: Overview

Ammonia fuel cells

Fuel cells represent a feasible solution for the decarbonisation of the maritime industry. They exhibit improved energy density compared with batteries and are less pollutant and more efficient than traditional internal combustion engines. In addition, fuel cells can be powered with green fuels (hydrogen, ammonia) which further increases their potential.

Fuel cells using ammonia have also been studied extensively for stationary power generation and as power sources for transport. Although most cells developed to-date are based on hydrogen as fuel, it is recognised that the storage of hydrogen for such purposes is still challenging and expensive. Methanol, ethanol, n-octane, ammonia and methane are potential candidates to supply H_2 to these fuel cells. Ammonia can be used indirectly to produce the required hydrogen for energy production in fuel cells, as the ammonia is cracked by the anode within the cell and thus there is no need for a fore-line ammonia reformer. Therefore, ammonia, as a well-established fuel with decades of synthesis, handling and utilisation expertise across the world, started attracting significant attention as fuel for fuel cells during the last decade [10].

Feasibility studies for ammonia fuel cells have been conducted on three types of fuel cells: alkaline FC, Solid oxide FC (SOFC) and Proton Exchange Membrane FC (PEM).

Ammonia combustion engines

Ammonia combustion engines work similarly to traditional fuel engines but bring unique characteristics that reshape how we understand fuel technology. In a typical ammonia-powered engine, the ammonia fuel is vaporised and ignited, just like in traditional vehicles.

This basic function resembles current fossil fuel engines, but several key differences exist.

- Ignition and Combustion Properties: Ammonia has different ignition and combustion properties in comparison to traditional fuels. It requires a higher ignition temperature, about 651°C, and the flame speed is considerably slower. Modifications to the engine's ignition system and control of the air-fuel mixture are necessary to optimise performance.
- Integration with Current Technology: Slight changes are needed to cater to the different properties of ammonia, but by and large, they are very similar to current fossil fuel engines. This compatibility means existing fleets can be retrofitted with ammonia-based technology without significant alterations, reducing implementation costs.
- Energy Density: Ammonia's lower energy density than traditional fuels may require additional considerations for storage and efficiency, especially for applications requiring high power output.
- Safety Considerations: Ammonia is toxic and corrosive, so storage and handling require careful consideration.

Ammonia can be used in a variety of marine engines, including dual-fuel engines that can switch between ammonia and conventional fuels. Its high energy density and low viscosity make it a suitable option for long-range shipping operations.

Whereas combustion of ammonia in compression-ignition engines is challenging due to its very low reactivity, which makes it more attractive for positive ignition. On the contrary, the recent interest in ammonia as fuel is mainly pushed by the marine shipping industry, which prominently runs with compression-ignition large-bore engines. In light of this, several solutions are under investigation to burn ammonia, either in pure or in dual-fuel mode, in compression-ignition engines [11].

Material Compatibility

In the case of ammonia, the benefits of greater versatility than hydrogen get slightly blurred as NH3 is incompatible with various industrial materials. NH3 is corrosive to copper, brass and zinc alloys, forming a greenish/blue colour corrosion. NH3 should not be mixed with bromine, chlorine, iodine and hypochlorite as ammonia is an alkaline reducing agent and reacts with acids, halogens, and oxidizing agents. Cole–Parmer have produced a comprehensive but not exhaustive list of compatibility results between ammonia and various industrial materials

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which are shown in the table. Thus, careful material selection needs to be performed when considering ammonia for power generation.

In table below, the letter A indicates an excellent compatibility, letter B indicates a good- minor effect, slight corrosion or discoloration, letter C indicates a fair- moderate effect, not recommended for continuous use, with softening or loss of strength, swelling may occur, letter D indicates that there is no compatibility between ammonia and that material and N/A stay for information not available [8].

Table 6 - Material compatibilities of ammonia

Compatibility A	Compatibility B	Compatibility C	Compatibility D
Aluminium	Carbon steel	Silicone	ABS Plastic
Carpenter 20	ChemRaz (FFKM)	Titanium	Brass
Cast Iron	LDPE		Bronze
CPVC	NORYL		Copper
EPDM			Fluorocarbon (FKM)
Epoxy			Hypalon
Kalrez			Natural rubber
Kel-F			Polycarbonate
Neoprene			Polyurethane
Nylon			Viton
Polypropylene			
PTFE			
PVC			
PVDF (Kynar)			
Stainless Steel 304 and 316			

In terms of structural damage, ammonia can cause stress corrosion cracking (SCC), a phenomenon that can occur in metals exposed to a combination of stress and corrosive environments. This produces cracks by destabilising the protective oxide layer without causing general corrosion under certain circumstances. In the process of failure, general external signs such as surface corrosion or reduction in thickness are not seen. In other words, when a structure or part is damaged due to SCC, the damage occurs suddenly without any warning signal, resulting in a large structural and economic loss due to an accident that cannot be prepared in advance [9].

Table 7 - Ammonia TRL

	Assessed TRL	**Explanation**
Resource availability and ammonia production pathways	**TRL 9**	The Haber–Bosch process is fully industrialised and globally deployed for more than a century. All colour pathways

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(Haber–Bosch, grey/blue/green ammonia)		(grey, blue, green) rely on mature synthesis technology; differences relate to upstream hydrogen production rather than ammonia synthesis itself.
Green hydrogen production routes (electrolysis, biomass, thermochemical, photocatalysis)	**TRL 7–9**	Alkaline and PEM electrolysis are at TRL 8–9 with large industrial plants operating; solid oxide electrolysis at TRL 6–7; photocatalysis and thermochemical splitting remain at TRL 3–5 and are not yet commercially viable.
Ammonia storage and transport (pressurised/refrigerated tanks)	**TRL 9**	Liquid ammonia storage and maritime transport are fully proven at commercial scale, supported by decades of operational experience in fertiliser and chemical industries.
Bunkering operations (STS, TTS, T-TS)	**TRL 7–8**	Demonstrated at pilot and demonstration scale (Rotterdam, Singapore, Japan, Australia). Procedures validated but not yet routine commercial operations worldwide.
Safety characteristics (toxicity, fire, explosion behaviour)	**TRL 8–9**	Physical and chemical properties are well understood and codified in industrial safety standards (NFPA, EPA AEGL). Marine-specific integration is still being refined.
Ammonia combustion engines (dual-fuel, ICE)	**TRL 6–7**	Large-bore engines under testing and early demonstration. Key challenges remain ignition stability, NOx control, and fuel handling integration.
Ammonia fuel cells (SOFC, PEM, alkaline)	**TRL 5–6**	Extensively studied and demonstrated in laboratories and pilot plants; limited maritime demonstrations; durability, cost, and scale-up still under development.
Material compatibility and SCC risks	**TRL 7–8**	Compatibility data is well established; SCC risks understood but require conservative

		design and operational margins for maritime deployment.
Global TRL for ammonia	**TRL 6–7**	Core technologies are mature, but full ship integration (engines, bunkering, fuel cells) is still transitioning from demonstration to early commercial deployment.

COMMERCIAL READINESS LEVEL

Robustness of the industrial supply chain and Scalability

More than half of currently available ammonia is produced in four countries (China, the US, India and Russia), using hydrogen formed from natural gas and coal, then combined with nitrogen separated from the air using electricity. The hydrogen production processes, coal gasification (26%) and steam methane reforming (73%), account for the majority of the CO2 emitted during ammonia production today.

Of which China and India, despite huge production, are also leading importers of ammonia, in contrast to Russia, which mainly exports NH3. Around 70% of ammonia (approx. 170 million tons) is intended for export. Ammonia is imported and exported to countries on all continents, as we can see in figure below.

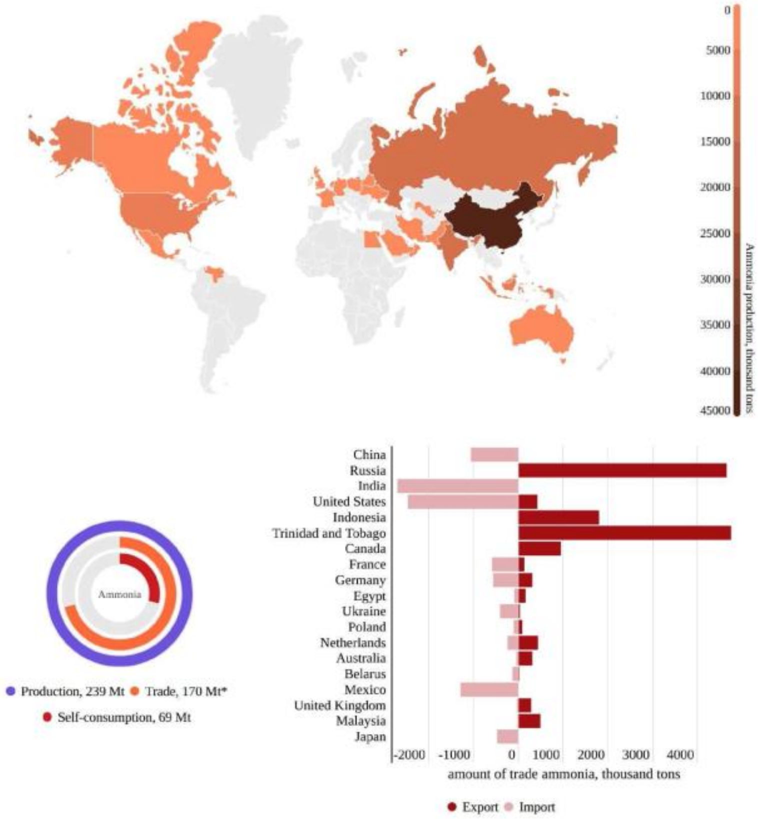

Figure 5 - Global ammonia production per country with import and export details

There is already an established and reliable infrastructure for ammonia production, storage and distribution with an annual global production of 150 million tonnes (in 2019) [12].

Ammonia (un)loading terminals are globally distributed. These facilities have a capacity of several dozens of kilotons. Smaller ammonia storages are widely available in the United States, where ammonia is directly used as a fertilizer. The United States houses more than 10,000 ammonia storage locations. A typical ammonia import terminal has a capacity in the range 30 to 50 kilotons of ammonia. The liquid ammonia is then stored at -33°C and near ambient pressure [13].

At present, ammonia bunkering infrastructure is still at an early stage of deployment, with only a limited number of ports having carried out pilot operations or developed specific readiness strategies. In Europe, the Port of Rotterdam has already completed a first ship-to-ship transfer of 800 m³ of ammonia, under cryogenic conditions at –33 °C, in an operation that lasted 2.5 hours and was performed without release incidents. The port authority, in collaboration with partners such as Gasunie and OCI Global, has also updated its Port Readiness Level assessment to enable ammonia bunkering on a project basis, anticipating commercial-scale operations by 2026. This positions Rotterdam as the leading European hub for low-carbon ammonia supply chains and maritime refuelling [14].

In Asia, Singapore has taken a strategic leadership role. The Maritime and Port Authority (MPA), in partnership with the Energy Market Authority (EMA), has launched an "Ammonia Fuel and Power" project, selecting two international consortia to design and operate facilities

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with a minimum annual bunkering capacity of 100,000 tonnes. In parallel, Fortescue successfully carried out the world's first ammonia bunkering trial at the Vopak Banyan terminal, supplying the Fortescue Green Pioneer with liquid ammonia under the supervision of DNV and the Singapore Registry of Ships. These initiatives confirm Singapore's ambition to become a primary bunkering hub for zero-carbon fuels in the Asia-Pacific region [15].

Meanwhile, Japan has pioneered small-scale operations. In July 2024, NYK Line completed the world's first truck-to-ship bunkering of a commercial vessel at the Port of Yokohama, fuelling the ammonia-ready tugboat Sakigake. The trial was conducted with the approval of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and classified by ClassNK, validating both technical feasibility and regulatory frameworks. Subsequent updates have confirmed the vessel's ongoing operation as a test platform for future regulatory alignment in Japan [16].

Beyond these regions, Australia has emerged as another frontrunner. In Pilbara (Western Australia), Yara Clean Ammonia conducted a groundbreaking offshore ship-to-ship transfer, demonstrating not only the technical viability of handling ammonia at anchorage but also the robustness of emergency procedures under real maritime conditions. The operation, supported by Woodside and Pilbara Ports Authority, was also monitored to collect safety, environmental, and logistics data, which will inform regulatory guidelines for future large-scale ammonia bunkering in Australia [17].

In Southern Europe, the ports of Huelva and Algeciras (Spain) have secured EU funding under the "Alternative Fuels Infrastructure Facility" to develop permanent ammonia and methanol bunkering infrastructure, aiming to integrate with Mediterranean shipping routes and establish redundancy in Europe's future green corridors [18].

Taken together, these initiatives indicate that ammonia bunkering is transitioning from experimental trials to structured deployment. Although most facilities are still in pilot or demonstration phases, the coordinated efforts of port authorities, classification societies, energy companies, and regulators suggest that commercial readiness is expected within this decade, aligned with the entry into service of the first generation of oceangoing ammonia-fuelled vessels.

In order to better contextualize the current state of ammonia bunkering infrastructure worldwide, Table below summarizes the main ports where pilot projects, demonstrations, or infrastructure developments are taking place. The comparison highlights the different bunkering methods being tested (ship-to-ship, truck-to-ship, and terminal-to-ship), the scale of operations achieved so far, and the current level of readiness of each port. As shown, the Port of Rotterdam has already demonstrated a successful large-scale ship-to-ship transfer and expects to move towards commercial readiness by 2026. Singapore, supported by the Maritime and Port Authority (MPA) and the Energy Market Authority (EMA), is combining demonstration activities with large-scale infrastructure planning, targeting an annual capacity exceeding 100,000 tonnes. Japan's Port of Yokohama has validated truck-to-ship operations on a smaller scale, while Australia's Pilbara region has conducted offshore pilot transfers to assess safety procedures and environmental safeguards. In Southern Europe, the ports of Huelva and Algeciras are developing terminal-to-ship facilities through EU funding, positioning themselves as future nodes for Mediterranean green shipping corridors.

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Table 8 - Comparative overview of ammonia bunkering ports worldwide

Port	Bunkering Method	Capacity / Scale	Status
Rotterdam (Netherlands)	Ship-to-Ship (STS)	800 m³ (pilot transfer, 2025)	Pilot completed; commercial readiness expected 2026
Singapore	Shore-to-Ship (TTS) & Truck-to-Ship (T-TS)	≥ 100,000 tonnes/year planned; demo fuelling of Fortescue Green Pioneer	Standards under development; pilot completed; large-scale infra planned
Yokohama (Japan)	Truck-to-Ship (T-TS)	First small-scale fuelling of tugboat 'Sakigake'	Demonstration completed; vessel in test operation
Pilbara (Australia)	Ship-to-Ship (STS) at anchorage	Pilot STS transfer; data collection for large-scale ops	Pilot completed successfully; procedures validated
Huelva & Algeciras (Spain)	Terminal-to-Ship (TTS, planned)	EU-funded infrastructure (volumes to be defined)	In development (EU-funded, implementation ongoing)

This comparative overview demonstrates that, while ammonia bunkering is still at a pilot or demonstration stage, several key ports across different regions are already preparing the transition towards regular commercial operations, laying the groundwork for the adoption of ammonia as a marine fuel within the next decade.

Bankability

The current European landscape offers an interesting public–private financing potential — driven by EU instruments and decarbonisation programmes — yet full bankability for ammonia as a marine fuel still requires: a stable regulatory framework, adequate port infrastructure, large-scale availability of green/blue ammonia, and clear visibility on economic returns.

Green and blue ammonia (produced respectively from renewable hydrogen or from fossil-based hydrogen with CCS) sits at the core of Europe's energy transition strategies. The Clean Hydrogen Partnership and the European Power-to-X (PtX) programme aim to accelerate these solutions. For instance, the cross-border Italy–Spain project for green ammonia — CICERONEGreenNH3stud — has received EU funding (several million euros) to assess plant development, market prospects, and infrastructure needs.

The CICERONEGreenNH3stud project, led by Iberdrola, will receive €3.4 million in EU funding to launch a comprehensive study on the development of renewable energy infrastructure,

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an electrolyser, and green ammonia production. The project will cover environmental assessment, market analysis, and the engineering design required for preliminary evaluation, due diligence, and regulatory compliance.

The initiative aims to build independent yet highly interconnected infrastructure assets located across multiple EU Member States. Specifically, to enable the development of a European cross-border value chain, the CICERONE project intends to install more than 800 MW of renewable energy (mainly photovoltaic) in Spain and Italy, a 120 MW green ammonia plant in Spain, and an ammonia terminal with a cracking facility in Rotterdam.

The European PtX initiative represents a major step toward a sustainable energy future by converting renewable electricity into multiple green products. Key elements include:

- Power-to-X (PtX): a process that transforms electricity into green products — such as green hydrogen or e-methanol — for use in heavy industry and transport.

Nonetheless, the effective bankability — meaning the ability to attract private capital into industrial or maritime ammonia-based projects — still depends on several factors: regulatory maturity, economies of scale in fuel production and use, and a reduction of perceived risks among investors and shipowners. As highlighted by industry experts such as DNV, moving from pilot projects to full commercial scale requires *"a standardised framework and a stable carbon price / clear rules."*

CAPEX & OPEX

According to DNV, ammonia costs fluctuate a lot over time and are not the same everywhere. In the recent decade, prices as low as 200 $/t and as high as 700 $/t have indeed been recorded. Due to market considerations for natural gas and ammonia supply, the value has been below 400 $/t since 2016 and is regularly 200 – 300 $/t. From 2008 through 2017, the average price per tonne was around $400. Depending on the natural gas pricing, natural gas provides 70 % to 85 % of the ammonia manufacturing cost in the United States. Several areas display similar outcomes as well. As a result, the cost of natural gas will be mostly determines by the local price, that has already been estimated to range from $100 per tonne in the Middle East to more than $400 per tonne in Western Europe as of 2013. [19]

Table below shows the typical efficiencies and capital expenditures along with typical US energy prices. Ammonia produced from coal will be more expensive than ammonia produced from natural gas due to lower efficiency and more Capital expenditures (CAPEX). Renewable ammonia, such as that produced by wind turbines, would be more costly than natural gas feedstock. This will be mostly determined by the cost of power, as well as developments in technology. The cost is projected to range between $ 2,200 and $ 3,500 per tonne of yearly production capacity, depending on the equipment scaling for the electrolyzer stacks. Based on a price of 1,000 $/ kW, the electrolyzers are estimated to contribute roughly 77 % of the CAPEX before scaling [19].

The electrolyzer price is approximately half as much as it was before scaling and electrolyzers account for 65 % of the CAPEX as Figure below shows. At this lower price point, greater electrolyzers have also been noted to be available. Renewable energy is on the verge of being competitive with coal based ammonia.

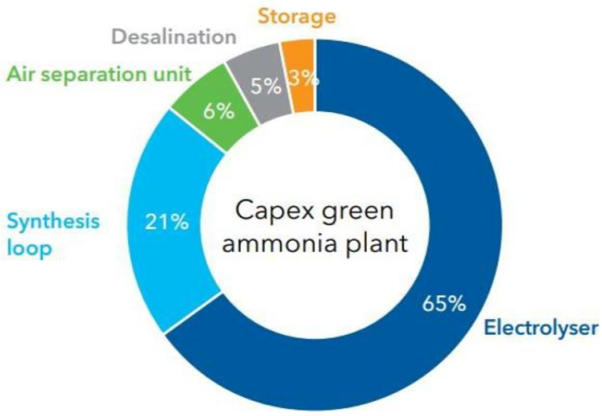

Figure 6 - CAPEX breakdown of a 300 t/day green ammonia plant with electrolyzer scaling

The cost of producing renewable ammonia will be primarily determined by two important factors:

I. Electricity prices
II. CAPEX

For a factory that produces ammonia from electricity, (DNV, 2020) estimated a potential ammonia production price as Figure 28 shows. This is evaluated as a function of electricity prices for multiple CAPEX values and is based on a project's internal rate of return of 1% over 20 years, with 52 % efficiency, a 5 % discount rate and yearly operating costs of 2.5% of the CAPEX. The cost of on-shore wind generation is mostly influenced by the CAPEX and capacity factor in favorable areas and it has been estimated at 0.04 to 0.05 $/kWh. According to the International Renewable Agency (IRENA), the global weighted average cost of on- shore wind power was 0.045 $/ kWh in 2020, while the PV solar cost was 0.048 $/kWh. The current renewable ammonia pricing, based on these numbers, would be between 650 and 850 $/t, however power costs for renewable energy from wind and solar will be significantly site specific. Furthermore, it fairly predicted that the cost of renewable energy will fall over time and that the cost of electrolysis will fall as well [19].

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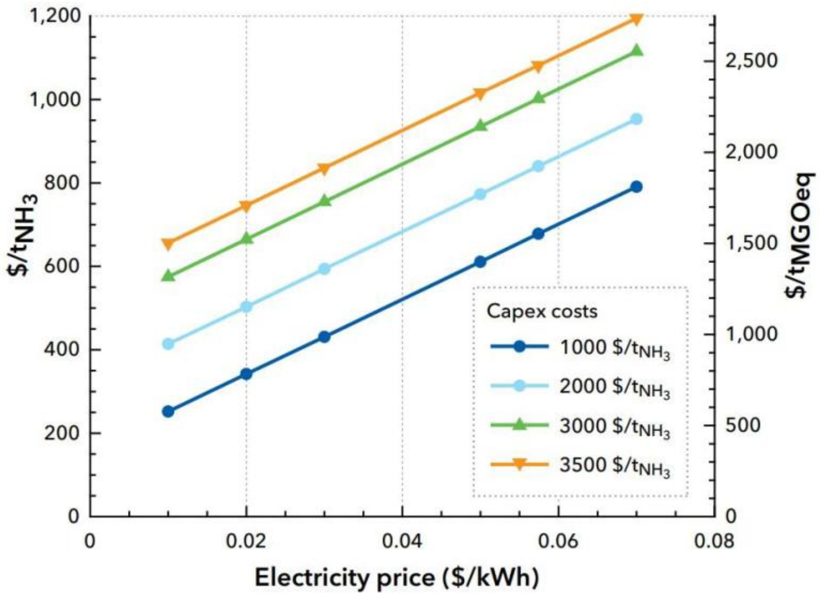

Figure 7 - Estimated production cost of renewable ammonia as a function of the electricity cost at various capital expenditures (per tonne annual production capacity)

In conclusion, adopting ammonia as a fuel entails a significant upfront capital expenditure (CAPEX) and potentially higher operational and fuel costs compared to a "business-as-usual" scenario. However, the combination of regulatory incentives, carbon pricing mechanisms, and the broader need for decarbonisation may ultimately justify the investment — particularly for operators with a long-term strategic outlook.

Chain of Custody Models

According to several industry studies and analyses conducted by DNV and ABS, ammonia offers a particularly relevant advantage compared with other alternative fuels: it already benefits from a highly developed global logistics chain. Internationally, more than 200 ports handle ammonia as a commodity, and over 20 million tonnes are transported annually on dedicated carriers [20]. This means that, unlike fuels such as liquid hydrogen or renewable methanol, there is an existing physical infrastructure (storage facilities, terminals, on-site pipelines) that can be partially repurposed, thereby reducing the need for entirely new infrastructure investments.

The ability to leverage existing assets provides a foundation for more flexible Chain of Custody (CoC) models, such as Mass Balancing, Book & Claim, or hybrid approaches. In a Mass Balancing system, volumes of green or blue ammonia are injected into a shared infrastructure (for example, port storage tanks also used for conventional ammonia) and certified through schemes that guarantee the "low-carbon" share available to the end user. This approach avoids the immediate construction of dedicated terminals and reduces both CAPEX and implementation timelines — a particularly critical factor in the early stages of the energy transition.

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According to DNV, a Mass Balancing model applied to the shipping sector could reduce initial port infrastructure costs by 40–60% compared with the development of segregated tanks or dedicated pipelines. This reduction is mainly driven by the utilisation of existing assets (low-temperature tanks, vaporizers, internal distribution lines, pumping systems), which generally require only limited retrofitting. However, this economic advantage is offset by the need to implement advanced certification and traceability systems, aligned with ISO standards, FuelEU Maritime requirements, and upcoming frameworks for renewable and low-carbon fuel certification.

Another key consideration concerns the reliability of tracking models. To ensure the environmental integrity of the product, Chain of Custody systems must be supported by certifications covering carbon content, energy source, and independent verification mechanisms. As highlighted by ABS, the effectiveness of Mass Balancing depends on the ability to conduct regular audits and apply transparent allocation rules across different end uses (chemical industry, fertilizers, maritime bunkering), avoiding double counting.

In conclusion, the existence of a mature infrastructure for ammonia and the possibility of adopting flexible Chain of Custody frameworks represent major enablers that can accelerate ammonia's uptake in the maritime sector. Certification requirements and procedural complexities remain relatively modest when compared with the potential infrastructure savings, making Mass Balancing models particularly attractive during the early phase of the transition.

Feedstock Availability & Competition

Ammonia is one of the most widely produced chemical commodities globally, with annual production exceeding 180 million tonnes, most of which is destined for fertilizers [21]. However, the availability of "clean" ammonia — i.e., green (electrolysis + Haber-Bosch) or blue (SMR + CCS) — will largely depend on the pace of low-emission hydrogen production capacity expansion. According to the IEA (2022), global green ammonia production is currently still marginal (<1% of total ammonia production), while the cost of renewable hydrogen remains a key factor for scalability.

The availability of the main feedstock, hydrogen, faces strong competition across sectors: aviation (e-jet fuel), refining, green steel, the chemical industry, heavy road transport, and, of course, maritime shipping. Various studies (IEA, 2023; Hydrogen Council, 2022) estimate that by 2030, low-carbon hydrogen demand could exceed supply by 5–8 million tonnes, potentially creating a bottleneck for low-emission ammonia production.

Competition is not limited to hydrogen but also involves the renewable electricity required for its production. In electrolysis-based models, energy accounts for 60–75% of total operating costs, depending on electrolyser CAPEX and local electricity prices. According to IRENA (2021), the cost of renewable electricity required to make green ammonia competitive should stabilise around $0.02–0.03/kWh, whereas in Europe in 2022, average renewable electricity costs ranged from $0.05 to $0.08/kWh, with peaks during periods of market stress.

Competition for feedstock and energy affects not only economics but also industrial planning. A recent study by the Brazilian government (MME, 2024) indicates that even in areas with high renewable potential, green ammonia availability by 2030 may be insufficient to simultaneously cover the projected growth in fertilizer, chemical, and shipping sectors without investments in new large-scale plants. Global scenarios evaluated by the IEA suggest that by 2050, the maritime sector could require 130–180 million tonnes per year of low-carbon alternative fuels. Ammonia could meet a significant share of this demand, but only with a coordinated expansion of production capacity and transport networks.

In conclusion, although conventional ammonia production is already large-scale, the effective availability of low-carbon ammonia will strongly depend on expanding clean hydrogen production, electrolysis systems, and optimised Haber-Bosch plants. Competition with other energy-intensive sectors may slow supply to the maritime sector in the short-to-medium term. Strategic planning and prioritisation of end-use will therefore be critical to ensure a stable and sustainable supply.

Table 9 - Ammonia CRL

	Assessed CRL	**Explanation**
Global ammonia production and trade infrastructure	**CRL 9**	A fully established global market with >180 Mt/year production, mature logistics, and extensive port infrastructure.
Low-carbon (blue/green) ammonia availability	**CRL 5–6**	Production capacity exists but remains marginal; large-scale deployment depends on hydrogen supply expansion and cost reductions.
Bunkering infrastructure at ports	**CRL 6–7**	Pilot and early demonstration projects are operational; commercial-scale infrastructure planned but not yet widespread.
Supply chain scalability and robustness	**CRL 7**	Conventional ammonia supply chains are robust; low-carbon variants face scaling constraints related to hydrogen, electricity, and CCS infrastructure.

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Feedstock competition (hydrogen and renewable electricity)	**CRL 5–6**	Strong inter-sectoral competition (steel, aviation, chemicals) introduces uncertainty in long-term supply availability and pricing.
CAPEX & OPEX economics	**CRL 6**	Cost structures are understood; green ammonia still significantly more expensive than fossil fuels but increasingly competitive under carbon pricing and incentives.
Bankability and financing landscape	**CRL 5–6**	Public funding and EU programmes are available, but private financing remains cautious due to regulatory and market uncertainty.
Chain of Custody models (mass balance, book & claim)	**CRL 7–8**	Certification and traceability models exist and are being adapted; significant cost advantages over segregated infrastructure.
Global CRL for ammonia	**CRL 6–7**	Commercial viability is emerging but still transitional; widespread adoption depends on fuel availability, regulation, and cost convergence.

SOCIETAL READINESS LEVEL

International regulation and consistency with European policies

Over the last two years, the international regulatory landscape has rapidly evolved toward establishing a framework for the use of ammonia as a marine fuel. The International Maritime Organization (IMO) has published provisional safety guidelines for ammonia-fuelled ships (Interim Guidelines on the Safe Use of Ammonia as Marine Fuel, MSC.1/Circ.1687). These guidelines adopt a risk-based approach covering design, storage, bunkering, and onboard operations. Although they are a key reference for administrations and operators, they remain non-mandatory and their effectiveness depends on national implementation, class society adoption, and future translation into prescriptive codes.

Complementing the IMO framework, the European Union has strengthened incentives and requirements for low-carbon marine fuels. Key initiatives include FuelEU Maritime, which mandates gradual reductions in the GHG intensity of marine fuels used in EU ports, and the extension of the EU ETS to the maritime sector, introducing a carbon-pricing mechanism likely to shift the economic balance between fossil fuels and low-carbon alternatives. Alignment between IMO guidance and EU policies is essential: coherent regulation reduces investment uncertainty, facilitates port harmonisation, and accelerates large-scale deployment of ammonia-powered vessels [22].

Despite regulatory progress, several gaps remain. First, IMO guidelines allow considerable national interpretation until they evolve into mandatory requirements; second, class societies and flag states must harmonise rules to avoid diverging safety expectations among ports and registries; third, economic instruments (FuelEU and EU ETS) require clear definitions of fuel origin (green/blue/grey ammonia), certification schemes, and accounting rules for GHG reductions. Moving from pilot projects to broad adoption requires:

I. converting IMO guidelines into mandatory, harmonised rules;
II. coordinated updates of class society requirements;
III. transparent certification and traceability systems aligned with EU legislation.

The regulatory framework is evolving rapidly and increasingly aligned with EU decarbonisation objectives, but full societal readiness requires further harmonisation, mandatory norms, and integrated certification policies.

Stakeholder acceptance: shipowners, ports, maritime authorities, crews, and industry actors

Stakeholder acceptance varies significantly depending on risk perception, familiarity with gaseous/cryogenic fuels, and confidence in mitigation measures. A large survey conducted by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping involving more than 2,000 seafarers and onshore workers shows that 59% of seafarers and 57% of shore-side staff are willing to work with ammonia-fuelled vessels provided that comprehensive and certified training is in place; however, a substantial share of respondents remain uncertain, largely due to concerns about toxicity and the risk of accidental release. Willingness is therefore closely tied to robust safety procedures and structured training programmes. [23]

Ports and logistics operators display strong operational engagement. The Port of Rotterdam conducted a ship-to-ship ammonia bunkering pilot (12 April 2025), transferring 800 m^3 of liquid ammonia at −33 °C and validating procedures, QRA analyses, and mitigation strategies, with no environmental release [24]. This real-world demonstration signals growing confidence among major EU ports. Similar feasibility studies and trials are underway across Europe, often supported by EU-funded projects (e.g., MAGPIE) [25]. Ports therefore act as crucial enablers of systemic acceptance.

Commercial acceptance among shipowners is more cautious: many operators await regulatory certainty, clear total cost of ownership (retrofit/newbuild costs, bunkering availability), and insurance guarantees. Maritime labour unions also stress that the adoption of ammonia must not compromise crew safety standards (emergency drills, PPE, rescue equipment). Overall, stakeholder readiness depends on three enabling conditions:

I. operational evidence from trials;
II. standardised, internationally recognised training;
III. regulatory and insurance clarity.

In conclusion willingness to adopt ammonia exists across industry segments, but remains conditional on demonstrated safety, structured training, and transparent regulatory/insurance frameworks.

Social and Territorial aspects

Deploying ammonia at port scale raises relevant concerns for local communities, public perception, and the “licence to operate” of port authorities. Ammonia is highly toxic and corrosive, and accidental releases can cause harmful concentrations at some distance from the source. For this reason, technical literature and EMSA analyses recommend detailed consequence modelling (including CFD), safety zones, and civil protection plans based on worst-case scenarios and predefined activation thresholds (evacuation or shelter-in-place).

Social acceptance depends heavily on three practical elements: transparent communication, continuous environmental monitoring, and emergency preparedness plans developed jointly with local communities. Evidence from demonstrator projects—such as the Rotterdam pilot—shows that when public information campaigns, community meetings, and joint emergency simulations are included in the deployment strategy, perceived risk declines significantly compared to projects implemented without community engagement. Early stakeholder mapping, public consultations, and accessible monitoring data are therefore essential for societal acceptance.[7]

Territorial impacts also include economic co-benefits (local skilled jobs, infrastructure investment, integration with local energy-transition strategies) and compensatory measures (environmental mitigation, healthcare preparedness). The combination of risk-reduction measures, transparent emergency planning, and clear socio-economic benefits tends to enhance acceptance among both communities and local decision-makers. Without such

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measures, however, public opposition expressed through local media or citizens' associations may delay or obstruct permitting processes.

Crew Safety & Training

Crew safety is a non-negotiable requirement for ammonia adoption. The latest operational guidelines (MTF/BIMCO SMS guidelines and IMO MSC.1/Circ.1687) provide a structured approach for adapting Safety Management Systems (SMS) to ammonia fuel, covering risk assessment, management of change, bunkering procedures, leak detection, and emergency response. They also address design and material compatibility. However, a major operational gap persists: current STCW provisions do not yet include comprehensive, ammonia-specific competencies. [26]

To address this, several organisations (class societies, research centres, BIMCO, MTF) have proposed structured training curricula including modules on: chemical and physical properties of ammonia, toxicology and first response, detection and alarm systems, use of specialised PPE, containment and decontamination techniques, and hands-on bunkering and transfer operations. Findings from the Mærsk Center show that willingness to work with ammonia increases significantly when internationally recognised certifications and practical training (simulators, drills) are provided.

From the classification standpoint, societies are issuing interpretative notes and technical recommendations on cryogenic tanks, piping systems, ventilation, and detection systems; however, harmonisation of ammonia-specific class rules is still ongoing and risks producing inconsistencies across flag states. Establishing a universally recognised WPT (Well-Practised Training) standard—potentially integrated into STCW or as an additional certification—appears strategic to reduce human-factor risks and ensure uniform emergency response and handling procedures among ship and port personnel.

Table 10 - Ammonia SRL

	Assessed SRL	**Explanation**
International regulation and EU policy alignment (IMO, FuelEU, EU ETS)	**SRL 6–7**	Regulatory frameworks exist and are evolving; however, guidelines remain partly non-mandatory and fragmented across jurisdictions.
Stakeholder acceptance (shipowners, ports, authorities)	**SRL 6**	Conditional acceptance: generally positive provided safety, insurance, and training requirements are clearly addressed.
Seafarer and workforce acceptance	**SRL 5–6**	Willingness increases significantly with structured training and certification; toxicity concerns remain a psychological barrier.

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Social and territorial acceptance (ports, communities)	**SRL 5–6**	Acceptance depends on transparent communication, emergency planning, and engagement; risk perception remains high near ports.
Crew safety frameworks and operational guidelines	**SRL 6–7**	Interim guidelines and SMS adaptations exist; lack of ammonia-specific STCW standards limits full readiness.
Training and competency development (WPT, STCW)	**SRL 5**	Training concepts are defined but not yet standardised or globally mandatory.
Public perception and media discourse	**SRL 5**	Mixed perception: ammonia viewed as toxic, but acceptance improves when framed within decarbonisation and safety governance.
Global SRL for ammonia	**SRL 6**	Societal acceptance is emerging but remains conditional on regulation, training, and demonstrated safety at scale.

3.2. LNG

Liquefied Natural Gas (LNG) has emerged over the last two decades as the most widely adopted alternative fuel in commercial shipping, representing a transitional solution between conventional oil-based fuels and future zero-emission energy carriers. Its development in the maritime sector has been primarily driven by the need to comply with increasingly stringent air-pollution regulations—particularly concerning sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter—while maintaining high energy density, operational flexibility, and compatibility with existing ship designs. From a technological standpoint, LNG propulsion systems are mature, well understood, and supported by a consolidated industrial supply chain, making LNG the reference benchmark against which emerging low- and zero-carbon marine fuels are often compared [27].

LNG is stored onboard at cryogenic temperatures (approximately –162 °C) in insulated tanks and used either in dual-fuel internal combustion engines or, less commonly, in gas turbines. Its gravimetric energy density remains high compared to other alternative fuels, and while its volumetric energy density is lower than marine diesel oil, the penalty is manageable for many vessel classes. This balance has enabled LNG adoption across a wide range of ship types, including large container ships, LNG carriers, cruise ships, Ro-Ro vessels, ferries, and offshore support vessels. The ability to retrofit existing ships, albeit with significant structural modifications, has further accelerated deployment, reinforcing LNG's role as a commercially viable solution at fleet scale [28].

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TECHNOLOGY READINESS LEVEL

Resource Availability and Production

Global LNG availability is fundamentally determined by the scale and geographical distribution of liquefaction capacity, which has expanded rapidly over the past two decades in response to growing demand from power generation and industrial users. Today, global LNG liquefaction capacity exceeds 450 million tonnes per annum, with major exporting regions including the United States, Qatar, Australia, Russia, and several African producers [29]. This infrastructure has been developed primarily to supply electricity generation, industrial processes, and residential heating markets, which together account for the majority of LNG consumption worldwide. As a result, the maritime sector—despite its growing visibility as a decarbonization pathway—remains a relatively small consumer of LNG, accounting for less than one tenth of total global demand. This structural imbalance means that shipping does not drive LNG production decisions but instead relies on surplus availability within a market shaped by power-sector demand cycles, seasonal consumption patterns, and geopolitical dynamics [30].

LNG use in the marine transport sector is expected to increase by 70% and reach nearly 44 bcm/yr by 2030. International maritime shipping, which includes both LNG carriers and commercial vessels powered by LNG, accounts for most of the increase, adding an estimated 15 bcm/yr between 2024 and 2030. Growth is driven by fleet expansion, the build-out of LNG bunkering infrastructure, IMO regulations and favourable economics compared with other alternative fuels. Another 3 bcm/yr increase could come from domestic LNG shipping, including inland waterway barges, ferries and offshore supply vessels. As a result, the maritime sector—despite its growing visibility as a decarbonization pathway—remains a relatively small consumer of LNG, accounting for less than one tenth of total global demand. This structural imbalance means that shipping does not drive LNG production decisions but instead relies on surplus availability within a market shaped by power-sector demand cycles, seasonal consumption patterns, and geopolitical dynamics [31].

Bunkering and Storage on board

LNG bunkering and onboard storage technologies have reached a **very high level of technological maturity**, reflecting decades of operational experience inherited from LNG carriers and more than ten years of application in LNG-fuelled commercial vessels. From a TRL perspective, both bunkering and storage systems can be assessed at **TRL 8–9**, corresponding to technologies that are fully developed, standardized, certified, and routinely operated in real maritime environments. **Shore-to-ship bunkering**, based on fixed onshore cryogenic tanks, insulated pipelines, loading arms, and vapor-return lines, represents the most mature configuration, with extensive deployment in major European and global ports and well-established operational procedures. **Ship-to-ship bunkering**, typically performed via dedicated LNG bunker barges, has similarly reached full operational maturity, providing flexibility while relying on the same cryogenic transfer principles, emergency shutdown systems, and safety architectures as shore-based solutions [32]. Both configurations are supported by detailed international regulations under the IMO IGF Code and classification society rules, which define design requirements, exclusion zones, emergency release systems, and operational protocols.

Onboard LNG storage technologies are equally mature. LNG is stored in **cryogenic tanks operating at near-atmospheric pressure**, with **Type C tanks** being the most widely adopted solution for ferries, offshore vessels, and container ships, and **Type A and Type B tanks** used in larger or more space-constrained installations. These tank technologies are fully standardized, certified, and extensively validated in service, justifying a **TRL 9** classification [33].

Table 11 - LNG Characteristics overview

LNG Characteristics	Type A / B Tanks	Membrane Tanks	Type C Tanks	Skid-Mounted Tanks
Retrofit suitability	Low – significant structural modification required	Very low – generally unsuitable for retrofit	High – widely used in retrofits	Very high – minimal hull integration
Pressurized storage	No – near atmospheric pressure	No – near atmospheric pressure	Yes – low to moderate pressure (typically up to ~10 bar)	Yes – similar to Type C
Secondary containment required	Yes – full secondary barrier	Yes – integral membrane barrier system	No – self-supporting	No – self-supporting
Space utilization	Good	Excellent	Moderate	Poor
Capacity > 1000 m³	Yes	Yes	Yes (modular arrangements)	Limited
Retrofit installation cost	High (~€900/m³)	Very high (~€1200/m³)	Medium (~€150–250/m³)	Low (~€100–150/m³)
Newbuild installation cost	High (~€700–900/m³)	Very high (~€1000+/m³)	Medium (~€500–700/m³)	Medium (~€400–600/m³)
Typical ship types	LNG carriers, large newbuilds	LNG carriers, very large vessels	Ferries, OSVs, container ships, Ro-Ro	Small vessels, pilot boats, early retrofits
Design maturity (TRL)	TRL 9	TRL 9	TRL 9	TRL 8–9

A key technical aspect of onboard storage is the management of **boil-off gas (BOG)**, which is an inherent and well-understood phenomenon caused by residual heat ingress. BOG handling systems—including controlled pressure management, routing of gas to dual-fuel

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engines, re-liquefaction units where required, and regulated venting under exceptional conditions—are integral parts of LNG fuel systems and are governed by stringent safety requirements. During bunkering operations, BOG is typically returned to shore facilities or bunker barges through vapor-return lines, ensuring pressure balance and minimizing methane emissions. The presence of redundant pressure sensors, gas detection, forced ventilation, automatic shutdown valves, and emergency release couplings further reinforces the maturity and robustness of the system [34].

LNG in Internal Combustion engine

The use of Liquefied Natural Gas in **internal combustion engines (ICE)** is the most established and technologically mature pathway for LNG utilization in the maritime sector. LNG-fuelled ICE systems—primarily dual-fuel and gas-only engines—are widely deployed across a broad range of vessel types, including container ships, cruise vessels, ferries, LNG carriers, and offshore support vessels. These engines operate either on low-pressure gas with pilot fuel ignition or on high-pressure gas injection, and their design and operational principles are fully aligned with conventional marine engine architectures. From a technological readiness perspective, LNG use in ICE applications has reached **TRL 9**, indicating full commercial maturity, extensive operational experience, and standardized certification pathways. The associated fuel-gas supply systems, control architectures, and safety measures are fully marinized and governed by well-established international regulations, notably the IMO IGF Code [35].

Current technological development in LNG-fuelled ICE systems is largely incremental and focused on optimization rather than fundamental innovation. Key areas of improvement include the reduction of methane slip, enhancement of combustion efficiency across variable load profiles, and improved integration with hybrid propulsion systems. Despite these ongoing efforts, LNG-ICE technology is considered fully proven, with minimal residual technical uncertainty [36].

LNG in Fuel Cells

The use of Liquefied Natural Gas as a fuel for **fuel cell-based maritime power systems** represents a technologically promising but still immature application within the LNG value chain. Unlike internal combustion engines, fuel cells cannot utilize LNG directly; the fuel must first undergo **reforming** to produce a hydrogen-rich gas suitable for electrochemical conversion. This reforming process—typically based on steam methane reforming or autothermal reforming—adds significant system complexity, requiring high-temperature reactors, heat integration, gas-cleaning units, and sophisticated control systems. In the maritime context, these additional subsystems must be fully marinized to withstand ship motions, vibrations, and variable load conditions, while complying with stringent safety and space constraints [37].

From a technological readiness perspective, LNG-fuelled fuel cell systems are currently positioned in the **TRL 4–6 range**, depending on system scale and level of integration. Laboratory and pilot-scale demonstrations, often coupling LNG reformers with **solid oxide fuel cells (SOFCs)**, have validated the fundamental technical feasibility and highlighted the potential for high electrical efficiencies and low local emissions. However, long start-up times, limited load-following capability, sensitivity to fuel impurities, and degradation under dynamic operating conditions remain key challenges. These factors currently restrict LNG-fuel-cell systems to auxiliary power generation or hybrid configurations rather than full propulsion roles [28].

The primary advantage of LNG-fuelled fuel cell systems is their **higher electrical efficiency** compared to internal combustion engines. While modern LNG dual-fuel ICEs typically achieve **thermal efficiencies in the range of 40–50%**, high-temperature fuel cells—particularly **solid oxide fuel cells (SOFCs)**—can reach **electrical efficiencies of 55–65%**, with even higher overall efficiencies when waste heat is recovered. This improved efficiency directly translates into lower fuel consumption and reduced CO_2 emissions on a tank-to-wake basis for the same energy output.

A second key advantage is the **near-elimination of local pollutant emissions**. Fuel cells operate through electrochemical conversion rather than combustion, resulting in **negligible NO_x, SO_x, and particulate matter emissions**. This makes LNG-fuelled fuel cells particularly attractive for vessels operating in emission-sensitive areas such as ports, coastal zones, and urban waterways, where air quality and noise are critical concerns.

Health and safety

From a safety perspective, LNG presents a fundamentally different risk profile compared to conventional liquid fuels, primarily due to its cryogenic temperature, flammability in gaseous form, and rapid phase change in the event of release. However, decades of experience from LNG carriers, combined with the extensive operational record of LNG-fuelled ships, have resulted in a comprehensive and well-tested safety framework. International regulations, notably the IMO IGF Code, together with classification society rules, establish strict requirements for tank design, fuel-gas handling systems, ventilation, gas detection, fire protection, and emergency shutdown procedures. These measures have proven effective in mitigating both occupational and public safety risks, enabling LNG operations to be conducted with a safety level comparable to—or in some cases exceeding—that of conventional marine fuels.

From a health perspective, LNG does not pose toxic risks in the conventional sense, as natural gas is non-toxic and does not produce harmful residues during normal operation. The primary health hazards are associated with **cryogenic exposure**, which can cause severe cold burns upon contact with liquid LNG or extremely cold surfaces, and **asphyxiation risks** in confined spaces due to oxygen displacement by vaporized gas. These hazards are addressed through strict access control to fuel spaces, mandatory personal protective equipment during bunkering operations, continuous gas monitoring, and dedicated crew training. Fire and explosion risks arise only when LNG vapor mixes with air within a specific flammability range; consequently, system design emphasizes leak prevention, rapid gas dispersion through ventilation, and automatic isolation of fuel systems in abnormal conditions. The widespread adoption of double-walled piping, inerted spaces, and intrinsically safe electrical equipment further reduces ignition risk.

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Table 12 - LNG TRL consideration

Aspect	Transportation (Shipping)	Electricity Generation
Safety	**Very critical** – cryogenic fuel stored onboard, proximity to crew and passengers, stringent IGF Code requirements	**Less critical** – fixed installations, controlled environments, restricted access
Fuel processing / cracking	**Not required** – LNG used directly in dual-fuel engines or gas turbines	**Not required** – LNG regasified and combusted in stationary turbines
Storage tank weight	**Critical** – cryogenic tanks add significant mass and affect stability, payload and vessel layout	**Not an issue** – stationary tanks with no weight constraints
Storage tank robustness	**Must be highly robust and protected** – designed for sloshing, impact, fatigue, and cryogenic conditions	**Existing industrial tanks are sufficient** – static loads only
Distribution	**Complex** – limited bunkering infrastructure, coordination with port operations, safety exclusion zones	**Relatively simple** – integrated into national gas grids or dedicated terminals
Start-up and commissioning	**Operationally sensitive** – cooldown, inerting, crew procedures, limited tolerance for errors	**Standardized** – well-established industrial start-up procedures
Operational handling	**Managed by ship crews** with specific LNG training and certification	**Handled by specialized professionals** in fixed facilities
Boil-off gas management	**Critical onboard issue** – must be consumed, reliquefied, or safely managed at all times	**Less critical** – BOG easily managed or reliquefied in large facilities
Maintenance and inspection	**More demanding** – limited access, marine environment, operational constraints	**Easier** – continuous access, controlled conditions

Explosion and fire

LNG itself is **non-flammable in liquid form**; however, when released and vaporized, natural gas can form a flammable mixture with air if the concentration falls within a narrow range (approximately 5–15% by volume). This characteristic defines the primary explosion hazard and dictates the engineering philosophy applied to LNG fuel systems. In the maritime context, explosion risk is managed through a layered safety approach that emphasizes **leak prevention, rapid gas dispersion, continuous monitoring, and automatic isolation** rather than containment of combustion events [34].

From a design standpoint, LNG fuel systems are arranged to minimize the probability of gas accumulation in enclosed spaces. Fuel tanks are located in dedicated, segregated compartments or on open decks, while fuel-gas supply systems are housed in gas-safe or

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ESD-protected spaces with forced ventilation. Double-walled piping, inerted annular spaces, and intrinsically safe electrical equipment are standard features designed to prevent ignition. Gas detection systems provide continuous monitoring, triggering alarms and automatic shutdowns at predefined thresholds. In the event of a leak, ventilation systems are designed to rapidly dilute gas concentrations below the lower flammability limit, thereby preventing the formation of explosive atmospheres.

Fire risk is addressed through passive and active protection measures. Structural fire protection, insulation, and separation distances are defined to prevent heat transfer to cryogenic tanks, while water spray and dry-chemical firefighting systems are deployed to control external fires. Importantly, LNG fires behave differently from oil-based fuel fires: LNG pool fires burn with relatively low radiant heat compared to heavy fuel oils and do not produce smoke or toxic combustion products under normal conditions. However, confined gas cloud ignitions can result in overpressure effects, making the avoidance of confinement and congestion a fundamental design principle.

Operationally, explosion and fire safety are reinforced through strict bunkering procedures, exclusion zones, emergency release couplings, and boil-off gas management systems. During bunkering, vapor return lines prevent uncontrolled pressure buildup and minimize methane release, while emergency shutdown systems allow immediate isolation of fuel transfer in abnormal situations. Extensive crew training, emergency drills, and port coordination are essential to ensure that procedural safeguards complement technical measures [28].

Material Compatibility

Material compatibility is a critical aspect of LNG systems in maritime applications, as the fuel's cryogenic temperature and gaseous properties impose specific constraints on structural materials, piping, seals, and auxiliary components. LNG is stored and handled at approximately –162 °C, a condition that renders many conventional shipbuilding materials unsuitable due to embrittlement, loss of ductility, or seal degradation. As a result, LNG fuel systems rely on a well-defined set of cryogenic-compatible materials, including austenitic stainless steels, aluminium alloys, and 9% nickel steels, which retain toughness and mechanical integrity at very low temperatures. These materials are widely used in LNG tanks, fuel-gas supply piping, valves, and instrumentation and have been extensively validated through decades of service in LNG carriers and, more recently, LNG-fuelled vessels.

From a naval engineering perspective, material compatibility also extends to secondary barriers, insulation systems, and containment structures, which must withstand repeated thermal cycling, vibration, and ship motions without degradation. Elastomers, gaskets, and sealing materials are selected to prevent leakage and maintain elasticity under cryogenic exposure, while insulation materials must ensure low heat ingress and resist moisture absorption and mechanical damage. Particular attention is given to interfaces between cryogenic and ambient-temperature components, where thermal gradients can induce stresses and fatigue if not properly managed [38].

In fuel utilization systems, compatibility requirements further include resistance to methane permeation, corrosion in marine environments, and compatibility with inert gases used for

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purging and safety systems. These aspects are comprehensively addressed in the IMO IGF Code and classification society rules, which prescribe approved materials, testing procedures, and certification pathways. As a result, material compatibility for LNG systems is considered a fully mature aspect of the technology, consistent with TRL 8–9, with no fundamental material limitations constraining deployment. Remaining challenges are largely related to quality control, fabrication practices, and inspection regimes rather than to the availability or performance of suitable materials [33].

COMMERCIAL READINESS LEVEL

Robustness of the Industrial Supply Chain and Scalability

Global LNG production and liquefaction are among the most mature and geographically diversified energy supply chains worldwide. LNG is produced by liquefying natural gas—primarily extracted via conventional gas fields and, increasingly, unconventional sources—and cooling it to approximately –162 °C for transport and storage. Global LNG production is concentrated in a limited number of major exporting countries, with the United States, Qatar, Australia, Russia, and Malaysia accounting for the majority of liquefaction capacity. Unlike ammonia, LNG production is almost entirely fossil-based, and its associated CO_2 emissions are largely generated during upstream gas extraction, processing, and liquefaction. Nevertheless, the industrial processes involved—gas separation, liquefaction, cryogenic storage, and maritime transport—are fully standardized and operate at very large scale [39].

The LNG market is strongly dominated by power generation, industrial use, and residential heating, which together account for more than 85–90% of global LNG consumption. In contrast, the maritime sector represents a comparatively small but rapidly growing share of demand. This asymmetry has important implications for scalability: LNG availability for shipping is not constrained by production capacity but rather by competition with other sectors and exposure to global gas-market dynamics. Despite this, the overall scale of LNG liquefaction—exceeding 450 million tonnes per annum globally—ensures that maritime demand can be absorbed without requiring dedicated upstream capacity, a key differentiator compared to emerging alternative fuels [29].

A defining strength of LNG is the existence of a fully established global infrastructure for production, storage, and distribution. LNG export terminals, import terminals, floating storage and regasification units (FSRUs), and a large global LNG carrier fleet provide a resilient backbone that supports reliable fuel availability. Onshore LNG storage facilities typically operate at scales ranging from tens to hundreds of kilotonnes, while bunkering-relevant storage capacities at ports commonly range from 10 to 50 kilotonnes. LNG is stored at cryogenic temperature under near-atmospheric pressure, a condition that is well understood and widely managed across industrial applications. This infrastructure maturity directly underpins LNG's high commercial readiness for maritime use.

LNG bunkering infrastructure is already deployed at commercial scale in multiple regions. In Europe, ports such as Rotterdam, Zeebrugge, Antwerp-Bruges, Barcelona, and Marseille-Fos have operational LNG bunkering services, supporting ship-to-ship, shore-to-ship, and truck-to-ship operations. The Port of Rotterdam, in particular, has emerged as a global LNG

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bunkering hub, with multiple dedicated bunker vessels and annual bunkering volumes exceeding one million cubic meters [40]. Northern Europe has similarly developed dense LNG bunkering networks, supporting ferries, container ships, and cruise vessels operating in the Baltic and North Sea. In Asia, Singapore has established itself as a leading LNG bunkering hub, with licensed bunker suppliers, dedicated LNG bunker vessels, and routine commercial operations supporting large oceangoing ships. China, Japan, and South Korea have also developed LNG bunkering infrastructure aligned with domestic LNG-fuelled fleets and regional shipping routes [41].

Beyond Europe and Asia, LNG bunkering has expanded in North America, particularly along the U.S. Gulf Coast, where proximity to liquefaction terminals and abundant gas supply has enabled early adoption. The presence of multiple bunkering modes and standardized operational procedures has allowed LNG bunkering to transition from early demonstration phases to routine commercial service in major ports worldwide. Unlike ammonia, LNG bunkering no longer relies primarily on pilot projects but operates as a commercial service with established pricing mechanisms, contractual structures, and safety regimes.

Taken together, these factors demonstrate that LNG possesses a highly robust and scalable industrial supply chain, supporting a Commercial Readiness Level assessed at CRL 8–9. The technology benefits from mature upstream production, globally distributed infrastructure, and widespread port readiness. Remaining uncertainties are not related to industrial scalability but rather to long-term policy alignment, methane-emission regulation, and the future availability of low-carbon LNG variants. In the near to medium term, however, LNG stands as the most commercially mature alternative fuel for maritime applications, with supply-chain robustness far exceeding that of emerging zero-carbon options [31].

Table 13 - Robustness of the Industrial Supply Chain and Scalability

Port	**Bunkering Method**	**Capacity / Scale**	**Status**
Rotterdam (Netherlands)	Ship-to-Ship (STS), Shore-to-Ship (TTS)	>1,000,000 m^3/year bunkered; multiple dedicated LNG bunker vessels	Fully commercial; global LNG bunkering hub
Zeebrugge / Antwerp-Bruges (Belgium)	Ship-to-Ship (STS), Shore-to-Ship (TTS)	~500,000–700,000 m^3/year; integrated with LNG import terminal	Fully commercial; large-scale operations
Singapore	Ship-to-Ship (STS), Truck-to-Ship (T-TS)	Several hundred thousand m^3/year; scalable via licensed suppliers	Fully commercial; Asia-Pacific LNG bunkering hub
Barcelona (Spain)	Ship-to-Ship (STS), Truck-to-Ship (T-TS)	~150,000–200,000 m^3/year; integrated with regas terminal	Commercial; expanding capacity
Marseille-Fos (France)	Ship-to-Ship (STS), Shore-to-Ship (TTS)	~100,000+ m^3/year; linked to Fos LNG terminal	Commercial; supporting Med routes

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Turku / Stockholm (Baltic region)	Truck-to-Ship (T-TS), Ship-to-Ship (STS)	Regional ferry demand; tens of thousands m³/year	Commercial; routine ferry operations
Yokohama (Japan)	Ship-to-Ship (STS), Truck-to-Ship (T-TS)	Regular LNG bunkering for domestic fleet	Commercial; aligned with LNG-fuelled vessels
Ulsan / Busan (South Korea)	Ship-to-Ship (STS)	Large-scale industrial LNG availability	Commercial; supporting container & industrial shipping
Jacksonville (USA)	Ship-to-Ship (STS)	Dedicated LNG bunker vessel; regional fleet supply	Commercial; early US LNG hub
Port Fourchon / Gulf Coast (USA)	Ship-to-Ship (STS)	Integrated with LNG production/export infrastructure	Commercial; offshore & industrial support

Bankability

LNG currently benefits from a **high level of bankability** in the maritime sector, underpinned by technological maturity, established regulatory frameworks, and a globally consolidated industrial and financial ecosystem [42]. LNG-fuelled vessels have been financed and deployed at scale for more than a decade, with strong participation from commercial banks, export credit agencies, leasing companies, and institutional investors. The availability of standardized engine technologies, certified storage and bunkering systems, and extensive operational track records significantly reduces technical and operational risk, allowing LNG projects to be financed using conventional ship-finance structures. From a lender's perspective, LNG-powered vessels constitute a well-understood asset class, with predictable CAPEX premiums, transparent OPEX profiles, and residual value assumptions that can be reliably assessed [43].

Within the European context, LNG has benefited from regulatory drivers linked to air-quality compliance and emission control requirements, which have provided a clear and stable investment rationale. These conditions have reinforced investor confidence by positioning LNG as a mature and compliant solution rather than an experimental technology. Unlike fuels that require the creation of entirely new production and distribution ecosystems, LNG leverages an existing global gas market and infrastructure, minimizing early-stage project risk and reducing dependence on public subsidies. As a result, LNG-fuelled vessels have generally achieved financial close without the need for dedicated public–private risk-sharing mechanisms, further strengthening their commercial attractiveness.

Nevertheless, the long-term bankability of LNG is increasingly influenced by **policy and transition risk** rather than by technical feasibility. While LNG remains cost-competitive and financeable in the short to medium term, investors are progressively assessing its alignment with long-term decarbonisation objectives, particularly in the context of evolving European climate policies, carbon pricing mechanisms, and lifecycle emissions accounting. This has led

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to a growing emphasis on investment strategies that preserve flexibility over the asset lifetime, such as compatibility with renewable LNG variants or design provisions that limit the risk of regulatory obsolescence. In this context, LNG can be regarded as a **highly bankable solution in the near term**, with continued access to capital largely dependent on regulatory clarity, stable carbon pricing, and credible pathways to reduce lifecycle greenhouse-gas emissions over the coming decades.

From a commercial and bankability standpoint, the competitiveness of LNG must increasingly be assessed relative to conventional marine fuels—such as marine gas oil (MGO) or very-low-sulphur fuel oil (VLSFO)—and to drop-in biofuels such as hydrotreated vegetable oil (HVO), particularly in light of the extension of the **EU Emissions Trading System (EU ETS)** to maritime transport. Traditional diesel fuels benefit from the lowest CAPEX, as they rely on fully depreciated engines, storage systems, and global bunkering infrastructure. However, they are associated with the highest lifecycle CO_2 emissions, resulting in a growing ETS cost exposure. At current emission factors (≈3.2 tCO_2 per tonne of fuel) and carbon prices in the range of **€70–100/tCO_2**, ETS penalties can add **€220–320 per tonne of fuel** to operating costs for voyages subject to the ETS, significantly eroding the apparent cost advantage of conventional fuels [44].

LNG, while requiring a higher upfront CAPEX due to cryogenic storage and fuel-gas systems, benefits from **lower tank-to-wake CO_2 emissions**, typically around **20–25% lower than diesel** on an energy-equivalent basis. As a result, LNG-fuelled vessels face proportionally lower ETS liabilities, reducing carbon-related operating costs by roughly **€40–80 per tonne of fuel equivalent**, depending on carbon price and engine methane-slip performance. When combined with periods of favourable gas pricing, this ETS advantage can partially or fully offset LNG's CAPEX premium over the vessel's operational lifetime, supporting continued bankability—particularly for ships with high utilisation in EU waters. Nevertheless, methane slip and upstream emissions remain critical variables, as stricter lifecycle accounting rules could reduce LNG's relative ETS benefit if not properly mitigated [37].

CAPEX & OPEX

The capital and operational expenditure profile of LNG as a marine fuel is well documented and benefits from extensive historical data derived from both the shipping and energy sectors. LNG prices have exhibited significant variability over time and across regions, largely reflecting fluctuations in global natural gas markets, geopolitical conditions, and competition with power generation and industrial demand. Over the past decade, LNG prices have ranged from below **USD 5/MMBtu** in periods of oversupply to peaks exceeding **USD 30/MMBtu** during market disruptions, particularly in Europe and Asia. In more stable market conditions, long-term average LNG prices have typically remained in the range of **USD 6–10/MMBtu**, corresponding to approximately **USD 300–500 per tonne of LNG**, depending on regional factors and contract structures. Feedstock natural gas cost remains the dominant contributor to LNG pricing, accounting for **70–85% of total production cost**, while liquefaction, storage, and transport represent the remaining share [29].

From a capital expenditure standpoint, LNG-fuelled vessels incur a higher upfront cost compared to conventional fuel oil designs, primarily due to cryogenic fuel storage tanks, fuel-gas supply systems, safety equipment, and additional space requirements. According to

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industry assessments, the incremental CAPEX for LNG propulsion systems typically ranges from **10% to 30%** of the vessel's baseline cost, depending on ship type, tank configuration, and whether the vessel is a newbuild or a retrofit. Onboard LNG storage systems represent a significant portion of this investment, with installation costs varying by tank type and scale. For newbuild vessels, LNG tank installation costs typically fall in the range of **€400–900 per cubic metre**, while retrofit installations can exceed **€900–1,200 per cubic metre** due to structural modifications and integration constraints. Fuel-gas supply systems, automation, and safety systems add further capital cost but benefit from standardized designs and mature supply chains [45].

Operational expenditure for LNG-fuelled vessels is influenced primarily by fuel price volatility, maintenance requirements, and efficiency gains. While LNG-fuelled engines often offer lower maintenance costs due to cleaner combustion and reduced wear, these savings can be offset by the need for specialized inspections, crew training, and maintenance of cryogenic systems. Fuel cost competitiveness is therefore highly location-dependent and sensitive to regional gas-market conditions. In periods of stable gas pricing, LNG has historically provided OPEX advantages relative to low-sulphur fuel oils, particularly when accounting for avoided costs related to exhaust-gas cleaning systems. However, exposure to gas-market volatility introduces a degree of uncertainty that must be factored into long-term operating cost projections.

Beyond fossil LNG, increasing attention is being directed toward **bio-LNG and synthetic LNG (e-LNG)** as means to reduce lifecycle greenhouse-gas emissions while leveraging existing LNG infrastructure. These variants are currently associated with significantly higher production costs, driven by feedstock availability, renewable electricity prices, and conversion efficiencies. Bio-LNG production costs are highly dependent on local biomass resources, while e-LNG costs are primarily determined by electricity prices and electrolysis CAPEX, making them substantially more expensive than conventional LNG in the near term. Nevertheless, cost reductions are anticipated over time as renewable electricity prices decline and power-to-gas technologies mature [37].

In conclusion, LNG adoption as a marine fuel involves a **moderate CAPEX premium and an OPEX profile strongly linked to gas-market dynamics**, but benefits from mature technology, standardized solutions, and well-understood cost drivers. While short-term economics remain favourable under certain market conditions, long-term cost competitiveness will increasingly depend on regulatory developments, carbon pricing, and the availability of lower-carbon LNG variants. These factors position LNG as a commercially viable and financeable option in the near to medium term, with economic performance that is predictable but increasingly shaped by transition-related considerations rather than by technological uncertainty.

SOCIETAL READINESS LEVEL

International Regulation and Consistency with European Policies

Over the last decade, the international regulatory framework for LNG as a marine fuel has reached a high level of maturity, reflecting its transition from an emerging option to a widely deployed solution. At the international level, the International Maritime Organization (IMO)

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has established a comprehensive and mandatory regulatory basis through the **International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)**. The IGF Code provides prescriptive requirements covering the design, construction, storage, bunkering, and operation of LNG-fuelled ships, adopting a safety-by-design approach grounded in extensive operational experience from LNG carriers and early LNG-fuelled vessels. Unlike provisional or interim guidelines applied to emerging fuels, the IGF Code is fully enforceable and consistently implemented by flag states and classification societies, providing a high degree of regulatory certainty.

At the European level, LNG regulation is embedded within a broader policy framework aimed at reducing emissions from maritime transport while maintaining competitiveness and energy security. Instruments such as **FuelEU Maritime** and the **extension of the EU Emissions Trading System (EU ETS) to shipping** directly influence the societal perception and regulatory positioning of LNG. While LNG enables compliance with air-pollution limits and offers moderate reductions in tank-to-wake CO_2 emissions, its fossil origin increasingly places it under scrutiny within EU climate policies that prioritize lifecycle greenhouse-gas reductions. Nevertheless, the alignment between IMO safety regulations and EU market-based instruments has so far ensured a coherent regulatory environment, allowing LNG-fuelled vessels to operate seamlessly across EU ports without regulatory fragmentation.

Despite this advanced regulatory maturity, several challenges affect LNG's long-term societal readiness. First, while safety regulations are fully harmonised, **climate-related policies increasingly differentiate fuels based on lifecycle emissions**, requiring clear accounting methodologies for methane slip and upstream emissions. Second, the treatment of **renewable and low-carbon LNG variants** within FuelEU Maritime and related certification schemes must be clarified to preserve consistency between safety regulation and decarbonisation objectives. Third, the coexistence of LNG as a transitional fuel alongside zero-carbon alternatives raises societal questions regarding potential technology lock-in and asset longevity beyond 2035–2040 [46].

Moving forward, maintaining high societal readiness for LNG requires:

(i) continued alignment between IMO safety frameworks and EU climate legislation;
(ii) transparent and harmonised lifecycle emissions accounting, including methane management;
(iii) regulatory recognition of renewable LNG pathways to support long-term compliance.

Overall, LNG benefits from one of the **most stable and harmonised regulatory frameworks** among alternative marine fuels, supporting a high level of societal acceptance in the short to medium term. However, its societal readiness increasingly depends not on safety regulation—which is already mature—but on its ability to remain consistent with evolving European decarbonisation policies and long-term climate objectives.

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Stakeholder Acceptance: Shipowners, Ports, Maritime Authorities, Crews, and Industry Actors

Stakeholder acceptance of LNG as a marine fuel is generally high and reflects its long-standing presence in maritime operations, particularly through LNG carriers and, more recently, LNG-fuelled commercial vessels. Acceptance levels are closely linked to familiarity with cryogenic fuels, confidence in established mitigation measures, and the availability of standardized safety and training frameworks. Surveys and industry feedback consistently indicate that seafarers and shore-side personnel display a high willingness to work with LNG-fuelled vessels, provided that certified training and clear operational procedures are in place. Unlike more novel fuels, LNG benefits from decades of operational experience, which has significantly reduced perceived safety risks related to cryogenic handling, gas dispersion, and fire prevention. As a result, concerns among crews tend to focus on procedural compliance rather than on fundamental doubts about the technology itself [47].

Ports and logistics operators play a central role in reinforcing stakeholder acceptance and are among the strongest proponents of LNG adoption. Major ports such as Rotterdam, Zeebrugge–Antwerp, Singapore, Barcelona, and Marseille-Fos conduct routine LNG bunkering operations using ship-to-ship, shore-to-ship, and truck-to-ship configurations. These operations have validated quantitative risk assessments, emergency response plans, and exclusion-zone management under real operational conditions, with a strong safety record and no major incidents. The normalization of LNG bunkering as a commercial service—rather than a pilot activity—has contributed substantially to confidence among port authorities and terminal operators, positioning ports as key enablers of system-wide acceptance [31].

Commercial acceptance among shipowners is also relatively high, particularly in segments where LNG offers clear regulatory and operational advantages, such as ferries, cruise vessels, container ships, and offshore support vessels. Shipowners value LNG's technological maturity, predictable performance, and compatibility with existing regulatory frameworks. Nevertheless, acceptance is increasingly conditional on long-term policy clarity, fuel-price volatility, and the evolving treatment of LNG within decarbonisation regulations. Maritime labour organisations and insurers emphasize the importance of maintaining high safety standards, including regular emergency drills, specialized personal protective equipment, and continuous training updates, but generally consider LNG risks to be well understood and manageable.

Overall, stakeholder acceptance of LNG is supported by three enabling factors:

(i) extensive operational evidence from commercial service;

(ii) standardized and internationally recognized training and safety procedures;

(iii) clear and harmonized regulatory and insurance frameworks.

In conclusion, LNG enjoys broad and well-established acceptance across shipowners, ports, maritime authorities, crews, and industry actors, reflecting its advanced technological and regulatory maturity. While future acceptance increasingly depends on alignment with long-term decarbonisation objectives, LNG's societal readiness from a stakeholder perspective is currently high and significantly more consolidated than that of less mature alternative fuels.

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Social and Territorial Aspects

The deployment of LNG at port scale interacts directly with local communities, urban environments, and the territorial “licence to operate” of port authorities, although the nature of the associated social concerns differs significantly from those of highly toxic fuels. LNG is **non-toxic and non-corrosive**, but its cryogenic nature and flammability in gaseous form require careful management to prevent accidental releases and fire or explosion scenarios. For this reason, safety assessments for LNG terminals and bunkering operations routinely include detailed **Quantitative Risk Assessments (QRA)**, dispersion modelling for vapor clouds, definition of safety and exclusion zones, and coordination with civil protection authorities. These measures are well established and have been applied for decades in LNG import terminals and carrier operations, contributing to a relatively high baseline level of public confidence [28].

Social acceptance of LNG infrastructure is strongly influenced by **visibility and familiarity**. In many port cities—particularly in Northern Europe, Asia, and North America—LNG terminals and bunkering operations are already perceived as part of the existing industrial landscape, reducing the novelty-related risk perception often associated with new fuels. Acceptance is further reinforced when port authorities adopt transparent communication strategies, provide accessible information on safety measures and monitoring systems, and engage local stakeholders through public consultations. Continuous environmental monitoring, real-time gas detection systems, and clearly communicated emergency response procedures contribute to maintaining trust, even in densely populated port areas.

Territorial impacts associated with LNG deployment often include tangible economic and environmental co-benefits. These include investments in port infrastructure, creation of skilled technical and operational jobs, and improvements in local air quality due to the displacement of heavy fuel oil and marine diesel. Reduced emissions of sulphur oxides, nitrogen oxides, and particulate matter generate direct health benefits for communities living near ports and shipping lanes, strengthening societal support. At the same time, port authorities typically integrate LNG deployment within broader territorial strategies for energy transition, logistics competitiveness, and industrial development, further embedding the technology within local policy objectives [47].

While public opposition to LNG infrastructure is generally limited compared to less mature or more hazardous alternatives, it can still arise in cases where projects are perceived as insufficiently transparent or as locking territories into fossil-fuel dependency without a clear transition pathway. As a result, maintaining social acceptance increasingly depends on demonstrating robust safety performance, ongoing community engagement, and credible alignment with longer-term decarbonisation strategies, including the potential use of renewable LNG variants. Overall, the combination of established safety practices, economic co-benefits, and familiarity positions LNG at a **high level of societal and territorial acceptance**, provided that ports continue to integrate technical risk management with proactive social engagement.

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3.3. BIOFUELS

In a maritime context, biofuels refer to liquid (or occasionally gaseous) fuels derived from biomass, biomass residues, or waste (vegetable oils, fats, waste cooking oils, forestry/agricultural residues), processed to meet fuel specifications usable in marine engines or adapted fuel systems. According to DNV, the main types relevant for shipping are FAME, HVO/HDRD (Hydrogen vegetable oil / Hydrogenation derived renewable diesel), and synthetic fuels derived from biomass (BTL; biomass-to-liquid), with a possibility of future gas-based biofuels (bio-LNG / bio-methanol) under consideration [48].

Here is an overview of key types:

Table 14 - Overview of biofuels key types

Type	Acronym / Common Name	Origin / Feedstock	Key Characteristics
Fatty Acid Methyl Ester	FAME (commonly biodiesel)	Vegetable oils, animal fats, waste cooking oils (triglycerides)	-Produced by transesterification/ methyl esters -Quality per EN 14214 / ISO 8217:2017 -Often blended with conventional marine diesel
Hydrotreated Vegetable Oil / Renewable Diesel	HVO/HDRD	Vegetable oils, waste fats, used oils	-Produced via hydrogenation / hydrotreating (fatty-acid hydrocarbon hydrotreatment) / paraffinic hydrocarbons -Drop-in renewable diesel, chemically similar to fossil diesel -Can be distributed via existing diesel infrastructure
Biomass-to-Liquid (BTL) / Synthetic Biofuels	BTL (FT-diesel, bio-FT)	Forestry/agricultural residues, waste biomass, non-food biomass	-Converts biomass into synthetic hydrocarbons -Potentially very drop-in
Bio-LNG / Bio-methanol / Bio-DME / Others	bio-LNG, bio-methanol, bio-FT-DME, etc.	Biomass, waste, biogas, synthesis routes	-Considered by EMSA among potential marine biofuels -Require adapted engines or fuel systems

Given this variety, any comprehensive analysis must consider a wide spectrum of biofuel types from near-term drop-in (FAME, HVO) to longer-term synthetic or advanced fuels (BTL, bio-methanol, bio-LNG, DME) [49].

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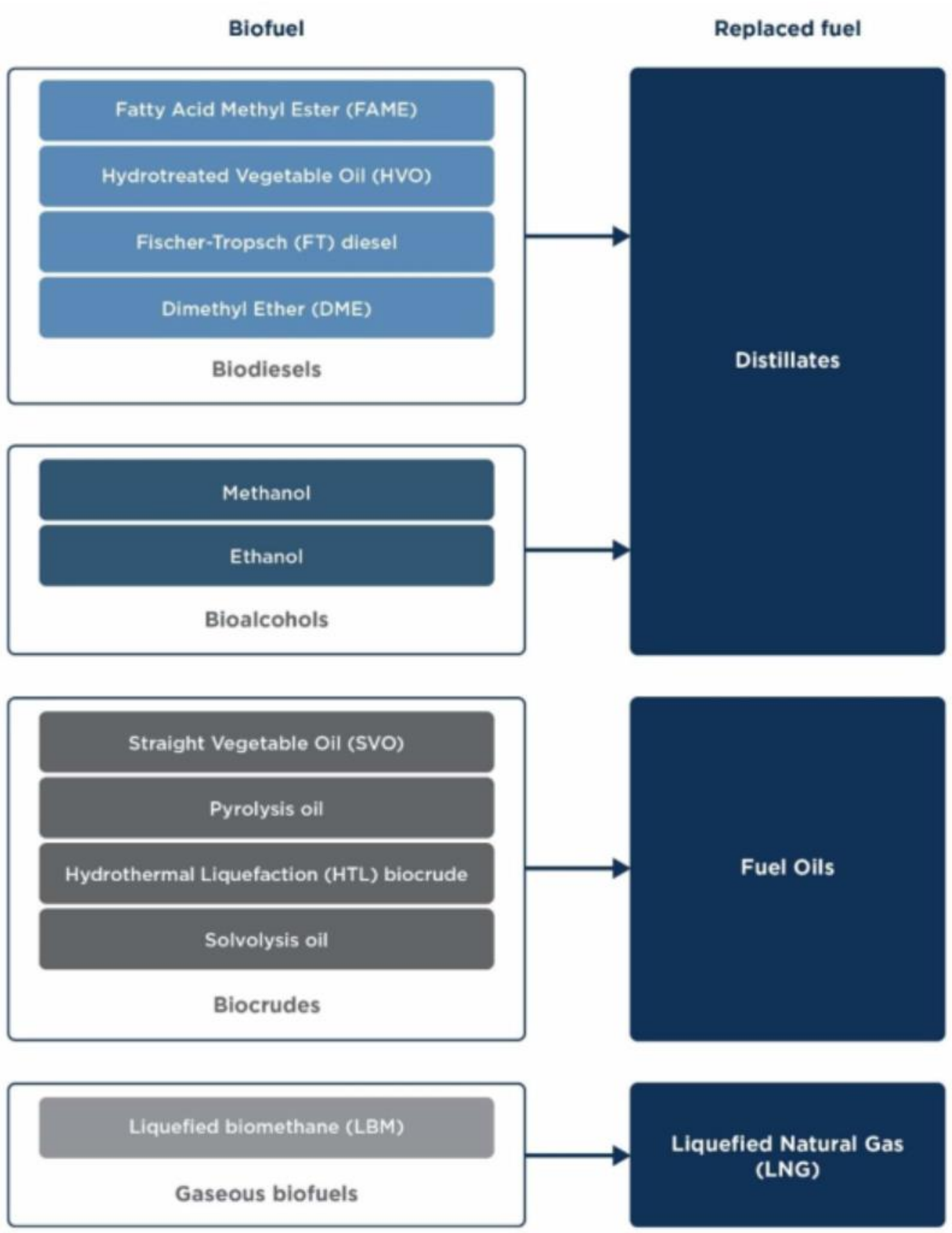

Figure 8 - Overview of biofuels, production pathways and biomass-feedstock groups

TECHNOLOGY READINESS LEVEL

The Technology Readiness Level (TRL) framework evaluates the technical maturity of marine biofuels across the full value chain from feedstock availability to onboard utilization.

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Resource Availability and Production

The upstream emissions profile and scalability of marine biofuels are strongly dependent on the feedstock chosen, which, in turn, influences sustainability and commercial viability [50].

The sustainability and availability of feedstocks directly influence the environmental and eco nomic viability of biofuels. Key feedstock categories:

- **Waste oils/fats and used cooking oils (UCO):** Low-risk, avoids land-use competition.
- **Residual fats, used greases, animal fats:** Also waste-based, lower ILUC (indirect land-use change) risk.
- **Non-food biomass & residues:** Forestry or agricultural residues, lignocellulosic biomass - suitable for advanced biofuels / BTL.
- **Crop-based vegetable oils (rapeseed, soy, palm):** Widely available but raise serious sustainability concerns (deforestation, land use change, food vs fuel) [51].

Important constraints:

- Global demand for biofuels across sectors (road, aviation, plastics, chemicals) competes for the same feedstocks. According to DNV, shipping accounted for only 0.6% of global liquid biofuel consumption in 2023 [52].
- Supply bottlenecks and uncertain sustainable feedstock availability represent a major risk for large-scale maritime adoption [53].
- Certification and chain-of-custody (sustainability certifications, Proof of Sustainability, ILUC accounting) are necessary to ensure real lifecycle GHG benefits - not all biofuels qualify [54].

Hence, waste-based and residue-based feedstocks are generally regarded as the most sustainable choice for marine biofuels to avoid food-fuel competition and indirect land-use change (ILUC) risks.

A. Feedstock Availability and Sustainability

Table 15 - Feedstock Availability and Sustainability

Feedstock Category	Availability & Sustainability Profile	TRL (Maturity)
Waste-based Lipids (UCO, tallow, residues)	These feedstocks exhibit a strong sustainability profile and generate deep GHG reductions (70% to almost 100% WtW reduction). They are favoured because they require no land conversion, thereby offering the deepest GHG emissions savings. Waste fats and oils (FOGs) are classified as Annex IX Part B feedstocks under the Renewable Energy Directive II (RED II). Utilization of waste and low-quality feedstocks represents a primary strategy for realizing cost reductions in fuel production.	**9 (fully commercial)**

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Crop-based Vegetable Oils (rapeseed, soy, palm)	While originating from technologically mature first-generation conversion systems, these feedstocks pose significant sustainability issues. They are linked to high Indirect Land Use Change (ILUC) emissions. Specifically, palm oil is officially classified as a high ILUC-risk biofuel by regulatory bodies.	**9 (fully commercial)**
Lignocellulosic Biomass (residues, forestry waste, black liquor)	Lignocellulosic feedstocks, encompassing agricultural and forestry residues, hold a large theoretical potential and are available in greater quantities than lipid wastes. They are central to emerging second-generation pathways, offering the greatest potential for meaningful GHG reductions in the long term. However, commercial production volumes remain limited.	**6-8 (demonstration scale)**

B. Fuel Production Robustness

The maturity of conversion technology determines the commercial readiness and inherent stability of the resulting biofuel product.

- Transesterification (FAME)

The traditional biodiesel process: triglycerides (vegetable oils / fats) react with methanol (or another alcohol) under a catalyst to produce methyl esters (FAME) and glycerol as by-product. This process is well established in road transport biodiesel production, and marine-grade FAME is produced accordingly [55].

Because FAME has different physical properties (viscosity, cold-flow behavior) than fossil diesel, blending (e.g., B20, B30) or heating may be required under certain conditions, especially depending on climate / ambient temperature [56].

- Hydrotreatment / Hydrogenation (HVO / Renewable Diesel)

HVO (also referred to as hydrotreated vegetable oil, HDRD, renewable diesel) is produced by hydrotreating vegetable oils or fats. In this process, hydrogen is used to remove oxygen and convert triglycerides into paraffinic hydrocarbons, yielding a fuel that is chemically similar to conventional diesel. DNV notes that HVO can be directly introduced into existing diesel distribution and bunkering infrastructures and used in marine diesel engines without modification [57].

This drop-in property makes HVO especially attractive for shipping, avoiding much of the infrastructure and engine-modification cost and risk.

- Biomass-to-Liquid (BTL) / Synthetic Biofuels (FT-Diesel, bio-DME, etc.)

For more advanced and scalable biofuel solutions, biomass (e.g., wood residues, agricultural residues, waste biomass) can be converted via thermochemical processes pyrolysis or gasification → synthesis gas → Fischer–Tropsch (FT) synthesis (or methanol-to-fuel

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processes) creating liquid hydrocarbons (drop-in capable) or alternative fuels (DME, bio-LNG, etc.). DNV and the European Maritime Safety Agency (EMSA) include FT-diesel, bio-methanol, bio-DME among the pre-selected biofuel candidates for shipping [48].

These advanced pathways hold promise for more scalable supply, but are currently less mature, more costly, and face feedstock and technological hurdles.

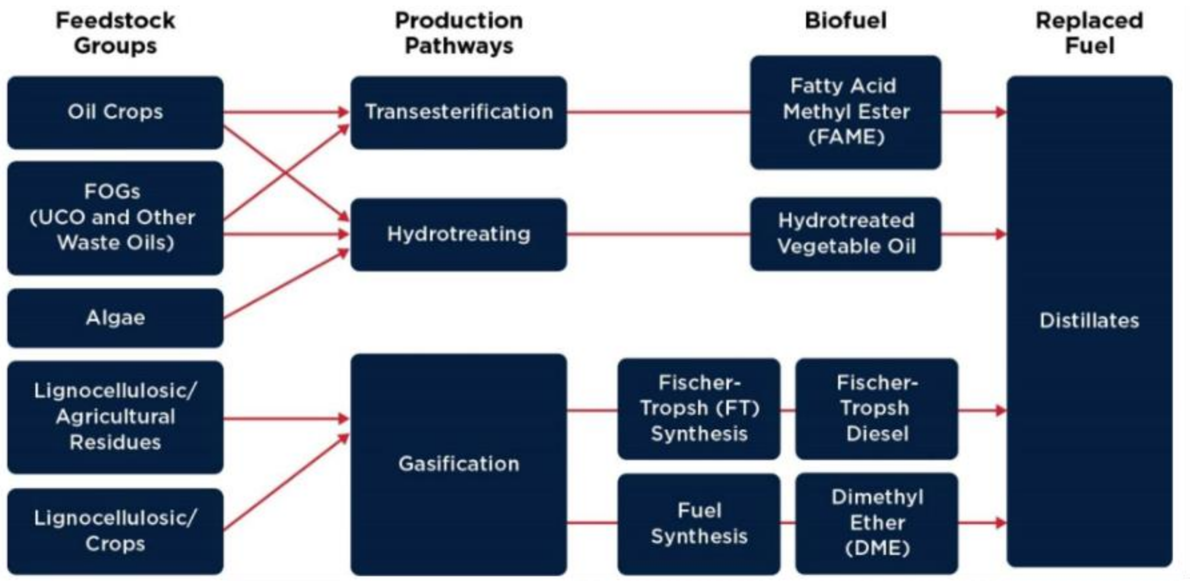

Figure 9 - Production Pathways for Biodiesels

Table 16 - Biofuels Production Pathway

Production Pathway	Technical Profile and Stability	TRL (Maturity)
FAME Biodiesel (Esterification/Transesterification)	The production process is a mature and fully developed technology. FAME is often limited to use in blends due to compatibility limitations with engine systems.	**9 (mature)**
HVO / Renewable Diesel (Hydrotreatment)	Production via hydrotreatment is a fully developed technology. HVO is highly compatible with a wide range of marine engines, positioning it as the cheapest and most commercially ready drop-in biofuel. HVO's paraffinic molecular structure yields high quality fuel with excellent stability. Key industry players utilize this pathway commercially.	**9 (mature)**

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BTL / FT-Biofuels (Fischer–Tropsch Synthesis)	This pathway utilizes gasification followed by Fischer-Tropsch synthesis. It is characterized by high capital investment costs and a relatively lower level of technological readiness than hydrotreated renewable diesel. The TRL forecast suggests that the pathway is moving toward commercial scale.	**6-8 (pilot/demo)**
HTL Biocrude (Hydrothermal Liquefaction)	HTL is demonstrated only at the bench or pilot scale. The raw biocrude is not a functional drop-in fuel and requires further upgrading to produce MGO or MDO.	**2-4 (low)**

Bunkering and Storage Onboard

The maturity of the bunkering infrastructure is highly dependent on the "drop-in" compatibility of the fuel, which directly influences its scalability and market adoption [58].

Table 17 - Biofuels Bunkering and Storage Onboard

Biofuel Category	TRL	Infrastructure and Availability Profile
FAME and HVO	**9**	These biofuels are designated as drop-in fuels and exhibit compatibility with existing diesel infrastructure. Consequently, their usage is already established within major bunkering hubs, including Rotterdam, Singapore, and the ARA region (e.g., Hamburg and Antwerp). Their commercial use and associated compliance are referenced by classification frameworks, notably the RINA BIOFUEL Notation.
Advanced Biofuels (FT-diesel, BTL)	**6-8**	These fuels are associated with emerging production technologies, such as Fischer-Tropsch (FT) synthesis, rated at a maturity level of TRL 6 to 8. Investment in new bunkering and distribution infrastructure is generally required to support the uptake of hydrogen derivatives. Fuels like Hydrothermal Liquefaction (HTL) biocrude currently exhibit a substantially lower readiness level of TRL 2 to 4.

The chemical properties of biofuels necessitate specific onboard handling protocols, especially concerning long-term storage stability:

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- **FAME (Fatty Acid Methyl Esters):** FAME is susceptible to degradation as it is hygroscopic (susceptible to water) and exhibits low oxidative stability. This leads to a risk of microbial contamination and the formation of acids and insoluble materials. The required management of stability and compatibility concerns is specifically addressed by class organizations, such as the RINA BIOFUEL Notation, which mandates technical files and risk assessments for FAME use [54].
- **HVO (Hydrotreated Vegetable Oil):** HVO possesses an excellent storage profile. Its composition, characterized by stable non-hygroscopic paraffins, renders it poorly subject to bacterial contamination and imparts good or comparable storage stability relative to conventional marine distillate fuels [52].
- **FT-diesel (BTL):** As synthetic paraffinic hydrocarbons, FT-diesel exhibits storage properties generally similar to marine gas oil (MGO) [48].
- **HTL Biocrude:** Unrefined biocrudes, such as pyrolysis oil (a comparable product), are notably acidic and corrosive, requiring specialized material considerations for storage tanks to prevent degradation [59].

Safety and Operational Requirements

Safety management for biofuels focuses on mitigating fire risk, operational integrity, and material degradation resulting from unique chemical characteristics.

Table 18 - Safety and Operational Requirements

Biofuel Type	TRL	Key Safety Characteristics and Risks
FAME	8-9	FAME exhibits an inherent safety advantage regarding flammability, featuring a high flash point (≥101 °C), significantly exceeding the marine distillate safety requirement of ≥60 °C. Primary operational risks include potential filter clogging due to microbial growth and the release of dissolved deposits. Mitigation requires mandatory cleaning and maintenance protocols.
HVO	**8-9**	HVO is chemically very similar to MGO, simplifying safety protocols. HVO is readily compatible with existing engine types and dual-fuel configurations, enabling seamless drop-in deployment.
Advanced Biofuels	**6-8**	FT-diesel (BTL) is considered safe and clean due to its inherent sulfur-free composition. HTL biocrude, conversely, is chemically unstable, corrosive, and poorly compatible, necessitating the development of new safety measures and significant fuel upgrading prior to use.

The assessment and compliance of biofuels on board are managed through prescriptive and risk-based methods:

- **Engine Compatibility:** Engine manufacturers typically provide acceptance for FAME blends (B30) or HVO (B100) use, confirming compliance with Tier I and Tier II NOx emission limits. The suitability of HVO for use in dual-fuel systems is affirmed by its high compatibility [56].

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- **Safety Management:** Class societies facilitate technical compliance. The RINA BIOFUEL Notation requires a comprehensive safety assessment to verify compliance, including testing for stability and compatibility and ensuring adherence to safety regulations and limits for FAME content. Risk assessments are crucial, addressing scenarios such as bio-fuel related hazards, system failures, and human factors/training [60].

Marinization and Performance Characteristics

The successful integration of biofuels, or marinization, involves assessing core operational characteristics, such as energy content, combustion behaviour, and maintenance implications, to ensure compatibility with existing marine power systems.

Fatty Acid Methyl Esters (FAME)

FAME biodiesel presents a constrained performance profile, notably featuring an energy density approximately 10-12% inferior to conventional Marine Gas Oil (MGO), a discrepancy which necessitates heightened fuel consumption or larger storage volumes to maintain cruising range. The combustion of this oxygen-rich fuel tends to result in a slight elevation in NOx emissions, potentially requiring minor engine adjustments or optimization (engine tuning) to maintain performance and regulatory compliance. Furthermore, the application of FAME requires attention to its interaction with engine lubricant, as components of the biofuel can contribute to deposits and compromise lubrication efficacy [50].

Hydrotreated Vegetable Oil (HVO) / Renewable Diesel

HVO offers superior compatibility, possessing an energy density nearly identical to fossil diesel on a mass basis, thereby minimizing operational impacts related to range and fuel volume. Due to its stable chemical composition (paraffinic hydrocarbons), HVO is recognized for its compatibility with all marine diesel engines, eliminating the need for substantial mechanical retrofits, a feature affirmed by major Original Equipment Manufacturers (OEMs) [57].

Advanced Synthesized Biofuels (BTL, FT Diesel)

Synthetic hydrocarbon fuels produced via advanced pathways, such as the Fischer-Tropsch (FT) process, are considered fully drop-in compatible. Their chemical purity and uniform molecular structure contribute to excellent combustion properties, positioning them as high-quality drop-in substitutes for conventional distillates [48].

HTL Biocrude

Hydrothermal Liquefaction (HTL) biocrude is chemically complex and requires substantive upgrading before utilization to meet engine fuel specifications. Without such processing, it remains poorly compatible with existing systems and is therefore not yet marinized [59].

Material Compatibility and System Integrity

Maintaining the physical integrity of the fuel handling system and engine components is essential when transitioning to alternative fuels.

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Table 19 - Material Compatibility and System Integrity

Biofuel Type	Compatibility Profile and Requirements
FAME	FAME exhibits a strong solvency capability and tendency to absorb moisture, leading to potential incompatibility with certain elastomers, rubber seals, and specific metals (e.g., copper and brass) within the fuel system. Classification societies, such as RINA, require a Biofuel Technical File and specific Risk Assessment to manage these issues and prescribe the use of approved coatings and materials for system integrity.
HVO	Due to its paraffinic composition, HVO is chemically similar to marine diesel, offering excellent compatibility with standard fuel handling equipment, storage materials, and engine components.
Advanced Biofuels (FT Liquids)	FT diesel and similar synthetic liquids exhibit full compatibility with existing marine fuel infrastructure, requiring no material modifications due to their pure hydrocarbon structure.
HTL Biocrude	Unrefined HTL biocrude contains corrosive and acidic compounds, necessitating the use of specialized, protective materials and coatings for storage and handling to prevent degradation and systemic failure.

Technology Readiness Level (TRL) Summary

The TRL assessment reflects the maturity of the biofuel application within the maritime environment, acknowledging the technical hurdles remaining for widespread, caveat-free adoption.

Table 20 - Biofuels Technology Readiness Level (TRL) Summary

Fuel	TRL	Notes
FAME (waste-based)	8	Production technology is mature, but the application faces ongoing technical challenges related to storage stability (oxidation/microbial growth) and material compatibility, requiring specific maintenance protocols and potential engine tuning due to increased NOx formation.
HVO / Renewable Diesel	9	Classified as a mature technology, HVO is fully drop-in compatible, possesses excellent storage stability, and is widely approved by major engine OEMs.
Rapeseed FAME/HVO	9	Production is technically mature, but its long-term viability is constrained by Indirect Land Use Change (ILUC) sustainability limits, rendering it climate-unfavourable unless produced from low-ILUC risk sources.
BTL / FT Diesel	6–7	This pathway is currently at the pilot or demonstration scale (TRL 6/8). The resulting fuels offer excellent combustion and physical properties (fully drop-in) but await full commercial scale-up.

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HTL Biocrude	5–6	This technology remains in the early development stage (TRL 2/4 in some conversion aspects). The product requires significant and costly upgrading to become a viable marine fuel.

PART 4 - COMMERCIAL READINESS LEVEL FOR MARINE BIOFUELS

The Commercial Readiness Level (CRL) assesses the viability, scalability, and integration compatibility of a fuel pathway within global maritime logistics, drawing heavily on the underlying Technology Readiness Level (TRL) for production. Biofuels demonstrate a heterogeneous commercial landscape defined primarily by feedstock availability and competition with other transport sectors.

Robustness of the Industrial Supply Chain and Scalability

Table 21 - Robustness of the Industrial Supply Chain and Scalability

Biofuel Type	Production Pathway	Commercial Maturity (CRL)	Scalability Status and Constraints
FAME	Transesterification (Waste-based)	8 (Commercial, Constrained)	Production is globally mature, with the EU being a primary producer, but feedstock scarcity severely limits maritime scale-up.
HVO	Hydrotreatment (Waste-based)	8-9 (Mature, Constrained)	HVO production is fully established, offering the cheapest and most commercially ready drop-in solution; however, intense competition from the aviation sector (SAF) restricts its long-term availability for shipping,.
BTL / FT-diesel	Fischer–Tropsch (Lignocellulosic)	4-5 (Early Commercial Readiness)	This path relies on emerging technology (TRL 6–8) but uses abundant lignocellulosic biomass. Commercial volumes are limited, with major scale anticipated only after 2035.
HTL Biocrude	Hydrothermal Liquefaction	3-4 (Developmental)	Currently restricted to the pilot and bench scales (TRL 2-4 to 4-5 by 2030). Requires expensive upgrading, adding capital and operating expenditure (CAPEX/OPEX), and lacks an existing large-scale supply chain.

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COMMERCIAL READINESS LEVEL

A. Fatty Acid Methyl Esters (FAME)

The production of FAME biodiesel is a globally mature market. The European Union is the main producer of FAME and hydrotreated vegetable oil (HVO), with volumes approximating 15 million tonnes per year for road transport. Maritime adoption is increasing rapidly in major bunkering hubs such as Rotterdam, Singapore, and the ARA region. FAME is typically produced from feedstocks such as rapeseed oil, palm oil, and used cooking oil (UCO).

However, the scalability of FAME is fundamentally limited by the availability of waste fats, oils, and greases (FOGs). Waste-based FAME is favored for its substantial well-to-wake (WTW) GHG emission reduction potential, but the finite supply of these feedstocks constrains the maximum achievable volume [61].

B. Hydrotreated Vegetable Oil (HVO) / Renewable Diesel

HVO production technology is fully commercial and mature. Key global producers include major energy companies, and the fuel has a strong industrial supply chain in Europe and the United States. HVO is often considered the cheapest and most commercially ready drop-in biofuel due to its high compatibility with marine engines.

HVO is widely available in maritime hubs, but its future capacity for shipping is severely challenged by intense competition from the aviation sector. Global HVO production is expanding rapidly, driven by the high demand for Sustainable Aviation Fuel (SAF), creating significant pressure on the limited FOG feedstock supply [53].

C. Advanced Biofuels: BTL / FT-diesel (Fischer–Tropsch liquids)

Biofuels produced via the Fischer-Tropsch (FT) synthesis process utilizing lignocellulosic biomass (BTL) are currently at a lower level of commercial maturity (TRL 6-8), with industrial capacity largely confined to pilot-scale or demonstration facilities. While the technology is emerging, the conversion pathway is complex, leading to relatively high and uncertain costs.

The primary commercial advantage of this pathway is its reliance on abundant lignocellulosic feedstocks, such as agricultural and forestry residues. However, major volumes are not projected to enter the maritime fuel market until after 2035 [48].

D. HTL Biocrude (Hydrothermal Liquefaction)

The Hydrothermal Liquefaction (HTL) pathway is in the early development stage, with technical readiness levels reported at TRL 2-4. This biocrude is not directly marinized, as it requires a costly subsequent upgrading process (hydrotreatment) to meet marine fuel specifications, substantially increasing its CAPEX/OPEX. Consequently, no large-scale maritime supply chain for HTL biocrude currently exists. Commercialization is generally projected to occur after 2030, following further technological maturation [59].

Bankability

Bankability is heavily correlated with regulatory certainty, supply chain maturity, and technological complexity.

Established Biofuels: FAME and HVO

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Biofuels derived via transesterification (FAME) and hydrotreatment (HVO) exhibit High Bankability due to their commercial maturity and regulatory status.

- **Regulatory Eligibility:** FAME and HVO pathways, particularly those utilizing waste fats, oils, and greases (FOGs), are eligible to meet compliance criteria across key regulatory frameworks, including the Renewable Energy Directive (RED II/III), FuelEU Maritime, and the EU Emissions Trading System (ETS). When fuels meet sustainability criteria, the biogenic carbon component of the combustion emissions is assigned a zero emissions factor (Cf=0) under the EU ETS, effectively zero-rating the fuel's tank-to-wake impact.
- **Minimal Capital Risk:** HVO is widely considered the most commercially ready drop-in biofuel. Its chemical structure allows for high compatibility with existing marine diesel engines and infrastructure, meaning that implementation requires minimal modification. This low barrier to entry and reliance on established supply logistics significantly reduces the capital investment (CAPEX) risk associated with adoption or retrofit programs [52].

Advanced Synthesis: BTL / Fischer-Tropsch

Biofuels produced via highly complex synthesis pathways, such as Biomass-to-Liquid (BTL) followed by Fischer–Tropsch (FT) conversion, represent a mid-to-high risk profile, resulting in a Low–medium Bankability assessment.

- **Substantial Investment and Complexity:** The high-cost nature of the FT synthesis pathway is a primary factor affecting its bankability. This thermochemical conversion requires substantially greater upfront investment in biorefineries compared to simpler first-generation pathways. The complexity of the gasification and synthesis processes used to convert lignocellulosic biomass results in inherent technological and financial risks.
- **Demand for Market Certainty:** Due to the high CAPEX and significant financial risk associated with these complex technologies, securing long-term economic stability is critical. This generally necessitates long-term offtake agreements and policy certainty to encourage investment and facilitate eventual market scaling [48].

Developmental Pathways: HTL Biocrude

The Hydrothermal Liquefaction (HTL) pathway remains in the early development phase, translating to a Low Bankability status for maritime application.

- **Technological and Market Immaturity:** HTL biocrude conversion is typically categorized at a low Technology Readiness Level (TRL) (e.g., TRL 2-4 or TRL 5-6 in some assessments), placing it at the research or pilot stage. The resulting biocrude is an unrefined product that is not directly marinized and requires costly further upgrading to meet fuel specifications, such as hydrotreating to produce marine gas oil (MGO).
- **High Uncertainty:** The financial viability of HTL biocrude is hampered by high uncertainty surrounding long-term cost projections and the absence of an

established commercial upgrading market. Currently, the pathway lacks the necessary market or technical maturity to be considered bankable for maritime use [59].

CAPEX & OPEX Implications

The commercial feasibility of marine biofuels is heavily influenced by their integration costs (CAPEX) and continuous operational expenses (OPEX), particularly comparative fuel costs and regulatory compliance fees.

A. Capital Expenditure (CAPEX) for Ship-Side Modifications

The required upfront investment to enable biofuel use on board varies significantly based on the fuel's chemical properties and its compatibility with existing engine and supply infrastructure.

Table 22 - Capital Expenditure (CAPEX) for Ship-Side Modifications

Biofuel Type	Technical Profile and Retrofit Costs
HVO / Renewable Diesel	Hydrotreated Vegetable Oil (HVO) is consistently identified as a fully functional drop-in fuel. Its high compatibility with existing marine diesel engines and systems generally results in minimal or zero additional capital expenditure for vessels designed to run on conventional Marine Gas Oil (MGO).
Advanced BTL / FT-Diesel	Synthetic hydrocarbons derived from biomass-to-liquid (BTL) or Fischer-Tropsch (FT) synthesis are typically pure drop-in fuels. Although the fuel price is often high, these require no major engine modifications to be utilized in diesel marine engines, incurring low capital costs related to adaptation.
FAME (Fatty Acid Methyl Esters)	FAME biodiesel introduces specific technical challenges that necessitate minor modifications and procedural requirements, resulting in low CAPEX. Due to FAME's solvency and susceptibility to microbial growth, ships require minor fuel conditioning upgrades, such as enhanced filters and water separators, along with initial cleaning of tanks. Classification guidelines require operators to submit a Biofuel Technical File and Risk Assessment to manage potential component damage and stability concerns.
HTL Biocrude	Hydrothermal Liquefaction (HTL) biocrude is not a viable drop-in fuel and cannot be used without substantial processing. It requires major capital investment for subsequent upgrading via hydrotreatment. This high retrofit CAPEX, coupled with the need for specialized materials to handle its corrosive properties, renders the unrefined biocrude not commercially viable for immediate marine use.

B. Operational Expenditure (OPEX) and Regulatory Exposure

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OPEX is driven by fuel procurement price, maintenance requirements associated with fuel properties, and the financial impact of environmental regulations.

Fuel Price Dynamics (MGO Equivalent)

While prices are volatile, conventional marine fuel serves as a cost baseline against which biofuels bear a significant price premium:

- **MGO/VLSFO** prices fluctuate, generally falling within a range that serves as the lower boundary for the competitive market, averaging around $800-$900 per metric ton in late 2023.
- **FAME (UCO-based)** and **HVO** consistently trade at a premium relative to MGO. Pure HVO ($1,000-$1,500/ton) and FAME B100 ($1,000–$1,500/ton) both represent a substantial increase in fuel costs.
- **FT-Biofuel** pathways often entail the highest fuel production costs due to feedstock scarcity and technological complexity, averaging up to three times the price of MGO [61].

Maintenance Costs

Maintenance OPEX is directly affected by the fuel's chemical stability and compatibility with engine systems:

- **FAME** typically incurs higher maintenance costs because its solubility may loosen deposits, leading to filter clogging, and its poor oxidative stability increases the risk of microbial growth and corrosion. These issues necessitate frequent filter changes, draining, and application of biocides.
- **HVO** is chemically stable, leading to operational handling and maintenance costs equal to or lower than conventional MGO. HVO's zero-sulfur content means it burns cleaner, potentially limiting ash content and preserving lubrication oil quality.
- **FT-Diesel** offers the prospect of the lowest maintenance costs due to its inherent clean-burning nature and minimal soot formation [55].

Emissions Cost Exposure (ETS and Fuel-EU Maritime)

Biofuels offer a considerable financial advantage under current and upcoming EU regulations because their biogenic origin is recognized for reducing life-cycle emissions.

- Under the EU Emissions Trading System (ETS) Directive, eligible biomass is assigned a zero emissions factor (Cf=0) for the CO_2 released during combustion, provided sustainability criteria are met. This offers a major cost advantage by offsetting the need to surrender allowances for the combustion phase [51].
- The Fuel-EU Maritime regulation employs a Well-to-Wake (WTW) methodology where fuels must demonstrate compliance with GHG intensity targets. Fuels produced from waste-based feedstocks (such as Used Cooking Oil, or UCO) demonstrate the highest WTW reduction potential (up to 88% reductions), ensuring they score favourably and minimize potential penalty exposure under this regulation [50].

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Chain of Custody Models

Certification schemes utilize various Chain of Custody (CoC) models to track sustainable fuel claims through complex supply chains, verifying compliance while facilitating blended fuel use.

1. **Mass Balance:** This model is critical for the wide-scale adoption of biofuels in shipping. It operates on the principle that sustainable fuel quantities allocated to a customer must equal the physical quantity produced, even if the certified sustainable molecules are physically mixed with fossil fuels during transport or storage. This fungibility enables fuel producers to leverage existing fossil fuel infrastructure-such as LNG terminals and natural gas pipelines-without the need for dedicated facilities, drastically reducing the capital expenditure (CAPEX) associated with infrastructure buildout. The Mass Balance system is accepted under the European Union's Renewable Energy Directive (RED II), ISCC, RSB, and implicitly by the Fuel-EU Maritime regulation for documenting Proof of Sustainability (PoS) [54].
2. **Segregated (Identity Preserved):** This model requires the biofuel to be physically separated from all other grades throughout the supply chain. While offering the highest level of physical traceability, adhering strictly to the Segregated model necessitates significant and costly investments in parallel infrastructure, making it the least scalable and most capital-intensive option.
3. **Book and Claim:** This method offers the highest logistical flexibility by permitting the transfer of sustainability credits (virtual units) without a corresponding physical movement of the sustainable fuel volume. This level of decoupling is expected to yield greater energy savings by eliminating the necessity for specific fuel routing [48].

The Mass Balance model is widely referenced by classification organizations, alongside DNV, as the currently only scalable approach for maritime bunkering. The adoption of flexible CoC models, such as Mass Balance, is considered essential to ensure maximum availability of low-GHG fuels at minimum cost.

Feedstock Availability and Cross-Sector Competition

The ultimate potential for marine biofuel adoption is constrained by the finite availability of sustainable biomass and overwhelming competition from other sectors undergoing decarbonization, particularly aviation and road transport.

Table 23 - Feedstock Availability and Cross-Sector Competition

Feedstock Category	Availability Profile	Competition and Regulatory Status
Waste-based Lipids (FOGs, UCO, Tallow)	Supply is severely limited and constrained.	These low-cost feedstocks are already in high demand from the aviation (Sustainable Aviation Fuel - SAF) and road transport sectors. The scarcity of waste FOGs is projected to be a major constraint on future supply for the marine sector.

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Vegetable Oils (Rapeseed, Soy, Palm)	Available in large volumes as a first-generation feedstock.	These feedstocks result in high Indirect Land Use Change (ILUC) emissions, compromising their GHG reduction potential. Palm oil is officially classified as a high ILUC-risk biofuel under EU sustainability rules, limiting its eligibility toward emissions targets.
Lignocellulosic Biomass	Globally abundant feedstock derived from forestry and agricultural residues, offering significantly greater quantities than lipid wastes.	The primary constraint is conversion capacity, as the complex production pathways (e.g., Fischer-Tropsch synthesis) required to process lignocellulosic biomass have high capital costs and lower technological readiness compared to lipid pathways. FT diesel utilizing this abundant feedstock offers significant long-term potential for deep GHG reductions.
HTL Feedstocks	Includes broad but currently scattered sources such as sewage sludge and wet biomass.	Production remains limited to the pilot or demonstration scale, necessitating expensive upgrading to meet marine fuel specifications. Consequently, these feedstocks are not yet mobilized at industrial scale for commercial marine use.

The analysis suggests that fuels derived from lignocellulosic biomass pathways (such as FT diesel and bio-methanol) offer the most favourable long-term potential for scaling, owing to their high availability, though major deployment is projected to be necessary after 2035 to meet decarbonization goals. Conversely, the technical readiness of waste lipids allows for immediate use, but their limited and contested supply undermines their overall scalability.

Commercial Readiness Level (CRL) Summary

The relative Commercial Readiness Level (CRL) of various biofuel pathways reflects the maturity of their supply chains, capacity for industrial scale-up, and economic viability within the competitive maritime fuel market.

Table 24 - Commercial Readiness Level (CRL) Summary

Fuel Type	Commercial Readiness Level (CRL)	Notes on Market Status and Constraints
FAME (Waste-Based)	7-8	Production technology is mature, but the pathway faces significant limitations imposed by the scarcity of waste-based feedstock, such as used cooking oil (UCO) and tallow, limiting its potential global supply for marine use.

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HVO / Renewable Diesel	8-9	This conversion route is fully commercial, utilizing established hydrotreating processes. Its immediate scalability is constrained primarily by intense competition from the Sustainable Aviation Fuel (SAF) sector, limiting the feedstock volume available for shipping.
Rapeseed FAME/HVO	8	While these crop-based pathways offer high volume due to readily available feedstock, they are severely restricted by Indirect Land Use Change (ILUC) sustainability concerns, which can undermine any potential GHG savings. Such fuels are often excluded or limited under stringent EU sustainability rules.
BTL / FT-Diesel	4-5	This pathway utilizes abundant lignocellulosic biomass, but its commercial capacity remains limited to pilot or demonstration facilities. Although costs are high, major scale-up and entry into the marine market are generally projected to occur after 2035.
HTL Biocrude	3-4	This bio-oil pathway is in the early commercial/development stage. The unrefined biocrude requires substantial and costly upgrading (e.g., hydrotreating) to meet marine fuel specifications, meaning it is not commercially viable for current marine application.

Analysis of Constraints and Future Proofness

1. **FAME and HVO from Waste Feedstock (CRL 7-9):** These lipid-based biofuels (FAME and HVO) are derived from commercially mature conversion processes, granting them high CRLs. Waste-based feedstocks (Annex IX Part B, e.g., UCO) offer high GHG reduction potential (up to 88% savings), making them preferred under regulations like FuelEU Maritime. However, the global supply of these waste feedstocks is severely constrained. For HVO, this supply constraint is intensified by overwhelming demand and preferential policy for Sustainable Aviation Fuel (SAF), which competes directly for the same feedstock pool.
2. **Crop-Based Biofuels (CRL 8):** Biofuels derived from traditional crops like rapeseed face increasing regulatory and market limitations due to high ILUC emissions, which can eliminate or reverse their intended GHG savings. This inherent sustainability risk depresses their overall viability, despite their strong technological maturity (TRL 10).
3. **Advanced Biofuels (FT-Diesel, DME, Bio-methanol) (CRL 4-5):** Pathways utilizing lignocellulosic biomass (Annex IX Part A) are technologically complex but benefit from high theoretical feedstock availability. FT-Diesel is rated at a lower CRL (4-5), reflecting its status in the pilot or demonstration phase (TRL 6-8). Significant commercial scaling of this pathway is projected to take place post-2035.
4. **Developmental Bio-crudes (HTL Biocrude) (CRL 3-4):** HTL biocrude remains at a low technical maturity level (TRL 2-4 to 4-5). The product's poor compatibility, high acidity, and requirement for expensive upgrading before it can be used in engines severely limit its current commercial viability.

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SOCIETAL READINESS LEVEL

International Regulation and Alignment with European Policies

The integration of sustainable biofuels into the global shipping industry is strongly driven by key international and regional regulatory frameworks that define accountability based on the full lifecycle emissions of the fuel.

A. IMO Regulatory Framework

The International Maritime Organization (IMO) has formalized a lifecycle assessment methodology to integrate biofuels into its primary decarbonization mechanisms.

1. **Life-Cycle Assessment (LCA) Framework:** Following MEPC 80 in 2023, the IMO approved preliminary guidelines regarding the Life Cycle Assessment (LCA) approach for marine fuels. This is codified within the Net-Zero Framework (NZF) (approved in principle April 2025), which mandates that GHG emissions intensity compliance must be measured on a Well-to-Wake (WTW) basis. The overall WTW methodology requires accounting for the biogenic nature of the fuel's carbon.
2. **Biogenic Carbon Accounting:** Under this framework, the CO_2 absorbed by the biomass feedstock during growth offsets the CO_2 released during combustion, a principle resulting in the zero-rating of the biogenic CO_2 component. This allows the CO_2 conversion factor to equal the WTW GHG emissions factor, provided the biofuel meets sustainability criteria.
3. **Sustainability Compliance:** The IMO requires that biofuel use be compatible with decarbonization measures, provided the fuel fulfills sustainability criteria and demonstrates a WTW reduction of at least 65% compared to fossil marine gas oil (MGO). To ensure compliance and accurate reporting, the NZF mandates that the GHG emission factors and sustainability aspects of the fuel must be verified through a recognized Sustainable Fuels Certification Scheme (SFCS).

The compatibility of certified biofuels, particularly those classified as waste-based and advanced, grants significant benefits toward mandatory IMO decarbonization instruments, including the Carbon Intensity Indicator (CII), the Data Collection System (DCS), and the Energy Efficiency Existing Ship Index (EEXI).

B. Fuel-EU Maritime

The European Union's Fuel EU Maritime Regulation (EU Regulation 2023/1805) sets a binding framework for reducing the GHG intensity of energy used by ships calling at EU/EEA ports.

1. **GHG Intensity Targets:** The regulation mandates a gradually decreasing target for the average GHG intensity of energy used by ships, commencing with a reduction of 2% by 2025 and escalating to 75% to 80% by 2050 relative to the 2020 baseline.
2. **Credit and Certification:** The regulation utilizes a WTW methodology for calculation and grants full biogenic CO_2 credit for certified sustainable biofuels. This certification relies on meeting the GHG saving criteria established by the Renewable Energy Directive (RED).
3. **Feasibility for Drop-in Fuels:** The inclusion of certified fuels via systems such as the mass balance chain of custody facilitates the use of drop-in solutions like FAME and

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HVO. Waste-based biofuels (e.g., used cooking oil or HVO) are highly valued under this scheme due to their inherently low WTW emissions (up to 88% reduction) and avoidance of Indirect Land Use Change (ILUC) risk.

4. **Penalties for High-Emission Fuels:** Conversely, fuels derived from dedicated food or feed crops (such as palm oil or soy) are generally assigned high ILUC emissions. If these fuels do not meet the mandated reduction targets, they are subject to penalties (non-compliance fees). The regulation explicitly notes that food and feed-based crops are considered equivalent to fossil fuels if sustainability requirements are met, restricting their use in achieving the necessary compliance factors.

C. EU Emissions Trading System (ETS) Maritime

The inclusion of the maritime sector in the EU Emissions Trading System (ETS) requires shipping companies to surrender allowances for GHG emissions.

1. **Zero-Rating of Biogenic CO2:** The ETS primarily focuses on Tank-to-Wake (TTW) emissions. Therefore, for certified biomass, the CO_2 conversion factor is set to zero. This effectively exempts the biogenic portion of the fuel from the obligation to surrender allowances.
2. **Proportional Reduction of Exposure:** The use of certified biofuels directly contributes to reducing financial exposure under the ETS. Biofuel blends reduce the ETS exposure proportionally to the certified blend percentage.
3. **Cost Implication (OPEX):** Because compliance involves surrendering EU Allowances (EUAs) for fossil CO_2, the utilization of biofuels directly reduces the carbon tax cost (OPEX), thereby yielding a financial benefit for shipping companies.

D. Classification Society Engagement and Systemic Readiness (SRL)

Classification societies and international industry associations play a crucial role in validating technical suitability and developing necessary safety frameworks, confirming the high Commercial and Societal Readiness Level (SRL) of mainstream biofuels.

Institutional Support and Safety Frameworks

Leading classification bodies actively support the adoption of compatible drop-in biofuels, developing specialized guidance to manage operational risks:

1. **RINA BIOFUEL Notation:** RINA assigns the BIOFUEL class notation (e.g., specifying BIODIESEL for FAME, BTL, and HVO) to vessels utilizing biofuels in their internal combustion engines or other consumers. This notation requires adherence to rigorous standards covering several technical and procedural aspects:

- **Biofuel Technical File:** Mandates documentation detailing the fuel's chemical composition, blending ratio, production process, and safety precautions.
- **Risk Assessment:** Requires assessment of risks concerning component damage, loss of function, and toxicity associated with the fuel.
- **Specification and Compliance:** Addresses storage practices, including tank material compatibility and stability testing.

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2. **IACS and ABS Guidelines:** The industry generally agrees that FAME and Hydrotreated Vegetable Oil (HVO) are readily compatible with existing infrastructure. The utilization of FAME and HVO in blends up to 100%, contingent upon engine manufacturer approval, is possible. However, specific operational protocols are necessary to mitigate inherent technical challenges:

- **FAME Monitoring:** Due to its composition, FAME is prone to microbial growth and oxidation. Successful operation requires frequent inspections, cleaning of fuel tanks and filter systems, and minimizing water accumulation to control microbial contamination.
- **ABS and Industry Trials:** Organizations like the American Bureau of Shipping (ABS) have engaged in joint industry projects to assess biofuel performance, demonstrating the industry's commitment to developing alternative fuel pathways.

Stakeholder Acceptance

The broad adoption of sustainable marine fuels depends significantly on the acceptance and institutional alignment across key industry stakeholders, including shipowners, engine manufacturers, ports, and regulators. Biofuels, particularly the immediate drop-in alternatives, currently enjoy high acceptance levels due to their technical compatibility and alignment with emerging regulatory incentives.

A. Shipowners and Operators

Interest in biofuels among shipowners and operators has increased rapidly, driven by converging economic and compliance factors:

1. **Regulatory Compliance:** The use of certified biofuels is critical for meeting short-term decarbonization targets mandated by regional and international regulatory bodies. Biofuels contribute directly to reducing carbon costs by helping ships achieve GHG intensity targets mandated by the Fuel-EU Maritime Regulation and avoiding penalties under the EU Emissions Trading System (ETS), which typically assigns zero CO_2 factor (Cf=0) to biogenic carbon.
2. **Low Barrier to Entry:** The commercial readiness and drop-in compatibility of liquid biofuels (FAME and HVO) present a low capital expenditure (CAPEX) solution for the existing fleet, as they typically require minimal or no modifications to engine systems or fuel infrastructure. This characteristic has led major organizations, including DNV, to identify biofuels as the only immediately scalable transition fuel option for existing ships.
3. **Operational Performance Validation:** The viability of biofuels has been proven through operational performance across various maritime regions, including in major trials in the North Sea and Baltic Sea [52].

The acceptance levels among operators vary based on fuel characteristics and sustainability profile:

- **HVO and Waste-Based FAME:** Acceptance is generally high to very high. HVO is chemically similar to fossil diesel, offering excellent performance and storage stability, making it the most technologically compatible drop-in solution. Waste-

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based FAME is highly favoured for its strong greenhouse gas (GHG) reduction potential.

- **Crop-Based Fuels:** Acceptance is declining or mixed. These fuels face severe constraints due to sustainability criteria, such as Indirect Land Use Change (ILUC) emissions, which may undermine the net emissions savings relative to fossil fuels.
- **Advanced Biofuels (BTL/HTL):** Acceptance is typically low due to the commercial immaturity of the production pathways (TRL 5-8) and their current lack of volume availability in the market [53].

B. Engine Manufacturers (OEMs)

The acceptance from engine manufacturers (OEMs) is crucial for validating the technical feasibility of using alternative fuels. Leading OEMs have provided extensive guidelines supporting the use of key biofuel types:

- **HVO (Hydrotreated Vegetable Oil):** Acceptance is excellent. HVO is endorsed by manufacturers, including MAN and Wärtsilä, as a full drop-in fuel (B100) compatible with existing engine platforms, typically requiring no technical changes. Wärtsilä generally confirms compatibility for any biofuel that meets established fuel standards.
- **FAME (Fatty Acid Methyl Esters):** Acceptance is good, but with restrictions. While lower concentration blends, such as B20 to B30, are widely approved for use, utilization up to pure B100 is often conditionally approved, requiring verification from the engine manufacturer or flag administration to ensure compliance, particularly concerning engine systems developed for a range of fuels.
- **Advanced Fuels:** Evaluation is ongoing. Due to their lower technology readiness and limited supply, the certification and evaluation of BTL and HTL pathways are still in development [57].

C. Port Authorities and Infrastructure

Port authorities have demonstrated a high readiness level by integrating biofuels into their bunkering infrastructure, particularly in major global hubs.

- **Availability and Market Growth:** Biofuel bunkering operations have been confirmed in over 60 ports worldwide since 2015. Key international bunkering hubs, including Rotterdam, Singapore, Hamburg, and Antwerp-Bruges, already offer certified biofuel bunkering services.
- **Fuel Types:** The majority of the biofuels supplied are bio-blended fuels (e.g., B24 and B30), primarily consisting of HVO or waste-based FAME.
- **Logistical Readiness:** Bunkering capacity is expanding rapidly. The total sales of bio-blended fuels in Singapore and Rotterdam increased substantially between 2021 and 2024. Singapore, for instance, tripled its biofuel bunkerings over a 12-month period in 2024. Ship-to-Ship bunkering is the most prevalent supply mode for biofuels by volume [61].

This aggregate evidence demonstrates a High Acceptance Level in Europe and expanding globally, confirming the immediate logistical viability of these fuels.

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Social and Territorial Aspects

The adoption of marine biofuels extends beyond technical and commercial feasibility, directly influencing air quality, land use, and the social acceptance of industrial infrastructure across various communities.

A. Local Air Quality Benefits

The transition to biofuels offers significant and immediate improvements in local air quality, particularly benefitting communities situated around ports and along major freight corridors.

- **Sulfur Oxides (SO_x):** Biofuels are characterized by their minimal or non-existent sulfur content, leading to SO_x emissions being reduced nearly to zero when used neat or proportionally in blends.
- **Particulate Matter (PM):** Biofuels substantially reduce PM emissions, with reductions ranging from 30% to 80% or more in some tests.
- **Carbon Monoxide (CO) and Hydrocarbons (HC):** The oxygenated composition inherent to biodiesel facilitates a more complete combustion process, significantly reducing emissions of both CO (up to 50% reduction) and HC.
- **Black Carbon (BC):** Trials have shown that combustion of FAME blends leads to a strong reduction of Black Smoke (BS), which is proportional to the FAME content, and Black Carbon (BC) is substantially reduced.

These emission reductions are crucial for enhancing air quality in coastal areas where marine activities are concentrated, fulfilling local, national, and international environmental objectives [51].

B. Sustainability and Ethics of Feedstocks

Social acceptance is fundamentally tied to the raw materials used for biofuel production, particularly concerning competition for resources and land utilization impacts.

- **Waste-Based Feedstocks:** Biofuels produced from waste fats, oils, and greases (FOGs) or advanced sources derived from wastes and residues (RED II Annex IX Part A and Part B feedstocks) enjoy high social acceptance. These sources typically involve no competition with food production and pose minimal risk of deforestation or land conversion.
- **Crop-Based Oils:** Conversely, biofuels derived from food and feed crops are deemed socially controversial. This controversy stems from the ethical conflicts related to the "food vs. fuel" debate, the risk of deforestation (e.g., linked to palm and soy production), and the high potential for Indirect Land Use Change (ILUC) emissions. This high ILUC-risk has led the EU to constrain their use toward renewable energy targets.
- **Advanced Lignocellulosic Fuels (BTL/FT):** Advanced biofuels derived from abundant lignocellulosic biomass (e.g., residues and forestry byproducts) are generally regarded as highly acceptable socially. While large-scale production capacity for these fuels remains a bottleneck, the long-term potential relies on abundant, non-food feedstocks [48].

C. Community-Level Considerations

While adopting sustainable feedstocks addresses high-level ethical concerns, implementation at the local level introduces practical challenges concerning logistics and public infrastructure:

- **Infrastructure and Logistics:** The mass mobilization of biomass requires increased feedstock transport in rural areas or along freight corridors. This massive logistics demand can lead to considerations regarding noise, traffic, and the acceptance of constructing new biomass processing plants or refineries near communities.
- **Feedstock Type Impact:** Advanced fuels derived from residue-based feedstocks (such as FT diesel/BTL) score highly because they minimize the risk of environmental degradation associated with agricultural expansion or monoculture crops, offering a more secure basis for long-term production compared to first-generation options.

5.4 Crew Safety, Training, and Operational Risk Management

The transition to marine biofuels introduces specific operational and safety risks requiring specialized procedures, crew training, and maintenance protocols. The necessary training intensity varies depending on the biofuel's properties and compatibility with existing vessel systems and infrastructure.

A. Fatty Acid Methyl Esters (FAME) Biodiesel Crew Requirements

FAME requires crew adherence to specific procedures to mitigate operational risks stemming from its chemical characteristics.

- **Risk Mitigation Protocols:** Crew must be trained to manage FAME's susceptibility to microbial growth and contamination, often necessitating the frequent draining of tanks and the potential application of biocide. Due to its low oxidative stability, FAME biodiesels are prone to degradation over time, which requires the crew to monitor oxidation stability closely and avoid long-term storage. FAME's poor cold flow properties (e.g., high pour point/cloud point) mandate that the crew diligently maintain appropriate temperature conditions in tanks and transfer lines to prevent viscosity increases and filter clogging.
- **Fuel Management and Compatibility:** The high solvency of FAME means initial use requires monitoring filters closely, as the biofuel can dissolve and dislodge deposits within the fuel tanks and lines, potentially leading to blockages.
- **Training Level:** Due to these unique handling challenges, FAME necessitates a moderate level of specialized crew training [55].

B. Hydrotreated Vegetable Oil (HVO) / Renewable Diesel Crew Requirements

HVO presents minimal new challenges as a drop-in fuel, aligning closely with procedures for conventional diesel fuels.

- **Handling and Risk:** HVO is regarded as a full drop-in fuel that is highly compatible with existing diesel engine platforms, often requiring no technical changes. Its properties, including similar flash points and good stability, mean its handling is often

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identical to Marine Gas Oil (MGO), minimizing the need for new maintenance procedures. HVO is less susceptible to microbial growth compared to FAME.

- **Training Level:** The training level required for HVO is very low due to its high compatibility and low associated risks [57].

C. Advanced BTL / FT-diesel Crew Requirements

Fischer-Tropsch (FT) diesel derived from Biomass-to-Liquid (BTL) is categorized as a synthetic drop-in fuel chemically similar to conventional diesel, simplifying handling.

- **Handling and Operational Awareness:** FT-diesel is a drop-in fuel that can be used "neat" or at high blends without requiring engine modification, and its handling is generally similar to conventional diesel.
- **Certification Requirements:** While technically compatible, its use requires crew awareness about its biogenic origin and sustainability certification (such as compliance with ISO 8217:2024 and accompanying sustainability schemes) for regulatory purposes.
- **Training Level:** The required training level is considered low [48].

D. HTL Biocrude Crew Requirements

Hydrothermal Liquefaction (HTL) Biocrude is an unrefined product characterized by features that make it incompatible with existing infrastructure, introducing severe safety risks.

- **Acidity and Toxicity:** HTL biocrude is typically acidic and corrosive and contains potential toxic compounds. The unrefined nature of HTL biocrude means it has poor compatibility with existing marine engines and is not a drop-in fuel.
- **Safety Requirements:** Due to its corrosive and potentially toxic nature, implementing this fuel would require specialized protective measures including upgraded tanks, new coatings, and heating systems, necessitating intensive hazardous material training for the crew. This pathway requires substantial system modifications before it is deemed safe for onboard operation.
- **Training Level:** The specialized handling, retrofitting, and inherent chemical hazards mean the training level required is very high, posing a Societal Readiness Level (SRL) bottleneck [59].

Societal Readiness Level (SRL) Summary Table

The Societal Readiness Level (SRL) assessment synthesizes the market, institutional, and safety factors influencing the widespread deployment of marine biofuels. The SRL evaluates acceptance among regulatory bodies, maritime stakeholders (shipowners, ports, OEMs), and operating crew, correlating with the financial feasibility determined by the Commercial Readiness Level (CRL).

Table 25 - Societal Readiness Level (SRL) Summary Table

Biofuel Pathway	SRL Score	Notes on Institutional Acceptance and Operational Constraints

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HVO (Waste-Based)	8-9	**Highest Commercial Maturity and Acceptance.** A widely recognized drop-in fuel that is compatible with existing infrastructure and requires minimal crew training, resulting in minimal capital investment (CAPEX) risk. Strong regulatory foundation is provided by inclusion in the ISO 8217:2024 fuel standard and zero emissions status under the EU-ETS and Fuel-EU Maritime regulations.
FAME (Waste-Based)	7-8	**High Acceptance with Operational Caveats.** Technology is mature, offering proven benefits in performance and lubricity. However, FAME introduces operational complexity due to its high solvency, reduced oxidative stability, risk of microbial growth, and lower cold-flow properties, necessitating higher maintenance operational expenditure (OPEX).
Crop-Based Biofuels	5-6	**Significant Societal and Regulatory Resistance.** These pathways are constrained by substantial ethical concerns regarding "food versus fuel" competition and high Indirect Land Use Change (ILUC) emissions. Regulatory action classifies palm oil as a high-ILUC-risk biofuel, severely limiting its eligibility toward climate targets.
BTL / FT-Diesel	6-7	**High Future Potential; Currently Resource Constrained.** Synthetic hydrocarbons offer excellent physical compatibility (drop-in) and the lowest projected maintenance costs due to clean combustion. Perceived positively due to reliance on abundant lignocellulosic feedstocks, long-term scalability is currently hampered by the technological complexity, high financial risk, and limited commercial capacity.
HTL Biocrude	3-4	**Immaturity and Safety Challenges are Primary Bottlenecks.** The unrefined biocrude is incompatible with current marine infrastructure, requiring high retrofit CAPEX and specialized onboard conditioning (e.g., tank heating/coatings). Low acceptance stems from safety risks, including material corrosivity and the potential presence of toxic compounds, mandating extensive crew hazardous material training.

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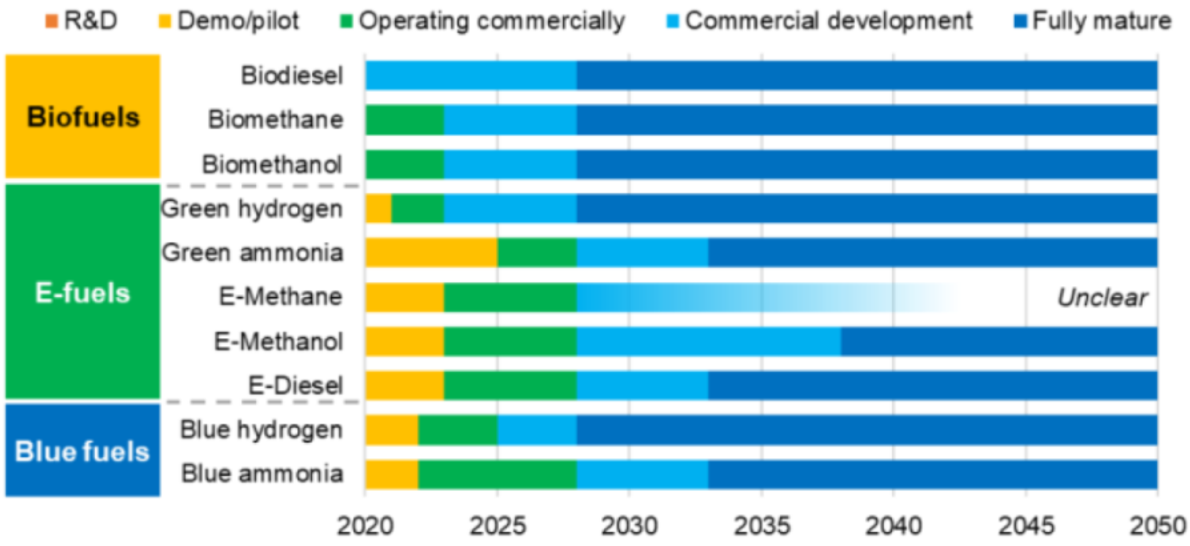

Figure 10 - Forecast of readiness and availability of different types of fuel for the maritime sector

SUMMARY TABLE & COMPARATIVE READINESS MATRIX

Table 26 - BIOFUELS SUMMARY TABLE & COMPARATIVE READINESS MATRIX

Fuel Type	TRL	CRL	SRL	Key Limiting Factors	Overall Assessment
HVO (waste-based)	9	8-9	8-9	Feedstock competition with SAF	Best near-term solution
FAME (waste-based)	8	7-8	7-8	Storage stability, microbial risk	Viable transitional fuel
FAME / HVO (crop-based)	9	8	5-6	ILUC, sustainability constraints	Regulatory-limited
BTL / FT-Biodiesel	6-7	4-5	6-7	High CAPEX, limited capacity	Medium-term potential
HTL Biocrude	5-6	3-4	3-4	Corrosivity, safety, upgrading	Long-term R&D option
Bio-methanol (advanced)	7-8	6-7	7	Infrastructure availability	Emerging option
Bio-LNG (biomethane)	7-8	6-7	7	Methane slip concerns	Transitional niche

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3.4. METHANOL

By 2030, the global fleet of vessels currently on order is expected to demand approximately 7 Mtoe of methanol. Securing an adequate supply of renewable fuels is essential to support this transition, but production capacity for 2030 remains uncertain [62].

Although biofuel use in marine engines is currently minimal – accounting for just 0.09% of total fuel use according to IMO's 2020 DCS – there is strong potential for growth, supporting EU and IMO goals for maritime GHG reduction [63] . Biofuels are considered a promising decarbonisation option for shipping largely because many can be used in existing vessels without major modifications. This drop-in capability applies especially to bio-methanol, which closely resembles its fossil-based counterparts – provided the right equipment is installed [64].

Methanol can be either bio-based or synthetic, depending on the feedstock and production process. For maritime applications, methanol can be used in internal combustion engines (ICE) as well as in fuel cells. However, the efficiency of methanol fuel cells is currently relatively low, around 20%. On a volumetric basis, methanol contains more hydrogen than liquid molecular hydrogen, making it a potentially more viable energy carrier for vehicles than hydrogen [65].

E-methanol offers significant greenhouse gas (GHG) savings, with reductions of up to 75–95% compared to conventional marine fuels, depending on the carbon source and energy mix used in its production. Bio-methanol's GHG reduction potential varies based on the feedstock. When produced from waste or residues, bio-methanol can achieve reductions of 80–95%, whereas biomass-derived bio-methanol typically results in reductions of 50–70%.

Methanol is easily absorbed through inhalation, ingestion, or skin contact, and it is rapidly distributed throughout the body. It is highly flammable and acutely toxic to both humans and mammals. Methanol poisoning can cause severe, irreversible nerve damage, with the optic nerve being especially vulnerable, potentially leading to blindness. However, given that methanol is unlikely to be ingested under normal handling conditions, the risk of poisoning is considered minimal. While methanol is more toxic to humans, it poses a lower threat to aquatic organisms (such as fish, invertebrates, algae, and microorganisms).

In the event of a methanol spill into seawater, it will generally disperse rapidly due to its high solubility. Depending on the temperature, some of the methanol may form a vapor phase above the water, which also disperses quickly. Methanol is fully biodegradable and does not bioaccumulate, making it less hazardous than fuels like diesel, heavy fuel oil, or ammonia. Nevertheless, these factors underscore the importance of adhering to strict safety protocols, especially in managing toxicity and preventing spills.

Overview of the information presented in Table 27:

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Table 27 - Comparison of renewable fuels of non-biological origin (RFNBOs) with the status quo of fossil HFO/MGO based on key criteria. Source: Institute for Applied Ecology (2023)

Criterium	E-Methanol	Hydrogen	E-Ammonia	HFO
GHG reduction potential (lifecycle)	5	5	4*	1
Air pollutants (incl. exhaust gas aftertreatment)	4	5	5	1
Aquatic ecotoxicity	5	5	2	1
Human toxicity	3	5	2	3
Flammability	2	1	2	5
Explosion risks	5	2	4	5
Infrastructure (plants, bunkering)	4	1	3	5
TRL production/engine, retrofits	3	1	2	5

Notes: Ranking: 1= high risk/ low performance to 5=low risk/ high performance, assuming fuel use in ICE with exhaust gas aftertreatment system; *uncertainty about N_2O emissions, TRL=technology readiness level.

TECHNOLOGY READINESS LEVEL

Engines powered by bio- and E-methanol have reached TRL 9, demonstrating success across a wide variety of vessel types. Methanol is already in active use within commercial operations [66]. TRL for methanol fuel cell electric ships is however only at 6 (full prototype) [67].

In terms of global availability, methanol is among the top five most transported chemical commodities each year. It is easily accessible through existing global terminal infrastructure worldwide, positioning it well to consistently meet the needs of the global maritime industry. However, specialised bunkering infrastructure for ships is still limited. Methanol can be delivered to vessels via truck or bunker vessel [68, p. 58].

Methanol-powered ship engines reached full technological maturity during the 2010s. In 2015, ME-LGIM engines were class-certified, and the first ocean-going methanol tanker [69], *Lindanger,* entered commercial service in 2016 [70] By 2023, the industry achieved operational maturity (see Figure 11). Methanol has been in use as fuel by chemical tankers since the mid-2010s. Some of these vessels are designed to run both methanol and conventional fuels, equipped with dual-fuel MAN designed Hyundai–B&W 6G50ME-9.3 ME-LGI engines, developed in collaboration with Marinvest [71].

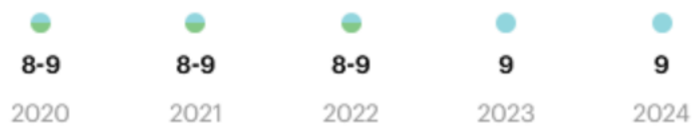

Figure 11 - Source: IEA 2024b [67]

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In 2023, the first methanol-powered container ship - "Laura Maersk"; IMO 9944546; with a cargo capacity of 2,136 TEU - made its maiden voyage from Ulsan in Korea to Copenhagen in Denmark (21,500 km) fuelled by green methanol [72]. "Laura Maersk" received green methanol from Equinor in the Port of Rotterdam [73] until European Energy starts its e-methanol production in their new solar-powered plant in Denmark with a capacity of 100,000 tonnes/year (construction is expected to begin in 2026, with the facility becoming operational by 2028/29) [74].

The number of users of methanol as a marine fuel is expected to increase due to the possibility of conversion. For example, MAN, the largest supplier of marine engines, will be offering a methanol retrofit set for four-stroke engines of the 48/60 engine series for methanol dual-fuel operation from 2025 [75]. Solutions for converting existing 4-stroke marine engines in the power range of 500 kW to 2,000 kW are already available for smaller engines, such as those offered by the Belgian engine manufacturer ABC [76].

MAN Energy Solutions operates approximately 22,000 two-stroke engines worldwide, with around 4,600 of them convertible to alternative fuels. Currently, MAN is testing a retrofit for methanol on its 51/60DF 4-stroke engine series at its Augsburg test bench. This retrofit is primarily intended for cruise ships and ferries with diesel-electric engines in operation globally [75]. Industry leaders widely agree that methanol will play a key role as a fuel of the future. MAN anticipates a blend of LNG and methanol dominating the container shipping sector within the next decade. Methanol offers significant advantages for retrofitting existing vessels, making it a more viable option compared to the complexities involved in converting ships to LNG or ammonia [77].

An example of a multi-fuel, medium-speed engine designed for newbuild projects, such as large workboats, tugs, and inland waterway vessels, is the Evolve 23 series. Launched in 2022 by AB.B.C., this engine is capable of running on a range of fuels, including biofuels, synthetic fuels, LNG, and emerging fuels like methanol and hydrogen. It is designed for ultra-low and zero emissions, with an operational range of 720–1,200 rpm and a power output between 1.23 and 2.16 MW [78].

The storage and bunkering of both bio- and E-methanol at ports are currently classified at TRL 6. While certian procedures have been developed and successfully tested at specific ports, further implementation across a wider range of locations and operational environments is still necessary. Various ports, such as Gothenburg, have already introduced or are working on regulations for methanol bunkering. In the near future, methanol may be bunkered using tank trucks, with bunker vessels expected to be the long-term solution due to their increased efficiency and flexibility [79]. Currently there are 24 active ports offering methanol bunkering and 22 still under development (based on WEB research from the Clarkson Research online database, mid-December 2025).

COMMERCIAL READINESS LEVEL

The projected fuel cost of bio-methanol is estimated at approximately €35/GJ in 2030 and €28/GJ in 2050. Particularly by 2050, bio-methanol could become an attractive fuel option compared to other alternative fuels, as it is not subject to the carbon costs associated with fuels such as VLSFO, HFO, or FAME [63].

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DNV [68] has calculated the total cost of ownership (TCO) for a 5,500 TEU methanol-fuelled container ship under various assumptions, estimating it to be approximately €423 million[1] over 25 years of operation. The total costs of ownership (TCO) for both the methanol-fuelled and methanol-ready designs are roughly 0.4% and 0.9% higher, respectively, compared to the conventional design. However, methanol-fuelled vessels offer a significant advantage over conventional oil-fuelled vessels: fuel flexibility. Future methanol-powered vessels are likely to be dual-fuel, capable of operating on both fuel oil and methanol.

The TCO for container ships in the 14,500–20,000 TEU range is influenced by the fuel properties, with lower energy-dense fuels resulting in higher bunkering costs. Figure 12 illustrates the annual TCO difference, expressed as percentage variations [63, p. 73].

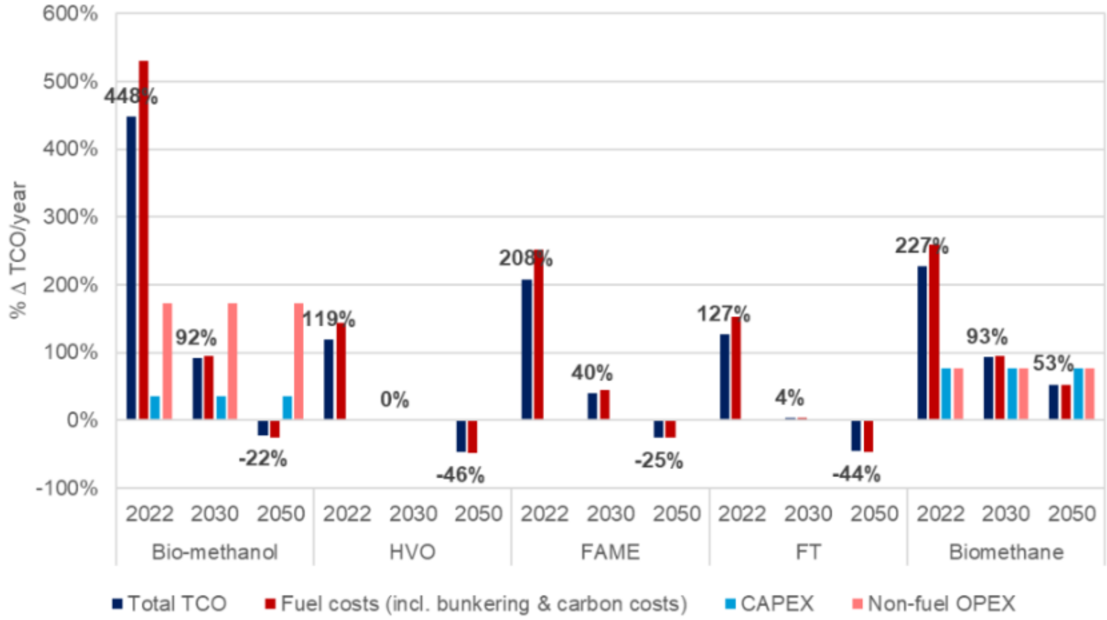

Figure 12 - Annual difference in TCO of alternative-fuelled container ships (14,500–20,000 TEU) with increased bunkering frequency - Source: [63]

The TCO for bulk carriers in the 35,000-60,000 DWT range using e-fuels is also estimated (see Figure 13), highlighting the increase in TCO for ships running on synthetic e-fuels. Fuel costs remain the largest component of TCO for all alternative-fuelled vessels. The analysis reveals that CAPEX for e-methanol-powered ships is roughly 50% higher, while the CAPEX for e-methane-powered bulk carriers is around 80% higher than for VLSFO-powered ships. This increased CAPEX for e-methane vessels is primarily driven by higher fuel storage and fuel supply system (FSS) costs [80].

[1] Original source: $ 494 million. Exchange rate USD in € 0,86 (22.08.2025)

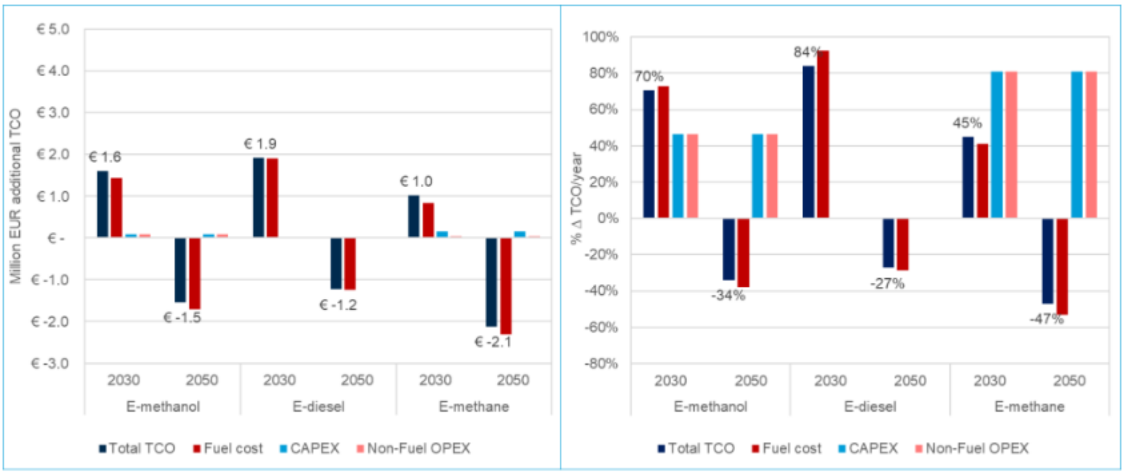

Figure 13 - Annual TCO comparison between E-fuels and VLSFO for bulk ships (35,000-60,000 DWT) - Source: [80]

EMSA [63] has calculated the TCO for bulkers using biofuels within the same category, revealing an increase in TCO for vessels powered by various alternative fuels (Figure 13). Fuel costs are the largest component of TCO for all alternative-fuelled ships. By 2030, the TCO for some alternatives (HVO and FT) will be similar to VLSFO, while others will remain higher, though lower than in 2022, due to rising oil prices, carbon costs, and decreasing cost differences between biofuels and VLSFO.

The total cost of ownership (TCO) for bulk ships in the 35,000–60,000 DWT range is influenced by the fuel properties, with lower energy-dense fuels resulting in higher bunkering costs. Figure 14 illustrates the annual TCO difference, expressed as percentage variations [63].

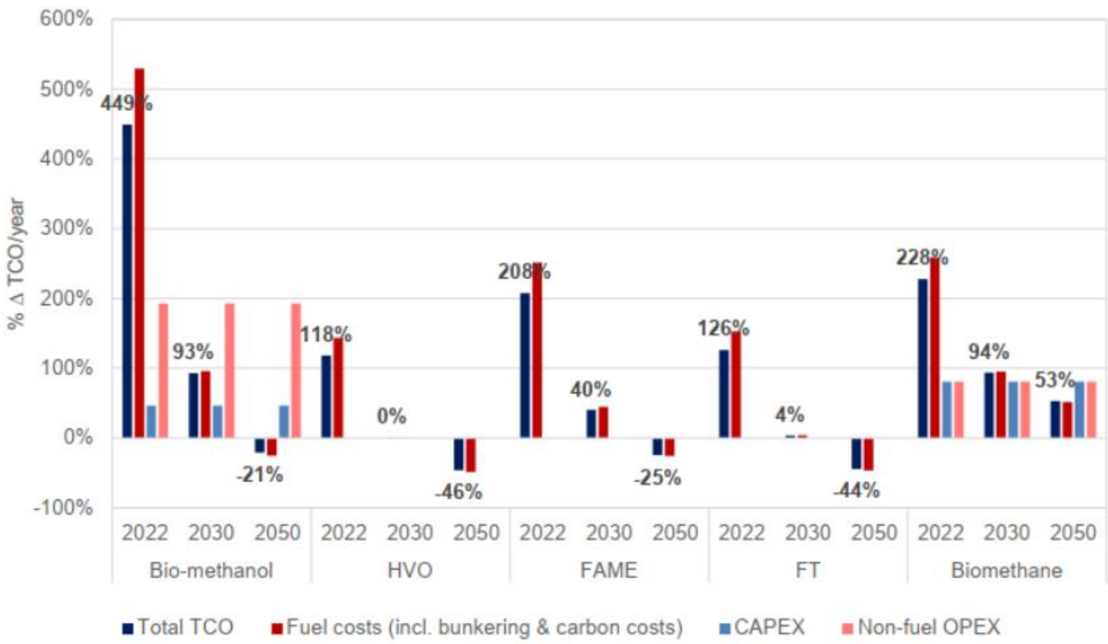

Figure 14 - Annual difference in TCO of alternatively fuelled bulk ships (35,000-59,999 dwt) with increased bunkering frequency - Source: [63]

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The investment costs associated with the methanol-fuelled fuel cell propulsion system are estimated at €265/kW for a four-stroke engine and €505/kW for a two-stroke engine, which are still lower compared to other fuel cell technologies [81].

SOCIETAL READINESS LEVEL

Stakeholder acceptance

Stakeholder acceptance of methanol as an alternative marine fuel is steadily increasing, as reflected in the growing number of methanol-powered vessels currently in operation and those planned for the future. As of mid-December 2025, there are 98 vessels operating on methanol, including primarily container ships (51), oil tankers (25), and chemical tankers (10). Additionally, there are 281 methanol-ready vessels in the existing fleet, the majority of which are containerships (92) and bulk carriers (195) (based on WEB research from the Clarkson Research online database, mid-December 2025).

In terms of new orders, 317 methanol-powered ships are currently on order, with the majority being container ships (153) and bulk carriers (55). These vessels are expected to be delivered by 2030. Furthermore, a total of 781 methanol-ready vessels are on order, the majority of which are containerships (92) (based on WEB research from the Clarkson Research online database, mid-December 2025).

Stakeholder acceptance of methanol as a marine fuel is reinforced by the increasing number of engine designers adopting methanol-powered systems. Leading engine manufacturers, such as MAN B&W and WinGD, play a significant role in this trend. MAN B&W accounts for 56.3% of the methanol-powered vessels on order, offering engine series like the G50ME, S50ME, S60ME, G80ME, and G95ME, with capacities ranging from 10.32 MW to 54.96 MW. WinGD follows with 18.8% of the orders, providing engine series such as X52DF, X62DF, X82DF, and X92DF, with capacities from 13.37 MW to 64.5 MW (based on WEB research from the Clarkson Research online database, mid-December 2025). Nevertheless, in 2024, total methanol bunker fuel sales in Singapore, the world's largest bunker port, accounted for just 0.003% (1,600 tonnes) of the total sales volume [82].

International regulations

The maritime industry is under increasing pressure to reduce its environmental impact, particularly concerning greenhouse gas (GHG) emissions. In response, international and regional regulations have been established to encourage cleaner shipping practices. The Methanol Institute [83] highlights that the FuelEU Maritime regulation and the EU Emissions Trading System (ETS) play a significant role in shaping the acceptance of alternative fuels within the maritime sector.

The **FuelEU Maritime** regulation, a key EU initiative, aims to reduce GHG emissions from shipping by setting specific decarbonisation targets. It applies to ships over 5,000 gross tonnage and covers energy use in EU ports, between EU ports, and on voyages to and from EU ports.

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The regulation sets annual GHG intensity reduction targets, starting with 2% by 2025, 6% by 2030, 14.5% by 2035, 31% by 2040, 62% by 2045, and 80% by 2050. It also includes a sub-target for RFNBOs, with a 2% target starting in 2034 and incentives to encourage RFNBO use until then. Failing to meet these reduction targets could result in significant penalties, thereby raising the economic cost of fossil fuels relative to alternative, cleaner options.

The **EU Emissions Trading System (ETS)** is a cap-and-trade programme that limits CO_2 emissions across various sectors, including maritime, starting in 2024. The scope of maritime emissions covered by the EU ETS will increase from 40% in 2024 to 100% by 2026. From 2024, the regulation applies to cargo and passenger ships over 5,000 gross tonnage, and from 2025, it extends to offshore ships of the same size. Smaller ships (400 to 5,000 gross tonnage) will be subject to monitoring and reporting from 2025, with potential inclusion in the ETS in 2027. Greenhouse gases covered include CO_2, CH_4, and N_2O, with CH_4 and N_2O included from 2026.

Shipping companies must purchase emission allowances, which are auctioned and tradable on secondary markets. The price of these allowances fluctuates, with forecasts predicting a gradual increase. From May 2021 to May 2024, allowance prices ranged from €50.45 to €104.81 per tonne. In January 2024, forecasts indicated an average price of €74 per tonne for 2024, rising to €100 by 2026.

3.5. NUCLEAR

Nuclear energy has played a strategic role in maritime operations for more than six decades, primarily in military vessels and icebreakers. Today, the global push toward deep decarbonisation, combined with technological advances in reactor safety, compactness and modularity, has renewed interest in nuclear propulsion for commercial shipping. To understand its potential, it is essential to introduce the physical principles of nuclear energy, the technological evolution of reactor systems, and the specific characteristics of the so-called "fourth generation" of reactors, which represent the most promising candidates for future civilian naval use. An introductory overview of the technology and of reactor generations is essential to properly contextualise the subsequent TRL, CRL, and SRL evaluations. [84] [85]

Nuclear fission occurs when the nucleus of a heavy atom—typically uranium-235 or plutonium-239—absorbs a neutron and splits into two lighter nuclei. [86] This process releases:

- a large amount of **thermal energy**,
- **secondary neutrons**, which propagate the reaction,
- **radiation** in the form of gamma rays and particles.

A reactor maintains a **controlled chain reaction**, where the rate of fission is kept stable so that the generated heat can be used to produce steam or drive a closed Brayton cycle, depending on the design.

The key components that make fission usable and controllable are:

- **control rods**, which absorb neutrons and regulate power output;

- **moderators** (water, graphite, or other materials), which slow neutrons to increase the probability of fission;
- **cooling circuits**, which remove heat from the core;
- **containment structures**, which ensure radiological protection. [84]

While the fundamental physics is universal, the engineering solutions differ significantly between land-based and naval reactors due to the latter's unique operational constraints.

Reactors installed on ships or submarines must withstand conditions that are not encountered in terrestrial nuclear plants. Naval reactors must be:

- **compact and lightweight**, so they can fit into the hull without compromising stability;
- structurally robust against **vibrations, shocks, roll, pitch and accelerations**;
- able to maintain safe cooling under dynamic conditions, including loss of ship stability;
- equipped with **multiple physical barriers** to protect the crew and environment;
- capable of operating for **long intervals without refuelling**, often spanning many years. [84]

Historically, these requirements led to the dominance of **Pressurized Water Reactors (PWRs)** in naval propulsion, chosen for their maturity, reliability, and compactness. In recent years, however, alternative reactor types—using gas, molten salts or liquid metals as coolants—have emerged as candidates for next-generation ships due to their inherent safety and high-temperature performance.

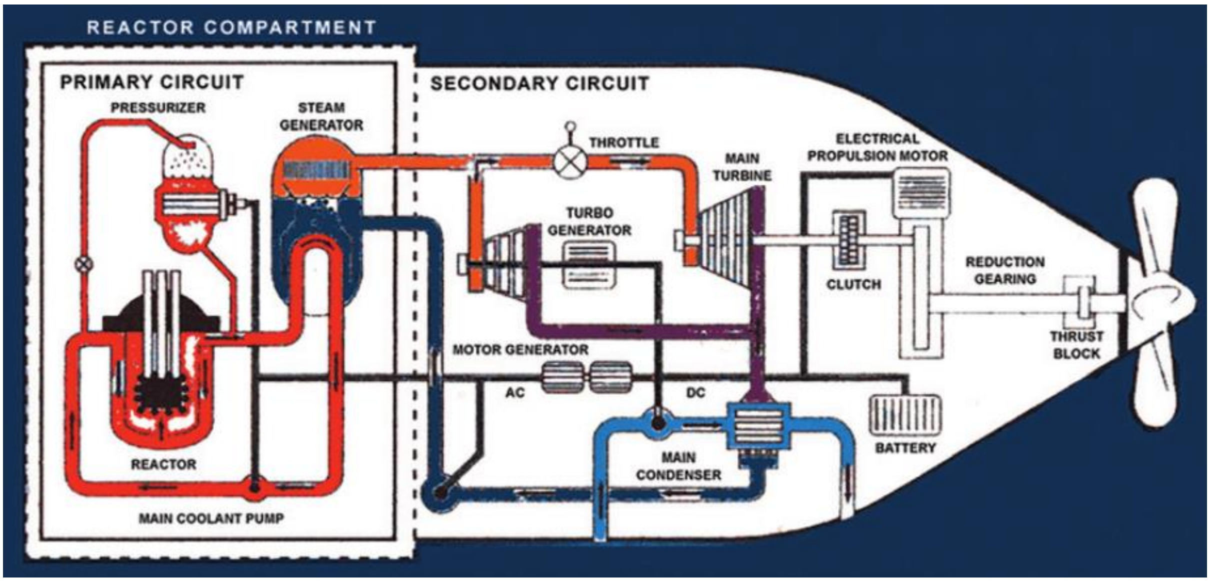

Figure 15 - Pressurized-water naval nuclear propulsion system. (Credit: World-nuclear.org

The development of nuclear reactors is commonly classified into technological "generations", each representing improvements in safety, efficiency, and sustainability.

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Generation I (1950s–1960s)

These were the first prototypes and early commercial reactors. They introduced the fundamental engineering concepts but relied heavily on active systems and lacked the safety refinements that came later. Early nuclear merchant ships, including pioneering vessels such as *NS Savannah*, used derivatives of these designs.

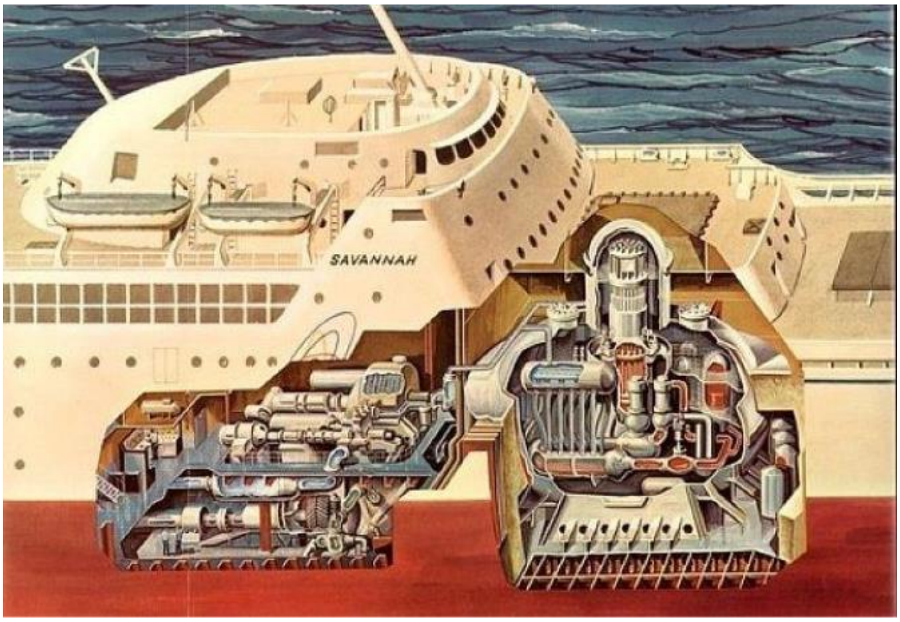

Figure 16 - NS Savannah Scheme

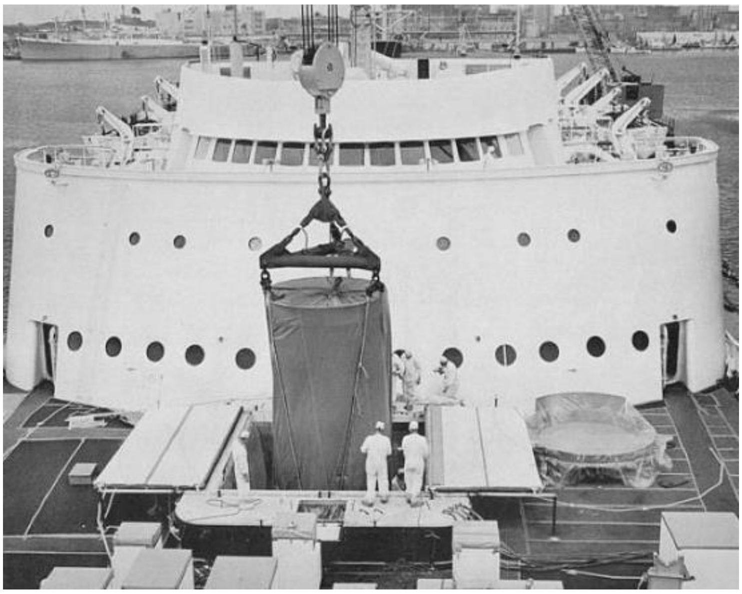

Figure 17 - NS Savannah during reactor's refuel

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Generation II (1970s–1990s)

This generation accounts for the bulk of the reactors operating worldwide today. Key characteristics include:

- standardized designs,
- improved reliability,
- safety systems primarily **active**, relying on pumps and mechanical components.

Most naval reactors in service today—particularly military reactors and Russian icebreaker reactors—derive from Generation II concepts, adapted to marine constraints. In the context of commercial applications, the Russian nuclear icebreakers provide a relevant example of Generation II technologies, as their continued development—often involving major European industrial partners such as Wärtsilä—demonstrates a clear trajectory of standardisation, technological refinement, and fleet consistency over time.

Generation III and III+ (2000s–present)

Generation III/III+ reactors introduced:

- **passive safety systems** that operate using natural forces (gravity, convection);
- improved thermal efficiency;
- enhanced core damage prevention features;
- extended operational lifetimes.

These reactors are widely regarded as a bridge technology toward next-generation naval SMRs, as they allow for reduced **Emergency Planning Zones (EPZ)**, potentially down to the ship's hull.

Table 28 - Chronological development of OK, KLT, and RITM reactor series

Reactor Type	Vessel Class	Period	Reactor Generation
OK-150	*Lenin*	1950s	**Gen I**
OK-900 / OK-900A	*Arktika* class	1970s–2000s	**Gen II**
KLT-40 / KLT-40M / KLT-40S	*Taymyr* class, floating plants	1980s–present	**Gen II (advanced)**
RITM-200 / 200M	*Project 22220*	2010s–present	**Gen III+**
RITM-400	*Project 10510* (*Leader* class)	in development	**Gen III+**

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Figure 18 - Russian operating Ice breaker

Generation IV (next–2040)

Generation IV reactors represent a major technological shift and are the focus of most studies exploring future nuclear propulsion for civilian ships. The internationally recognized Generation IV systems include:

1. **VHTR – Very High Temperature Reactor** (helium-cooled, TRISO fuel),
2. **GFR – Gas-cooled Fast Reactor**,
3. **MSR – Molten Salt Reactor**,
4. **SFR – Sodium-cooled Fast Reactor**,
5. **LFR – Lead-cooled Fast Reactor**,
6. **SCWR – Supercritical Water Reactor**.

They share several advantages highly relevant for maritime use:

- **inherent safety** features, with coolants operating at near-atmospheric pressure and excellent heat capacity (e.g., molten salts, lead);
- **higher thermal efficiency** (up to and beyond 45%);
- **long core life**, often many years without refuelling;
- **compact, modular architectures**, enabling Small Modular Reactors (SMRs) and micro-reactors;
- potential for **significant waste reduction**, especially in fast-spectrum systems.

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These characteristics make fourth-generation technologies an attractive solution for deep-sea commercial shipping, where high power demand, long endurance, and zero-emission operation are critical.

The progression from the early generations of nuclear reactors (Gen I through Gen III/III+) to the emerging Generation IV systems represents not merely an incremental technical improvement but a profound transformation in safety philosophy, operating conditions, fuel-cycle sustainability, and system integration. Earlier generations—especially Gen I and Gen II—were based on high-pressure light-water technology, characterised by complex multi-loop cooling circuits and a strong reliance on engineered, predominantly **active safety systems**, meaning that accident mitigation depended on the correct operation of pumps, valves, and powered components. These systems, while historically robust, provided only moderate thermal efficiency and required periodic refuelling due to the limitations of once-through uranium oxide fuel cycles. Generation III and III+ reactors introduced useful advancements—such as simplified layouts, **enhanced passive safety features** (gravity-driven cooling, natural circulation), and extended design lifetimes—but still retained the fundamental constraints of high-pressure water reactors. By contrast, Generation IV reactors reflect a decisive shift in technological philosophy, emphasising **inherent safety**, **high-temperature performance**, **closed fuel cycles**, and **modular integration**. Key distinguishing elements include:

• coolants such as helium, molten salts, liquid sodium or lead that enable **low-pressure operation** and strong natural-circulation behaviour;

• **much higher outlet temperatures** (500–900°C), supporting Brayton-cycle efficiencies exceeding 40–50%;

• **advanced fuels and closed fuel cycles** with the capacity to recycle actinides and significantly reduce long-lived waste;

• **ultra-long core lifetimes**, often 10–20 years or more without refuelling;

• compact, integrated reactor modules in which the core, heat exchangers and shielding are factory-assembled as a single unit suitable for installation aboard ships.

These innovations shift the technological baseline from one in which reactor safety and performance depend on engineered systems, to one in which the **thermophysical properties and reactor physics** provide stability by design. As a consequence, while earlier reactor generations successfully demonstrated the feasibility of nuclear propulsion in icebreakers and naval vessels, their size, operational complexity and maintenance requirements limited their adoption in commercial maritime contexts. Generation IV concepts, by contrast, offer high-efficiency, inherently safe, long-endurance, and logistically simplified power systems, creating a substantially more favourable platform for large-scale, zero-emission propulsion in commercial shipping over the 2030–2050 timeframe.

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Figure 19 - 4th gen molten salt reactor

TECHNOLOGY READINESS LEVEL

The Technology Readiness Level (TRL) associated with nuclear propulsion for maritime applications reflects both the long operational history of naval reactors and the emerging potential of advanced Generation IV systems. Proven marine reactors based on Generation II and III technologies—such as the Russian icebreaker reactors OK-900A, KLT-40 series, and the more recent RITM-200 Generation III+ systems—demonstrate that compact pressurised-water reactors are already capable of delivering reliable propulsion in harsh polar environments, offering decades of accumulated reactor-years of experience and a high level of technological maturity. These systems benefit from well-established design standards, industrial experience, and predictable behaviour under marine operating conditions, positioning them at **TRL 7–9** depending on configuration and specific deployment context. However, while earlier reactor generations have proven their viability, they remain constrained by the inherent limitations of high-pressure water-cooled technology, active safety architectures, moderate thermal efficiencies, and periodic refuelling requirements. By contrast, Generation IV concepts—such as Very High Temperature Reactors (VHTR), molten-salt reactors (MSR), and fast-spectrum liquid-metal designs (SFR, LFR)—represent a substantial shift in readiness trajectory.

Their defining features, including **inherent safety derived from low-pressure coolants**, **high outlet temperatures enabling thermal efficiencies above 40–50%**, **closed fuel cycles with reduced waste**, **ultra-long core lifetimes**, and **integrated modular reactor architecture**, align closely with the operational needs of commercial shipping. These advantages suggest a strong potential for future maritime adaptation; however, because such systems have not yet been deployed at sea, their readiness remains at **TRL 4–6**, depending on the design and testing maturity. The convergence of increasing industrial interest—exemplified by partnerships involving major shipyards and reactor developers—and the suitability of Generation IV systems for long-range, zero-emission propulsion indicates that the TRL of advanced nuclear solutions for commercial vessels may rise significantly over the 2030–2050 timeframe. Nonetheless, bridging the gap between demonstrated naval technologies and next-generation reactors will require not only technological validation but also regulatory evolution and maritime-specific demonstration projects to elevate these systems to high TRL levels.

Very High Temperature Reactor (helium-cooled, TRISO fuel) (VHTR)

The Technology Readiness Level of Very High Temperature Reactors (VHTRs) results from a combination of mature high-temperature reactor technologies and the absence of operational marine deployment to date. VHTRs evolve from the High-Temperature Gas-Cooled Reactor (HTGR) family, which has accumulated substantial operational experience through terrestrial prototypes such as AVR and HTTR, confirming the maturity of key enabling technologies—namely helium coolant, graphite moderation, and TRISO fuel particles. [87] TRISO fuel in particular has undergone decades of qualification and is recognised for its exceptional retention of fission products even at temperatures exceeding 1600 °C, providing a strong basis for the inherent safety claims of VHTR systems. The recent commissioning of the HTR-PM in China demonstrates the industrial feasibility of modular HTGR designs and positions terrestrial VHTR technology at approximately TRL 6–7. [88]

However, transferring these systems into the maritime environment introduces integration challenges that have not yet been validated experimentally, including the thermohydraulic behaviour of helium-cooled cores under ship motion, the integration of high-temperature Brayton-cycle turbomachinery within marine propulsion architectures, and the adaptation of passive decay-heat removal systems for naval constraints. Although none of these challenges is fundamental, all require targeted prototyping and at-sea demonstration. For this reason, while the underlying reactor physics and fuel technology are at mid-TRL, the readiness of VHTRs for naval propulsion remains in the **TRL 4–5 range**, reflecting conceptual design maturity and partial subsystem validation but no full maritime integration or operational demonstration.

Given their combination of inherent safety, high thermal efficiency, low-pressure operation, and very long core lifetimes, VHTRs remain among the most promising Generation IV candidates for large-scale, zero-emission commercial shipping in the 2030–2050 timeframe. Their TRL is expected to rise significantly as maritime-specific SMR prototypes progress, supported by increasing industrial interest and long-term decarbonisation pressures in the shipping sector.

Molten Salt Reactors (MSR)

Molten Salt Reactors (MSRs) represent one of the most innovative branches of Generation IV technology because they fundamentally alter the reactor architecture by using a liquid fuel and coolant, typically fluoride or chloride salts operating at low pressure. The technology foundations of MSRs date back to the Molten Salt Reactor Experiment (MSRE) at Oak Ridge

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National Laboratory in the 1960s, which provided extensive data on salt chemistry, corrosion behaviour, fuel-salt dynamics, and online fuel processing. [89] Modern MSR programmes—such as those pursued in the United States, Europe, and China—have significantly advanced materials science, salt purification methods, and corrosion-resistant alloys. [90] The inherent safety characteristics of MSRs arise from their low-pressure operation, strong negative temperature coefficients, and the ability to drain the fuel salt into passively cooled tanks in the event of overheating. These features position MSRs as highly promising for maritime propulsion, where stability, compactness, and passive safety are essential.

However, MSRs have not yet reached the same degree of prototype maturity as HTGR-based systems. Several key challenges remain, including the optimisation of salt chemistry for long-term operation, qualification of structural materials under simultaneous high-temperature and corrosive conditions, and the integration of drain tanks and salt-handling systems within confined maritime environments. While terrestrial MSR development is progressing toward demonstration units, maritime-specific applications remain at TRL 3–4, requiring validation of fuel-salt behaviour under ship motions, development of compact containment modules, and demonstration of salt freeze–thaw cycles in marine operating conditions. Despite this, the MSR concept's combination of inherent safety, high thermal efficiency, and potential for closed fuel cycles places it among the most compelling candidates for long-term commercial shipping decarbonisation.

Lead-cooled Fast Reactors (LFR)

Lead-cooled Fast Reactors (LFRs) are among the most advanced Generation IV systems and are particularly relevant for maritime applications due to the favourable thermophysical properties of liquid lead or lead–bismuth eutectic (LBE). These coolants operate at **low pressure**, have excellent heat capacity, and are chemically inert in contact with air or water, making them well-suited for passive safety and harsh environments. Historically, LBE reactors were deployed in Soviet Alfa-class submarines, providing valuable operational experience with fast-spectrum liquid-metal systems, albeit with material challenges. [91] Modern LFR programmes—such as the European Lead-cooled Reactor (ELFR) and developments by Newcleo—have significantly advanced structural materials, corrosion control, and fuel performance, placing terrestrial LFR technology at approximately **TRL 5–6**. [92]

For maritime use, LFRs offer compelling advantages: very long core lifetimes (10–20 years), high power density, and the ability to operate without high-pressure coolant systems. Their compactness and resistance to coolant boiling or pressurisation events make them particularly attractive for large commercial vessels. Nevertheless, the maritime TRL remains at **TRL 4–5**, as integration challenges persist, including coolant solidification management, fuel handling strategies, and thermal–hydraulic performance under ship motion. Ongoing industrial–shipbuilding partnerships are expected to accelerate readiness over the next decade, positioning LFRs as one of the strongest candidates for marine SMR deployment in the 2035–2050 window.

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Sodium-cooled Fast Reactors (SFR)

Sodium-cooled Fast Reactors (SFRs) are among the most mature advanced reactor technologies, with extensive experience from prototypes such as EBR-II, Phénix, Monju, and BN-series reactors. [93] Liquid sodium provides excellent heat transfer and enables high-temperature, low-pressure operation, supporting fast-spectrum fuel cycles capable of recycling actinides. This technical maturity positions terrestrial SFR systems at **TRL 6–7**. However, sodium's strong chemical reactivity with air and water introduces safety concerns that complicate maritime deployment, where seawater exposure and dynamic environments increase the likelihood of coolant compatibility events. [94] [95] While modern designs include advanced leak detection and inert cover gas systems, additional barriers would be required for shipboard integration, including double-walled secondary loops and containment isolation structures.

For these reasons, although SFRs are technologically mature on land, their **maritime TRL is significantly lower (TRL 3–4)**. The need to manage sodium–water reactions, ensure safe operation in confined hull spaces, and validate natural circulation behaviour under ship dynamics remains unaddressed. Despite these challenges, the high efficiency and closed fuel cycle potential of SFRs maintain their strategic relevance for long-term maritime decarbonisation, though they are considered less favourable than LFR or VHTR systems for near-term deployment.

Gas-cooled Fast Reactors (GFR)

Gas-cooled Fast Reactors (GFRs) combine the advantages of fast-spectrum reactors with the engineering simplicity of gas coolants, typically high-pressure helium. In principle, GFRs offer high thermal efficiencies, compact high-temperature turbomachinery, and the potential for closed fuel cycles. [96] However, unlike VHTRs, GFRs must rely on ceramic or composite fuel elements that can withstand high fast-neutron fluxes while maintaining structural integrity, and such fuel forms remain under development. The thermal inertia of gas coolants is significantly lower than that of liquids, making passive decay heat removal more challenging; this places additional demands on reactor geometry, active–passive hybrid systems, and heat removal pathways. [97]

As a result, GFRs are at a comparatively early readiness stage, typically TRL 3–4, with substantial R&D still required in fuel qualification, high-temperature materials, thermal–hydraulic modelling, and industrial-scale prototype development. For maritime applications, where natural circulation cooling and inherent safety are critical, GFRs currently present significant integration challenges. Nonetheless, their potential for very high efficiency and compact power conversion systems continues to make GFRs a long-term candidate for high-performance marine propulsion beyond 2040.

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Table 29 - Nuclear technology readiness level

Reactor Type	Description	Current TRL (Terrestrial)	Current TRL (Maritime)	Forecast TRL 2030 (Maritime)	Forecast TRL 2050 (Maritime)	Key Factors Influencing TRL Growth
Generation I	Early prototype reactors (1950s–1960s); first marine units (OK-150)	**TRL 7–8** (historical)	**TRL 7** (historical)	**7** (unchanged)	**7** (unchanged)	Legacy systems; not considered for future deployment.
Generation II	Standardised PWRs; mature naval icebreaker reactors (OK-900, KLT-40)	**TRL 9**	**TRL 8–9**	**8–9**	**8–9**	Fully mature technology; no major evolution expected.
Generation III / III+	Advanced PWRs with passive safety; includes RITM-200	**TRL 8–9**	**TRL 7–8**	**8–9**	**9**	Commercial and naval demonstration ongoing; strong near-term adoption potential.
VHTR (Gen IV)	Very High Temperature Reactor; helium-cooled with TRISO fuel	**TRL 6–7**	**TRL 4–5**	**6–7**	**8–9**	High maturity of TRISO fuel; strong suitability for maritime SMR integration.
MSR (Gen IV)	Molten Salt Reactor; liquid fuel or coolant	**TRL 4–6**	**TRL 3–4**	**5–6**	**7–8**	Major material and salt chemistry progress expected; maritime prototypes possible after 2035.
LFR (Gen IV)	Lead-cooled Fast Reactor;	**TRL 5–6**	**TRL 4–5**	**6–7**	**8–9**	Very promising for maritime due to low-pressure

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	lead or LBE coolant					operation and long core life; strong industrial interest (e.g., Newcleo).
SFR (Gen IV)	Sodium-cooled Fast Reactor	**TRL 6–7**	**TRL 3–4**	**4–5**	**6–7**	Technically mature but sodium reactivity limits maritime applicability; slower TRL growth expected.
GFR (Gen IV)	Gas-cooled Fast Reactor; high-pressure helium	**TRL 3–4**	**TRL 3**	**4–5**	**6–7**	High efficiency potential; requires major advances in fuel and passive safety.

FINAL CONSIDERATIONS TRL

In summary, the assessment of Technology Readiness Levels across reactor generations reveals a clear separation between the **fully mature technologies**—namely Generation II and III/III+ marine reactors—and the **promising but still emerging** Generation IV systems. Today, only water-cooled naval reactors reach operational TRLs of **8–9**, supported by decades of deployment in icebreakers and military vessels. By contrast, Generation IV concepts, despite their strong alignment with the long-term needs of commercial shipping—low-pressure operation, inherent safety, high thermal efficiency, and long core lifetimes—remain at **TRL 3–5** for maritime integration. However, forecasts to 2030 indicate substantial progress, especially for **VHTR** and **LFR** systems, which are expected to reach **TRL 6–7** as industrial prototypes mature and as major shipbuilders begin designing hulls compatible with modular reactor installation. By 2050, VHTR and LFR technologies are projected to attain **TRL 8–9**, becoming viable options for routine commercial use, whereas **MSR** systems may progress to **TRL 7–8**, and **SFR** and **GFR** are expected to remain at comparatively lower TRLs due to coolant compatibility and fuel technology constraints.

From the perspective of maritime architecture, the vessels most likely to adopt advanced nuclear propulsion in the 2030–2050 horizon are **large ocean-going ships** with high and continuous power demand. Preliminary integration studies suggest that a single modular Gen IV reactor in the 30–80 MW thermal range would be suitable for **container ships above**

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8,000–10,000 TEU, **tankers exceeding 120,000 DWT**, or **bulk carriers above 150,000 DWT**, with minimum ship lengths generally **above 230–260 metres** and beam dimensions **above 40 metres**. [98] [99] These geometries are necessary to accommodate the reactor module, shielding, auxiliary systems, and propulsion conversion equipment while preserving cargo capacity and complying with stability and survivability requirements. By 2050, larger modular reactors (100–150 MW thermal) could enable nuclear propulsion for **mega-container ships over 18,000 TEU** and **ultra-large crude carriers (ULCCs)**, provided that shipyard infrastructure evolves to support nuclear-ready hull construction. Ultimately, the TRL trajectory indicates that while near-term nuclear propulsion for commercial shipping will continue relying on mature Gen II/III designs in specialised vessels, the long-term decarbonisation targets for deep-sea shipping will converge with the maturation of **Generation IV reactors**, enabling a new class of large, zero-emission cargo vessels in the 2030–2050 timeframe.

COMMERCIAL READINESS LEVEL

The Commercial Readiness Level (CRL) of nuclear propulsion technologies captures the extent to which a complete industrial, regulatory, financial, and operational ecosystem exists to support commercial deployment. While TRL reflects technical feasibility, CRL determines whether a technology can realistically enter the maritime market. In nuclear shipping this distinction is crucial: even robust and proven reactor technologies may remain commercially non-viable if port access, insurance frameworks, and construction certification pathways are not in place.

CRL of Established Technologies (Gen II and Gen III/III+)

Commercial readiness is currently highest for **Generation II and III/III+ water-cooled reactors**, the only systems with decades of operational experience in civilian–government fleets such as the Russian icebreakers. Their operation demonstrates that nuclear propulsion can be industrialised under state-backed programmes. However, despite their technological maturity, commercial deployment is severely limited by insurance constraints, the absence of harmonised international regulation, and port-state restrictions, which confine their CRL to **6–7**.

CRL of Emerging Technologies (Generation IV Reactors)

Generation IV reactor systems remain at **CRL 2–3**, as no end-to-end commercial maritime supply chain exists to support their construction, fuelling, lifecycle management, or port-state acceptance. Shipyards are not yet certified to build nuclear-ready commercial hulls, classification societies are only beginning to formalise rules for advanced marine reactors, and financial institutions still treat maritime nuclear propulsion as a high-risk, non-bankable proposition. Early industrial partnerships—such as emerging collaborations between reactor developers and major shipyards—are nonetheless laying the groundwork for future commercial viability. [100] Among Gen IV concepts, **LFR** and **VHTR** systems show the strongest commercial promise due to their inherent safety features, modularity, and compatibility with shipyard workflows, whereas MSR systems face materials-qualification challenges and SFR/GFR systems face coolant or fuel development hurdles.

Commercial Barriers and Enabling Conditions

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Key barriers to commercialisation include:

- the lack of **internationally harmonised regulation**, as current IMO frameworks date from the naval era; [101]
- the absence of **viable insurance and liability structures**, which presently render nuclear merchant vessels non-bankable; [102]
- limited **shipyard readiness**, as only a few facilities worldwide could accommodate nuclear-compliant construction;
- incomplete **fuel-cycle infrastructure** for maritime HALEU, TRISO, lead-based, or molten-salt systems;
- **port authority acceptance**, which remains uncertain outside of state-operated corridors.

These constraints currently dominate CRL progression.

Forecast CRL 2030

By 2030, incremental progress in demonstration initiatives, classification-society rule development, and maturing industrial partnerships is expected to elevate VHTR and LFR systems to **CRL 3–4**. Gen III/III+ technologies may reach **CRL 7** if early commercial-pilot vessels—such as research ships or specialised Arctic logistics vessels—obtain operational authorisation. Nevertheless, broad commercial deployment before 2035 remains unlikely due to the slow pace of regulatory modernisation and limited financial instruments for nuclear shipping.

Forecast CRL 2050

By 2050, **VHTR and LFR** technologies are projected to achieve **CRL 6–7**, enabling deployment in selected commercial corridors such as trans-Arctic routes, large-tonnage global container trades, and energy-intensive bulk transport. MSRs may reach **CRL 5–6**, while SFRs and GFRs are expected to remain below CRL 5. Nuclear propulsion is likely to penetrate first into **large deep-sea energy-intensive vessels**, where nuclear endurance and high power density provide compelling economic advantages.

Ship Types and Market Segments Likely to Adopt Nuclear Propulsion

Early adoption is expected in **large ocean-going cargo vessels**, whose operational profiles best match nuclear propulsion. Ships between **250–400 m in length**, beams above **40 m**, and displacements exceeding **100,000 tonnes** can feasibly integrate modular nuclear reactors, shielding structures, heat-rejection systems, and emergency cooling architecture without compromising stability or payload. [103] These categories include ultra-large container ships (8,000–24,000 TEU), VLCC/ULCC tankers, capesize bulk carriers, and specialised Arctic or offshore logistics vessels. [104]

CAPEX – OPEX considerations and preliminary notes

Although no commercial nuclear-powered merchant fleet is currently in operation, preliminary CAPEX and OPEX assessments can be derived by analogy with existing nuclear maritime systems, including Russian icebreakers, floating nuclear power units, and historical merchant nuclear vessels. Evidence from these programmes indicates that capital expenditure for a nuclear-propelled ship is substantially higher than for conventionally

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powered vessels, primarily due to the cost of reactor modules, nuclear-grade construction requirements, and shielding installations. [105] [106] A modern container vessel in the 12,000–20,000 TEU range typically requires an investment of €130–250 million, whereas integration of a modular Generation III+ or IV reactor (30–150 MWth) increases projected construction costs to approximately €450–900 million. This envelope includes reactor procurement, nuclear-specific systems, and structural adaptations, with the expectation that serial production could reduce costs significantly once supply chains mature. In contrast to the elevated CAPEX profile, the operational costs of nuclear propulsion may prove advantageous over the vessel's lifetime. Nuclear fuel, though costly on a per-unit basis, is consumed slowly and refuelling cycles may extend over 10–20 years, resulting in annualised fuel costs well below those associated with conventional marine fuels. Operational expenditure is instead dominated by regulatory compliance, specialised crew training, periodic reactor maintenance, and insurance. Benchmarks from existing nuclear marine operations suggest that maintenance and technical oversight may range between €10–20 million annually, while crew-related costs may increase by €2–4 million per year due to the requirement for nuclear-qualified personnel. Insurance and liability structures remain the greatest source of uncertainty and may introduce annual costs on the order of €10–30 million until international frameworks evolve. Even under conservative assumptions, the replacement of fossil fuels with nuclear propulsion can reduce overall OPEX by 30–60%, while providing predictable long-term energy costs, multi-decadal endurance, and complete insulation from fuel price volatility. Accordingly, although nuclear propulsion introduces higher upfront capital costs, its long-range economic performance, combined with emissions-free operation, positions it as a potentially competitive solution for large commercial vessels in the 2030–2050 timeframe.

Table 30 - Nuclear CAPEX – OPEX considerations and preliminary notes

Cost Category	**Conventional HFO/LSFO**	**LNG Dual-Fuel**	**Methanol / Ammonia Ready**	**Nuclear (Gen III+/IV SMR)**	**Notes / Drivers**
CAPEX – Ship Construction	€130–180 M	€160–220 M	€180–260 M	**€450–900 M**	Nuclear requires reactor module, shielding, containment boundaries, specialised construction
Propulsion System CAPEX	€20–30 M	€40–60 M	€50–80 M	**€250–550 M**	Reactor cost dominates; modular units expected to reduce costs after FOAK
Fuel Storage & Infrastructure	Low	High (cryogenic tanks)	Very High (large tanks)	**Low**	Nuclear fuel extremely compact; minimal storage needs

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Total CAPEX (Range)	€150–210 M	€210–280 M	€230–340 M	**€450–900 M**	Nuclear 2–3× conventional CAPEX for first-of-a-kind vessels
Annual Fuel OPEX	**€25–60 M**	€20–50 M	€30–70 M	**< €1 M**	Nuclear fuel amortised over 10–20 years; negligible annual cost
Maintenance & Technical OPEX	€8–15 M	€10–18 M	€12–20 M	**€10–20 M**	Nuclear maintenance similar to icebreaker experience; periodic inspections
Crew OPEX	€5–8 M	€5–8 M	€5–8 M	**€7–12 M**	Nuclear-qualified officers and radiation-protection staff required
Insurance & Liability	€2–5 M	€3–6 M	€3–6 M	**€10–30 M**	Largest uncertainty for nuclear until international liability reforms
Total Annual OPEX	€40–80 M	€45–85 M	€50–95 M	**€25–50 M**	Nuclear becomes cost-competitive after amortisation, despite higher insurance
Energy Autonomy	Low (fuel intensive)	Low	Low	**Very High (10–20 years)**	Key operational advantage of nuclear
GHG Emissions	Very High	Medium	Low	**Zero (operational)**	Nuclear eliminates propulsion-related emissions
Fuel Price Volatility	Very High	High	High	**None**	Major advantage of nuclear for long-term economic predictability

Table 31 - Nuclear CRL

Reactor Type	Commercial Readiness Level (Current)	CRL Forecast 2030	CRL Forecast 2050	Commercial Outlook for Maritime Use
Generation I	**CRL 1 (retired / historical)**	1	1	No commercial relevance; obsolete systems with no future deployment potential.
Generation II	**CRL 6–7**	6–7	6–7	Mature water-cooled reactors used in icebreakers; commercially viable only in

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				state-run fleets, not private merchant shipping.
Generation III / III+	**CRL 6**	**7**	**8**	Most commercially relevant near-term option; potential pilot commercial ships after 2030 under strict regulatory frameworks.
VHTR (Gen IV)	**CRL 2–3**	**3–4**	**6–7**	Strong candidate for commercial deployment post-2040 due to passive safety, long core life, and modularity.
MSR (Gen IV)	**CRL 2–3**	**3–4**	**5–6**	Commercialisation slowed by materials qualification and salt-handling challenges; medium-term potential.
LFR (Gen IV)	**CRL 2–3**	**4–5**	**6–7**	One of the strongest Gen IV candidates for commercial shipping; good fit for marine conditions and long-life sealed cores.
SFR (Gen IV)	**CRL 2**	**3–4**	**4–5**	Terrestrial maturity higher than marine; commercial adoption slowed by sodium's reactivity and complex safety case.
GFR (Gen IV)	**CRL 1–2**	**2–3**	**4–5**	Low commercial readiness due to unproven fuel systems and limited passive safety; long-term research candidate.

SOCIETAL READINESS LEVEL

International regulation and consistency with European policies

International regulation and consistency with European policies represent the foundational pillars for enabling societal acceptance of nuclear propulsion in commercial shipping. Today, the global governance landscape for maritime nuclear technology remains fragmented and outdated, with current IMO provisions largely inherited from legacy codes that were originally designed for early-generation naval reactors rather than modern civilian applications. [107] These frameworks do not reflect the characteristics of advanced reactors, particularly Generation IV systems with inherent safety features, long core lifetimes, and modular architectures. [108] As a result, port states, classification societies, insurers, and shipowners lack the regulatory certainty required to support nuclear-powered merchant vessels.

Within Europe, this challenge is further amplified by the interaction between maritime regulation and nuclear governance under Euratom, WENRA, and national nuclear authorities. [109] The European Union's climate objectives—particularly Fit for 55, the EU Emissions Trading System extension to maritime transport, and the FuelEU Maritime regulation—recognise the need for deep decarbonisation but do not explicitly address nuclear propulsion as a viable compliance pathway. [110] This omission creates ambiguity

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for stakeholders and prevents nuclear propulsion from being fully assessed within the strategic decarbonisation mix. At the same time, European nuclear safety frameworks are among the most stringent globally, implying that any nuclear-propelled vessel operating in EU waters would be subject to multilayered requirements that go beyond IMO guidelines, encompassing nuclear licensing, waste and fuel transport rules, radiological protection standards, and emergency preparedness systems. [111]

For societal readiness to advance, a coherent governance architecture must emerge that aligns IMO maritime safety instruments, EU regulatory frameworks, and national nuclear legislation. This includes defining liability and insurance regimes compatible with commercial operations, establishing port-entry protocols, harmonising emergency response procedures, and creating classification rules tailored to advanced marine reactors. Without such harmonisation, public confidence and institutional acceptance will remain limited, restricting SRL progression and delaying the integration of nuclear propulsion into the maritime sector's 2030–2050 decarbonisation strategy.

Stakeholder acceptance: shipowners, ports, maritime authorities, crews, and industry actors

Stakeholder acceptance is a decisive factor shaping the societal readiness of nuclear propulsion, as its deployment requires coordinated support across the entire maritime value chain. Shipowners remain cautious, balancing the long-term advantages of nuclear propulsion—fuel autonomy, stable operating costs, and zero-emission performance—against uncertainties in regulatory approval, port access, liability exposure, and the substantial upfront investment required. Port authorities, central to the operational viability of nuclear vessels, generally lack the regulatory frameworks, dedicated emergency response capabilities, and political mandate needed to receive nuclear-powered merchant ships, resulting in a fragmented acceptance landscape. Maritime administrations and classification societies, while historically conservative, are beginning to show more structured engagement, with several actively developing draft standards tailored to advanced reactor integration.

A notable evolution is occurring among **major shipbuilding players**, whose strategic commitments are actively reshaping stakeholder perceptions. **Fincantieri**, for example, has openly aligned with advanced reactor developers in Europe, signalling industrial readiness to design nuclear-capable hulls and integrate modular reactors as part of long-term decarbonisation strategies. Similarly, Chinese shipbuilders—supported by national initiatives in SMR development and large-scale maritime innovation—are positioning themselves to become early adopters and global suppliers of nuclear-propelled vessels. These industrial movements significantly influence the broader shipping community by demonstrating that nuclear propulsion is transitioning from a theoretical option to a credible future market segment.

Acceptance among seafarers and crews remains mixed, reflecting concerns about specialised training requirements, operational responsibilities, and long-term career implications, although advanced reactors promise safer working conditions compared with traditional engine rooms. Meanwhile, insurers, logistics providers, and supply-chain actors remain cautious but increasingly engaged as major builders and energy-sector firms validate the

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economic and operational potential of nuclear technologies. Overall, while stakeholder acceptance today remains uneven, the commitment of influential shipbuilding groups and advanced reactor developers is beginning to shift the trajectory, accelerating the conditions under which SRL can rise from exploratory phases toward structured demonstration and eventual commercial adoption.

Social and Territorial Aspects

The deployment of nuclear-powered commercial vessels introduces significant social and territorial considerations that extend far beyond the maritime domain. At the societal level, public perceptions of nuclear safety, environmental impact, and emergency preparedness shape the willingness of communities to support the presence of nuclear-powered ships along coastal regions. These perceptions are often influenced by past nuclear incidents, local familiarity with nuclear technologies, and the level of transparency provided by operators and regulators. Territorial acceptance is closely tied to the capabilities and confidence of local institutions: port cities with established nuclear infrastructure, trained emergency services, and experience in hosting other high-risk industrial activities are more likely to accept nuclear-powered vessels than regions with limited technical capacity or strong anti-nuclear sentiment. Moreover, the transformation of port areas to accommodate nuclear propulsion—through emergency response facilities, radiological monitoring systems, and controlled access procedures—has territorial planning implications that require engagement with municipal governments, regional authorities, and local communities. The economic dimension also plays a pivotal role: regions with large shipyards, maritime clusters, or nuclear technology industries may view the introduction of nuclear propulsion as an opportunity for industrial growth, job creation, and strategic positioning within emerging zero-emission shipping markets. Conversely, territories dependent on tourism or with high-density coastal populations may perceive the technology as a potential risk to their economic identity and environmental integrity. Overall, social and territorial acceptance of nuclear propulsion will evolve in a highly differentiated manner across regions, depending on local socio-economic structures, institutional capacity, cultural attitudes toward nuclear energy, and the perceived balance between economic benefit and environmental or safety concerns.

3.6. HYDROGEN

TECHNOLOGY READINESS LEVEL

Resource Availability and Production

Hydrogen is increasingly regarded as one of the most promising zero-emission energy carriers for the future of maritime transport, yet it represents a fundamentally different class of fuel compared to both conventional hydrocarbons and other alternative options. First of all, it is of utmost importance to clarify that hydrogen is not a naturally available energy source in its pure form; it must be extracted through energy-intensive chemical processes, such as steam methane reforming, water electrolysis, or biomass conversion, making it a

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secondary energy vector rather than a primary fuel. This characteristic complicates direct comparisons with other marine fuels and shifts attention toward the carbon intensity and energy efficiency of its production pathways [112].

Steam Methane Reforming (SMR) — Grey Hydrogen

Method: Hydrogen is produced by reacting methane (natural gas) with steam at high temperature, yielding hydrogen and carbon dioxide.
TRL: 9 — Commercially Mature. SMR is the dominant industrial hydrogen production method worldwide and is fully established at large scale. Just think that the hydrogen produced with this technology is between 50-60% in the world and 95% in the United States of America [113].
SMR with CCS forms "blue hydrogen," still reliant on fossil feedstocks but with reduced emissions compared to grey hydrogen.

Electrolysis — Green and Renewable Hydrogen

Method: Water (H_2O) is split into hydrogen and oxygen using an electric current. When electricity is derived from renewables, the resulting hydrogen can be considered *green*.
TRL: 7–9, depending on technology variant:

- **Proton Exchange Membrane (PEM)** electrolysers are at the higher end of readiness and are increasingly used in commercial projects.
- **Alkaline electrolysers** also show established commercial use especially at large scales.
- **Solid Oxide Electrolyser Cells (SOECs)** are at an earlier stage with high potential efficiency but still in demonstration phases.
  this technology is known for its very low life-cycle carbon emissions when powered by renewables, but as well for its
  higher capital costs compared to SMR; depends on availability of affordable renewable electricity [114].
  Industry forecasts see electrolysis scaling significantly by 2050 as renewable deployment expands, potentially becoming the dominant production method.

Coal Gasification / Oil Reforming — Hydrogen from Fossil Feedstocks

Method: Hydrogen is produced by gasifying coal or reforming oil-based feedstocks, converting carbon-rich materials into hydrogen and carbon oxides via high-temperature chemical reactions.
TRL: 8–9: Coal gasification and oil reforming are mature technologies with decades of industrial use, capable of high production volumes. They leverage existing fossil-fuel infrastructure but generate significant CO_2 emissions unless paired with carbon capture and storage (CCS), which adds cost and operational complexity. As such, these pathways are often considered "blue hydrogen" when CCS is applied, but their environmental benefits depend heavily on the effectiveness of carbon sequestration. While industrially viable, their relevance for maritime hydrogen fuel is limited in the context of decarbonization goals, and adoption would need to balance availability, cost, and sustainability constraints [115].

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Bunkering and Storage on board

Producing hydrogen is only part of the maritime supply chain. Realizing its use on ships requires supporting technologies and infrastructure, including **bunkering systems, onboard storage, and propulsion systems**, to be rated at high TRLs as well. According to LR's Zero Carbon Fuel Monitor, hydrogen propulsion readiness and related infrastructure are progressing, but many components remain in pilot or early commercial stages, especially for long-distance and larger vessel applications [116].

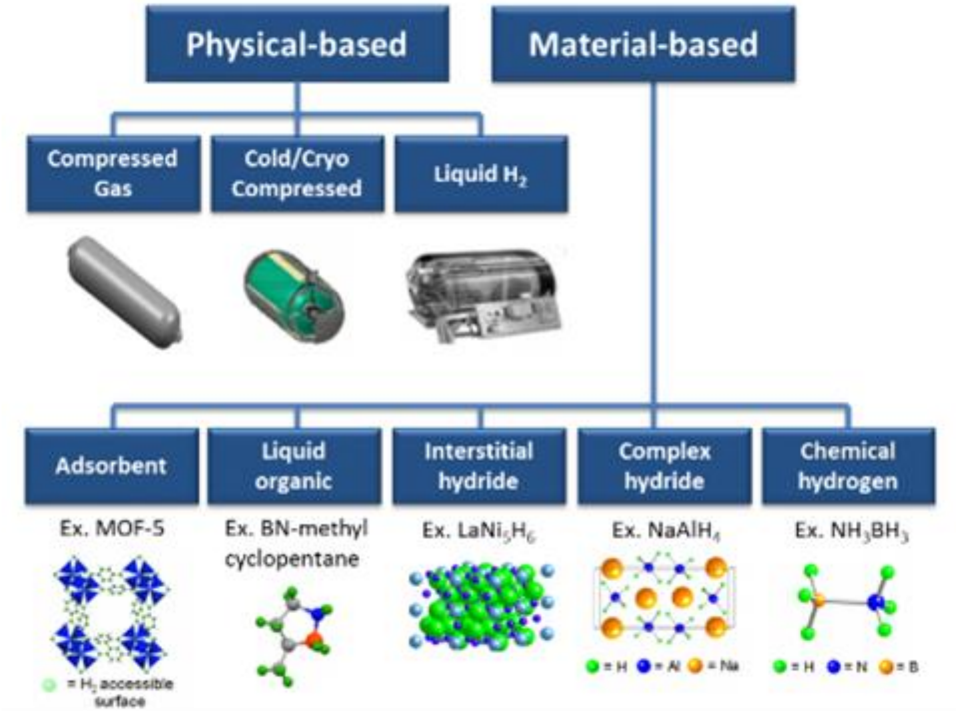

Figure 20 - Bunkering and Storage on board

The 4 main different H2 storage system suitable for marine application are the following:

- Liquefied Hydrogen (LH_2)
- Compressed Hydrogen (CH_2)
- Metal Hydride Hydrogen (MH_2)
- Liquid Organic Hydrogen Carrier (LOHC)

Liquefied Hydrogen (LH_2) *- TRL 6 → 7 (near-term demonstration / early operational demos)*

The shipping industry has accumulated valuable experience with cryogenic fuels through the adoption of liquefied natural gas (LNG), which has attracted interest due to its lower carbon content compared with conventional marine fuels. However, the challenges associated with liquid hydrogen (LH_2) are significantly greater than those of LNG: LH_2 must be stored at temperatures roughly 90 °C lower, and it has a lower density and specific heat capacity (9.44 J/(g·K)), making thermal management more demanding. Nevertheless, the development of LNG as a marine fuel provides a substantial knowledge base from which lessons can be transferred and adapted to LH_2 applications. Beyond the maritime sector, extensive

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expertise in handling liquid hydrogen already exists, particularly in aerospace programs where LH_2 has long been used as a high-performance cryogenic propellant [112].

The liquefaction of hydrogen, however, remains one of the most energy-intensive steps in the supply chain. Industrial liquefaction plants typically require 12.5–15 kWh per kilogram of H_2, corresponding to approximately 37–45% of hydrogen's lower heating value (LHV), especially when using liquefied nitrogen for precooling. This substantial energy demand is a key factor influencing both the economic and environmental performance of LH_2 as a marine fuel [117].

After the cooling process, the hydrogen must be stored at temperatures below its boiling point at -253 °C. To deal with this issue, tanks made of super isolating materials are used and the design of the tank is spherical since this lowers the surface to volume ratio of the tank. However, the boil off rate of hydrogen is higher than LNG and currently only pressure vacuum multilayer insulated tanks seem to be promising to satisfy the required holding time for seagoing ships [118].

Compressed Hydrogen CH_2 *- TRL 7 (prototype systems proven in operational environment / short-sea vessels)*

The currently most developed and widely used method to store hydrogen is by compression. Five different types of storage tanks have been developed and are used to store hydrogen at increased pressures (from 10–20 to 70 MPa). These tank types are generally denoted by Roman numerals, I, II, III, IV and V based on the complexity of the storage tank. Type I pressure vessels are metallic, type II vessels are made of a combination of a polymer liner wrapped around a metallic tank, but with the polymer liner only wrapped around the cylindrical part of the vessel. Type III tanks build on the type II vessels with the addition of a metallic liner fully wrapped with the composite fibre for support. Type IV pressure vessels consist of a polymeric liner that is fully wrapped with composite fibres. They do not require the use of a metal vessel body, and this benefits their gravimetric efficiency, but decreases the system's thermal resistance. For the type V tanks a patent has been submitted in 2014, and these are all composite tanks without any liner and claim to work at pressures above 700 bar. However, there are only limited applications of these type V tanks [119].

Metal Hydride Storage MH_2 *- TRL 3 → 4 (experimental / lab validation → early component proof-of-concept)*

Some metals and alloys can absorb hydrogen and form hydrides, which are classified as metallic hydrides or complex hydrides, depending on whether the bonding remains metallic or becomes ionic/covalent after hydrogen uptake. Storing hydrogen inside the lattice of metals or compounds offers some of the highest volumetric energy densities, but hydrogen must be released by heating the hydride to a material-specific temperature.

Among solid-state materials, magnesium hydride (MgH_2) is attractive thanks to its abundance and good storage capacity: with a density of 1.45 g/cm³, it provides 7.6 wt% hydrogen and 13.22 MJ/L. Its drawbacks are slow kinetics and the need for high temperatures (260–425 °C) for reversible storage, although catalytic and structural modifications can partially improve performance.

Aluminium hydride (AlH_3) behaves differently: it releases hydrogen rapidly at ≈100 °C due to its low dehydrogenation enthalpy (7 kJ/mol) and offers a high theoretical capacity of 10.1

wt%. However, the reaction is practically irreversible, since AlH_3 cannot be regenerated from aluminium and hydrogen except at extreme pressures, limiting its use in closed-cycle systems.

For marine applications, major challenges include:

- high system weight, due to low gravimetric capacity;
- demanding thermal management, as absorption is exothermic and desorption endothermic;
- slow kinetics for many hydrides;
- limited regenerability for complex hydrides like AlH_3;
- integration complexity, including heat exchangers, insulation, and control systems.

As a result, solid-state hydrogen storage is promising for safety and volumetric density but remains suitable mainly for niche or small-scale marine applications until significant material and system advances are achieved [120].

Liquid Organic Hydrogen Carrier LOHC *- TRL 6 → 7 (pilot / on-ship demos & AiP awarded)*

Liquid Organic Hydrogen Carriers (LOHCs) are organic liquids that can chemically store and release hydrogen while remaining liquid under ambient conditions. Hydrogen is bound to the carrier through reversible hydrogenation and dehydrogenation reactions, allowing the liquid to act as a safe, high-density hydrogen vector suitable for marine applications.

Hydrogen is initially stored in the LOHC through hydrogenation, typically performed in industrial plants at 150–200 °C. In this form, the LOHC is stable, non-flammable, and can be transported and stored using conventional liquid tanks, avoiding the need for high-pressure or cryogenic systems [121].

On board ships, hydrogen is released via dehydrogenation in a reactor, an endothermic process requiring high temperatures (≈280–320 °C for DBT). The released hydrogen can then feed fuel cells or engines, while the unloaded LOHC can be returned to a hydrogenation facility for reuse, creating a closed-cycle system [122].

LOHCs provide several advantages for marine applications:

- High volumetric hydrogen density compared to compressed hydrogen.
- Safety and stability, as the liquid is non-flammable and non-cryogenic.
- Transportability, using standard fuel tanks and existing infrastructure.

However, challenges remain:

- The high dehydrogenation temperature requires significant heat input, reducing overall efficiency.
- System complexity, including reactors, heat management, and liquid handling.
- Recycling logistics, as unloaded LOHC must be returned for hydrogenation [123].

LOHC technology is currently at TRL 6–7 for maritime applications, with pilot ships and demonstration projects showing its potential. Overall, LOHC is especially suited for medium-to-large vessels, where safe liquid storage, transport flexibility, and volumetric density outweigh the energy and system complexity costs [124].

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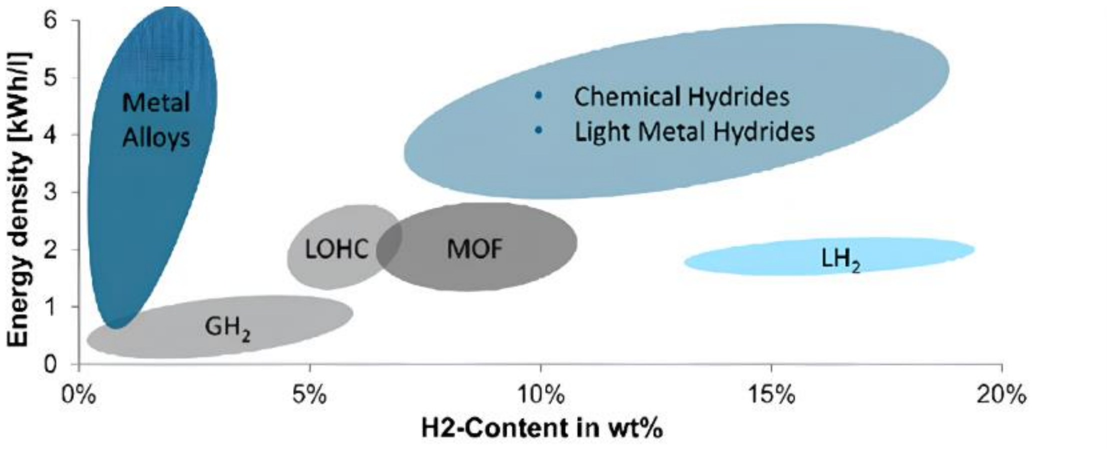

Figure 21 - Comparison of different hydrogen storage technologies [125]

Safety on Board

Health and safety

From a health and safety engineering perspective, the integration of hydrogen systems on board ships introduces failure modes and exposure scenarios that are not yet fully covered by prescriptive maritime regulations. The main contributors to risk are associated with the physical storage state of hydrogen (compressed or cryogenic), the integrity of high-pressure or low-temperature components, and the interaction between hydrogen systems and the ship environment, which is characterized by confined spaces, dynamic loads, and continuous human presence [126].

Hydrogen itself is non-toxic; therefore, health risks are primarily indirect and linked to system failures or abnormal operating conditions. High-pressure gaseous storage systems involve stored energies comparable to those of conventional pressure vessels used in industrial applications, but are subject to additional marine-specific loads such as vibration, fatigue, and sloshing-induced stresses. Liquid hydrogen systems introduce cryogenic hazards, including cold burns, rapid phase change, and material degradation due to hydrogen embrittlement or low-temperature brittleness. In both cases, unintended releases may lead to oxygen displacement in enclosed spaces, creating acute asphyxiation hazards that require dedicated ventilation capacity and fast-response gas detection [127].

From a design and approval standpoint, hydrogen fuel systems for marine use are currently assessed predominantly through risk-based methodologies. Formal safety assessment techniques, including HAZID, HAZOP, failure mode and effects analysis (FMEA), and quantitative risk assessment, are systematically applied to demonstrate that individual and societal risks remain within acceptable limits. However, the lack of extensive operational data for hydrogen-fuelled ships introduces uncertainties in failure rate assumptions and consequence modeling, which are often compensated for through conservative design margins and operational restrictions [33].

The resulting safety architecture typically includes strict segregation of hydrogen systems from accommodation and machinery spaces, controlled access to fuel-related compartments, redundancy in critical safety functions, and enhanced monitoring of pressure, temperature, and gas concentration. Crew health and safety are further addressed through specialized training and procedures aimed at managing hydrogen-specific hazards, such as invisible flames and rapid gas dispersion. From a technology readiness perspective, these measures indicate that the fundamental safety principles are well established, but their validation under routine commercial ship operation remains limited, placing hydrogen marine systems at an intermediate TRL in terms of health and safety maturity.

Explosion and fire

Explosion and fire risk dominate the safety case for hydrogen as a marine fuel and represent the primary limiting factor for technology readiness. Hydrogen–air mixtures are flammable over a very wide concentration range and are characterized by extremely low minimum ignition energy and high flame propagation velocities. These properties increase sensitivity to ignition and amplify the consequences of releases in confined or partially confined spaces, which are typical of shipboard installations. While detonation is generally not expected under normal shipboard conditions, deflagration with significant overpressure remains a credible scenario in congested geometries [128].

Engineering design therefore focuses on minimizing both the frequency and the consequences of hydrogen releases. Preventive measures include high-integrity storage vessels, pressure relief devices, leak-before-break design principles, and the use of double-walled piping or ventilated enclosures for fuel distribution systems. Hydrogen tanks and fuel processing equipment are preferentially located on open decks or in dedicated compartments with direct venting to atmosphere, in order to exploit hydrogen's low density and buoyancy and to prevent gas accumulation [119].

Detection and isolation are key safety functions and are typically implemented with low-threshold hydrogen sensors, redundant shutdown logic, and fast-acting isolation valves. Ventilation systems are designed based on dispersion analyses to ensure that, following a credible leak, hydrogen concentrations remain below the lower flammability limit. Electrical and electronic equipment in hydrogen zones is specified to be intrinsically safe or explosion-protected, and strict control of hot surfaces and electrostatic discharge is required [127].

In the event of ignition, hydrogen fires are characterized by high flame temperatures, low radiant heat, and limited smoke production, but their near-invisible nature complicates detection and emergency response. Fire protection strategies therefore prioritize rapid shutdown, controlled depressurization, and structural protection of adjacent systems rather than conventional fire suppression. Passive fire protection and separation distances are applied to prevent escalation and to maintain the integrity of storage systems under external fire exposure.

From a TRL perspective, the individual components and safety concepts applied to hydrogen explosion and fire protection are largely derived from mature industrial and energy-sector applications. However, their integration into a marine system-level safety case, validated through long-term operational experience and standardized design rules, is still incomplete. Consequently, hydrogen technologies for marine propulsion can be considered at a low-to-intermediate TRL with respect to explosion and fire safety, with further full-scale

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demonstrations, incident data collection, and regulatory harmonization required to progress toward higher readiness levels [126].

Marinization

Hydrogen is increasingly viewed as a key enabler for meeting the upcoming decarbonization requirements of the maritime sector, although significant challenges remain concerning its very low volumetric energy density, the complexity of cryogenic storage at –253 °C, and the immaturity of large-scale shipboard systems [129].
In the near term, hydrogen-enriched LNG offers a practical transitional pathway, as it can be used directly in internal combustion engines with progressively higher hydrogen blending ratios. Experimental and pilot-scale studies have already demonstrated that adding hydrogen to LNG results in more efficient combustion, reduced CO_2 emissions, and, in some cases, lower methane slip, with the benefit increasing as the hydrogen fraction rises [130].

Beyond internal combustion engines, hydrogen can also be employed in fuel cells to generate electricity, allowing it to replace auxiliary diesel generators and, in certain small-scale or specialized applications, even serve as the primary power source when coupled with electric propulsion systems. This opens the possibility of hybrid configurations where hydrogen supports both propulsion and hotel loads with significantly lower emissions.

One possible strategy to gradually introduce hydrogen as a maritime fuel is the installation of on-board hydrogen production systems, such as steam methane reforming (SMR) units. Producing hydrogen directly on the vessel could, in principle, mitigate several of the major challenges associated with hydrogen adoption, namely storage volume constraints, cryogenic or high-pressure handling requirements, and dedicated bunkering infrastructure. By reforming LNG already available on board, ships could generate hydrogen on demand for combustion enhancement or fuel cell supply, while relying on widely established LNG logistics and safety frameworks. However, such an approach would also necessitate careful consideration of reformer efficiency, CO_2 capture or management, integration with existing energy systems, and compliance with evolving IMO safety regulations [131].

Material Compatibility

From a materials-readiness perspective, the TRL of components intended for hydrogen service is strongly influenced by their resistance to hydrogen embrittlement and high-temperature hydrogen attack, both of which can critically affect structural integrity. Materials selected for liquid, cold, or gaseous hydrogen systems must therefore demonstrate proven compatibility through historical service experience and validated testing standards. In current industrial practice, austenitic stainless steels such as 304, 304L, 316, and 316L (solution-treated), as well as aluminium alloys including 1100, 6061-T6, and 7075-T73, are generally regarded as mature, high-TRL options due to their established record of successful use in cryogenic and hydrogen environments [127].

For components continuously exposed to liquefied or cold hydrogen, the mechanical performance requirements and impact-testing procedures defined in the ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Part 3, Section 3.11 remain the reference standard. Verification of hydrogen compatibility typically involves dedicated embrittlement

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testing, with the Slow Strain Rate Tensile (SSRT) test being the primary method. Two specimen types are normally required: a plain round-bar tensile specimen of the base material, and a notched round-bar tensile specimen, used to evaluate crack-initiation sensitivity [128].

Overall, while several metallic materials used for hydrogen storage, piping, and containment systems have reached high TRL levels (7–9) due to decades of use in aerospace, industrial gas handling, and cryogenic systems, continued testing and qualification remain essential for maritime applications, where operating conditions, thermal cycling, and fatigue loads differ from those in established land-based industries.

Table 32 - Hydrogen TRL

	TRL	**Explanation**
Hydrogen production – Steam Methane Reforming (SMR)	**9**	SMR is fully commercial and globally deployed at industrial scale, representing the dominant hydrogen production route worldwide.
Hydrogen production – Electrolysis (Alkaline, PEM, SOEC)	**7–8**	Alkaline and PEM electrolysers are commercially available, while SOEC remains at demonstration level; overall readiness varies by technology variant.
Hydrogen production – Coal gasification / oil reforming	**8**	Mature industrial technologies with long operational history, though limited relevance for low-carbon maritime applications without CCS.
Liquefied hydrogen (LH_2) storage onboard	**6**	Cryogenic LH_2 storage has reached demonstration stage for shipping, but remains constrained by liquefaction energy demand and boil-off management.
Compressed hydrogen (CH_2) storage onboard	**7**	High-pressure storage systems are proven in operational environments for short-sea and port vessels.
Metal hydride storage (MH_2)	**3–4**	Technology remains at experimental to early proof-of-concept stage, unsuitable for large-scale marine deployment.
Liquid Organic Hydrogen Carrier (LOHC)	**6–7**	Pilot and early on-ship demonstrations exist, with system integration and efficiency still limiting full maturity.
Hydrogen safety systems (fire, explosion, detection)	**5–6**	Safety principles and components are mature, but system-level validation in routine maritime operation is limited.
Material compatibility for hydrogen systems	**8**	Suitable materials are well established in industrial and cryogenic applications, requiring only marine-specific qualification.
Overall TRL	**6**	The overall TRL is constrained by onboard storage technologies and system-level safety integration, which remain at demonstration to early operational stage.

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COMMERCIAL READINESS LEVEL

Robustness of the Industrial Supply Chain and Scalability

From a commercial readiness perspective, hydrogen's viability as a marine fuel depends less on isolated technological performance and more on the robustness and scalability of the end-to-end industrial supply chain. Commercial deployment requires the ability to deliver low-carbon hydrogen at predictable volumes, schedules, and prices across multiple ports and regions. At present, this condition is only partially met [113].

The hydrogen supply chain remains fragmented and regionally concentrated. Electrolyser manufacturing capacity is expanding rapidly, but remains exposed to bottlenecks in stack production, balance-of-plant components, power electronics, and skilled manufacturing labour. Reported capital costs for alkaline and PEM electrolysers (on the order of ~1,600–2,000 €/kW) still dominate project economics and delivery timelines, while upstream OPEX is strongly driven by renewable electricity availability and price volatility. Downstream, bulk storage and long-distance transport infrastructure—whether via pipelines, liquid hydrogen shipping, or conversion to carrier molecules—remains limited and unevenly distributed [114].

In the maritime context, the bunkering segment introduces additional scaling constraints. Ports require dedicated hydrogen reception, storage (pressurised or cryogenic), safety systems, and reliable interfaces for ship-to-ship or shore-to-ship transfer. While several port-scale hydrogen hub projects demonstrate technical and organisational feasibility—particularly in Northern Europe—current capacities are typically limited to single-digit or low-hundreds of kilotonnes of hydrogen per year. This is orders of magnitude below the multi-megatonne annual volumes that would be required to support widespread adoption in deep-sea shipping.

Scalability risks are therefore multi-layered: industrial equipment supply (electrolysers, tanks, compressors), infrastructure construction and permitting capacity, availability of renewable electricity feedstock, and the absence of globally standardised bunkering interfaces. Without accelerated deployment trajectories and harmonisation of technical standards, current developments risk producing geographically isolated "islands" of supply rather than a fungible global hydrogen market. From a CRL standpoint, the supply chain can support pilot and early commercial projects, but lacks the depth and redundancy required for large-scale, system-wide deployment [132].

Bankability

Bankability is a central determinant of commercial readiness, as it governs whether hydrogen projects can attract debt financing at scale rather than relying predominantly on public support or corporate balance sheets. For hydrogen in shipping, bankability is improving but remains non-routine [113].

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Lenders and institutional investors consistently identify four primary risk factors: offtake uncertainty, technology and integration risk, regulatory ambiguity, and revenue volatility. Early hydrogen production and bunkering projects are therefore treated as first-of-a-kind infrastructure, characterised by higher required equity shares, shorter debt tenors, and elevated cost of capital. Financial close is typically achievable only where long-term offtake agreements with creditworthy counterparties are in place, or where public de-risking instruments (such as contracts for difference, guaranteed price floors, or concessional finance) materially reduce downside risk.

Two bankability pathways are emerging. The first relies on anchor off-takers—major shipping companies, energy incumbents, or state-backed entities—committing to long-term volume or price contracts that stabilise cash flows. The second is policy-led, involving blended public–private financing structures, government guarantees, and standardised contractual frameworks designed to lower transaction costs and perceived risk. Where these mechanisms align, hydrogen bunkering and production projects have reached final investment decision; where they do not, projects frequently stall at the permitting or commercial negotiation stage [131].

Insurance and liability considerations further affect bankability. Until international standards for hydrogen bunkering, onboard storage, and risk management are fully harmonised, underwriters apply conservative assumptions, increasing insurance premiums and financing costs. This creates a feedback loop in which higher capital costs reinforce hydrogen's lack of short-term price competitiveness, thereby increasing dependence on policy support. From a CRL perspective, hydrogen projects are financeable under specific, well-structured conditions, but have not yet achieved the level of contractual standardisation and risk familiarity associated with mature marine fuel markets.

CAPEX and OPEX

Capital and operating expenditures remain a decisive barrier to hydrogen's commercial readiness in maritime applications. Unlike conventional marine fuels, hydrogen requires significant investment across the entire value chain, including production, logistics, port infrastructure, and onboard systems.

Upstream, electrolyser CAPEX and renewable electricity costs dominate hydrogen production economics. While learning curves and economies of scale are expected to reduce costs over time, current green hydrogen prices remain multiple times higher per unit of energy than fossil-based marine fuels. Logistics and conversion steps—such as liquefaction or transformation into carrier molecules—add further capital intensity and efficiency losses, particularly for long-distance transport.

At the port level, hydrogen bunkering infrastructure entails substantial fixed investments in storage tanks, safety systems, vapour handling, and transfer equipment. Onboard, hydrogen propulsion systems impose additional CAPEX penalties due to fuel cells or hydrogen-capable engines, balance-of-plant complexity, and the volumetric energy density disadvantage of hydrogen, which requires larger tanks and can reduce cargo capacity or operational flexibility. Retrofit scenarios are particularly capital-intensive and operationally disruptive [116].

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From an OPEX perspective, fuel cost per unit of delivered energy remains the dominant factor, followed by maintenance, bunkering frequency, and infrastructure utilisation rates. Techno-economic assessments consistently show that hydrogen approaches economic viability first in applications with short ranges, predictable routes, and centralised bunkering—such as ferries, harbour craft, and certain offshore service vessels—especially when carbon pricing or emission constraints are internalised. For deep-sea bulk and container shipping, however, current CAPEX and fuel cost differentials render hydrogen commercially unattractive without substantial and sustained policy support.

Sensitivity analyses indicate that significant reductions in electrolyser CAPEX (on the order of 30–50%) combined with continued declines in renewable electricity prices are prerequisites for broader competitiveness by 2030. Absent these developments, hydrogen's role is likely to remain confined to niche maritime segments rather than serving as a universal fuel solution [112].

Commercial Readiness Synthesis

In summary, hydrogen has reached a level of commercial readiness suitable for targeted, controlled maritime applications, supported by pilot projects, early commercial deployments, and credible industrial investment plans. However, at the scale required to decarbonise global deep-sea shipping, commercial readiness has not yet been achieved.

The principal constraints are: (i) insufficiently scaled and standardised supply chains, (ii) limited bankability without extensive de-risking mechanisms, and (iii) higher CAPEX and OPEX relative to competing fuel pathways. Recent policy and industry literature converges on a pragmatic strategy: prioritise hydrogen deployment where its operational advantages create clear value, accelerate standardisation of bunkering and safety frameworks, and deploy financial instruments that bridge the gap between early commercial projects and a mature, self-sustaining market.

Table 33 - Hydrogen CRL

	CRL	Explenation
Industrial hydrogen supply chain robustness	**4–5**	Supply chains exist but remain fragmented, regionally concentrated, and insufficiently scaled for maritime demand.
Port bunkering infrastructure readiness	**4–5**	Early hydrogen hubs are emerging in Europe, but global bunkering coverage and standardisation are lacking.
Scalability for deep-sea shipping	**3–4**	Current hydrogen production and logistics capacities are far below the volumes required for deep-sea shipping.
Bankability of hydrogen projects	**5**	Projects are financeable only under specific conditions, typically relying on public de-risking instruments or anchor offtakers.
CAPEX and OPEX competitiveness	**3–4**	High capital intensity and fuel costs limit competitiveness compared to conventional fuels without strong policy support.

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Early commercial deployment and replication	**5–6**	Pilot and first-of-a-kind projects exist, but business models are not yet widely replicable.
Overall CRL	**4**	Commercial readiness remains limited by high costs, scaling challenges, and dependence on policy support rather than market-driven deployment.

SOCIETAL READINESS LEVEL

International regulation and consistency with European policies

The international regulatory framework governing the use of hydrogen as a marine fuel is undergoing rapid development but has not yet reached full maturity. Within the International Maritime Organization (IMO), hydrogen is currently addressed under the overarching structure of the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code), which entered into force in 2017 and was originally conceived with a primary focus on LNG. While the IGF Code establishes goal-based functional requirements applicable in principle to gaseous fuels, it did not initially include hydrogen-specific provisions, resulting in a regulatory gap given hydrogen's distinct physical, chemical, and safety characteristics.

To address this gap, the IMO Sub-Committee on Carriage of Cargoes and Containers (CCC) has developed interim guidelines for ships using hydrogen as fuel, following a structured and iterative process involving correspondence groups and technical working sessions starting in the early 2020s. This effort culminated at CCC 11 (September 2025) with the finalization of draft interim guidelines covering liquefied hydrogen, fixed compressed hydrogen, and portable compressed hydrogen systems. The guidelines define functional safety requirements for fuel storage, system layout, ventilation, leak detection, monitoring, material selection, and segregation, and are explicitly designed as supplements to the IGF Code rather than as a standalone regulatory instrument. Approval by the IMO Maritime Safety Committee is anticipated at MSC 111 (May 2026), with subsequent integration into the IMO regulatory framework [133].

Despite this progress, the hydrogen guidelines remain non-mandatory at present, meaning that their practical enforcement depends on national administrations and classification societies through alternative design approvals under SOLAS. As a result, hydrogen-fuelled ship projects are still assessed largely on a case-by-case basis, relying on risk-based design and formal safety assessment rather than prescriptive rules. Draft amendments to related instruments, including the International Gas Carrier (IGC) Code, are under development and are expected to enter into force in the late 2020s, subject to formal adoption. Until then, regulatory certainty remains limited, particularly for propulsion concepts combining hydrogen storage, fuel cells, and hybrid power systems.

At the regional level, the European Union is providing a stronger market signal through climate-driven regulation rather than safety codes. The FuelEU Maritime regulation, effective from January 2025, establishes progressively tightening greenhouse gas intensity

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limits for energy used on board ships, thereby incentivising the uptake of low- and zero-carbon fuels, including hydrogen and hydrogen-derived fuels. Renewable fuels of non-biological origin (RFNBOs), such as green hydrogen, benefit from temporary double-counting mechanisms to accelerate early adoption. However, these climate-oriented instruments do not directly resolve safety standardisation issues and require alignment with IMO rules to avoid regulatory fragmentation.

Overall, the regulatory ecosystem for hydrogen as a marine fuel can be characterised as transitioning from an exploratory to a consolidation phase. The underlying safety principles are increasingly well defined, and hydrogen-specific requirements are approaching formal adoption at IMO level. Nevertheless, full regulatory readiness has not yet been achieved. Key gaps remain in the mandatory status of international rules, harmonisation across jurisdictions, integration into class society standards, and the establishment of robust fuel certification schemes. Consequently, from a regulatory and institutional perspective, hydrogen for marine use can be considered at an intermediate stage of readiness, with further codification and alignment required before widespread commercial deployment can proceed under a fully mature and predictable regulatory regime.

Stakeholder acceptance: shipowners, ports, maritime authorities, crews, and industry actors

Stakeholder acceptance of hydrogen as a marine fuel is currently **mixed and conditional**:

Shipowners and commercial operators are cautiously interested but emphasize the need for reliable cost data and risk management frameworks. Hydrogen fuel systems — particularly cryogenic LH_2 — require significant redesign of storage and supply infrastructure, and uncertainty about total cost of ownership (fuel, engine conversions, safety systems) remains a barrier. Economic incentives in regulations like FuelEU Maritime help, but without clear scaling of fuel supply and bunkering infrastructure, many operators are hesitant.

Maritime authorities and classification societies are actively preparing for hydrogen. For example, **Bureau Veritas** has published classification rules (NR678) addressing safe bunkering, storage, and fuel system design specific to hydrogen, covering issues like high flammability and cryogenic handling at low temperatures. These rules also include provisions for “hydrogenprepared” vessels allowing future retrofit.

Crew and training stakeholders face safety concerns tied to hydrogen’s properties — namely, its **wide flammability range and low ignition energy**. In response, the IMO is developing **interim training guidelines** specific to hydrogen and other alternative fuels, to be incorporated into the STCW Convention training standards. Certified training and emergency response preparedness are repeatedly cited by seafarers as essential for confidence.

Port operators are early movers. Key European ports like **Rotterdam** are building hydrogen infrastructure systems that combine production, storage, and potential bunkering services, positioning themselves as hydrogen hubs for Northwest Europe. In **Ostend, Belgium**, a dedicated hydrogen refuelling station opened in 2025 to serve offshore wind vessels and potentially future hydrogen bunkering efforts.

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Pilot vessels and demonstrators also contribute to acceptance: the **MV Hydrotug 1**, a hydrogenpowered tug using compressed hydrogen, entered operational service in **2024**, providing practical experience with hydrogen propulsion in port operations.

Enabling conditions for stakeholder readiness:

- Operational data and safety validation from realworld pilots (e.g., hydrogen tugs, refuelling stations).
- Standardised, internationally recognised training programs.
- Regulatory and insurance clarity reducing risk perception and cost uncertainty.

Overall, acceptance exists but is tied to demonstrable safety performance, infrastructure buildout, and alignment of commercial incentives [116].

Social and Territorial aspects

Deploying hydrogen at port scale introduces specific community and territorial concerns tied to **public safety perception, land use, and economic impacts**.

Hydrogen is **highly flammable** and diffuses rapidly, which necessitates advanced safety planning, consequence modelling, and clearly communicated risk mitigation strategies. Ports adopting hydrogen infrastructure must engage local stakeholders early to explain safety measures, emergency response plans, and monitoring systems. Evidence from port projects elsewhere shows that when public consultations, transparent data sharing, and joint emergency preparedness drills are included, community opposition tends to decrease relative to projects without engagement [126].

Territorial acceptance also hinges on socioeconomic benefits. Hydrogen infrastructure investments can generate **local skilled jobs**, industrial diversification, and integration with regional energy transition plans. For example, local hydrogen value chains may link renewable power generation with port supply facilities, attracting wider stakeholder support [132].

Without proactive engagement and visible community benefits, social resistance — including mobilisation through local media or civil society groups — can delay permitting and implementation.

Table 34 - Hydrogen SRL

	SRL	Explanation
International regulation (IMO, IGF Code, interim guidelines)	**5–6**	Hydrogen-specific rules are under development at IMO level but remain largely non-mandatory and applied case-by-case.
Consistency with European policies (FuelEU, EU ETS)	**6–7**	EU climate regulations provide strong incentives for hydrogen uptake, improving policy alignment and market signals.
Shipowner and operator acceptance	**5**	Acceptance is cautious and conditional on cost certainty, safety validation, and infrastructure availability.

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Port and maritime authority acceptance	**6**	Ports and authorities are proactive, particularly in Europe, with hydrogen strategies and pilot infrastructure in place.
Crew safety and training readiness	**4–5**	Hydrogen-specific training standards are emerging, but widespread crew familiarisation is still limited.
Social and territorial acceptance	**5–6**	Public acceptance is achievable with transparent engagement and local benefits, but remains sensitive to perceived safety risks.
Overall SRL	**5**	Societal readiness is moderate, with growing institutional support but persistent concerns around safety, training, and public perception.

3.7. Energy converters and generation systems

This section evaluates the readiness of different onboard energy conversion and storage technologies. Fuel cells (PEM, SOFC) are progressing through pilot installations, demonstrating high efficiency and zero local emissions, but their durability, cost, and sensitivity to fuel purity remain major challenges. [134] Maritime battery systems, mainly based on lithium-ion technology, are already commercially deployed in short-sea applications, with solid-state batteries representing a potential breakthrough in safety and energy density at lower TRL. Hybrid solutions combining batteries with combustion engines or fuel cells are gaining traction as transitional architectures that optimise energy use and reduce emissions. The assessment positions batteries as commercially available, fuel cells as pre-commercial, and hybrid systems as an increasingly relevant integration pathway.

ELETTROCHEMICAL ACCUMULATOR AND SUPERCAPACITORS

Electrochemical energy storage has rapidly emerged as a central technology in the modernisation of maritime propulsion systems, driven by decarbonisation objectives, operational efficiency gains, and the increasing electrification of onboard systems. Lithium-ion batteries—particularly lithium-iron-phosphate (LFP), nickel-manganese-cobalt (NMC), and lithium-titanate (LTO) chemistries—currently represent the state of the art, enabling applications ranging from hybrid propulsion and peak shaving to fully electric operations on short-sea routes. These systems offer high energy efficiency, rapid response times, modular design flexibility, and continuously improving safety performance, making them increasingly attractive for ferries, offshore support vessels, harbour tugs, and inland waterway ships. [135] In parallel, supercapacitors have gained traction as complementary high-power devices capable of delivering extremely fast charge–discharge cycles, making them suitable for dynamic peak-load management, manoeuvring, and regenerative energy capture. [136] Although current electrochemical storage technologies are not yet viable for long-range deep-sea shipping due to limitations in energy density, cost, and system weight, their adoption in short-to-medium-range vessels is accelerating rapidly, supported by growing industrial production capacity, the standardisation of battery safety regulations, and demonstrable operational benefits. [137] As technological advances continue to increase battery

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performance, reduce lifecycle costs, and improve system integration, electrochemical accumulators and supercapacitors are expected to play an expanding role in future maritime energy architectures, particularly as hybrid enablers in conjunction with alternative fuels or next-generation low-carbon propulsion systems.

TECHNOLOGY READINESS LEVEL

General consideration about the technology

Lithium-ion batteries dominate current maritime electrification thanks to their maturity, safety performance, and adaptability across vessel classes. Among them, three chemistries—**LFP**, **NMC**, and **LTO**—are the most relevant for naval applications. Each offers distinct electrical and operational characteristics that influence vessel design, integration complexity, and mission suitability. Their limitations, particularly in energy density and spatial integration, define the boundaries of battery-powered propulsion at sea.

Lithium-Iron-Phosphate (LFP) batteries currently represent the mainstream solution for battery-electric ferries, inland cargo vessels, and short-sea service craft. Their strong safety profile, thermal stability, and the absence of cobalt or nickel make them particularly attractive for maritime environments where fire safety and supply-chain robustness are critical. As follows the main technical features of this type of battery:

- **Energy density:** ~120–160 Wh/kg (gravimetric), ~300–350 Wh/L (volumetric)
- **Power capability:** Moderate; suitable for steady propulsion loads
- **Cycle life:** High (3,000–10,000 cycles depending on C-rate)
- **Thermal stability:** Excellent; low thermal runaway risk

LFP's relatively low energy density compared to NMC increases the volume and mass of battery rooms, impacting vessel layout and stability, especially in retrofits. For ferries or vessels operating on fixed, short-duration routes, these constraints remain manageable. However, the limited onboard energy storage restricts applications to short-sea missions with predictable charging intervals. Beyond this operational range, LFP systems would require impractically large installation volumes and weight, ruling out deep-sea applications.

Nickel-Manganese-Cobalt (NMC) batteries provide higher energy density than LFP, making them attractive where available hull volume is limited or where hybrid systems require compact energy storage modules. They are widely used in hybrid offshore support vessels, Ro-Pax ferries, and high-power auxiliary systems. As follows the main technical features of this type of battery: [135]

- **Energy density:** ~180–250 Wh/kg (gravimetric), ~400–600 Wh/L (volumetric)
- **Power capability:** High; suitable for hybrid manoeuvring and load balancing
- **Cycle life:** Moderate (1,500–4,000 cycles)
- **Thermal stability:** Lower than LFP; requires robust safety engineering

NMC's higher energy density reduces space requirements in battery rooms, but introduces thermal-management challenges, requiring sophisticated cooling, fire suppression, and cell-

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level monitoring. In hybrid naval architectures—DP vessels, Ro-Ro ferries, cruise auxiliaries—it is often the preferred option due to compactness and high discharge rates. Yet, despite the improved density, the technology still cannot approach the energy-per-mass performance required for multi-day propulsion. The dependence on cobalt and nickel also raises environmental and social concerns that affect long-term societal acceptance and supply stability.

Lithium-Titanate (LTO) batteries occupy a specialised niche where extreme power demand, fast charging, and long cycle life outweigh the need for high energy density. They are especially relevant for harbour tugs, high-speed ferries, offshore vessels with peak-power DP operations, and other high-C-rate applications. As follows the main technical features of this type of battery:

- **Energy density:** ~70–90 Wh/kg (very low compared to LFP/NMC)
- **Power capability:** Exceptional (supports very high charge/discharge rates)
- **Cycle life:** Extremely high (10,000–20,000+ cycles)
- **Thermal stability:** Very high; best-in-class safety

LTO excels where propulsion systems experience rapid load changes or require fast cycling without degradation. However, its low energy density imposes severe mass and volume penalties, making it unsuitable for anything beyond short-duration, high-power missions. Even in hybrid systems, LTO's integration requires careful weight distribution and structural accommodation. For small vessels with frequent docking cycles, LTO is an ideal technology, but for endurance-oriented missions, it becomes impractical.

Despite their widespread adoption, all lithium-ion chemistries share inherent constraints that limit full electrification beyond short-sea and inland operations: [138]

- **Energy density ceilings** prevent supplying the multi-day propulsion demands of large cargo vessels.
- **Battery mass and volume** scale non-linearly with vessel endurance, overwhelming naval architecture constraints.
- **Thermal management systems** increase integration complexity and reduce effective usable space.
- **Safety compartmentalisation** (ventilation, fire zoning, gas detection) further reduces layout flexibility.
- **Charging infrastructure dependence** restricts operations to ports with grid capacity and fast-charging systems.
- **Technological plateau** in Li-ion chemistry means only incremental improvements to energy density are expected to 2030.

This makes lithium-ion batteries highly suitable for ferries, inland craft, harbour tugs, and hybrid offshore vessels, but fundamentally limits their role in long-range maritime propulsion.

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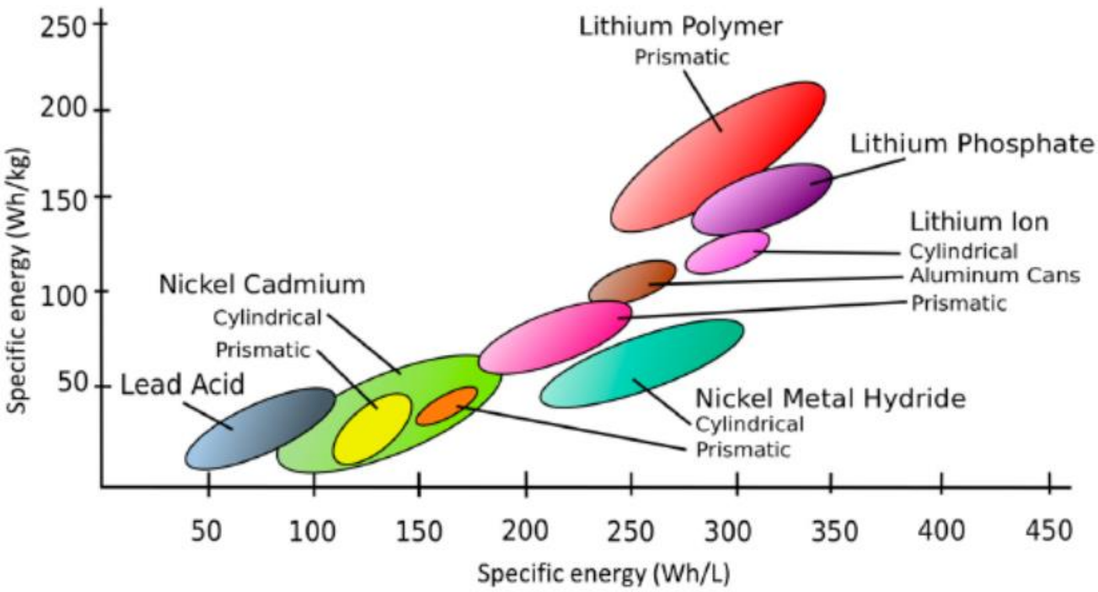

Figure 22 - Specific energy of different type of batteries - Lucà Trombetta, G.;Leonardi, S.G.; Aloisio, D.; Andaloro,L.; Sergi, F. Lithium-Ion Batteries onBoard: A Review on Their Integrationfor Enabling the Energy Transition inShipping Industry. Energies 2024

Beyond lithium-ion systems, a growing set of non-lithium battery technologies is emerging as potentially valuable alternatives for maritime applications, particularly where safety, cost stability, or sustainability considerations dominate. Although these technologies generally lag behind lithium-ion in technological maturity and energy density, they offer distinct advantages that address some of the structural limitations inherent to LFP, NMC, and LTO chemistries. **Sodium-ion (Na-ion)** batteries are currently the most promising near-term candidate: they deliver moderate energy density with excellent thermal stability and rely on abundant, geopolitically uncritical materials such as sodium, iron, and manganese. For inland vessels, short-range ferries, and port-support craft—where weight and volume constraints are less severe—Na-ion batteries have the potential to become a low-cost, high-acceptance alternative aligned with circular-economy principles. In the stationary domain of shore-side infrastructure, **vanadium redox flow batteries (VRFBs)** are gaining traction as ideal solutions for onshore power supply (OPS) buffering, offering virtually unlimited cycle life, intrinsic safety, and stable long-duration energy storage; however, their low energy density prevents meaningful shipboard propulsion applications. Additional non-lithium concepts such as **zinc-based batteries** (including Zn-air and Zn-hybrid chemistries) bring advantages in safety, low material cost, and full recyclability, making them attractive candidates for future port-based storage or low-power maritime systems once their cycle life and power capability improve. More speculative technologies—including **metal-air systems** (Al-air, Li-air) and advanced aqueous batteries—offer the possibility of extremely high theoretical energy densities, but remain at low TRLs and face fundamental engineering challenges such as rechargeability, electrode stability, and oxygen management that currently preclude naval adoption.

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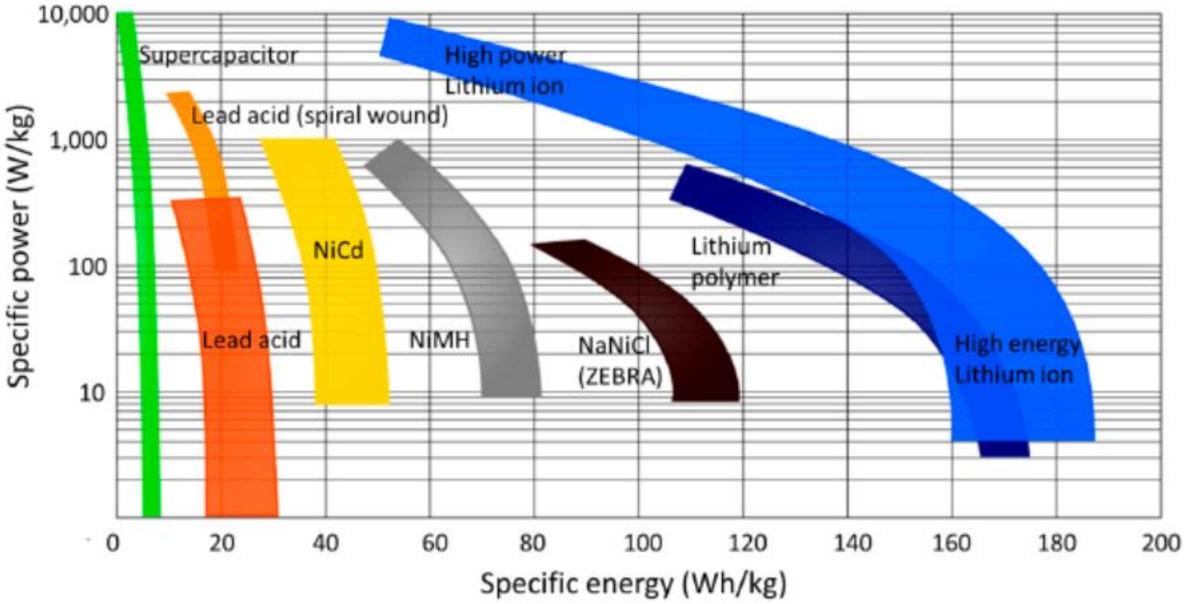

Figure 23 - Specific energy vs power of different type of batteries - Lucà Trombetta, G.;Leonardi, S.G.; Aloisio, D.; Andaloro,L.; Sergi, F. Lithium-Ion Batteries onBoard: A Review on Their Integrationfor Enabling the Energy Transition inShipping Industry. Energis 2024, 17,1019. https://doi.org/10.3390/en17051019

From a naval engineering perspective, non-lithium chemistries today serve primarily as **complementary rather than competitive solutions** to lithium-ion systems. Their lower energy densities, immature certification pathways, and limited operational history mean they cannot presently support propulsion on commercial vessels except in niche or hybrid contexts. Nonetheless, their inherent advantages—particularly **improved safety profiles**, **use of abundant materials**, **reduced fire risk**, and **strong alignment with EU sustainability regulations**—position them as strategically important elements of future maritime energy ecosystems. As charging infrastructures expand and the environmental footprint of battery production becomes a central societal concern, non-lithium chemistries are expected to play an increasingly significant role in **port electrification**, **shore-side buffering**, and potentially, by 2035–2050, in onboard energy storage for specific vessel classes with moderate endurance requirements. Their long-term relevance is therefore not in replacing lithium-ion technologies outright, but in **broadening the technological landscape** and enabling a more resilient, diversified, and socially accepted maritime electrification pathway.

Resource Availability and Production

The rapid expansion of battery deployment in the maritime sector raises important questions regarding the availability of raw materials and the scalability of global production chains. Lithium-ion batteries—currently the dominant electrochemical storage technology for

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onboard applications due to their mature performance, favourable energy density, and evolving safety features—depend on materials whose extraction, processing, and distribution are geographically concentrated and subject to supply risk. Global demand for lithium, nickel, cobalt, graphite, and copper is expanding rapidly as electrification accelerates across transport, industrial, and stationary storage sectors. According to recent analyses, global lithium-ion cell manufacturing capacity has increased from approximately 150 GWh/year in 2018 to around 700 GWh/year in 2022, with projections reaching 1700 GWh/year by 2025 and potentially 4700 GWh/year by 2030. This expansion reflects both market demand and acceleration in industrialisation of battery production, but also places substantial pressure on upstream resource extraction.

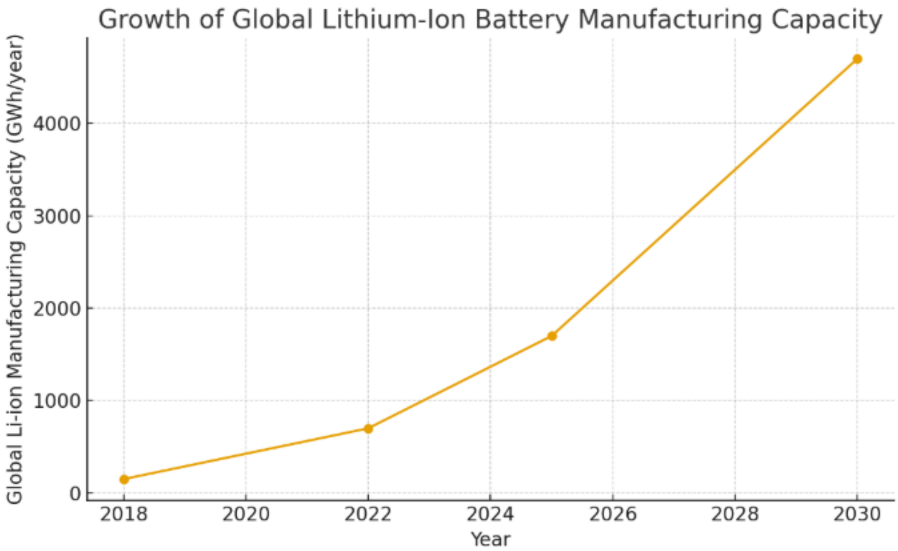

Figure 24 - Global battery manufacturing capability

Lithium supply must significantly increase to meet expected demand growth, while cobalt remains particularly sensitive due to its strong geographic concentration, with more than 70% of global output sourced from the Democratic Republic of Congo. This concentration has raised concerns regarding supply security, price volatility, and ethical issues linked to artisanal mining. As a result, there is a growing industrial shift toward cobalt-lean or cobalt-free chemistries, especially lithium-iron-phosphate (LFP), which is increasingly attractive for maritime applications due to its safety, thermal stability, and favourable resource profile. Nickel demand is also rising, particularly in markets adopting high-nickel cathodes, though supply diversification is more robust than for cobalt. Graphite, essential for anode manufacturing, remains another bottleneck: natural and synthetic graphite production is dominated by a limited number of countries, raising concerns about export restrictions and supply chain resilience.

Supercapacitors, by contrast, rely predominantly on carbon-based materials rather than critical metals, reducing resource constraints but limiting their application to high-power, short-duration services due to inherently lower energy density. Overall, while global battery manufacturing capacity is expanding at a record pace, the maritime sector must recognise that it competes with much larger markets—particularly automotive and grid-scale storage—

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potentially affecting long-term price stability and availability of critical materials. Consequently, marine battery adoption increasingly favours chemistries with stable and scalable supply chains, such as LFP or LTO, while recycling technologies capable of recovering lithium, cobalt, nickel, and graphite will play a progressively central role in ensuring supply resilience. However, recycling processes are not expected to materially offset primary extraction before the mid-2030s, making raw material availability a key determinant for large-scale electrochemical storage integration in shipping.

Bunkering (Battery Charging) and Storage on Board

The transition from conventional fuels to electrochemical energy storage fundamentally reshapes the concepts of bunkering and onboard storage within the maritime sector. Unlike liquid or gaseous fuels, bunkering for battery-electric and hybrid vessels refers primarily to **high-capacity charging operations**, which depend on the availability of robust port-side electrical infrastructure capable of delivering large power flows in short time windows. As vessel power demands increase—particularly for ferries, short-sea cargo vessels, and offshore support units—the required charging capacities can reach tens of megawatts, necessitating significant upgrades to port electrical grids, the installation of dedicated substations, and integration of smart-charging systems capable of managing peak loads. The feasibility of rapid turnaround operations relies on both the **power rating** and **redundancy** of these shore-charging systems, with many ports currently evaluating the adoption of automated connection interfaces, onshore energy storage buffers, and load-levelling strategies to avoid grid saturation.

Onboard storage requirements present additional constraints. Electrochemical systems such as LFP, NMC, or LTO batteries require substantial volumetric and weight allocation, influencing vessel design, stability, and cargo layout. Battery rooms must meet strict safety standards, including fire suppression, temperature control, ventilation, and segregation from critical systems. Supercapacitors, although smaller in energy terms, also require dedicated spaces close to high-power loads to minimise resistive losses. Safety considerations—thermal runaway management, early detection systems, and fault-tolerant architectures—are central to storage integration and are increasingly codified in classification-society rules. Because recharging operations may occur multiple times per day, the choice of battery chemistry strongly affects operational flexibility: fast-charging-capable systems such as LTO or LFP enable high-frequency operations, while high-energy NMC systems may require longer rest periods to preserve lifetime.

Across Europe, the landscape of ports equipped with high-power charging infrastructure and cold ironing is rapidly expanding, though deployment remains strongly uneven between pioneering regions and ports where implementation is still at the planning or early construction stage. Northern Europe continues to lead the sector thanks to early mass adoption of electric and hybrid ferries. In Denmark, the Port of Søby hosts the fast-charging installation for the fully electric E-Ferry *Ellen*, whose 4.3 MWh battery pack is charged via a 4 MW ramp-integrated system capable of transferring more than 1 MWh during short port calls. On the Lavik–Oppedal route in Norway, the *MF Ampere* is charged via shore-side battery banks that buffer the public grid and deliver roughly 1 MW of fast charging within minutes, using automated connection systems. Finland's *Elektra* ferry, operating between Nauvo and Parainen, relies on high-power shore charging fed through a 20 kV supply and stepped down to 690 V onboard, demonstrating the feasibility of fast charging in challenging winter environments. In Iceland, the hybrid ferry *Herjólfur* uses an automatic connector at Landeyjahöfn delivering approximately 2.5 MW to a 3 MWh battery system, allowing fully electric operation on shorter segments. Norway, supported by structured modelling tools such as DNV's ReCharge platform and a strong policy push for zero-emission fjord operations, has by far the densest network of maritime charging installations globally.

In the Mediterranean and Atlantic regions, deployment has focused more on cold ironing for cruise, Ro-Pax and container ships than on fast charging for fully electric ferries, but the modernisation trajectory is clear. Barcelona has emerged as a major reference point: the BEST container terminal hosts the first Mediterranean OPS system for container vessels, while the Grimaldi ferry terminal began connecting ships to OPS in 2025, supported by the large-scale Nexigen programme that aims to electrify all cruise and ferry terminals. Marseille Fos has likewise upgraded its OPS systems, becoming one of the few Mediterranean ports offering high-voltage cold ironing for both Corsica ferries and cruise ships, with more than €50 million already committed to expanding shore-power capabilities. Across the wider Mediterranean and Atlantic basins, the EU-funded EALING project has standardised technical and governance frameworks for cold ironing in at least sixteen ports—from Valencia and Barcelona to Ancona, Trieste, Koper, Piraeus, Burgas and Varna—many of which now have detailed engineering designs ready for construction or already under way. These investments are complemented in Italy by national PNRR-funded plans to deploy at least fifteen cold-ironing installations in ten major ports.

In inland waterways, OPS deployment is progressing but still fragmented. Along the Austrian Danube, ports such as Linz and Wildungsmauer have installed 400 V shore-power terminals with multiple CEE outlets, serving cargo and passenger vessels during layovers. EU regulatory frameworks under AFIR and the TEN-T revision require every core inland port to offer shore-side electricity by 2024 and every comprehensive port by 2029, pushing Rhine and Danube ports toward systematic modernisation even where today's demand is still limited. Early OPS pilots in Cologne, Basel and other Rhine–Danube cities generally begin with lower power ratings focused on hotel loads, but are designed for scalable expansion as hybrid and electric inland vessels become more common.

Despite these advances, Europe as a whole remains behind the deployment curve. A recent screening of 31 major European ports shows that only around a fifth of the OPS connections required under EU law for 2030 are currently installed or contracted, with container terminals lagging significantly behind cruise and ferry berths. Nonetheless, the pioneering Nordic, Mediterranean and inland installations demonstrate that the key technological building blocks—megawatt-scale electrical feeders, frequency and voltage converters, shore-side energy storage buffers, and automated connection solutions—are mature and already operating successfully. These examples provide concrete references for the concept of "electrical bunkering" and offer realistic benchmarks for the infrastructure that will be

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required as battery-electric and hybrid vessels scale across European short-sea and inland waterway transport.

Health and Safety

The integration of electrochemical accumulators and supercapacitors into maritime operations introduces a distinct set of health and safety considerations that must be addressed both onboard and within port infrastructures. Lithium-ion batteries, regardless of chemistry, pose inherent risks related to thermal runaway, off-gassing, and fire propagation, requiring dedicated battery rooms equipped with advanced temperature monitoring, ventilation, fire suppression systems, and physical segregation from critical ship systems. Classification societies have progressively codified these requirements—mandating fault-tolerant architectures, isolation zones, and early-warning systems capable of detecting cell-level anomalies long before they escalate into hazardous conditions. Safety is strongly influenced by the chemistry selected: LFP and LTO batteries generally offer higher thermal stability than high-energy NMC variants, reducing the likelihood of rapid heat release, though all chemistries require robust containment strategies.

High-power charging operations introduce additional safety challenges. Frequent connection and disconnection cycles, often involving automated or robotic interfaces, must be designed to withstand harsh marine environments, mechanical misalignment, and exposure to salt spray. Ports must implement rigorous electrical protection measures—ground fault detection, isolation transformers, interlocks, and controlled connection sequences—to prevent arcing or unintended energisation. On-shore energy storage buffers, sometimes used to stabilise grid demand during peak charging, carry their own safety obligations, including compliance with local fire regulations and emergency-response protocols. Crew training is essential: personnel must understand the specific hazards of electrochemical systems, proper handling of charging equipment, emergency shutdown procedures, and the use of personal protective equipment. In the event of battery failure or fire, emergency response strategies differ markedly from those used for hydrocarbon fuels, requiring dedicated firefighting agents, cooling techniques, and isolation protocols.

Overall, the adoption of large-scale battery systems at sea and in ports demands a systematic approach to health and safety that spans vessel design, port engineering, operational procedures, and human factors. While modern technologies and regulations provide strong mitigation capabilities, the rapid expansion of electrochemical storage in maritime applications makes continuous updating of standards, training, and monitoring essential to ensure safe and resilient operation across the vessel–port interface.

Fire Onboard

Fire onboard remains one of the most critical safety considerations when integrating large electrochemical storage systems into maritime vessels. Lithium-ion batteries, particularly those with high energy density, can enter thermal runaway when exposed to mechanical damage, internal short circuits, overcharging, or elevated temperatures. Once initiated, thermal runaway can release flammable gases, reach extremely high temperatures, and propagate rapidly between adjacent cells, creating a complex fire scenario fundamentally different from those involving traditional fuels. [139] Battery rooms must therefore be

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designed as independent fire zones equipped with specialised detection systems—such as gas sensors capable of identifying early-stage electrolyte vapours, infrared or thermal monitoring for hotspot identification, and multi-stage alarms that enable rapid intervention before a critical threshold is exceeded. Conventional fire suppression agents are often ineffective in stopping cell decomposition, meaning fire-fighting strategies typically focus on containment, cooling, isolation, and prevention of propagation rather than extinguishment alone.
Maritime fire management protocols must account for the difficulty of accessing battery compartments during an active event. Automatic suppression systems—ranging from water mist and foam solutions to innovative aerosol and encapsulation agents—play a central role, but must be complemented by structural fire barriers, forced ventilation with gas evacuation capability, and secure shutdown and isolation procedures. Crew training is equally essential: unlike fuel-based fires, battery fires cannot always be approached directly, and operators must be prepared to apply correct cooling techniques, isolate damaged modules, and manage toxic or flammable off-gassing. Furthermore, onboard high-power charging increases the risk of electrical faults or connector overheating, particularly in harsh marine environments, making preventive maintenance and correct connection procedures vital. As battery systems grow in size and voltage to support larger vessels, the complexity of onboard fire scenarios similarly increases, reinforcing the need for rigorous design, robust monitoring architectures, and harmonised safety standards across classification societies.

Marinization
The marinization of electrochemical energy storage systems refers to the set of adaptations—technical, environmental, operational, and regulatory—that enable battery technologies and supercapacitors to function safely and reliably under maritime conditions. These conditions include exposure to vibration, shock loads, humidity, salt spray, temperature fluctuations, restricted ventilation spaces, and stringent fire protection requirements. Not all electrochemical technologies developed for land-based applications are immediately suitable for marine deployment, and each chemistry exhibits different degrees of maturity when subjected to these constraints. Lithium Iron Phosphate (LFP) batteries currently demonstrate the **highest TRL (8–9)** within the naval sector, owing to their intrinsic thermal stability, long cycle life, and compatibility with maritime fire-safety architectures. They are already widely adopted in electric and hybrid ferries across Scandinavia and represent the prevailing standard for short-sea electrification. Nickel Manganese Cobalt (NMC) batteries also achieve **TRL 7–8**, offering higher energy density but requiring stricter thermal management and sophisticated battery management systems due to increased susceptibility to thermal runaway; they are typically favored where space and weight constraints dominate. Lithium Titanate Oxide (LTO) systems, although less energy-dense, reach **TRL 8** in maritime contexts thanks to exceptional power capabilities, long cycle life, and extreme fast-charging tolerance, making them ideal for high-frequency shuttle ferries. Other chemistries, such as Sodium-ion (Na-ion) batteries, remain at **TRL 4–5**, with promising cost and safety benefits but limited marine operational experience.
Supercapacitors, which provide high power over short durations, currently stand at **TRL 7–8** for maritime use, having proven their value in peak shaving, manoeuvring assistance, and load smoothing in hybrid propulsion systems; however, their low energy density confines them to auxiliary roles rather than primary propulsion functions. Solid-state batteries, often cited for

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their potential to revolutionize energy density and safety, remain at **TRL 3–4**, with no marine-certified systems available to date and significant challenges in manufacturability, thermal robustness, and lifecycle performance. [140] Flow batteries, including Vanadium Redox (VRFB) systems, sit at **TRL 4–5**, offering attractive safety characteristics and long lifetimes but suffering from low energy density and system complexity, limiting near-term use at sea. Similarly, metal–air systems (such as zinc–air) hold theoretical promise but remain largely experimental at **TRL 2–3**.

Overall, marinization efforts are most advanced for LFP, LTO, and NMC batteries, which already power a growing fleet of electric and hybrid ferries, tugs, and inland cargo vessels. Supercapacitors are technically mature and operationally validated in several naval architectures but serve primarily as power buffers rather than propulsion enablers. Emerging chemistries show long-term potential but require substantial technological maturation and robust validation under maritime environmental and regulatory constraints before reaching commercial viability. As decarbonization policies accelerate, the marinization of these technologies will continue to evolve, with TRL progression strongly influenced by safety certification pathways, industrial-scale production, system integration strategies, and real-world operational feedback from early adopter fleets.

Table 35 - ELETTROCHEMICAL ACCUMULATOR AND SUPERCAPACITORS TRL

Technology	Current TRL (2025)	TRL Forecast 2030	TRL Forecast 2050	Key Marinization Factors
LFP (Lithium Iron Phosphate)	**8–9**	**9**	**9**	High thermal stability; well-established marine installations; cobalt-free; suitable for ferries and hybrid vessels.
NMC (Nickel Manganese Cobalt)	**7–8**	**8–9**	**9**	Higher energy density but more complex safety management; thermal runaway risk; strong BMS requirements.
LTO (Lithium Titanate Oxide)	**8**	**8–9**	**9**	Extremely long cycle life; fast charging; excellent for high-frequency routes; limited range due to low energy density.
Na-ion (Sodium-ion)	**4–5**	**6–7**	**8–9**	Low-cost and cobalt-free; improving energy density; promising for short-sea vessels; lower raw-material constraints.
Supercapacitors	**7–8**	**8–9**	**9**	Mature for peak shaving and manoeuvring; not suitable for main propulsion; high power, low energy density.
Solid-State Batteries	**3–4**	**5–6**	**8–9**	High theoretical safety and energy density; significant manufacturing, cost, and certification challenges remain.
VRFB (Vanadium Redox Flow Batteries)	**4–5**	**6**	**7–8**	Very safe; scalable; long life; limited by large volume/weight; suitable for stationary vessels, ports, offshore platforms.
Zinc–Air / Metal–Air	**2–3**	**3–4**	**6–7**	High theoretical energy density; rechargeability challenges; early experimental stage.
Hybrid Battery–Supercapacitor Systems	**7**	**8–9**	**9**	Effective for dynamic load profiles; improves battery lifetime; requires advanced control strategies.

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OVERALL TRL ASSESSMENT

The overall Technology Readiness Level assessment for electrochemical energy storage in the maritime sector shows that only a limited subset of battery technologies is sufficiently mature for widespread operational deployment by 2030, while others remain in earlier development stages and will require substantial advancement before becoming viable in commercial shipping. High-TRL chemistries such as LFP, NMC, and LTO—as well as supercapacitor systems—have demonstrated sound marinization performance, with robust safety architectures, increasing standardisation from classification societies, and a growing operational track record in ferries, offshore support vessels, harbour craft, and inland shipping. Emerging technologies such as sodium-ion, solid-state batteries, vanadium flow batteries, and metal–air systems show promising characteristics but remain at TRL levels too low for immediate adoption at sea. Their future contribution to maritime decarbonisation will depend on breakthroughs in energy density, manufacturing scalability, and the development of marine-specific certification pathways, with meaningful commercial adoption likely only after 2040.

However, the TRL assessment must be understood in the context of the inherent physical and operational constraints that limit the applicability of electrochemical energy storage across the full spectrum of ship types. Current battery technologies are well suited to **short-sea and high-frequency operations**, including passenger ferries, Ro-Pax shuttle vessels, inland cargo barges, service operation vessels, and harbour tugs—segments in which mission durations are short, power profiles are predictable, and opportunities for frequent charging are readily available. For these categories, the technological maturity of batteries aligns well with operational requirements, and the integration challenges are manageable within contemporary naval architecture.

By contrast, fully electric propulsion rapidly becomes impractical for larger or long-distance ships due to a combination of **power, size, weight, endurance, and infrastructure limitations**. Large ships with lengths exceeding 150–200 m, displacements above 20,000–30,000 GT, or propulsion power demands greater than 5–10 MW require such extensive battery installations that the resulting mass and volume render the design infeasible. Battery rooms occupy valuable internal volume and require reinforced structural compartments, specialised fire zoning, ventilation, and thermal management systems, all of which reduce payload and revenue-earning capacity. Endurance constraints are even more critical: voyages extending beyond one to two hours at service speed quickly exceed storage capacity unless battery weights reach hundreds or thousands of tonnes, undermining stability and cargo efficiency. High-energy-density chemistries cannot fully solve this issue, as even projected 2050 performance remains insufficient to support transoceanic voyages for bulk carriers, tankers, large Ro-Ro vessels, container ships above 3,000 TEU, or cruise ships with inherently high hotel loads. Operational constraints further limit applicability: large vessels require significant power reserves for heavy-weather manoeuvring, while port-side charging infrastructure capable of delivering multi-megawatt-hour recharges within short turnaround windows is currently available only in a small number of advanced Northern European ports.

Taken together, these considerations reinforce that while electrochemical storage technologies have achieved high TRLs for specific maritime applications, their deployment remains fundamentally constrained by ship size, mission profile, energy demand, and global infrastructure readiness. Batteries will therefore form an essential part of the maritime energy ecosystem—particularly for short-range and hybrid vessels—yet they cannot, even in 2050, serve as a universal solution across all ship classes. The broader decarbonisation pathway will require complementary technologies such as hydrogen, ammonia, methanol, or nuclear propulsion, each addressing mission profiles beyond the feasible reach of electrochemical systems. The TRL outlook for batteries is thus highly positive for near-coastal and inland shipping, but intrinsically limited for long-range and high-displacement vessels, where physics and naval architecture impose constraints that technological maturity alone cannot overcome.

Table 36 - TRLs for specific maritime applications

Ship Type / Segment	Mission Profile	2025 TRL + Feasibility + Battery Type	2030 TRL + Feasibility + Battery Type	2050 TRL + Feasibility + Battery Type	Key Limiting Factors
Passenger Ferries (short sea)	5–20 km	**TRL 8–9 — Full-Electric** (LFP, LTO)	**TRL 9 — Full-Electric** (LFP, LTO; early Na-ion)	**TRL 9 — Full-Electric** (LFP/Na-ion; Solid-State emerging)	Infrastructure; peak power.
Passenger Ferries (medium range)	20–60 km	**TRL 6–7 — Hybrid / Limited Full-Electric** (NMC, LFP)	**TRL 7–8 — Hybrid & Partial Full-Electric** (LFP, NMC; Na-ion emerging)	**TRL 8–9 — Full-Electric feasible** (Solid-State, Na-ion, improved NMC)	Volume/weight; recharge time.
Urban Water Buses / Inland Passenger	Short routes	**TRL 8–9 — Full-Electric** (LFP)	**TRL 9 — Full-Electric** (LFP, Na-ion)	**TRL 9 — Full-Electric** (Solid-State, Na-ion)	Nearly no constraints.
Harbour Tugs	High power bursts	**TRL 7–8 — Hybrid** (LTO + Supercaps)	**TRL 8–9 — Hybrid / Some Full-Electric** (LTO, LFP, Supercaps)	**TRL 9 — Full-Electric feasible** (Solid-State + Supercaps)	Peak loads; cooling.
Offshore Support Vessels (OSV/SOV)	DP ops	**TRL 6–7 — Hybrid** (NMC, LFP)	**TRL 7–8 — Advanced Hybrid** (LFP, Na-ion)	**TRL 8–9 — Hybrid dominant** (Solid-State, Na-ion)	Hotel loads; endurance.
Inland Cargo Barges	Low-speed	**TRL 7–8 — Full-Electric / Hybrid** (LFP)	**TRL 8–9 — Full-Electric** (LFP, Na-ion)	**TRL 9 — Full-Electric** (Na-ion, Solid-State)	Power low; space available.
Short-Sea Ro-Ro / Small Ro-Pax	Regional	**TRL 6–7 — Hybrid** (NMC, LFP)	**TRL 7–8 — Hybrid / Partial Full-Electric** (LFP, Na-ion)	**TRL 8 — Full-Electric feasible for many routes** (Solid-State)	Cargo capacity; charging.
Coastal Fishing Vessels	Daily sorties	**TRL 5–6 — Hybrid** (LFP)	**TRL 6–7 — Hybrid / Limited Full-Electric** (LFP, Na-ion)	**TRL 8–9 — Full-Electric feasible** (Na-ion, Solid-State)	Remote port charging.
Large Cruise Ships	High hotel load	**TRL 3–4 — Hybrid (auxiliary only)** (NMC, LFP)	**TRL 4–5 — Hybrid expanded** (Na-ion, LFP)	**TRL 5–6 — Advanced Hybrid** (Solid-State for peak shaving)	Mass, endurance, hotel load.
Container Ships < 3,000 TEU	Regional	**TRL 4–5 — Hybrid limited** (NMC, LFP)	**TRL 5–6 — Hybrid expanded** (LFP, Na-ion)	**TRL 6–7 — Hybrid mature** (Solid-State, Na-ion)	Energy demand high.

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Container Ships > 3,000 TEU	Deep sea	**TRL 2–3 — Not feasible** (batteries auxiliary only)	**TRL 2–3 — Not feasible**	**TRL 3–4 — Auxiliary hybrid only** (Solid-State for hotel loads)	Massive propulsion demand.
Bulk Carriers / Tankers (regional)	Medium endurance	**TRL 4–5 — Hybrid (auxiliary)** (LFP, NMC)	**TRL 5–6 — Hybrid mature** (LFP, Na-ion)	**TRL 6–7 — Hybrid standard** (Solid-State)	Continuous power demand.
Bulk Carriers / Tankers (deep sea)	Transoceanic	**TRL 2–3 — Not feasible**	**TRL 2–3 — Not feasible**	**TRL 3–4 — Not feasible**	Endurance impossible with batteries.
High-Speed Craft / Fast Ferries	Very high power	**TRL 6–7 — Hybrid / Some Full-Electric** (LTO, NMC)	**TRL 7–8 — Hybrid & selective Full-Electric** (LTO, LFP)	**TRL 8 — Broad Full-Electric feasibility** (Solid-State)	Discharge rates; cooling.
Research Vessels / Patrol Craft	Silent modes	**TRL 6–7 — Hybrid** (LFP, NMC)	**TRL 7–8 — Advanced Hybrid** (Na-ion, LFP)	**TRL 8–9 — Partial Full-Electric possible** (Solid-State)	Endurance vs. silent operation.
Ice-Class Vessels	Harsh climate	**TRL 3–4 — Limited Hybrid** (LFP)	**TRL 4–5 — Hybrid improving** (Na-ion, LFP)	**TRL 5–6 — Hybrid mature** (Solid-State)	Cold derating; high power.

COMMERCIAL READINESS LEVEL

Robustness of the industrial supply chain and Scalability

The robustness and scalability of the industrial supply chain for electrochemical energy storage represent critical factors in assessing the commercial readiness of battery technologies for maritime deployment. Over the past decade, global lithium-ion cell manufacturing capacity has expanded at unprecedented speed, largely driven by the electric vehicle (EV) market, which continues to dominate both technological direction and raw material demand. Worldwide annual production capacity grew from approximately **150 GWh in 2018** to over **700 GWh in 2022**, with forecasts projecting **1.7 TWh by 2025** and **4–5 TWh by 2030**, underpinning a high degree of scalability for mature chemistries such as LFP and NMC. This rapid industrial expansion ensures that the maritime sector can access increasingly standardised, modular battery formats, although shipbuilding remains a niche consumer—representing **well below 1% of global battery demand**—and thus remains price-taker in a market primarily shaped by automotive and stationary-storage demand trends. [141]

The supply chain for LFP cells is the most robust and globally diversified. China currently accounts for more than **70% of global LFP production**, with major manufacturers scaling annual output to hundreds of gigawatt-hours. This dominance ensures high availability, stable pricing, and a deeply standardised ecosystem of modules, battery management systems, and pack integration solutions. Europe's emerging gigafactory landscape—supported by the European Battery Alliance—will add significant regional resilience over the next decade, though LFP supply chains will remain globally skewed. NMC production is also well-established but structurally exposed to upstream raw material volatility: cobalt supply is heavily concentrated in the Democratic Republic of Congo (approximately **70% of global output**), while nickel supply faces geopolitical and environmental risks, especially from

Indonesia and Russia. These dependencies create price and availability uncertainties, making NMC less attractive for maritime applications requiring supply stability and long-term service arrangements.

Sodium-ion (Na-ion) batteries are expected to enter mass production between 2025 and 2030, with several gigafactories already under construction in China and initial pilot lines in Europe and India. Na-ion's raw material base—primarily sodium, iron, and carbon—avoids most of the geopolitical bottlenecks associated with lithium, nickel, and cobalt. [142] If industrial scaling proceeds as projected, Na-ion could become a highly scalable, low-cost option for vessels with moderate energy-density requirements, although marine-certified systems will require several years of operational validation. Solid-state batteries, while promising in terms of safety and energy density, remain limited by the immaturity of their production ecosystem. Current pilot lines operate at megawatt-hour scale, orders of magnitude below what would be required for maritime use, and depend on materials such as solid electrolytes and lithium metal foils that lack mature supply chains.

Beyond cell production, the scalability of the maritime supply chain depends on integrators, shipyards, classification societies, and port infrastructure. Northern Europe has already achieved a high level of industrial coherence: shipyards such as Vard, Havyard, and Cemre, integrators like Corvus Energy, Leclanché, and Siemens, and ports equipped with high-power charging form a complete commercial ecosystem capable of delivering dozens of electric or hybrid vessels per year. This ecosystem demonstrates practical scalability for ferries, tugs, and service vessels. In contrast, Mediterranean and Baltic shipyards, despite significant progress, remain in earlier stages of industrial coordination, with fewer standardised design frameworks and limited capacity for series production of electric vessels. Port infrastructure scalability remains uneven across Europe: only a handful of ports currently support MW-scale fast charging, although large OPS and grid-upgrade programmes (e.g., TEN-T, Fit for 55, EALING) are expected to enhance scalability significantly by 2030.

Overall, the supply chain for maritime battery systems shows **high robustness for LFP and NMC**, **emerging scalability for Na-ion**, and **long-term but uncertain scalability for solid-state and metal-air systems**. The maritime sector will continue to rely heavily on global industrial trends shaped outside shipping, but the rapid maturation of European gigafactory capacity and increasing standardisation in vessel design suggest that large-scale deployment of battery-powered vessels is commercially scalable for short-sea and inland segments. For larger ships, scalability remains constrained by the underlying physical limits of battery technologies rather than supply chain maturity alone. [143]

Bankability

At present, the bankability of battery-powered vessels is highest in short-sea and inland markets where route profiles are predictable, regulatory drivers for zero-emission operations are strong, and the cost-benefit ratio is well understood. Electric ferries in Norway, Denmark, and Finland have repeatedly demonstrated reliable performance, stable OPEX reduction, and reduced exposure to fuel price volatility. These proven operational records significantly reduce perceived lender risk, enabling favourable financing terms and, in some cases, lower required return on equity. Bankability is further supported by the modularity of battery systems, which reduces integration uncertainty and allows vessel designs to evolve toward repeatable, series-produced configurations—a key enabler for institutional financing and public–private investment models.

However, several factors still constrain bankability across the wider maritime sector. First, CAPEX remains substantially higher than that of conventional diesel solutions. A typical electric ferry requires several megawatt-hours of batteries, representing a capital cost that is often **20–40% higher** than an equivalent diesel design. While OPEX savings from electricity and reduced maintenance can offset this difference, the payback period is highly sensitive to local energy pricing, charging tariffs, and electricity market volatility—all of which introduce uncertainty into long-term cash-flow models. Financial institutions therefore remain cautious in markets lacking stable policy frameworks or where port-side charging infrastructure is not guaranteed.

Second, the bankability of large-scale hybrid or electric projects is tightly coupled to **infrastructure availability**. Lenders evaluate not only the vessel but the entire operating ecosystem. Ports without committed financing, procurement, or timelines for grid reinforcement and high-power charging installations are often viewed as high-risk contexts, reducing financing appetite for vessel owners. In contrast, ports participating in EU-supported programs (TEN-T, CEF, EALING) or national decarbonization strategies offer higher certainty and therefore higher bankability. [144]

Third, lifecycle and residual value risk remain important concerns. Battery degradation profiles, replacement schedules, and end-of-life value streams—whether recycling, second-life use, or disposal—are still evolving and not yet reflected in widely accepted valuation models. As a result, financial institutions often discount residual values or require guarantees from OEMs or shipyards. Battery leasing or "energy-as-a-service" models are emerging as risk-sharing mechanisms, improving bankability by shifting performance risk to technology providers and enabling shipowners to avoid large upfront investments.

For deep-sea and large commercial vessels, bankability remains structurally low due to fundamental constraints on feasibility and expected profitability. Even hybrid systems for cruise ships, large Ro-Ro vessels, and tankers require substantial CAPEX and offer returns that are uncertain given fuel price dynamics, regulatory trajectories, and the limited ability of batteries to offset propulsion energy demand. As long as battery systems remain auxiliary rather than transformational for these ship types, financial institutions are unlikely to view them as high-confidence investments except within targeted green-finance frameworks.

Looking ahead to 2030, battery-electric vessels in short-sea and inland markets are expected to reach high bankability levels, supported by maturing infrastructure, declining battery costs, standardised designs, and stricter emission regulations that make zero-emission vessels commercially competitive. By 2050, the bankability of hybrid systems across medium-sized ships will significantly improve, though deep-sea applications will continue to rely on alternative fuels, with batteries supporting only auxiliary roles. Overall, bankability strongly aligns with operational predictability, policy alignment, and technology scalability, creating a stable investment environment primarily for ferries, inland vessels, and coastal fleets, while presenting much higher uncertainty for ocean-going maritime segments.

CAPEX and OPEX

The economic assessment of electrochemical propulsion in the maritime sector reveals a distinct imbalance between comparatively high CAPEX and significantly lower OPEX, shaping a long-term cost structure very different from conventional diesel-driven ships. The largest CAPEX component is the battery installation, with marine-certified chemistries exhibiting substantial variability in €/kWh cost. Current indicative values include:

- **LFP: 220–350 €/kWh**
- **NMC: 280–450 €/kWh**
- **LTO: 650–900 €/kWh**
- **Marine supercapacitors: typically >900 €/kWh (energy basis)**

Given these unit costs, the battery systems of a typical short-sea ferry require investments in the order of:

- **1–2 million € for 3–5 MWh of installed capacity**

Additional battery-related subsystems—thermal management, BMS units, fire-safe enclosures, high-capacity cabling and power electronics—commonly add:

- **+20–40% to the initial battery CAPEX**

Vessel-level adaptations increase integration costs by:

- **+10–20%** compared to a conventional diesel vessel, due to reinforced structures, dedicated battery rooms, enhanced ventilation and fire zoning.

Port infrastructure also represents a major CAPEX item, especially for high-frequency electric ferries. Typical investment elements include:

- **High-power transformers (1–10 MW): 0.5–3 million €**
- **Grid reinforcement and cabling: 0.3–2 million €**
- **Automated charging interfaces (pantograph/robotic): 0.5–1.5 million €**
- **Shore-side battery buffers (0.5–3 MWh): 0.3–1.2 million €**

When combined, these components bring the cost of electrifying a single ferry route to:

- **4–6+ million € in port-side infrastructure alone**

Consequently, CAPEX multipliers relative to diesel vessels typically fall within:

- **1.3–1.6× for fully electric vessels**
- **Up to 1.8× for high-power harbour tugs**
- **1.1–1.3× for hybrid vessels**

On the OPEX side, electric propulsion benefits from dramatically higher energy efficiency—typically **85–92%**, compared with **40–50%** for diesel engines—resulting in major reductions in energy consumption. [145] Depending on electricity tariffs and vessel utilisation, operators may achieve:

- **50–80% savings in propulsion energy costs**

Maintenance savings add further OPEX reductions in the order of:

- **20–40%**, due to reduced engine wear, minimal lubrication needs, and fewer moving parts.

Battery replacement remains the principal long-term cost driver within OPEX. Typical lifetimes and replacement values are:

- **NMC: 6–10 years**
- **LFP: 8–12 years**
- **LTO: 15–20 years**
- **Replacement costs: 500–1,200 €/kWh**

Port OPEX may include:

- **Grid-access fees**
- **Charging tariffs and energy balancing charges**
- **Peak-power penalties (where applicable)**

Across a 20-year lifecycle, these combined effects often yield:

- **10–30% lower TCO for fully electric ferries and inland vessels**
- **5–15% lower TCO for hybrid propulsion systems**
- **Payback times of 5–8 years in regulated markets**, and longer (10–12 years) where electricity pricing or regulatory incentives are less favourable.

Looking toward the future, CAPEX is expected to decline as LFP and Na-ion production scales, while OPEX competitiveness will be enhanced by rising carbon prices and fossil fuel volatility. By **2030**, full-electric propulsion is anticipated to be the cost-optimal solution for short-sea and inland segments, while hybrid systems become the rational choice for medium-sized vessels. By **2050**, even with improvements in solid-state battery technology, deep-sea shipping will remain beyond the feasible operational envelope of battery propulsion, confirming that electrochemical systems will dominate cost structures only for short-range vessels and hybrid architectures, while long-range maritime transport will continue to depend on alternative fuels or nuclear-based solutions.

Table 37 - ELETTROCHEMICAL ACCUMULATOR AND SUPERCAPACITORS CRL

Technology	Description / Use Case	CRL 2025	CRL 2030 (Forecast)	CRL 2050 (Forecast)	Commercial Evolution & Notes
LFP – Lithium Iron Phosphate	Dominant chemistry for ferries and inland vessels	8–9	9	9	Continues as the global workhorse chemistry; strong supply chain; cost leadership; high safety; fully bankable.
NMC – Nickel Manganese Cobalt	Hybrid systems where energy density matters	7–8	8	8–9	Improved supply diversification and thermal stability expected; still vulnerable to nickel/cobalt markets.
LTO – Lithium Titanate	High-power/fast-charging use (tugs, DP vessels)	6–7	7–8	8	Niche, high-cost chemistry stabilizes; remains commercially strong where power, not energy density, is key.
Supercapacitors	Peak shaving, DP operations	7–8	8–9	9	Gains widespread adoption alongside hybrid propulsion; cost reductions expected but niche focus remains.

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Na-ion – Sodium-Ion	Low-cost, safe alternative for ferries and inland ships	**4–5**	**7–8**	**9**	Major production scaling expected by 2030; maritime certification likely mid-2030s; strong long-term adoption.
Solid-State Lithium Batteries	High-energy-density next-generation chemistry	**2–3**	**4–5**	**7–8**	Breakthroughs expected 2030–2040; initial commercial use in aviation/EVs; maritime adoption later due to safety standards.
Vanadium Redox Flow (VRFB)	Port-side storage for OPS buffers	**4–5 (ship), 6–7 (port)**	**5–6 (ship), 8 (port)**	**6–7 (ship), 9 (port)**	Strong future for port-grid buffering; onboard use limited by volume constraints.
Zinc-Based Batteries (Zn-air, Zn-hybrid)	Safe low-cost chemistries	**3–4**	**5–6**	**7–8**	Manufacturing expansion expected post-2030; high safety profile supports maritime acceptance.
Metal-Air Batteries (Al-air, Li-air)	Ultra-high future energy density	**1–2**	**2–3**	**4–5**	Remains experimental; theoretical interest high but commercial viability unclear; possible niche adoption post-2045.
Second-Life EV Batteries	Reused EV packs for port/inland or low-demand vessels	**3–4 (ship), 5–6 (port)**	**4–5 (ship), 7–8 (port)**	**6–7 (ship), 8–9 (port)**	Strong growth for stationary port energy storage; shipboard use rises as certification frameworks mature.

SOCIETAL READINESS LEVEL

International Regulation and Consistency with European Policies

The societal readiness of electrochemical energy storage in maritime applications is deeply influenced by the international regulatory framework and its alignment with European policies, which together establish the legitimacy, safety standards, and strategic direction for battery-powered vessels. At the global level, the International Maritime Organization (IMO) has progressively strengthened its climate and environmental ambitions through measures such as the revised GHG strategy, EEXI, CII, and the development of life-cycle assessment (LCA) guidelines for marine fuels. Although batteries are not explicitly regulated as a standalone propulsion system, their deployment is enabled through IMO's interim guidelines on safe battery installations (MSC circulars), fire-safety codes, and the overarching regulatory ecosystem governing ship electrical systems (SOLAS, FTP Code, IEC standards). These frameworks, while not yet fully harmonized, provide the baseline for safe global operation and support the early societal acceptance of battery-electric and hybrid vessels by ensuring minimum safety and reliability thresholds.

Within Europe, regulatory alignment is considerably more advanced and is a major driver behind the high societal readiness of battery technologies. EU climate legislation—including the Fit for 55 package, FuelEU Maritime, the EU ETS extension to maritime transport, and the Alternative Fuels Infrastructure Regulation (AFIR)—creates strong incentives for ports and shipowners to adopt low- and zero-emission technologies. The mandatory rollout of shore-side electricity (OPS) at core TEN-T ports by 2030 directly promotes the integration of battery systems onboard and ashore, fostering the emergence of green maritime corridors where electrified operations become the norm. European classification societies such as DNV, ABS (through EU subsidiaries), Bureau Veritas, and Lloyd's Register have also developed detailed rule sets for lithium-ion battery installations, thermal-runaway mitigation, EMC requirements, energy-management systems, and hybrid propulsion architectures, greatly reducing uncertainty for shipyards and enabling the standardization of maritime battery solutions. [27]

Moreover, European policy frameworks emphasize supply-chain sustainability, recycling, and ethical sourcing through the EU Battery Regulation—setting binding requirements for carbon footprint disclosure, material traceability, minimum recycled content, and extended producer responsibility. This creates a uniquely strong societal foundation for battery adoption by ensuring that the upstream environmental and social impacts of battery production are transparently managed, addressing concerns related to critical raw materials and end-of-life handling. Beyond regulatory mandates, EU research and funding programmes such as Horizon Europe, the Innovation Fund, CEF Transport, and the Waterborne Partnership actively support pilot deployments, hybridization projects, and port electrification efforts, reinforcing societal and institutional confidence.

Overall, the high degree of coherence between IMO frameworks and EU climate and energy policies forms a robust regulatory environment that supports the societal readiness of battery-electric and hybrid technologies. Europe's ambitious decarbonization agenda, combined with stringent safety rules and forward-looking infrastructure policies, not only accelerates adoption but also strengthens public trust, industry acceptance, and long-term strategic legitimacy of electrochemical energy storage in the maritime sector.

Stakeholder Acceptance: Shipowners, Ports, Maritime Authorities, Crews, and Industry Actors

Among shipowners, acceptance varies significantly by segment: operators of short-sea ferries, inland vessels, tugs, and service craft generally demonstrate high willingness to adopt battery technologies, supported by proven operational experience in Northern Europe, clear OPEX advantages, and alignment with corporate decarbonization strategies. Conversely, owners of deep-sea cargo vessels remain more cautious, seeing limited value in technologies that cannot deliver full-propulsion capability for long voyages and that require costly, non-standardized infrastructure. Port authorities, particularly in Europe, show strong acceptance due to the clear local environmental benefits—reduced air pollution, lower noise levels, improved public health—and the strategic alignment with port electrification initiatives such as OPS deployment and Green Shipping Corridors. Their support is reinforced by access to EU funding mechanisms that offset infrastructure CAPEX, strengthening the institutional foundation for battery integration.

Maritime authorities and regulators increasingly view battery systems as a reliable and controllable technology, thanks to the development of dedicated class rules, safety guidelines, and certification pathways that address fire safety, thermal runaway, emergency procedures, and system redundancy. This regulatory clarity has substantially improved institutional acceptance and has given stakeholders higher confidence in approving or investing in battery-powered vessels. Crew acceptance has also improved significantly over the past decade: while early deployments raised concerns about safety, new training frameworks, automated monitoring, standardized emergency protocols, and improved

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fireproof compartment designs have helped normalize battery operations onboard. Crews frequently report operational benefits such as reduced vibration, smoother maneuvering, lower noise, and more predictable energy management. [146]

Industry actors—including shipyards, integrators, OEMs, and component suppliers—generally display strong acceptance driven by clear market expansion opportunities. Major European shipbuilders (e.g., Vard, Damen, Cemre), integrators such as Corvus Energy, Leclanché, Siemens, Wärtsilä, ABB, and classification societies like DNV and BV have invested heavily in standardizing modular battery rooms, thermal management systems, and hybrid propulsion architectures. Their commitment has allowed the supply chain to mature to a level where commercial risk is reduced and the technology is perceived as dependable, repeatable, and scalable. The willingness of industrial actors to co-invest in battery technology—seen in large-scale port electrification projects and shipowner partnerships—further accelerates ecosystem acceptance.

Overall, stakeholder acceptance is high in segments where technical feasibility and economic incentives are clear, particularly in coastal, inland, and port operations. Acceptance is more cautious in long-range shipping, where batteries are viewed as complementary rather than transformative. Nonetheless, across the maritime ecosystem, the collective readiness of shipowners, ports, regulators, crews, and industry actors strongly supports the continued expansion of battery-electric and hybrid architectures through 2030 and provides a solid foundation for mainstream adoption by 2050 in short- and medium-range maritime sectors.

Social and Territorial Aspects

The societal readiness of battery-electric and hybrid maritime propulsion is also shaped by broader social and territorial dynamics that extend beyond the maritime sector itself. Battery-powered vessels interact directly with coastal communities, port cities, inland waterways, and regions with strong environmental agendas, and the social acceptance of these technologies is strongly influenced by their perceived contribution to local quality of life. In densely populated port areas, the transition away from diesel propulsion is widely welcomed owing to visible reductions in air pollution, particulate emissions, noise, and vibrations. These improvements generate significant territorial benefits, particularly in urban environments where maritime traffic is a major contributor to poor air quality. As a result, regions such as Scandinavia, the Netherlands, and select Mediterranean metropolitan areas demonstrate very high public acceptance and strong political mandates for maritime electrification. This territorial alignment has reinforced the emergence of Zero-Emission Ports, Green Shipping Corridors, and EU-funded electrification initiatives, creating a positive socio-spatial ecosystem that supports rapid deployment. [147]

At the same time, social and territorial acceptance varies widely across Europe depending on local infrastructure maturity, socio-economic priorities, and public familiarity with battery technology. In areas where port electrification requires substantial grid reinforcement, community concerns may arise regarding land use, the visual impact of new substations, or the perceived burden of large public investments. Inland regions with limited industrial activity may perceive battery shipping infrastructure as less immediately beneficial, lowering societal support for major capital-intensive projects. Furthermore, territorial disparities in electricity prices, renewable generation capacity, and grid stability influence public perception of the fairness and feasibility of large-scale electrification efforts. Communities in

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regions with strong renewable energy identities tend to view battery-powered vessels as natural extensions of local environmental policies, while regions dependent on fossil-based power generation sometimes question the net benefit of electrification, especially if the environmental gains are not immediately visible.

Life-cycle considerations also play an increasingly important role in territorial acceptance. Concerns related to the sourcing of raw materials, end-of-life battery management, and recycling capacity can shape public attitudes toward maritime electrification. The EU's Battery Regulation, with its strict requirements for carbon-footprint reporting, recycled material content, and producer responsibility, addresses many of these concerns and enhances societal confidence that the environmental benefits of battery-powered vessels extend beyond their operational phase. [148] Territorial stakeholders—municipalities, regional governments, environmental organizations, and citizen groups—are increasingly attentive to the entire battery value chain, expecting transparency, circularity, and alignment with broader sustainability goals.

Moreover, the distribution of economic benefits influences territorial acceptance. In regions where shipbuilding, port infrastructure upgrades, or electrification projects create local employment opportunities, societal support tends to be very high. Conversely, areas that face declining maritime traffic or insufficient access to modernization funds may perceive battery adoption as an uneven or exclusionary transition. As the maritime sector evolves, managing these asymmetries will be crucial to maintain social cohesion and ensure that electrification is perceived as a collective advancement rather than a geographically uneven burden.

Overall, social and territorial aspects play a central role in determining the societal readiness of battery-electric maritime propulsion. Acceptance is strongest in regions with clear environmental benefits, supportive policy frameworks, and visible local advantages, while more complex in areas requiring significant grid upgrades or facing socio-economic constraints. These dynamics underscore the importance of integrating maritime electrification into broader territorial planning, ensuring that community engagement, environmental justice, and regional equity are embedded in the transition toward a decarbonized maritime future.

OVERALL SRL ASSESSMENT

The following table summarizes the SRL for the principal battery technologies considered in this deliverable, providing a current assessment for 2025 and forward-looking projections for 2030 and 2050. These forecasts incorporate expected developments in regulatory frameworks, supply-chain sustainability, public awareness, operator experience, and territorial integration. The SRL values illustrate how different technologies vary not only in technical maturity but also in societal fit, reflecting the extent to which each technology is perceived as safe, trustworthy, beneficial, and aligned with long-term environmental and community goals. This overview serves as a foundation for understanding how societal dynamics influence the feasibility and acceptance of maritime electrification across different regions and vessel segments.

Table 38 - ELETTROCHEMICAL ACCUMULATOR AND SUPERCAPACITORS SRL

Technology	SRL 2025	SRL 2030 (Forecast)	SRL 2050 (Forecast)	Key Drivers of Societal Acceptance

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LFP – Lithium Iron Phosphate	**SRL 8–9**	**SRL 9**	**SRL 9**	High safety perception; no cobalt/nickel; strong support from port cities and ferry operators; aligns with EU sustainability frameworks.
NMC – Nickel Manganese Cobalt	**SRL 7–8**	**SRL 8**	**SRL 8–9**	Widely accepted in hybrid vessels; concerns about raw material sourcing gradually mitigated by EU Battery Regulation.
LTO – Lithium Titanate	**SRL 7**	**SRL 8**	**SRL 8–9**	Strong acceptance in safety-critical applications (tugs, DP vessels); extremely long cycle life perceived positively by regulators and operators.
Supercapacitors	**SRL 7–8**	**SRL 8–9**	**SRL 9**	High trust due to safety and reliability; widely adopted in ports and offshore operations; low societal controversy.
Na-ion (Sodium-ion)	**SRL 5–6**	**SRL 7–8**	**SRL 9**	Strong territorial acceptance potential due to sustainable materials; expected to become a mainstream "socially preferred" option by 2050.
Solid-State Lithium Batteries	**SRL 3–4**	**SRL 5–6**	**SRL 7–8**	Expected breakthrough in safety and energy density increases societal trust; adoption grows after certification and early maritime demonstrations.
Vanadium Flow Batteries (VRFB)	**SRL 5–6 (shipboard), 7 (port)**	**SRL 6–7 (ship), 8–9 (port)**	**SRL 7–8 (ship), 9 (port)**	Very strong acceptance for port-side OPS buffers; low acceptance onboard due to volume constraints but no safety controversies.
Zinc-based batteries (Zn-air, Zn-hybrid)	**SRL 4–5**	**SRL 6–7**	**SRL 8–9**	Safe, low-cost, geopolitically neutral materials support strong long-term societal acceptance.
Metal-Air Batteries (Al-air, Li-air)	**SRL 2–3**	**SRL 3–4**	**SRL 5–6**	Perceived as experimental; societal acceptance grows only after technological and safety breakthroughs.
Second-Life EV Batteries	**SRL 5 (ship), 6–7 (port)**	**SRL 6–7 (ship), 8 (port)**	**SRL 7–8 (ship), 9 (port)**	Strong societal support for circular economy; port communities favour reuse; acceptance onboard rises as certification matures.

FUEL CELLS

TECHNOLOGY READINESS LEVEL

Maturity and Reliability of the Technology

Fuel cell technology has seen significant advancements over the past few decades, with increasing deployment across various sectors including automotive, stationary power generation, and industrial applications [149]. However, its integration into marine applications introduces unique challenges that need to be evaluated, especially in terms of maturity and reliability. These aspects are critical for assessing whether fuel cells can meet the stringent demands of long-term, high-performance operation in any environment, and specifically in maritime conditions [150].

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State of Technical Development

The most widely deployed fuel cell types are Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC). PEMFCs are particularly well-established due to their application in the automotive sector. Commercial PEMFC modules with ratings from **10 kW to over 300 kW** have been widely tested and demonstrated, and these systems are well-understood in terms of both performance and degradation behavior. In automotive and stationary applications, PEMFCs have demonstrated **electrical efficiencies** between **45% and 60%**, depending on load conditions [151]. The current state of technical development for PEMFCs can be considered relatively mature, with the technology being at **TRL 7** in applications where systems have been demonstrated in operational environments, such as in buses, trucks, and some stationary power units. This level of maturity is characterized by substantial operational data from prototype systems, confirming the fuel cell's ability to operate reliably over long periods in real-world conditions [152].

In contrast, Solid Oxide Fuel Cells (SOFCs) are still developing, with a growing interest in their use for stationary power generation due to their high efficiency and fuel flexibility. SOFCs operate at much higher temperatures (between **600°C and 1,000°C**), which allows for more efficient energy conversion but introduces significant engineering challenges [153]. These systems have the potential to reach **efficiencies of up to 65%** in electrical output, and even higher when used in Combined Heat and Power (CHP) configurations. However, despite their high potential, SOFCs are still considered to be at **TRL 6** or **7**, as there is limited experience with large-scale deployment and operational longevity, especially under variable load conditions [154].

Technical Lifetime and Durability

The reliability of fuel cell systems is primarily determined by their **operational lifetime** and the degradation rates of their components, including membranes, catalysts, and electrodes. For PEMFC systems, the lifetime is influenced by several factors such as operating temperature, fuel quality, and the frequency of load cycling [151]. Under typical operating conditions, PEMFCs are designed to last for around **20,000 to 30,000 hours**. However, ongoing research is focused on increasing the operational lifetime to **40,000 hours** or more, which would make fuel cells comparable to internal combustion engines in terms of durability [155].

SOFCs, with their higher operational temperatures, generally experience slower degradation due to reduced catalyst poisoning. As a result, they are expected to achieve lifetimes in the range of **30,000 to 40,000 hours**, with **target lifetimes of up to 80,000 hours** in stationary applications. The longer lifespan of SOFCs is one of the key advantages over PEMFCs, although their high operating temperature makes them more sensitive to thermal cycling and material degradation, particularly during frequent start-ups and shutdowns [153].

The degradation mechanisms in fuel cells vary significantly between different technologies. In PEMFCs, the primary cause of degradation is the **loss of catalyst activity**, especially in the **platinum-based catalysts** used at the electrodes. **Membrane degradation**, typically due to hydration or poisoning by contaminants in the fuel, also significantly contributes to

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performance decline. For SOFCs, the main degradation processes include **thermal cycling**, which stresses the ceramic materials, and **interconnect corrosion**. Furthermore, SOFCs can experience **material cracking** over time, especially in systems that undergo frequent load changes [151].

Maintenance and Operational Considerations

Fuel cell systems, like other power generation technologies, require maintenance to ensure continued high performance. However, fuel cells do not have the same mechanical wear issues as internal combustion engines, as there are no moving parts in the electrochemical process. Instead, maintenance primarily involves **stack replacement**, which is typically necessary after **20,000 to 30,000 hours** of operation, depending on the specific system configuration and operating conditions [150].

The absence of moving parts results in reduced maintenance compared to conventional engines, but fuel cells still require **frequent inspection** of their components, particularly the **electrodes**, **fuel processing units**, and **heat management systems**. In general, the maintenance intervals for PEMFCs are relatively predictable, though operational conditions such as fluctuating loads, fuel quality, and humidity can influence both degradation rates and the frequency of maintenance required. For SOFCs, the higher operational temperature means that more care must be taken in the **thermal management** of the system, and there may be additional maintenance required to address issues related to **material expansion and contraction** over time [154].

Reliability in Various Applications

The reliability of fuel cells also varies based on their specific application. For stationary power generation, fuel cells can generally be expected to perform reliably over the long term, particularly in **CHP applications** where waste heat can be used effectively. In automotive applications, PEMFCs have been used in **Fuel Cell Electric Vehicles (FCEVs)** for several years, with growing fleets of vehicles demonstrating their **reliability** in varied environmental and operational conditions. **Toyota's Mirai**, for example, has demonstrated **over 5 years of operational data**, which suggests that fuel cell vehicles can achieve **long lifespans** comparable to traditional internal combustion vehicles [155].

In contrast, the use of fuel cells in more variable, non-automotive applications — such as remote or backup power for critical infrastructure, or larger marine vessels — still requires substantial demonstration to prove their **long-term reliability** in these specific environments. For marine applications, especially for **propulsion** or **power generation**, fuel cells are still in the early stages of full system integration, with some pilot projects demonstrating the potential for long-term use, but not yet reaching the full commercial maturity required for large-scale adoption.

In conclusion, fuel cell technology has reached a high degree of maturity in terms of individual components and system integration, particularly for **PEMFCs** in automotive and stationary applications. However, when considering fuel cells for **maritime applications**, the technology is still in the process of being validated for long-term reliability and performance under real-world maritime conditions. While **PEMFC systems** are near **TRL 7**, with successful

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demonstrations in operational environments, **SOFCs** are still at **TRL 6** due to challenges related to high-temperature operation and thermal management. The reliability and lifetime of fuel cells, while competitive with other power generation technologies, are subject to degradation mechanisms that must be addressed through ongoing research to enhance the **durability** and **maintenance intervals** of these systems. As such, fuel cells hold significant promise for the maritime sector, but further long-term demonstrations are needed to reach the final stages of commercial maturity [27].

Marinization

Unlike terrestrial installations, marine fuel cells must withstand **continuous mechanical stress, corrosive atmospheres, restricted space, and complex integration with existing vessel systems**. Demonstrating performance under such conditions is essential for raising the Technology Readiness Level (TRL) of these systems from laboratory and pilot environments to commercial deployment [156].

A number of real-world vessels and demonstration projects illustrate how fuel cells are being adapted and tested for maritime use. One of the most prominent examples is the **MF Hydra**, a Norwegian passenger and car ferry powered by **liquid hydrogen fuel cells** with two Ballard 200 kW FCwave™ modules. Introduced into operation in **March 2023**, this ferry carries up to 295 passengers, 80 vehicles, and has completed multiple operational voyages on a scheduled route in Norwegian fjords, marking one of the earliest commercial applications of fuel cells for larger ship propulsion (MF Hydra). The project also played a key role in establishing early regulatory frameworks for hydrogen propulsion with classification societies such as DNV and the Norwegian Maritime Authority, a critical step for maritime deployment [157].

Another high-profile commercial application is the **MV Sea Change**, the first hydrogen fuel cell ferry launched in the United States in **2021**. This 70-foot catamaran operates in San Francisco Bay and is equipped with a **360 kW PEM fuel cell** and hydrogen storage system, serving as a demonstrator for zero-emission ferry operations in a busy passenger transport environment. The *Sea Change* project highlights both the feasibility of fuel cells for continuous public transport and the real challenges associated with fuel logistics and safety certification in a regulated maritime context.

In inland waterways, several European initiatives showcase early commercial use of fuel cells on cargo and logistics vessels. The **FLAGSHIPS** project deployed two hydrogen-powered vessels to demonstrate the versatility of fuel cell propulsion in real logistics operations:

- **H2 Barge 2**, a retrofitted container vessel operating between **Rotterdam (NL)** and **Duisburg (DE)**, equipped with a **1.2 MW PEM fuel cell system** combined with batteries, transporting goods on a regular route and thereby validating fuel cell propulsion for heavier duty cycles;
- **Zulu 06**, a purpose-built self-propelled barge on the **River Seine** in Paris, using twin 200 kW PEM fuel cells supplied by Ballard and integrated by ABB Marine & Ports, illustrating a second path to commercial scalability through newbuild design rather than retrofits [156].

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These practical examples highlight the broadening scope of fuel cell applications in maritime contexts — from small passenger ferries and inland cargo barges to larger car/passenger ferries — and reflect different stages of **TRL advancement**. Projects like MF Hydra and Sea Change indicate **TRL levels approaching 7–8** for specific classes of vessels where fuel cells have been integrated into commercial operations. Inland and demonstration vessels such as those in the FLAGSHIPS program contribute additional operational data, pushing the maturity of fuel cell systems when adapted for marine conditions but still under controlled logistics environments [150].

Despite these successful implementations, widespread adoption in high-power, ocean-going vessels remains in earlier stages. Many projects are ongoing or in planning phases, indicating that while fuel cell marinization is progressively moving toward commercialization, TRL remains contingent upon **extended operational data, fuel logistics solutions, safety standardization, and system integration experience** in a wide range of ship types.

Table 39 - Fuel cells implementation

Vessel / Project	**Vessel Type**	**Fuel Cell Technology**	**Installed Power**	**Fuel Type**	**Operational Status**	**Main Purpose**	**Estimated TRL**
MF Hydra (Norway)	Passenger & car ferry	PEMFC (Ballard FCwave™)	400 kW (2 × 200 kW)	Liquid hydrogen	In commercial operation since 2023	Propulsion and onboard power	7–8
Sea Change (USA)	Passenger ferry (catamaran)	PEMFC	~360 kW	Compressed hydrogen	Operational demonstrator since 2021	Zero-emission passenger transport	7
H2 Barge 2 (FLAGSHIPS)	Inland container vessel (retrofit)	PEMFC + batteries	~1.2 MW	Compressed hydrogen	Demonstration on regular route	Cargo transport (range extender)	6–7
Zulu 06 (France)	Inland cargo barge (newbuild)	PEMFC	400 kW (2 × 200 kW)	Compressed hydrogen	Operational demonstration	Zero-emission logistics	7
Nemo H_2 (Netherlands)	Passenger ferry	PEMFC	~60 kW	Compressed hydrogen	Long-term operation	Urban passenger transport	7
Zemships / Alsterwasser (Germany)	Passenger vessel	PEMFC	~100 kW	Compressed hydrogen	Demonstration project	Public transport	6–7

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Varanasi H_2 Ferry (India)	Passenger catamaran	PEMFC + batteries	~200 kW	Compressed hydrogen	Commercial service since 2025	Urban river transport	7
MSC Cruise Ships (planned)	Large cruise vessels	Fuel cells (hotel load)	Not disclosed (MW-scale planned)	Hydrogen / alternative fuels	Design & construction phase	Auxiliary power / hotel loads	6
Prince Madog (retrofit)	Research vessel	PEMFC (hybrid)	~100–200 kW	Hydrogen	Planned demonstration (2025)	Research & validation	6

Energy Efficiency

Energy efficiency represents a critical factor in evaluating the readiness and viability of fuel cell systems for maritime applications, as it directly affects operational costs, fuel consumption, and potential contributions to emission reduction regulations. Proton Exchange Membrane Fuel Cells (PEMFC) typically demonstrate **electrical efficiencies ranging from 45% to 60%**, depending on system design, operating load, and cooling strategy. The efficiency tends to peak at nominal load, while part-load operation can reduce system efficiency due to auxiliary power requirements and voltage losses in the stack. Solid Oxide Fuel Cells (SOFC), operating at higher temperatures, can achieve **electrical efficiencies up to 60–65%**, with further gains possible through Combined Heat and Power (CHP) integration, leveraging waste heat to improve overall energy utilization. These performance metrics highlight the technological advantage of fuel cells over conventional internal combustion engines, particularly in applications where high conversion efficiency is a priority [149].

The efficiency of a fuel cell system is intrinsically linked to the **electrochemical conversion process** and the management of system-level losses. Voltage losses from activation, ohmic resistance, and mass transport within the cell can reduce the net electrical output, while auxiliary systems such as pumps, compressors, and cooling units further impact overall efficiency. PEMFC systems are particularly sensitive to fuel humidity and purity, which can influence membrane conductivity and catalyst activity, leading to variations in energy conversion efficiency. SOFC systems, though less affected by fuel impurities, require precise thermal management to maintain optimal operating temperatures and prevent efficiency degradation due to thermal gradients.

From a design perspective, energy efficiency also has implications for compliance with maritime emission reduction indices, such as the Energy Efficiency Existing Ship Index (EEXI) and Energy Efficiency Design Index (EEDI). High-efficiency fuel cell systems can reduce the total energy input required for a given output, thereby contributing to lower calculated indices and enabling compliance with stricter environmental regulations. This potential, however, is contingent upon the integration of fuel cells within the overall energy system, including auxiliary power management, load sharing with conventional generators, and optimization of the ship's energy management system. Even small reductions in system losses or improvements in stack performance can have measurable impacts on fuel consumption over the operational lifetime, enhancing both economic and environmental performance [27].

System-level efficiency is also influenced by operational strategies and load profiles. Real-world operational conditions, including transient loads, start-stop cycles, and partial-load operation, can reduce the effective efficiency compared to theoretical or laboratory values. PEMFCs typically experience efficiency drops of 5–10% under fluctuating load conditions, while SOFC systems may see efficiency reductions due to thermal cycling or delays in reaching optimal operating temperatures. Accurate modeling and control strategies are therefore essential to maintain high efficiency across the full operational envelope, and these considerations are integral to evaluating the Technology Readiness Level of fuel cell systems in a maritime context.

In summary, fuel cell systems demonstrate high intrinsic energy efficiency relative to conventional power generation technologies, with PEMFCs offering reliable moderate efficiency and SOFCs providing higher efficiency potential, particularly when combined with heat recovery. The consistent performance of these systems under variable load conditions, along with integration into the ship's energy system, remains a critical determinant of operational viability. Energy efficiency, combined with technical reliability and ongoing validation of system behavior, informs the assessment of TRL, indicating that while fuel cells have matured in controlled environments, full demonstration under representative operational conditions is necessary to advance toward higher readiness levels [150].

Safety on Board

Safety on board is a fundamental consideration in the deployment of fuel cell systems in maritime environments, encompassing both the inherent risks associated with the technology and the operational integration with the ship's energy management and control systems [158]. Fuel cells, while mechanically simpler than internal combustion engines due to the absence of moving parts, introduce specific hazards primarily related to **fuel handling, high-pressure gas systems, high-temperature operation, and electrical integration**. Proton Exchange Membrane Fuel Cells (PEMFC) typically operate with hydrogen at elevated pressures, requiring robust containment, leak detection, and ventilation systems to prevent the accumulation of flammable gases. Solid Oxide Fuel Cells (SOFC), in contrast, operate at temperatures exceeding 600 °C, necessitating comprehensive thermal insulation, heat management, and fire safety measures to mitigate the risk of thermal runaway or material failure.

Beyond the intrinsic technological risks, the integration of fuel cells with the ship's electrical infrastructure and energy management system is critical for operational safety. Fuel cells must provide stable and reliable power to both propulsion and auxiliary systems, often in conjunction with batteries, conventional generators, or other power sources. This requires sophisticated **control algorithms and safety interlocks** capable of managing transient loads, sudden demand spikes, and potential fault conditions without compromising system stability or crew safety. Redundant systems, emergency shutdown procedures, and fail-safe designs

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are therefore essential components of the overall safety strategy, ensuring that any single point of failure does not propagate into critical system failures [150].

Operational considerations further influence safety requirements. Crew training and familiarity with fuel cell systems, emergency response protocols, and maintenance procedures all contribute to the overall safety envelope. Systems must be designed to **minimize human error**, for example through automated monitoring, clear diagnostic indicators, and user-friendly interfaces. In addition, predictive maintenance based on continuous monitoring of key performance indicators, such as stack voltage, temperature, and pressure, helps prevent unexpected failures that could compromise both efficiency and safety [159].

The Technology Readiness Level (TRL) of fuel cell systems in terms of safety is directly linked to the extent of operational validation under realistic conditions. While component-level safety measures and industrial best practices are well established, full integration into a vessel's operational framework, including interaction with shipboard electrical grids and compliance with maritime safety regulations, is still limited to pilot projects and demonstration vessels. Consequently, the TRL related to onboard safety ranges from **TRL 6 to TRL 7**, reflecting successful demonstrations in controlled but relevant environments, with further long-term operational experience required to achieve full commercial readiness [158].

In conclusion, safety on board fuel cell-powered vessels encompasses a combination of intrinsic technological hazards, system integration challenges, and operational management requirements. The maturity of these safety measures, along with validated performance in representative operational conditions, is a key determinant of the overall TRL of fuel cell systems for maritime applications. While existing technology provides robust frameworks for safe operation, ongoing validation, crew training, and system optimization are essential to achieve the highest levels of readiness and ensure safe, reliable deployment in commercial shipping.

Table 40 - Fuel Cells TRL

	TRL	**Explanation**
Technical development (PEMFC vs SOFC)	7 (PEMFC), 6–7 (SOFC)	PEMFC has operational demonstrations in buses, trucks, and stationary units (TRL 7), while SOFC has limited large-scale deployment experience (TRL 6–7).
Technical lifetime and durability	6–7	PEMFC: 20,000–30,000 h, SOFC: 30,000–40,000 h; systems validated but further long-term testing needed for marine conditions.
Maintenance and operational considerations	6	Maintenance is predictable and lower due to no moving parts, but marine systems require further operational testing and thermal management.

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Reliability in different applications	6–7	Demonstrations exist in land-based and marine vessels (ferries and pilot projects); long-term reliability for large ships is not yet fully verified.
Marinization / Real-world projects	7	Projects like MF Hydra, Sea Change, FLAGSHIPS indicate TRL 6–8 depending on vessel class, showing significant progress for maritime applications.
Energy efficiency	6–7	PEMFC: 45–60%, SOFC: 60–65%; efficiency proven in labs and pilot applications, but affected by real operational conditions.
Onboard safety	6–7	IMO guidelines and pilot vessels demonstrate controlled safety, but full integration into ship systems and operations requires further validation.
Global TRL analysis	**6–7**	Fuel cell technology is mature for terrestrial and small/medium maritime projects, with PEMFC more advanced. SOFC and large vessel applications need more testing and operational validation.

COMMERCIAL READINESS LEVEL

Robustness of the industrial supply chain and scalability

The industrial supply chain for fuel cell technologies is relatively mature in non-maritime sectors, particularly in automotive, stationary power generation, and material handling applications. Major manufacturers such as **Ballard Power Systems, Bosch, Plug Power, Toyota, Hyundai, Bloom Energy, and Cummins** have established large-scale production capacities for proton exchange membrane fuel cells (PEMFC) and, to a lesser extent, solid oxide fuel cells (SOFC). Global manufacturing capacities for PEM fuel cell stacks already exceed several hundred megawatts per year, with announced expansion plans targeting the gigawatt scale, driven primarily by road transport and stationary markets.

However, the translation of this industrial robustness to the maritime sector remains only partial. Marine-specific fuel cell systems require adaptations in terms of redundancy, durability, power density, shock resistance, and integration with shipboard energy systems. At present, only a limited number of suppliers offer **marine-certified fuel cell modules**, and these are typically deployed in pilot or first-of-a-kind vessels rather than series-built ships. Classification society approvals are still technology- and project-specific, which constrains scalability [113].

From a scalability perspective, fuel cells are intrinsically modular and theoretically well suited to scale from kilowatt-level auxiliary power units to multi-megawatt propulsion systems. Demonstration projects such as **MF Hydra (2 MW PEMFC)** and large SOFC-based auxiliary power concepts illustrate technical feasibility. Nevertheless, current production systems are not yet optimized for the power levels and volumes required by deep-sea shipping. Scaling up to tens of megawatts per vessel would require parallelization of multiple modules, increased balance-of-plant complexity, and a supply chain capable of delivering

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large quantities of stacks, power electronics, and hydrogen-compatible components within shipbuilding timelines.

Supporting infrastructure for installation, commissioning, and maintenance is also unevenly distributed. While Europe, Japan, South Korea, and parts of North America host well-developed fuel cell ecosystems, global shipbuilding regions and ports often lack trained personnel and service networks, limiting near-term deployment at scale [150].

Bankability

The bankability of fuel cell technologies in the maritime sector is currently moderate and strongly dependent on public support mechanisms. Fuel cells are widely recognized by policymakers as a key enabler of maritime decarbonization, which has translated into significant funding opportunities through **EU programs (Horizon Europe, Innovation Fund, CEF Transport), national hydrogen strategies, and regional green shipping initiatives**. These schemes have been instrumental in de-risking early projects by covering a substantial share of capital costs and demonstration risks [27].

Private investment interest is growing but remains cautious. While fuel cell manufacturers and system integrators benefit from diversified revenue streams across multiple sectors, shipowners and financiers face uncertainties related to fuel availability, long-term operating costs, residual asset value, and regulatory alignment. As a result, most maritime fuel cell projects to date have relied on **public–private partnerships**, with limited exposure of commercial banks or traditional ship finance institutions.

Dedicated green finance instruments, such as sustainability-linked loans and green bonds, are increasingly accessible for zero-emission vessels, but fuel cell-powered ships are still perceived as higher-risk compared to battery-electric or LNG-based solutions. The absence of long-term operational data at scale, combined with uncertainties in hydrogen pricing and supply chains, constrains creditworthiness assessments. Consequently, fuel cell systems have not yet reached full commercial bankability without substantial public co-financing or contractual risk-sharing mechanisms [152].

CAPEX and OPEX

Fuel cell systems are characterized by **high capital expenditure (CAPEX)** compared to conventional internal combustion engine solutions. Current estimates indicate that marine-grade fuel cell systems can be several times more expensive per installed kilowatt than diesel or dual-fuel engines, largely due to stack costs, balance-of-plant components, power electronics, and redundancy requirements. Additional CAPEX arises from hydrogen or alternative fuel storage systems, safety measures, and vessel retrofitting or redesign [150].

Operating expenditure (OPEX) remains highly sensitive to fuel costs. Hydrogen, whether compressed, liquefied, or derived from carriers such as ammonia or methanol, is currently more expensive than conventional marine fuels on an energy-equivalent basis, particularly when produced from low-carbon pathways. Maintenance costs for fuel cells are expected to decrease over time but are still influenced by stack lifetime, degradation rates, and replacement intervals, which are not yet fully validated under maritime operating profiles [113].

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From a regulatory perspective, fuel cell-powered vessels benefit from **reduced or zero emissions costs**. Compliance with **CII, FuelEU Maritime, and EU ETS** significantly improves the economic case compared to fossil-fuel-based solutions, particularly as carbon prices increase and fuel intensity limits tighten. The avoidance of NO_x, SO_x, and particulate matter emissions also reduces the need for exhaust after-treatment systems, partially offsetting CAPEX and OPEX disadvantages.

Overall, while total cost of ownership remains unfavourable under current market conditions, regulatory incentives and carbon pricing mechanisms are progressively narrowing the cost gap.

Logistics dependency

The economic viability of fuel cell technologies in the maritime sector is strongly dependent on **onshore infrastructure and logistics chains**. The availability of hydrogen bunkering facilities, fuel production hubs, and standardized handling procedures is a critical prerequisite for widespread deployment. At present, hydrogen and hydrogen-derived fuel infrastructure is limited to a small number of ports, primarily in Northern Europe and East Asia, restricting operational flexibility.

For applications involving onboard carbon capture combined with fuel cells or hybrid systems, additional logistics challenges arise from the need to transport and manage captured CO_2. The absence of mature port-side infrastructure for carbon offloading, temporary storage, and onward transport to sequestration or utilization sites significantly affects operational costs and feasibility.

Shore power (OPS) infrastructure can partially mitigate these constraints by allowing fuel cell-equipped vessels to reduce onboard fuel consumption while at berth. However, OPS availability remains uneven across global ports, and compatibility with high-power fuel cell systems is not yet standardized [113].

As a result, fuel cell adoption is currently most viable in **short-sea shipping, ferries, and fixed-route operations**, where logistics chains can be tightly controlled. For deep-sea and tramp shipping, logistics dependency remains one of the main barriers to commercial readiness.

Table 41 - Fuel Cells CRL

	CRL Level (0-9)	**Explanation**
Industrial supply chain robustness & scalability	5–6	PEMFC supply chain is well-established for automotive/stationary markets, but marine-certified modules are limited to pilot/first-of-a-kind vessels.
Bankability	5	Significant public funding supports projects, but private investment is cautious due to fuel availability, cost, and lack of long-term operational data.

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CAPEX and OPEX	4–5	High capital costs per kW compared to diesel engines; operational costs sensitive to hydrogen price; incentives partially offset costs.
Logistics dependency	4–5	Hydrogen bunkering infrastructure is limited; deployment feasible mainly for short-sea shipping, ferries, or controlled routes.
Global CRL analysis	**4–6**	Commercial deployment is mostly limited to pilot projects or controlled fleets. Large-scale adoption requires infrastructure development, cost reduction, and supply chain consolidation.

SOCIETAL READINESS LEVEL

The societal readiness of fuel cell technology in maritime applications reflects the degree to which regulatory frameworks, economic incentives, stakeholder acceptance, and human factor preparedness coalesce to support its adoption beyond mere technical feasibility. On the regulatory side, the International Maritime Organization (IMO) and European Union have initiated significant policy developments that enhance the broader societal and institutional environment for fuel cell uptake. The IMO has established interim safety guidelines specifically for fuel cell power installations (MSC.1/Circ.1647), which aim to ensure that fuel cell systems — regardless of specific fuel type — deliver electrical and thermal energy with a level of safety and reliability comparable to conventional machinery, addressing risks related to ventilation, gas detection, hazardous areas, and fire protection. These guidelines are actively maintained and remain a reference point while more comprehensive safety provisions are developed [158].

Concurrently, IMO's SubCommittee on Human Element, Training and Watchkeeping (HTW) has promulgated **generic interim training guidance** for seafarers on alternative fuels and new technologies — with **fuel cellspecific training modules** under development and scheduled for consideration in 2026 — which is expected to inform future mandatory standards under the revised STCW Convention.

At the European level, the **FuelEU Maritime Regulation** represents a robust policy driver for zero and lowemission technologies, including fuel cells, by imposing gradually tightening greenhouse gas (GHG) intensity limits on the onboard energy used by commercial vessels above 5,000 gross tonnage calling at EU/EEA ports. From an initial 2 % reduction target in 2025 to an ambitious 80 % reduction by 2050 relative to 2020 baseline values (91.16 gCO_2eq/MJ), these standards provide longterm incentives for operators to invest in alternative energy solutions that can meet lifecycle GHG constraints [160]. The extension of the **EU Emissions Trading System (ETS) to the maritime sector** in 2024 further embeds carbon pricing into operational costs, encouraging early adopters of low and zerocarbon technologies such as fuel cells (notwithstanding current concerns about supply costs and infrastructure).

Despite these regulatory signals, the SRL for maritime fuel cells remains **intermediate**: structured frameworks exist but are often **still evolving**. While interim IMO safety guidelines and class society rules — such as **Bureau Veritas' NR547 for ships using fuel cells** — provide

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key technical reference points for design, installation, and onboard safety, they are not yet consolidated into universally enforceable international codes, and further refinements are anticipated as technologies scale and operational experience grows [161].

The **acceptance among stakeholders** also varies. Shipowners increasingly evaluate fuel cells as part of broader decarbonisation strategies due to regulatory drivers and potential operational cost benefits over lifecycle emissions, yet concerns persist regarding **fuel availability**, **capital costs**, and **uncertainties in regulatory alignment**, especially when compared to more mature alternative fuels such as LNG or methanol. Ports and flag administrations have welcomed the highlevel policy direction but emphasize the need for harmonized safety and bunkering standards. Crews and maritime labour organisations prioritise clarity on risk management and competency development, given the novel hazards associated with highpressure gases, electrochemical systems, and integrated power electronics typical of fuel cell installations [27].

Crew safety and **training readiness** constitute a critical dimension of societal integration. IMO's generic interim training provisions for alternative fuels set foundational competencies, while emerging fuelspecific modules will address unique knowledge areas such as fuel cell chemistry, emergency response, and system operation — competencies that extend beyond traditional STCW training. Standardised curricula and certification pathways are progressively being discussed within industry bodies and training institutes to ensure personnel are prepared for safe operation and maintenance of fuel cell systems, reducing perceived risk and enhancing operational confidence [159].

In summary, while **fuel cell technology has reached significant technological maturity in niche maritime applications**, its societal readiness — reflecting regulatory clarity, stakeholder acceptance, and human preparedness — is **still developing**. Regulatory policies from IMO and the EU are advancing in parallel with training frameworks and class society guidance, but the **integration into universally recognised codes and widespread industry acceptance** will require continued evolution of regulations, fuel infrastructure rollout, and harmonised seafarer training standards to support safe, scalable adoption across the global fleet.

Table 42 - Fuel Cells SRL

	SRL Level (0-9)	**Explanation**
Regulatory framework (IMO, EU)	6	IMO guidelines and FuelEU Maritime provide a solid foundation, but universally enforceable codes are not yet fully implemented.
Stakeholder acceptance	5–6	Shipowners are increasingly interested, but uncertainties remain on costs, fuel availability, and regulatory alignment; ports and authorities require standardization.

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Crew training and preparedness	5–6	IMO generic guidance exists; fuel cell-specific modules are in development (planned for 2026), full standardized training is not yet established.
Social & industrial integration	5–6	Adoption remains limited to pilot projects and demonstration fleets; integration into global maritime practice is ongoing.
Global SRL analysis	**5–6**	Society and industry are adapting to the technology, but regulations, training, and widespread stakeholder acceptance still need consolidation for large-scale adoption.

3.8. Energy efficiency devices and technologies

This section covers technologies that improve energy efficiency by reducing fuel consumption and thus emissions. Propeller and rudder optimisation devices, such as fins, ducts, and improved propeller designs, are widely applied and achieve measurable fuel savings. Wind-assisted propulsion solutions, including rotor sails, kites, and rigid sails, are at varying TRL levels, with several commercial demonstrations already proving significant performance gains under suitable conditions. Advanced hull designs and coatings enhance hydrodynamic efficiency, while waste-heat recovery and onboard energy optimisation systems contribute to overall savings. [162] [163] These technologies typically exhibit higher TRLs compared to alternative fuels or fuel cells, but their effectiveness is strongly dependent on vessel type, operational profile, and integration with other systems.

3.8.1 WAPS

Wind Assisted Propulsion Systems (WAPS) are technologies designed to harness wind power to supplement a vessel's conventional propulsion system, thereby maximizing fuel efficiency and reducing emissions. Utilizing wind as an inexhaustible, free, and zero-carbon energy source, WAPS represents a significant contribution to the maritime industry's decarbonization efforts. [163] Under IMO regulations, WAPS is categorized as an innovative energy efficiency technology, specifically Category B-2, meaning it reduces propulsive power but operates optimally only under certain environmental conditions. [164]

Types and Mechanisms of WAPS

A variety of WAPS technologies are currently in use or under development, leveraging different physical principles to generate thrust:

Table 43 - Types and Mechanisms of WAPS

Technology	Mechanism	Examples & Notes
Rotor Sails	Utilizes the Magnus effect, where the active rotation of vertical cylinders in the wind generates lift and forward thrust.	Norsepower Rotor Sails (available in heights up to 30m), Anemoi Rotor Sails, and EcoFlettner. Rotors are

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		mechanically driven by electric motors.
Suction Wings	Non-rotating, wing-shaped sails that use an internal fan/vents to create boundary-layer suction, significantly enhancing lift (thrust).	VentiFoils (Econowind) and eSAIL (bound4blue). They typically deliver optimal thrust in side winds.
Rigid Sails	Solid, high-lift airfoils (wing sails) that operate like airplane wings, relying on aerodynamic lift and drag. They are often rigid, automated, and rotational for optimizing wind capture.	WindWings (BarTech), Oceanwings (AYRO), Wind Challenger (MOL), and SolidSail (Chantiers de l'Atlantique).
Kites	Large parafoils tethered to the bow, flying at high altitudes (100-500 m) to access stronger, more stable winds. Dynamic kites move in patterns (e.g., figure-eight) to maximize lift.	Seawing (Airseas). Kites require minimal deck space.
Soft Sails	Flexible sails, often modern automated versions of traditional sailing rigs, such as the DynaRig concept.	WISAMO inflatable sail (Michelin).
Hull Form	Hull designs shaped like symmetrical aerofoils to generate propulsion force.	Proposed designs like the Vindskip.

Classification and Regulatory Context

WAPS technologies are often categorized by the extent of their power contribution relative to the vessel's total propulsion needs:

- **Wind-Assist:** Systems delivering, on average, less than 50% of the total propulsive energy required, typically added as retrofits to motor vessels.
- **Primary Wind:** Systems designed to provide 50% or more of the vessel's propulsive energy, primarily through hull optimization and integrated designs on newbuilds.

Classification societies assign specific notations based on the potential effective power supplied by the WAPS:

- **WAPS-A (Auxiliary):** Effective power is equal to or less than 15% of the propulsion power.
- **WAPS-H (Hybrid):** Effective power is more than 15% but up to 60% of the propulsion power.
- **WAPS-M (Main):** Effective power exceeds 60% of the propulsion power.

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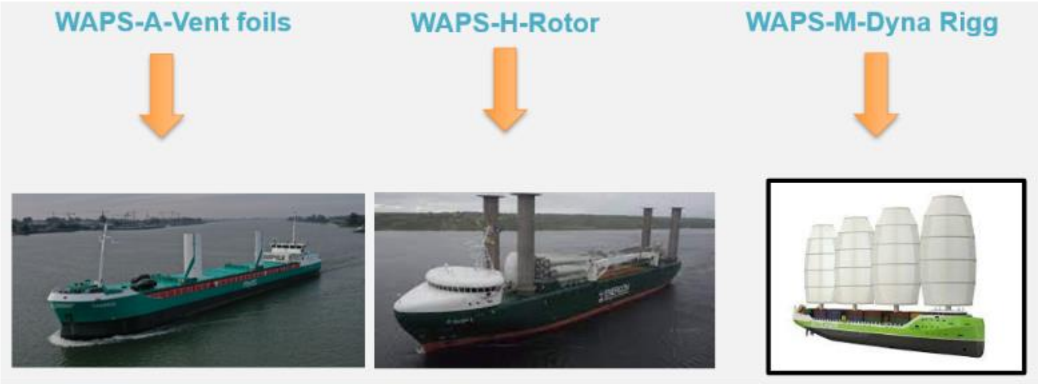

Figure 25 - Class Notations Example

Regulatory Framework:

The IMO incorporates WAPS into the calculation of the Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) via the 2021 Guidance (MEPC.1/Circ.896). [164] This guidance defines the contribution as "available effective power," calculated using the wind propulsion system force matrix and the global wind probability matrix. [165]

TECHNOLOGY READINESS LEVEL

The Technology Readiness Level (TRL) of Wind Assisted Propulsion Systems (WAPS) varies by technology type, but several systems have achieved market maturity, supported by extensive operational testing, regulatory framework integration, and established safety protocols. [166]

Maturity and Reliability of the Technology

WAPS technologies are broadly categorized based on their technical maturity. Rotor sails (Flettner rotors), hard sails (wingsails/rigid sails), and suction wings are typically designated as mature technologies (TRL 9), having demonstrated operational success and been fully proven in the maritime environment. [166] In contrast, systems like kites and modern soft sails are considered near-mature (TRL 7 or 8), actively undergoing demonstration and testing, though they currently have limited full-scale commercial application. Rotor sails are noted for their high degree of technological stability and maturity. [167] [168]

Regarding reliability and lifespan, WAPS installations are generally designed for extended technical lifetimes, comparable to the vessel itself, with many systems carrying 20-25 year warranties. For example, the main bearings in Norsepower Rotor Sails are designed for a life of around 25 years. Early operational data supports high reliability; one vessel equipped with rotor sails demonstrated a system availability exceeding 98%. [168] Maintenance procedures are structured, ranging from crew-performed daily checks to annual technical check-ups performed by the technology provider, with remote monitoring often used to support troubleshooting and predictive maintenance.

Marinization

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The process of marinization involves ensuring the WAPS are compatible with harsh marine operating environments and ship integration requirements:

- **Testing under Operating Conditions:** WAPS technologies have undergone rigorous testing, including initial sea trials and long-term performance monitoring, adhering to adapted procedures derived from international standards like ISO 15016 and ITTC guidelines. [167] These tests evaluate system stability, endurance, and operational efficiency under fluctuating wind, wave, and speed conditions. [169]
- **Compatibility and Layout:** Compatibility with existing cargo operations and air draft limits (due to bridges or port infrastructure) is a primary concern for commercial viability. Manufacturers address this with flexible designs, such as tiltable, foldable, retractable, or rail-mounted systems. Containerized WAPS solutions, like certain suction wings, are also available, facilitating quick installation and removal. The increased weight of WAPS typically does not result in a major reduction of the vessel's cargo-carrying capacity, especially for large vessels.
- **Stability and Risks:** Incorporating large WAPS units significantly increases the vessel's windage area and vertical center of gravity (VCG), posing challenges to intact stability and manoeuvrability. Compliance requires structural reinforcement and adherence to IMO stability criteria, sometimes necessitating hull shape adjustments or design modifications. [170] Specific risks considered during design and installation include vibrations (especially from rotating components), noise emissions, ice accumulation, and green water loads. Risk assessments, such as HAZID studies, are routinely conducted to mitigate these hazards. [162]

Energy Efficiency

WAPS are primarily deployed to harness wind energy as a pure zero-emissions source to supplement main engine power, leading directly to fuel savings and reduced emissions.

- **Theoretical/Design Efficiency:** WAPS retrofits typically aim to deliver annual fuel and emission reductions between 5% and 20%, potentially rising to 30% with voyage optimization. Optimized newbuild designs hold the potential for 50% to 80% or more of propulsive energy from wind. Ship trials have confirmed these operational benefits; for example, a Flettner rotor installation on the *m/v Copenhagen* demonstrated a 3.9% annual power reduction. Certain designs, such as the rotor sail system installed on the *m/v Annika Braren*, achieved up to 15% net power saving under optimal wind conditions. [167] [168]
- **EEDI/EEXI Impact:** The International Maritime Organization (IMO) classifies WAPS as an innovative energy efficiency technology, specifically Category (B-2), which reduces propulsion power (P_P) but operates optimally only under limited conditions. The calculation of the WAPS contribution to the Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) is governed by IMO MEPC.1/Circ.896.
  - The calculation uses a sophisticated formula that determines the available effective power ($f_{eff} . P_{eff}$) by combining the specific thrust performance (force matrix $F(V_{ref})_k$) with a statistical distribution of wind conditions (global wind probability matrix W_k) and subtracting the WAPS's own power consumption.

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    - To better reflect real-world operation, the formula instructs calculating effective power based on only the highest-performing 50% of wind conditions included in the matrix.

Safety on Board

Safety and operational integration are managed through compliance with international conventions and robust system design, particularly focusing on how novel technologies interact with commercial operations and ship systems. [170] [171] [172]

- **Safety and Commercial Operations:** All WAPS must comply with SOLAS and COLREGS. Safety considerations are extensive, encompassing fire safety, crew safety, lightning protection, and the mitigation of risks related to extreme weather, manoeuvring, and potential obstruction of navigational equipment or escape routes. The ability of systems to be quickly folded or stowed is critical to avoiding interference during cargo handling operations.
- **Handling of Novel Technologies:** Modern WAPS are characteristically highly automated to minimize workload and human error, allowing the crew to initiate the system via a simple control panel and focus on other tasks. Training is generally provided by the technology vendor to cover system awareness, operational parameters, and emergency procedures.
- **Integration with Grid and EMS:** Successful integration is paramount for maximizing efficiency, as the WAPS must seamlessly manage the main engine's performance despite fluctuating wind power. The vessel's Energy Management System (EMS) must prevent the main engine from running at inefficient loads (higher Specific Fuel Oil Consumption, SFOC) when wind power reduces the necessary propulsion load. Integrating WAPS controls into the vessel's overall energy management system is intended to compensate for this potential loss of efficiency. Classification societies approve specialized performance prediction software like Pelican, which is designed to simulate this complex system integration and optimization.

Based on the evaluation of contemporary commercial installations, testing, and regulatory integration (EEDI/EEXI), the Technology Readiness Levels (TRL) for Wind Assisted Propulsion Systems (WAPS) are segmented into three main categories:

Mature (TRL 9), Near-Mature (TRL 7 or 8), and Non-Mature (TRL ≤ 6).

The following table summarizes the TRL status of different WAPS technologies:

Table 44 - WAPS TRL

WAPS Technology Type	Technology Readiness Level (TRL)	Supporting Evidence/Maturity Status
Rotor Sails (Flettner Rotors)	**Mature (TRL 9)**	Rotor sails are considered mature technologies that have demonstrated operational success and are fully proven in

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		the maritime environment. This technology is noted for its high degree of technological stability and maturity. They are the most popular form of WAPS, with installations having proven their technological readiness.
Suction Wings (VentiFoils, eSAIL)	**Mature (TRL 9)**	This technology is typically designated as mature (TRL 9) and has achieved readiness rapidly, with installations demonstrating they are technologically ready. Suction wings, like VentiFoils, are noted as a ready and tested solution.
Hard Sails / Rigid Sails (Wing Sails, Oceanwings, WindWings)	**Mature (TRL 9)**	Hard sails are regarded as mature technologies and have been proven to be technologically ready. Designs such as the Oceanwings are described as having technology that is easily adaptable to all needs. However, some industry assessments note that hard sail suppliers are currently at a slightly lower stage of development compared to rotor sails and suction wings, having primarily one or two installations each to date. [173]
Soft Sails (Dynarig, WISAMO)	**Near-Mature (TRL 7 or 8)**	Soft sails are generally categorized as near-mature. Modern soft-sail systems have been installed on superyachts as wind-assisted propulsion but have had no pilots on large maritime transport vessels yet. A prototype of Michelin's WISAMO soft-sail is currently being tested on a Ro-Ro vessel. [174]
Kites (Towing Kites, Seawing)	**Near-Mature (TRL 7 or 8)**	Kites are considered near-mature technologies, actively undergoing demonstration and testing, but with limited full-scale commercial application. Although testing is underway and further systems are planned, these applications are still supported by government funding, indicating a lower stage of commercial maturity compared to other core WAPS types.
Hull Form (Vindskip)	**Non-Mature (TRL ≤ 6)**	A vessel hull shaped like a symmetrical aerofoil to generate propulsion is currently the only non-realised technology among

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		WAPS categories. The focus remains on design concepts (like Vindskip) with implementation typically limited to research initiatives.
Wind Turbines	**Non-Mature (TRL ≤ 6)**	Research in wind turbines for direct propulsion remains limited, with no large-scale prototypes developed and associated startups showing minimal sustained activity.

COMMERCIAL READINESS LEVEL

The commercial readiness of Wind Assisted Propulsion Systems (WAPS) is evidenced by a growing market presence, established manufacturing capacity, validated operational performance, and integration into global maritime regulatory frameworks aimed at decarbonization.

Robustness of the Industrial Supply Chain and Scalability

The WAPS market is transitioning from a developmental phase to mainstream commercial adoption, with a variety of manufacturers offering market-ready solutions supported by expanding industrial capacity. [175]

Market Penetration and Growth: WAPS uptake is currently accelerating and nearing a crucial tipping point, with installed and planned installations identified on 101 vessels as of February 2024. The trend shows increasing confidence, particularly through the growing number of units per vessel and an increasing shift toward WAPS integration in newbuild designs.

Supply Chain Status: Approximately 16 companies are active in supplying WAPS technologies. However, the capacity to meet projected future demand remains a significant challenge. To fulfill the highest estimates of potential installations by 2030 (around 10,700 units), suppliers would require a nearly 100-fold increase in current production capability. Even meeting existing orders requires delivering 2.5 times the number of units installed over the past five years.

Scalability Measures: Technology suppliers are actively addressing this scalability gap through strategic innovations and partnerships:

- Modularization and Portability solutions, such as containerized or flatrack-mounted units (e.g., Econowind's VentiFoils), allow for easier installation, removal, and transferability between vessels, maximizing utility and streamlining logistics.
- Manufacturers are partnering with established producers (e.g., a suction wing supplier secured production capacity from a European wind turbine producer), enabling the rapid establishment of high-volume manufacturing lines.
- Focus on the standardization of design and production processes aims to reduce unit costs and accelerate dissemination.

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Installation Capacity: Shipyard capacity presents a short-term constraint, as only about 16 yards have performed WAPS retrofits to date. This necessitates rapid scaling up of expertise, especially considering that 72% of planned installations are scheduled for newbuild yards. The industry addresses this through the concept of 'wind-ready' vessels, where foundational structures and cabling are prepared during the building phase or scheduled drydocking, significantly simplifying the final WAPS installation.

Bankability

WAPS technologies demonstrate increasing bankability through diverse financing models, supported by growing investment and a clear pathway to regulatory compliance benefits.

Investment and Market Confidence: Publicly announced finance commitments are robust, reaching hundreds of millions of USD dedicated to production capacity expansion, validating market confidence in the technology segment. The sector sees extensive collaboration, frequently involving larger partners (OEMs, shipyards, and cargo owners) in joint development projects.

Financing Models: The fundamental advantage of WAPS, using a zero-cost energy source, facilitates alternative financing schemes that shift the initial capital burden (CAPEX) to operational expenses (OPEX), thereby mitigating the key barrier of high upfront costs:

- **Leasing Systems:** The technology can be leased, where the fuel cost savings generated during operation cover the lease payment.
- **Pay-As-You-Use/Save Models:** CAPEX is paid down by sharing the realized fuel savings with the technology provider over a fixed term.
- **Performance Guarantees:** Vendors often provide warranties and performance guarantees (up to 25 years on lifetime), especially for vessels on predictable routes, enhancing the attractiveness of the investment.

Compliance as Financial Assurance: The certainty provided by mandatory regulations (EEXI, CII, FuelEU Maritime) transforms WAPS into an essential investment rather than an optional efficiency measure, making WAPS highly bankable by guaranteeing reduced exposure to rising carbon costs and future compliance penalties.

CAPEX and OPEX

WAPS investments involve substantial Capital Expenditure, but yield significant Operating Expenditure savings primarily through fuel reduction and avoided carbon costs. [162] [163]

Capital Expenditure (CAPEX): The costs vary widely by technology, size, and installation complexity:

- **Unit Costs:** Rotor sails generally cost between US$500,000 and US$1 million per unit. Suction wings range from €200,000 to €900,000 per unit.
- **Installation Costs:** Average installation cost (excluding the unit cost) for a typical retrofit WAPS system is estimated around US$2.5 million. Retrofitting tends to incur costs about 25% higher than installation during a newbuild project.

Operating Expenditure (OPEX):

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- **Maintenance:** Annual maintenance and repair costs vary but are estimated at approximately 2% to 5% of the initial CAPEX annually.
- **Power Consumption:** Active systems like rotor sails require electrical input, with large models consuming up to 110 kW, though this is far outweighed by the thrust generated.
- **Fuel Savings and ROI:** WAPS typically delivers annual fuel savings ranging from 5% to over 20%, potentially reaching up to 30% with operational optimization. This reduction directly lowers OPEX. For a mid-sized vessel, integrating WAPS resulted in an estimated Return on Investment (ROI) of around 8 years when fuel prices were at $750/t. This ROI period is projected to decrease further due to anticipated drops in WAPS production costs and increases in future alternative fuel prices.

Emissions Costs and Regulatory Impact:

- **EU ETS:** Reduction in fuel consumption directly translates to reduced carbon emissions, minimizing the costs associated with purchasing EU Allowances (EUA) required by the EU Emissions Trading System.
- **CII/EEXI:** The implementation of WAPS contributes positively to the Energy Efficiency Design Index (EEDI) and Existing Ship Index (EEXI), improving the vessel's compliance rating (e.g., RINA assigns WAPS notations based on quantified power contribution).
- **Fuel-EU Maritime:** This regulation explicitly rewards WAPS usage, providing up to a 5% reduction in a vessel's calculated GHG intensity for ships utilizing wind power for 15% or more of propulsion energy.

Logistics Dependency

The commercial viability of WAPS is generally independent of traditional fuel logistics chains but requires careful mitigation of physical interference risks related to vessel structure and port operations.

Onshore Infrastructure (Port Compatibility): The primary logistical challenge is ensuring that the installed systems do not interfere with cargo handling equipment (cranes, hatches) or air draft limitations (bridges, port infrastructure).

- **Mitigation: This is overcome by adopting flexible designs:**
- **Movable Systems:** Using rail deployment systems allows units to be moved longitudinally to clear deck space for cargo operations.
- **Tiltable/Foldable Systems:** Retractable or hinged designs allow the WAPS units to be lowered or folded, mitigating interference with cranes or overcoming air draft restrictions.

Dependency on CO2 Disposal/Carbon Capture: WAPS technology does not rely on CO_2 disposal infrastructure because wind energy is a pure zero-emissions source. The primary environmental benefit of WAPS is the avoidance of GHG emissions, eliminating the need for carbon capture and storage (CCS) logistics chains or upstream fossil fuel dependency.

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WAPS inherently increases the vessel's resilience and reduces energy security risks, as the energy source is free, abundant, and delivered directly to the point of use, independent of complex global energy markets and infrastructure.

Based on the comprehensive assessment of market penetration, investment, and operational data, the commercial readiness level (CRL) of Wind Assisted Propulsion Systems (WAPS) varies significantly across technologies.

Commercial Readiness Level (CRL) Comparison for WAPS Technologies

Table 45 - Commercial Readiness Level (CRL) Comparison for WAPS Technologies

WAPS Technology Type	Commercial Readiness Level (CRL)	Market Penetration & Scale	CAPEX/OPEX & Financial Viability	Commercial Barriers & Solutions
Rotor Sails (Flettner Rotors)	**8-9**	**Most mature installed base:** 13 vessels installed and 25 on order by early 2024 (38 total vessels). Leading technology by installed units (30 installed, 54 on order; 84 total units). Demonstrating high market confidence with increased units per vessel.	Asset costs: EUR 560k to 1,050k per unit. Retrofit installation costs up to EUR 263k per unit. Proven ROI, often projected around 4-8 years depending on fuel price and carbon costs. Fuel savings: verified annual savings ranging from 6.1% to 8.2% on trials.	Robust supply chain actively scaling production capacity. Adaptable to air draft and cargo operations using tiltable or rail deployment systems. Strong bankability due to proven stability and reliable data.
Suction Wings (VentiFoils, eSAIL)	**8-9**	Rapidly accelerating, potentially overtaking rotors in number of vessels due to order book (7 installed, 37 on order by early 2024). Strong	Asset costs: EUR 200k to 900k per unit. Known for high relative savings potential (up to 20% advertised). Immediate ROI	Excellent modularization (e.g., flatrack/containerized units) allowing quick installation/removal (e.g., MV *Frisian Sea* retrofit in one day). Scaling achieved through rapid

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		uptake in general cargo.	possible via leasing or pay-as-you-use models, as monthly savings cover financing costs.	manufacturing partnerships.
Rigid Sails (Hard Sails, Wing Sails)	**7-8**	Significant market traction, particularly in newbuild optimization (7 installed, 9 on order by early 2024). Installed on large tonnage vessels (VLCCs, Capesize bulkers, Ro-Ro). Highly varied supplier base (AYRO, MOL, BarTech).	Asset costs: EUR 438k to 876k per unit. Higher operational savings potential in optimized newbuild designs (up to 50% advertised). LR noted potential for costs higher than EMSA estimates.	Requires robust retractable, tiltable, or foldable systems (e.g., Wind Challenger) to manage extreme size, air draft, and cargo clearance. Widely integrated into modern shipbuilding projects (Oceanbird, Neoliner).
Kites (Towing Kites)	**6-7**	Niche installations (2 installed, 1 on order by early 2024), but large reported pipeline/contracts (e.g., 51 Seawing orders for Airseas).	Asset costs highly variable, EUR 340k to 2,345k per unit, reflecting size dependency. Projected savings of 20-40% claimed by technology providers.	Major advantage in minimal deck space required, making it suitable for container ships where other WAPS face constraints. Complexity lies in automated deployment/retrieval at high altitude.
Soft Sails (Dynarig, WISAMO)	**4-5**	Very limited commercial application on large merchant vessels. Currently seen mostly in prototypes or pilot projects (e.g., WISAMO prototype testing on	Cost and performance data primarily derived from specialized yacht projects, limiting commercial certainty for	Designs often face challenges related to deck layout and high structural complexity, leading some developers to favor hard sails for commercial applications.

		Ro-Ro vessel *MN Pelican*).	cargo applications.	
Hull Form	**4-5**	Non-realized technology; application restricted exclusively to newbuild design concepts (e.g., Vindskip).	Commercial costs purely theoretical; significant capital investment required for dedicated R&D and construction of novel hull forms.	Requires substantial upfront R&D investment to develop beyond the conceptual stage. Commercial readiness is highly dependent on securing initial newbuild funding.

Commercial Barriers (CRL)

The maritime industry's adoption of WAPS is rapidly approaching a tipping point, expected to pass 100 installations in the next 2-3 years, driven primarily by cost and compliance requirements such as CII and FuelEU Maritime.

Key commercial aspects influencing CRL:

1. **Supply Chain and Scalability:** To meet market potential estimated up to 10,700 units by 2030, a 100-fold increase in existing production capacity would be required, posing a massive challenge to the 16 active suppliers. However, mature suppliers (Rotor Sails, Suction Wings) are developing manufacturing partnerships to accelerate scale.
2. **Installation Capacity:** Only about 16 yards have experience conducting WAPS retrofits to date. The accelerating trend toward newbuild integrations (72% of planned installations are newbuilds) requires shipyards to rapidly acquire competence.
3. **Financial De-risking:** High initial CAPEX (Capital Expenditure, estimated at around $2.5 million for an average wind assist retrofit) remains a primary barrier. To mitigate this, alternative financing methods like leasing and "pay-as-you-use" models are being commercialized, shifting the financial risk away from the shipowner's capital costs and toward the predictable OPEX (Operational Expenditure) savings generated from free wind energy.
4. **Verification and Standardization:** A major commercial challenge is the lack of standardization for validating and verifying fuel savings claims, increasing investment uncertainty. Classification societies (such as LR, DNV, RINA) are actively developing standardized rules and performance assessments (e.g., the RINA WAPS notation and LR Guidance Notes) to formalize compliance and improve commercial trust.

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SOCIETAL READINESS LEVEL

The Societal Readiness Level (SRL) of Wind Assisted Propulsion Systems (WAPS) reflects the integration of these technologies into the complex regulatory, organizational, and community fabric of the global maritime industry. While technological and commercial challenges are being systematically addressed, stakeholder trust, regulatory harmonization, and the standardization of crew training remain focal points for achieving widespread societal adoption. [162]

International Regulation and Consistency with European Policies

The integration of WAPS into the international regulatory framework is well underway, although refinements are continuously being sought to ensure a level playing field.

- **IMO Regulations:** WAPS are formally recognized by the International Maritime Organization (IMO) as an innovative energy efficiency technology classified under Category (B-2), meaning they operate optimally under limited conditions and reduce propulsion power. The 2021 Guidance on EEDI/EEXI (MEPC.1/Circ.896) specifically includes a methodology for calculating WAPS contribution, permitting the use of the highest-performing 50% of wind conditions in the global wind probability matrix to reflect operational experience more accurately. The IMO's revised GHG Strategy aims for net-zero emissions by or around 2050, including an ambition for 5-10% uptake of zero or near-zero GHG energy sources by 2030, a goal WAPS implicitly contributes toward. WAPS energy is included in IMO Life Cycle Analysis (LCA) guidelines as a zero-emissions pathway.
- **European Union Policies (FuelEU Maritime, EU ETS):** The EU's "Fit for 55" package explicitly incentivizes WAPS:
- **FuelEU Maritime (effective 2025)** grants a reward factor of up to 5% reduction in the GHG intensity calculation for vessels where WAPS supplies 15% or more of the propulsive energy.
- **EU Emissions Trading System (EU ETS)** (effective 2024) implicitly incentivizes WAPS because the use of wind reduces overall fuel consumption and thus minimizes exposure to carbon costs.
- **Consistency Challenges:** Despite recognition, challenges exist, notably in ensuring a "technology neutral" stance against "fuel-centric" approaches. For instance, Fuel-EU Maritime grants a 2x multiplier for Renewable Fuels of Non-Biological Origin (RFNBOs) but only a 1-5% reward for WAPS. Furthermore, wind propulsion is currently not included in the list of renewable energy sources under the Renewable Energy Directive (RED) framework.

- **IACS and Classification Rules:** Major classification societies (LR, RINA, ABS, DNV) actively support WAPS integration. RINA assigns specific class notations (WAPS-A, WAPS-H, WAPS-M) based on the percentage of available effective power supplied by the WAPS. Class rules cover essential safety and structural aspects, including load

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determination, structural integrity, electrical systems, and lightning protection. However, there is a recognized need to harmonize and standardize these diverse class rules, particularly concerning primary wind vessels.

Stakeholder Acceptance

Acceptance among major industry actors is accelerating, driven by confirmed performance data and regulatory drivers. [163]

- **Shipowners and Industry Actors:** The WAPS market is approaching a tipping point, moving past initial singular pilot projects toward multiple unit installations and integrated newbuild designs. This trend demonstrates growing confidence in the technical feasibility and fuel-saving potential. WAPS are generally perceived positively for providing a zero-emissions energy component, contributing to energy security, and offering predictability against volatile fuel markets. However, ongoing barriers include upfront capital expenditure (CAPEX) and the initial lack of industry familiarity with the novel technologies.
- **Maritime Authorities and Safety Regulators:** Regulatory bodies actively manage WAPS risks. EMSA conducted Hazard Identification (HAZID) studies on various WAPS types and concluded that no major risk was identified that cannot be resolved. Class societies facilitate risk assessment (HAZID) and compliance studies. Nonetheless, the industry highlights regulatory gaps, particularly concerning non-conventional issues like stability (heeling moments), manoeuvrability, and bridge visibility, which need specific updates to IMO safety codes (SOLAS, IS Code).
- **Ports and Infrastructure:** Port operations present the main physical obstacle, primarily related to air draft restrictions (bridges, cranes) and interference with cargo handling. WAPS technology providers mitigate this through tiltable, retractable, or rail-mounted systems. Furthermore, ports like Vancouver offer economic incentives (discounts on harbor fees) for wind-assisted vessels.
- **Crews and Operators:** Acceptance by operational staff is strong because modern WAPS operate with a high degree of automation. The automation minimizes crew workload, allowing staff to focus on other tasks.

Social and Territorial Aspects

WAPS deployment offers significant social benefits, particularly relating to environmental health and local economic development.

- **Environmental and Health Impact:** WAPS contribute to a direct and absolute reduction in fuel consumption, leading to a corresponding reduction in GHG emissions and air pollutants (SOx, NOx, Particulate Matter). This directly benefits local communities, such as citizens near ports, by reducing exposure to harmful emissions. An additional co-benefit is the reduction of Underwater Radiated Noise (URN), as WAPS reduce engine load and propeller cavitation, thereby protecting the marine ecosystem.

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- **Public Acceptance and Brand Image:** The highly visible nature of WAPS technologies enhances the brand image of adopting companies. Public surveys indicate a highly favourable impression of companies utilizing renewable energy for shipping.
- **Socio-Economic/Regional Development:** WAPS creates significant economic opportunities in design, manufacturing, and maintenance services. Regional "wind propulsion clusters" are emerging in areas such as Nantes/Saint-Nazaire, France, with forecasts anticipating a substantial creation of direct and indirect jobs by 2030. Moreover, supporting small sail cargo vessels could help revitalize small ports and short-sea shipping networks, contributing to regional energy resilience and trade activity.

Crew Safety & Training

While the technology is inherently automated, standardizing the human element integration is critical for ensuring long-term operational excellence and safety.

- **System Operation and Safety:** Crew safety considerations are incorporated into class guidelines and regulatory review processes (HAZID). Key safety concerns include lightning protection, structural integrity against extreme weather (e.g., ice accumulation), collision avoidance (visibility), and emergency stowage procedures. The crew is responsible for monitoring operational status and engaging safety protocols (e.g., activating E-STOPs).
- **Need for Standardized Training:** Currently, no standardized training curriculum exists across the industry; instruction is primarily provided by the WAPS vendors. However, the maritime community recognizes the need for consistency in system awareness, operational parameters, and emergency preparedness. Initiatives, such as the DIGI4MER project and ongoing efforts by the International Windship Association (IWSA) and its regional partners, are actively working to develop a standardized theoretical training curriculum and digital simulation materials for seafarers.

Societal Readiness Level (SRL)

Comparison for WAPS Technologies

The following table synthesizes the relative societal integration and readiness based on regulatory acceptance, stakeholder trust, and social implications observed in the source material:

Table 46 - Societal Readiness Level (SRL) Comparison for WAPS Technologies

WAPS Technology Type	International Regulation & Policy	Stakeholder Acceptance	Social & Territorial Aspects	Overall SRL Assessment

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Rotor Sails (Flettner Rotors)	High. Strong EEDI/EEXI precedent (Category B-2). Widest application in class rules/AiP.	High. Largest installed base. Proven reliability and automation. Good crew familiarity.	High. Strong case studies demonstrating URN/air pollutant reduction. Noise/vibration concerns addressed by placement.	8-9
Suction Wings (VentiFoils, eSAIL)	High. Rapid acceptance due to modular, containerized options. EEDI/EEXI precedent established.	High. High interest from general cargo sector due to quick installation/removal/flexibility. Concerns over air draft minimized by foldability.	High. Strong appeal for short-sea trades (general cargo/feeder routes) connecting ports, enhancing air quality benefits.	8-9
Rigid Sails (Wing Sails, Hard Sails)	Medium-High. Established EEDI precedents. High adoption in newbuild segment (VLCCs, Bulk).	Medium-High. Strong confidence for integrated newbuild designs. Acceptance lower for retrofits due to large space/structural requirements.	Medium. Excellent potential contribution for primary wind ships (up to 90% savings in optimized designs).	**7-8**
Kites (Towing Kites)	Medium. Included in EEDI scope. Recognized for ability to use higher-altitude winds.	Medium. Attractive for container ships due to minimal deck space. Deployment/retrieval complexity increases operational risk perception.	Medium. Strong savings potential (20–40% claimed). Low physical profile reduces interference with local infrastructure.	6-7
Soft Sails & Hull Form	Low. Limited large commercial	Low. Limited operator experience; potential high	Low. Conceptual, pending	**4-5**

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	applications; reliance on concepts/prototypes.	maintenance/complexity of soft rigs.	successful demonstration of feasibility and reliable performance data.	

3.8.2 AIR LUBRICATION SYSTEM, BULB OPTIMIZATION AND PROPELLER OPTIMIZATION

These three technologies are mature, incremental energy-efficiency measures (rather than fuels). They are complementary: ALS reduces frictional resistance, propeller ESDs / optimisation improve propulsive efficiency, and bulbous-bow shapes reduce wave making so each analysis treats the three measures together (synergies, trade-offs and common integration issues). Together they deliver meaningful fuel and CO_2 reductions when properly matched to hull form, speed profile and engine/rudder interaction [27].

TECHNOLOGY READINESS LEVEL

The three technologies form a **mature package of hydrodynamic / propulsive efficiency measures** rather than a single novel system, but their TRL assessment needs to account for different maturity sub-components and integration complexity when they are combined on the same ship.

Overall maturity & reliability

Propeller optimisation techniques (geometric re-design, advanced blade sections, boss-cap fins such as PBCF, ducts and nozzle designs, and cavitation mitigation) and bulbous-bow optimisation are **long-established** naval-architecture solutions with decades of full-scale experience and large statistical bases of performance data [176] [177]. PBCF is an industrialised, mass-deployed Energy Saving Device: manufacturers and shipowners report average fuel savings in the **~3–5%** range for many vessel types and thousands of installations (MOL reports >4,000 installations for PBCF and long cumulative CO_2 savings) [178].

Bulbous bows are a classic naval architecture solution; optimization via CFD and model tests is standard design practice. Numerous studies (including MDPI journals) quantify how bulb geometry influences wave-making resistance across speeds and loading conditions. For many hull forms and service speeds, an optimised bulb yields measurable fuel savings; for others (low-speed or highly variable service) a bulb may be neutral or detrimental.

Active air lubrication systems have progressed from model-scale R&D and pilot installations to multiple full-scale commercial retrofits and trials. DNV's industry reports and Maritime Forecast highlight ALS as a commercially deployable energy-efficiency technology with demonstrated fuel savings (case-dependent) and growing vendor maturity: ALS has progressed from model-scale experiments to an increasing number of full-scale retrofits and newbuild orders (DNV reports cites >160 operating systems and several hundred on order), and recent open-access parametric CFD and full-scale analyses show **gross friction**

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reductions that can be substantial (model studies report up to ~19% gross power saving; net savings after accounting for compressor parasitic load often reported in the order of **~10–15%** in optimistic configurations but vary strongly with speed, hull form and seakeeping) as per the MDPI parametric study and IJNAOE meta-analysis. Field results vary by hull form, speed and air system design [179] [180].

These three devices are mature, with known maintenance regimes and predictable lifetimes. Empirical and CFD literature supports this: comprehensive parametric and optimisation studies demonstrate reliable efficiency gains when propeller/hull/appendage matching is properly performed [181].

PBCFs and other boss-mounted devices are also mechanically simple, made from robust materials; maintenance schedules are similar to routine underwater appendage inspections. Potential risks include increased fouling, mechanical wear and need for occasional re-profiling; but overall lifetime is comparable to other hull appendages [178].

For ALS the Key components are compressors, piping and air-release hardware. Reliability depends on marine-grade design (corrosion protection, filtration) and maintenance of compressors and valves. Guidance notes and class rules require in-service surveys; vendors report typical equipment lifetimes comparable to other auxiliary machinery (years to decade scale), with maintenance intervals driven by compressor hours and fouling conditions and classification societies now include survey requirements for them [182].

For the bulb the technical lifetime and maintenance intervals is even easier, in fact bulb is part of the hull and has no moving parts; maintenance is standard hull care (anti-fouling, inspection for damage)and durability is long — decades — unless struck or damaged.

Marinization & integration risks

When considered together, the integration complexity grows non-linearly. Propeller and bulbous solutions are primarily passive hydrodynamic or structural changes; their marinization concerns revolve around mechanical strength, cavitation and vibration tuning, and hydrodynamic interaction with rudder and hull (well covered by industry CFD + model tests). ALS introduces active machinery (compressors, control valves, piping, air outlets) that must be marinized to withstand salt spray, vibration, condensate, biological fouling and thermal cycles. Guidance notes from class societies illustrate the kinds of approval, structural, piping and electrical considerations required to make ALS robust in a shipboard environment.

ALS components are already covered in class guidance and rules for piping, compressors and instrumentation; DNV and Lloyd's Register provide specific guidance on marine integration (valving, non-return valves, remote operation, instrumentation, drains). Deck and double-bottom piping, compressor rooms, power supply and control redundancy must be assessed; ALS must be integrated in hull structural and stability analyses. Full-scale tests and sea trials are used to validate model extrapolations because model-to-full-scale scaling of air layer behaviour can be challenging [182].

For propellers designs are tailored by propeller and rudder matching studies; CFD-based hull/propeller matching is standard practice for newbuilds and retrofits. Manufacturers provide shop fabrication tolerances and fatigue assessments. Marinization challenges are

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limited relative to novel fuels—compatibility with shaft line, stern geometry and cavitation behaviour must be assessed [181].

Finally, Bulb design must be matched to the ship's operational speed and loading; retrofitting a bulb requires dry-dock and careful weight/balance assessment. Marinization issues are well understood (structural reinforcement, appendage attachments) [177].

The **combined** configuration must address interactions: e.g., ALS alters hull boundary conditions in the stern wake — which in turn changes propeller inflow and could shift the operating point of propeller ESDs and chine/bulb hydrodynamics. Therefore, full-scale sea trials and iterative CFD/hydro modelling are essential to validate the integrated package.

In terms of **Reliability, lifetime & maintenance forecast the** Passive devices (propeller optimisations, bulbs) have long lifetimes (decades) and maintenance cycles aligned with routine hull care (anti-fouling, inspection at dry-dock). PBCFs and analogous ESDs are robust and typically inspected during scheduled underwater surveys. ALS mechanical components (compressors, valves) have maintenance cycles similar to other auxiliary systems; however, compressor health, filter replacement, and nozzle fouling create additional scheduled and unscheduled maintenance events which must be accounted for in maintenance planning. Recent studies and operational reports quantify compressor parasitic power and note that maintenance intervals depend on water quality and fouling rates, so owners should expect condition-based maintenance and remote health monitoring to be best practice [183].

Energy-efficiency performance & EEDI/EEXI implications

All three technologies directly target reduction of delivered shaft power for a given service speed and therefore improve EEDI/EEXI and operational CO_2 intensity. Propeller optimisation and bulbous-bow tuning reduce wave-making and improve propulsive efficiency with predictable translation into EEDI gains when the ship operates near the design point. PBCF and related ESDs reduce hub vortex and recover slipstream energy, producing single-digit percentage efficiency boosts in many cases (literature reports vary with vessel type and loading). Optimised propellers directly improve propulsive efficiency, reducing delivered shaft power and therefore EEDI/EEXI. Case studies show quantifiable EEDI improvements when propulsive efficiency increases. The net benefit depends on propeller-hull-engine matching and operational load spectrum; off-design performance must be evaluated as gains may reduce at low or high speed extremes.

optimised bulb can reduce wave making and therefore delivered power at design speed—benefits translate directly into improved EEDI/EEXI. However, benefits are speed- and load-dependent; off-design performance must be carefully evaluated. Case studies show substantial savings when design conditions are met.

ALS reduces viscous friction and can lower delivered shaft power at a given speed. Reported gross friction reduction can be significant in optimal conditions (MDPI parameter studies show up to ~19% gross power saving in model conditions; net savings will be lower after air supply energy is deducted) but field results have wider spread due to sea-state sensitivity and hull form dependence. The net EEDI/EEXI benefit depends on ship operational profile,

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compressor efficiency and added weight/drag of the system. Proper system sizing and controls to minimize parasitic power (compressors) are critical to realize net EEDI gains [27].

Combined application can be **synergistic**: a bulb/propeller optimised for the ALS-modified hull may recover additional benefit beyond the sum of individual effects — but it requires integrated design and verification because the ALS changes stern inflow and effective wake fraction used in propeller matching calculations. Recent data-driven frameworks and model calibration studies provide methods to forecast net savings and identify operating envelopes where ALS is beneficial (e.g., specific speed ranges where net benefit >0 once compressor load is subtracted) [179].

Safety on board

Passive devices add minimal safety challenge beyond structural integrity and sonar/noise considerations; ALS introduces active system failure modes (air leakage, compressor failure, overpressure events, control faults) that must be handled by SMS, interlocks and redundancy. Class guidance prescribes automatic shutdown, isolation valves, and integration tests [182]. Moreover, ALS requires integration with the vessel automation and Energy Management System (EMS) for optimized operation (turn on/off at speeds where benefit exists, safety interlocks). EMS must be capable of managing transient conditions: compressors cycling, rapid changes in sea state that change ALS effectiveness, and dynamic matching of engine maps to new propulsive characteristics. Modern integrated automation systems can accommodate these needs but require commissioning, testing and crew familiarization. Safety issues relate mostly to machinery space arrangements, overpressure protection, water ingress detection and emergency shutdown procedures. Class guidance prescribes automatic shutdown and remote operation pathways. Integration with ship EMS is technically straightforward for modern ships but requires software/hardware commissioning and testing [183].

Instead for the propeller optimization Integration is largely mechanical; impact on safety is minimal when installed correctly. There is a need for updated maintenance procedures and possibly for updated engine control maps if propulsive characteristics change; EMS integration for route-optimisation and engine matching is straightforward [178].

About the bulb optimization there aren't active system and the integration with ship EMS is not applicable. Safety issues relate to structural integration and potential change in seakeeping/added resistance in waves—addressed through design and testing [177].

TRL conclusion:

Table 47 - AIR LUBRICATION SYSTEM, BULB OPTIMIZATION AND PROPELLER OPTIMIZATION TRL

	Level (0–9)	Explanation
Overall maturity & reliability (propeller optimisation, bulbous bow, ALS)	8–9 (propeller & bulb), 7–8 (ALS)	Propeller optimisation and bulbous bows are long-established naval architecture solutions with decades of full-scale operational data. ALS has progressed to full-scale commercial installations

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		but still shows performance variability across hull forms.
Propeller optimisation (geometry, PBCF, ducts, cavitation mitigation)	9	Industrialised, mass-deployed technologies with thousands of installations and statistically robust fuel-saving evidence (typically 3–5%).
Bulbous-bow optimisation	8–9	Fully mature structural solution, routinely optimised using CFD and model testing. Performance is well understood but speed/load dependent.
Air Lubrication Systems – technical development	7–8	ALS has moved from R&D and pilot projects to commercial retrofits and newbuilds, with increasing operational data but still hull- and speed-sensitive performance.
Technical lifetime & durability	8–9 (passive), 7–8 (ALS)	Propellers and bulbs have lifetimes comparable to hull structures (decades). ALS components (compressors, valves) have auxiliary-machinery lifetimes with predictable maintenance needs.
Marinization & integration risks	7–8	Passive devices pose limited integration risk. ALS introduces active systems requiring careful marinization, piping, power, control integration, and validation via sea trials.
Energy-efficiency performance & EEDI/EEXI impact	8	All technologies directly reduce delivered shaft power and improve EEDI/EEXI, with predictable gains for propeller/bulb and more variable but potentially higher gains for ALS.
Safety on board	7–8	Passive devices introduce minimal safety concerns; ALS adds machinery-related risks that are well covered by class guidance and modern automation systems.
Global TRL analysis	**8**	Propeller and bulbous-bow optimisation are fully mature (TRL 8–9). ALS is slightly less mature (TRL 7–8) due to performance predictability and integration complexity, but is clearly beyond pilot stage.

COMMERCIAL READINESS LEVEL

When considered as a **single operational package**, the three technologies present a strong commercial case for most merchant segments — but different economic drivers and financing mechanisms apply to each element and to the combined retrofit/newbuild business case.

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Bankability

Propeller optimisation and bulbous-bow optimisation are **low-risk, bankable investments**: short payback, modest CAPEX, and a long history of performance guarantees from vendors make them attractive to shipowners and lenders. Many yards and vendors offer performance guarantees and post-installation verification, which lowers lender perceived technology risk. PBCF in particular is well-established commercially with manufacturer track records and widespread adoption that support credit-worthy performance claims.

ALS is financially attractive in many scenarios but exhibits **greater variability** in predicted ROI due to sensitivity to operational profile (speed range), hull form and sea states which determine net savings after compressor energy draw. Industry forecasts (DNV) and academic meta-analyses indicate that ALS retrofits can be bankable where predicted net fuel savings exceed parasitic energy and additional OPEX. This usually implies operation in an applicable speed band and relatively calm sea areas or hull forms with large flat bottom area suitable for air coverage. DNV's Maritime Forecast and IJNAOE analyses provide frameworks owners can use to make project-level investment cases and de-risk via trials [180].

ALS projects are generally investment-grade for shipowners seeking short payback efficiency measures. Many retrofit projects are financed internally or through green loans; ALS is often eligible for energy efficiency grants, and classification/approval-in-principle reduces perceived technology risk. Multilateral lenders and commercial banks see ALS as a lower-risk decarbonisation measure relative to novel fuels, improving bankability.

Propeller optimisation and PBCFs are low-risk investments with relatively short payback times; they are easily bankable as retrofit measures when backed by model and trial data. Vendors and yards often offer performance guarantees, improving bankability. Bulb optimizations (newbuild or retrofit) are bankable where design speed is consistent with bulb effectiveness. They are often part of ship upgrade packages and can be financed as part of retrofit loans [27].

From a **bankability perspective**, propeller optimisation and bulbous-bow optimisation are among the most mature and financially attractive efficiency measures currently available. Propeller optimisation solutions—including propeller re-pitching, re-profiling, replacement with high-efficiency designs, and the installation of energy-saving devices such as Propeller Boss Cap Fins—are widely deployed across all major ship segments. The technology benefits from decades of empirical validation, extensive CFD and model testing, and a large installed base. Reported fuel savings typically range between 3% and 5%, with higher values observed in vessels where the original propeller was poorly matched to the wake field. Due to low technical risk, predictable performance, and limited installation complexity, propeller optimisation is commonly associated with payback periods below two years, making it highly attractive to lenders and well suited to green financing instruments.

Bulbous-bow optimisation shows similarly strong bankability, although its performance is more sensitive to the vessel's operational speed profile. Hydrodynamic redesign of the bulb—often undertaken during scheduled dry-docking—can deliver fuel savings in the range of 2% to 7% when the vessel operates close to its design speed. The underlying hydrodynamic principles are well understood, and the engineering process relies on mature CFD and finite element methods. Because bulb modifications are structural and have a lifespan comparable to the vessel itself, they are considered low-risk investments with durable benefits. As a result, financiers generally perceive bulb optimisation as a stable, long-term efficiency upgrade, particularly when combined with propeller optimisation to maximise wake-field synergies.

Air Lubrication Systems, while increasingly deployed, present a different bankability profile. ALS installations require higher upfront investment and introduce additional operational complexity due to the need for compressors, piping, and control systems. Typical CAPEX for ALS ranges from approximately one to two million euros for newbuilds, increasing to around 1.2 to 2.5 million euros for retrofits, depending on vessel size and system configuration. While model-scale and sea-trial results indicate potential gross resistance reductions of up to 15–20%, real-world net fuel savings are generally reported in the range of 3% to 15%, reflecting variations in speed, sea state, hull form, and system optimisation. Financial institutions tend to view ALS as bankable when supported by operational data, performance guarantees, and integration within broader efficiency packages. However, the variability of savings introduces a higher perceived risk compared to purely passive hydrodynamic measures [184].

In terms of **CAPEX and OPEX**, the three technologies differ substantially. Propeller optimisation typically requires modest capital investment, ranging from below one hundred thousand euros for minor modifications or energy-saving devices, up to approximately one million euros for full propeller replacement on large vessels. Operating costs are negligible, limited to routine inspections and integration with standard hull and propeller maintenance schedules. Similarly, bulbous-bow optimisation involves capital expenditures typically between three hundred thousand and one million euros, mainly associated with design engineering, steel fabrication, and dry-dock installation. Once installed, the bulb does not introduce additional operational costs beyond standard hull inspections, making its OPEX impact effectively marginal.

By contrast, ALS introduces both capital and operational costs. In addition to the initial investment, ALS increases OPEX through electrical energy consumption for compressors, which can account for approximately 1–5% of main engine power demand. Depending on fuel prices and operating hours, this translates into additional annual operating costs that can range from tens of thousands to several hundred thousand euros per year. Additional maintenance requirements for compressors, filters, valves, and control systems further contribute to OPEX, although these costs remain modest relative to total ship operating expenses [52].

When assessed collectively, these technologies offer a **compelling economic proposition**. Propeller and bulbous-bow optimisation deliver highly predictable fuel savings with minimal operational risk and low ongoing costs, making them ideal baseline measures for energy efficiency improvements. ALS, while more capital-intensive and operationally complex, can significantly enhance total fuel savings when deployed on suitable vessels and routes. Combined implementations of the three technologies can realistically achieve net fuel reductions in the range of 8% to 20%, with higher values observed in vessels with stable operating profiles and favourable hull forms [179].

Propeller and bulb optimisations are **very high CRL** (low CAPEX, short payback, mature market). ALS is **moderately to highly bankable** where operational profiles match the ALS design envelope; its CRL is increasing rapidly as more field data and orders accumulate

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(industry statistics and DNV forecasts show growing adoption). For integrated projects, the combined CRL is high provided the business case and contractual risk allocation explicitly address ALS variability (use case selection, pilot verification, measurement-based acceptance).

CRL conclusion

Table 48 - AIR LUBRICATION SYSTEM, BULB OPTIMIZATION AND PROPELLER OPTIMIZATION CRL

	Level (0–9)	**Explanation**
Bankability – propeller optimisation	9	Very low technical and financial risk, short payback periods (often <2 years), strong vendor guarantees, and widespread lender acceptance.
Bankability – bulbous-bow optimisation	8–9	Highly bankable when operational speed profile matches design assumptions; long-lasting structural benefits and low perceived risk.
Bankability – Air Lubrication Systems	8	Increasingly bankable with growing operational data, class approvals, and eligibility for green finance, though ROI variability remains higher than passive devices.
CAPEX and OPEX – propeller optimisation	9	Modest CAPEX, negligible OPEX, integration with routine maintenance; very attractive cost-benefit profile.
CAPEX and OPEX – bulbous-bow optimisation	8–9	Moderate CAPEX typically linked to dry-docking; virtually no added OPEX; lifetime benefits support strong investment cases.
CAPEX and OPEX – ALS	7–8	Higher CAPEX and added OPEX due to compressor power and maintenance; still attractive where net fuel savings are well demonstrated.
Combined economic performance	8–9	Integrated application can achieve 8–20% net fuel savings, especially for vessels with stable operational profiles and favourable hull forms.
Logistics dependency	9	No dependence on new fuels or bunkering infrastructure; implementation is independent of port-side energy logistics.
Global CRL analysis	**8–9**	Propeller and bulb optimisations are among the most commercially mature efficiency measures available (CRL 9 and 8–9). ALS has rapidly reached high CRL (≈8) and is widely considered investment-grade when properly matched to vessel operations.

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SOCIETAL READINESS LEVEL

The societal readiness of the combined hydrodynamic package is **generally high** compared with fuelswitch options because these technologies do not require new onshore hazardous fuel infrastructure or change bunkering practices. Nevertheless, some societal, regulatory and human-factors issues must be addressed explicitly to realize broad adoption.

International regulation & consistency with European policy.

The technologies are fully consistent with IMO and EU decarbonisation goals: EEDI/EEXI frameworks quantify improvements in energy efficiency attributable to hull and propulsive modifications, and FuelEU/EU ETS policies further increase the economic attractiveness of efficiency measures by widening the fuel price gap between conventional fuels and decarbonised fuels. IMO/industry guidance) specifically lists ALS, propeller optimisation and hull form improvements among the near-term measures to reach decarbonisation targets; the major classification societies publish technical guidance and approval frameworks for ALS and ESDs, which helps harmonize class approval and supports regulatory acceptance. Because these are not fuel-type changes, they raise fewer legal and environmental permitting hurdles than fuel switching, simplifying regulatory pathways in many jurisdictions [27].

Stakeholder acceptance (owners, ports, authorities, crews, industry).

- *Shipowners & operators:* Generally positive — these measures are proven ways to lower fuel bill and regulatory exposure (EEDI/EEXI compliance). Owners appreciate short payback devices (propeller/bulb) and are increasingly interested in ALS to extend decarbonisation gains before committing to fuel conversion.
- *Shipyards & manufacturers:* Positive — established business for propeller/bulb work and growing opportunities for ALS suppliers and retrofits. Shipyards must adapt scheduling and install capabilities for ALS piping/equipment.
- *Crews:* Acceptance depends on training and proven safety. For propeller/bulb modifications minimal crew change is required beyond maintenance training; ALS requires familiarisation with compressors, interlocks and operational constraints. Studies on operational ALS installations highlight the need to incorporate ALS procedures into SMS and training curricula to build crew confidence. Well-designed training and transparent operating procedures strongly increase crew willingness to operate ships equipped with ALS.
- *Ports & authorities:* Neutral to positive — these changes do not significantly alter port operations or create hazardous bunkering scenarios. Ports may welcome the CO_2 reduction benefits and the lower port emissions associated with fuel savings [184] [183].

Social & territorial aspects

Because the package does not change fuel type or create new onshore fuel terminals, **local**

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social impacts are minimal compared with a switch to an alternative fuel (e.g., ammonia). Noise, vibration and small increases in compressor room activity (ALS) are shipboard concerns rather than local community issues. The principal social benefit is indirect: fleet fuel savings reduce greenhouse gas and local air pollutant emissions over a ship's operational life, which aligns with community and policy goals for cleaner shipping corridors. Communication of benefits (CO_2 avoided, local air improvement) supports public acceptance.

Crew safety & training

Propeller and bulb changes do not pose novel chemical hazards, but they can change vibration/noise and seakeeping; engineers must be trained in revised vibration monitoring and hull inspection. ALS requires **targeted training modules** covering compressor operation, air-system safety, emergency shutdown procedures, leak detection, and integration in the ship's SMS. Class guidance and industry bodies advise incorporating ALS topics into familiarisation and duty-specific training; maritime training providers should develop standardized modules (practical drills, simulator training for compressor faults and emergency scenarios). Because ALS is an active system with failure modes, standardized WPT-style curricula (well-practised training) and certification are recommended to ensure consistent competence across fleets. Research indicates that crew willingness and operational safety are strongly correlated to training depth and frequency [182].

SRL conclusion

Table 49 - AIR LUBRICATION SYSTEM, BULB OPTIMIZATION AND PROPELLER OPTIMIZATION SRL

	Level (0–9)	Explanation
Regulatory alignment (IMO, EU policies)	9	Fully aligned with EEDI/EEXI, FuelEU Maritime, and EU ETS; explicitly recognised as near-term decarbonisation measures.
Stakeholder acceptance – shipowners & operators	9	Strong acceptance due to short payback, regulatory compliance benefits, and low operational disruption.
Stakeholder acceptance – yards, ports, authorities	8–9	Generally positive; no hazardous fuels or port infrastructure changes required; ALS requires some yard capability upgrades.
Crew impact & operational acceptance	8–9	Minimal impact for propeller/bulb solutions; ALS requires additional training and SMS integration but is well accepted when training is provided.
Social & territorial impacts	9	No new onshore hazards or community impacts; societal benefits through reduced CO_2 and air pollutant emissions.
Crew safety & training readiness	8–9	Passive measures require minimal additional training; ALS requires targeted but manageable

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		training modules that are already being standardised.
Global SRL analysis	**9 (passive), 8–9 (ALS)**	The combined package has very high societal readiness. Propeller and bulb optimisation are fully accepted (SRL 9). ALS is slightly lower but rapidly converging toward SRL 9 as training and standardisation mature.

4. Comparative Analysis of Technologies

4.1. Cross-technology comparison in terms of readiness, costs, and environmental benefits

In order to ensure a robust, transparent, and methodologically sound representation of the actual maturity of the technologies under consideration, it is essential to move beyond a single-dimensional assessment of readiness. While the Technology Readiness Level (TRL) provides valuable insight into the degree of technical development and validation, it does not, on its own, fully capture the broader conditions required for effective deployment and uptake. For this reason, the present analysis adopts an integrated assessment framework that simultaneously considers TRL, CRL and SRL, thereby enabling a more comprehensive evaluation of each technology's overall state of readiness.

By analysing these three dimensions in parallel, it becomes possible to define the maturity of a given technology from a systemic and holistic perspective. This approach allows technical performance, market preparedness, and societal acceptance to be examined as interrelated factors rather than as isolated indicators. As a result, the analysis more accurately reflects real-world conditions, in which technological feasibility, economic viability, and social legitimacy must progress in a coherent and balanced manner in order to support successful implementation.

To operationalise this integrated assessment, the subsequent table (Table 50) reports the TRL, CRL, and SRL values for all technologies included in the study. The technologies are grouped according to their nature, allowing for a clearer comparison within and across homogeneous categories. In addition to the individual readiness indicators, a set of aggregate metrics has been calculated for each technology, including the arithmetic mean of the three readiness levels, their variance, and the cumulative sum of the indices. These complementary metrics are intended to support both qualitative interpretation and quantitative comparison across the analysed technologies.

The calculation of the average readiness level provides a synthetic indication of the overall maturity of each technology, offering a useful reference for high-level comparisons. At the same time, the inclusion of the variance serves a critical analytical purpose, as it highlights the degree of alignment, or misalignment, between the different readiness dimensions. A low variance suggests a balanced progression across technical, commercial, and societal aspects, whereas a high variance indicates the presence of significant gaps that may represent barriers to deployment. The cumulative sum of TRL, CRL, and SRL further

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reinforces the comparative analysis by emphasising the combined readiness achieved across all dimensions.

Table 50 - Cross-technology comparison

		TRL	CRL	SRL	Mean	Variance	Sum
Alternative Fuels	AMMONIA	6-7	6-7	6	6.33	0.08	19.0
	Hydrogen	6	4	5	5.00	1.00	15.0
	Methanol	8	7-8	8	7.67	0.08	23.5
	Fuel Cells	6-7	4-6	5-6	5.67	0.58	17.0
Biofuels	HVO (waste-based)	9	8-9	8-9	8.67	0.17	26.0
	FAME (waste-based)	8	7-8	7-8	7.67	0.17	23.0
	FAME / HVO (crop-based)	9	8	5-6	7.50	6.50	22.5
	BTL / FT-Biodiesel	6-7	4-5	6-7	5.83	2.67	17.5
	HTL Biocrude	5-6	3-4	3-4	4.17	2.67	12.5
	Bio-methanol (advanced)	7-8	6-7	7	7.00	0.50	21.0

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	Bio-LNG (biomethane)	7-8	6-7	7	7.00	0.50	21.0
NUCLEAR	Generation I	7	1	2-3	3.50	19.50	10.5
	Generation II	8–9	6–7	2-3	5.83	18.67	17.5
	Generation III / III+	8–9	7	2-3	6.00	19.50	18.0
	VHTR (Gen IV)	6–7	3–4	2-3	4.17	8.67	12.5
	MSR (Gen IV)	5–6	3–4	2-3	3.83	4.67	11.5
	LFR (Gen IV)	6–7	4–5	2-3	4.50	8.00	13.5
	SFR (Gen IV)	4–5	3–4	2-3	3.50	2.00	10.5
	GFR (Gen IV)	4–5	2–3	2-3	3.17	2.67	9.5
ELETTROCHEMICAL ACCUMULATOR AND SUPERCAPACITORS	LFP – Lithium Iron Phosphate	9	9	9	9.00	0.00	27.0
	NMC – Nickel Manganese Cobalt	8–9	8	8	8.17	0.17	24.5

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	LTO – Lithium Titanate	8–9	7–8	8	8.00	0.50	24.0
	Supercapacitors	8-9	8–9	8–9	8.50	0.00	25.5
	Na-ion (Sodium-ion)	6-7	7–8	7–8	7.17	0.67	21.5
	Solid-State Lithium Batteries	5–6	4–5	5–6	5.17	0.67	15.5
	Vanadium Flow Batteries (VRFB)	6	5–6 (ship), 8 (port)	6–7 (ship), 8–9 (port)	6.00	0.50	18.0
	Zinc-based batteries (Zn-air, Zn-hybrid)	3–4	5–6	6–7	5.17	4.67	15.5
	Metal-Air Batteries (Al-air, Li-air)	3-4	2–3	3–4	3.17	0.67	9.5
	Second-Life EV Batteries	8-9	4–5 (ship), 7–8 (port)	6–7 (ship), 8 (port)	6.50	8.00	19.5

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WIND ASSISTED PROPULSION SYSTEMS	Rotor Sails (Flettner Rotors)	9	8-9	8-9	8.67	0.17	26.0
	Suction Wings (VentiFoils, eSAIL)	9	8-9	8-9	8.67	0.17	26.0
	Hard Sails / Rigid Sails (Wing Sails, Oceanwings, WindWings)	9	7-8	7-8	8.00	1.50	24.0
	Soft Sails (Dynarig, WISAMO)	7-8	4-5	4-5	5.50	6.00	16.5
	Kites (Towing Kites, Seawing)	7-8	6-7	6-7	6.83	0.67	20.5
	Hull Form (Vindskip)	6	4-5	3-4	4.67	3.17	14.0

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	Wind Turbines	6	7-8	8-9	7.33	3.17	22
Ship design	ALS	7-8	8	8-9	8.00	0.50	24.0
	BULB Optimization	8-9	8-9	9	8.67	0.17	26.0
	Propeller optimization	8-9	9	9	8.83	0.17	26.5

Overall, the cross-technology comparison presented in Table 50 highlights a highly heterogeneous readiness landscape, reflecting the different stages of technological development, market consolidation, and societal acceptance across the analysed solution domains. Technologies characterised by incremental innovation, standardised components, and direct compatibility with existing ship designs and operational practices, such as waste-based biofuels, electrochemical energy storage systems (notably lithium-based batteries and supercapacitors), wind-assisted propulsion systems, and ship design optimisation measures, consistently exhibit high average readiness levels and low variance. This indicates a balanced and mature progression across TRL, CRL, and SRL, suggesting that these solutions are already well positioned for large-scale deployment and can deliver tangible environmental benefits in the short to medium term with relatively limited implementation risk.

Conversely, technologies associated with more disruptive transitions, including alternative fuels such as hydrogen and ammonia, advanced biofuels, next-generation nuclear systems, and emerging battery chemistries, tend to show lower average readiness levels and, in several cases, higher variance values. These discrepancies reveal structural misalignments between technical maturity, commercial viability, and societal acceptance. In particular, solutions that are technically advanced but commercially constrained or socially sensitive may face non-technical barriers that significantly delay adoption, despite their potential long-term environmental advantages. Similarly, technologies with promising environmental performance but limited technical validation or infrastructure readiness require sustained research, demonstration, and regulatory support to progress towards deployment.

The analysis also underscores the importance of variance as a diagnostic indicator. Technologies with comparable average readiness levels may present fundamentally different risk profiles depending on the degree of balance among TRL, CRL, and SRL. High variance values signal the need for targeted interventions (whether in policy, market incentives, public engagement or standardisation) to address specific bottlenecks. In contrast, low variance across all three dimensions points to solutions that are not only mature, but also systemically robust.

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4.2. Interdependencies and potential integration pathways

Beyond the individual assessment of readiness levels, costs, and environmental benefits, a meaningful evaluation of decarbonisation options requires explicit consideration of the interdependencies among technologies and the ways in which they can be integrated into coherent system-level solutions. In practice, most of the technologies analysed do not operate in isolation; rather, their effectiveness, feasibility, and overall impact are strongly influenced by the availability, maturity, and compatibility of complementary technologies, as well as by the surrounding infrastructural, regulatory, and operational context.

A clear example of such interdependence can be observed in the case of fuel cells, whose deployment is intrinsically linked to the availability of suitable energy carriers, most notably hydrogen and, in certain configurations, ammonia or methanol. While fuel cell technologies show moderate to high levels of technical maturity, their commercial and societal readiness is constrained by upstream challenges related to fuel production, storage, distribution, and bunkering infrastructure. The widespread adoption of fuel cells therefore presupposes parallel investments in port infrastructure, safety standards, certification schemes, and regulatory frameworks capable of addressing the specific risks associated with these alternative fuels. Without such coordinated development, progress in one domain risks being decoupled from progress in others, limiting real-world applicability.

Electrochemical energy storage systems, particularly batteries, represent another key enabling technology whose role is often maximised when integrated into hybrid configurations rather than deployed as a standalone solution. Batteries can effectively complement fuel cells or internal combustion engines by providing peak-shaving capabilities, improving load management, and increasing overall system efficiency. In this context, batteries act as flexibility enablers, allowing energy converters to operate closer to their optimal efficiency range while reducing transient loads, fuel consumption, and emissions. This hybridisation potential is particularly relevant for vessels with variable operational profiles, such as ferries, offshore support vessels, and short-sea shipping, where frequent load fluctuations are common.

Wind-assisted propulsion systems further illustrate the systemic nature of decarbonisation pathways. By reducing the overall energy demand of a vessel, these technologies generate benefits that are largely independent of the primary energy source. Whether combined with conventional fuels, alternative fuels, fuel cells, or battery systems, wind-assisted propulsion contributes to lower fuel consumption, reduced emissions, and improved energy efficiency. In this sense, such technologies function as cross-cutting efficiency measures that enhance the performance and feasibility of a wide range of propulsion configurations, while also reducing the scale and cost requirements of onboard energy storage and fuel systems.

These examples highlight that the transition towards low- and zero-emission shipping is unlikely to be driven by a single dominant technology. Instead, the evidence points towards a layered and modular integration of multiple solutions, tailored to specific vessel types, routes, operational patterns, and regulatory contexts. The optimal technology mix for a long-haul ocean-going vessel is likely to differ substantially from that of a short-sea or inland vessel, just as the requirements of port-based operations differ from those of deep-sea navigation.

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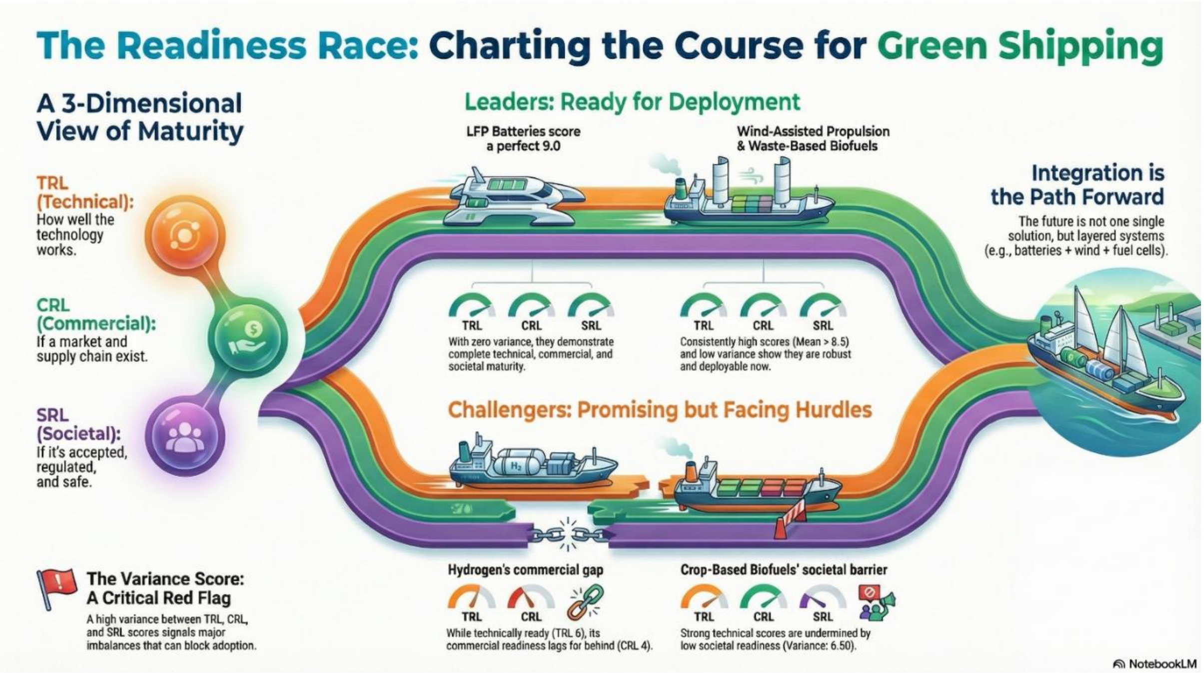
Figure 26 - Comparative Analysis of Technologies results



5. European Research contribution to TRL progress towards ZEWT

The analysis of the EU ZEWT project database shows that EU policies and funding instruments have been effective in driving formal increases in Technology Readiness Level (TRL), and to a lesser extent in Capability Readiness Level (CRL) and Social Readiness Level (SRL), particularly in areas linked to decarbonisation, alternative fuels, digitalisation and energy efficiency.

However, a critical reading of the data highlights a structural limitation in how these readiness advancements are interpreted and communicated. The recorded TRL increases associated with EU-funded projects are typically linked to highly specific components, subsystems, software modules or laboratory-scale processes, rather than to the full technology chain required for large-scale deployment. In many cases, the advancement from, for example, TRL 4–5 to TRL 6–7 reflects successful validation of a single element under controlled or semi-relevant conditions, without addressing integration constraints, operational robustness, supply-chain maturity, crew interaction, safety certification, or long-term reliability in real operational environments. This is particularly evident for complex maritime technologies such as alternative fuel systems, energy management platforms, and advanced propulsion architectures, where subsystem-level maturity does not automatically translate into system-level readiness. The database further suggests that CRL and SRL progression often lags behind declared TRL gains, indicating that while technical feasibility is being demonstrated, the capability to manufacture, install, operate and maintain these technologies at fleet scale remains underdeveloped. EU policy frameworks, by design, prioritise innovation acceleration and risk-sharing at early and mid-TRL stages, but this can lead to an optimistic perception of market readiness if TRL indicators are interpreted as proxies for deployability. In practice, the transition from EU-funded demonstration to widespread adoption requires additional non-technical enablers, including regulatory harmonisation, class rule consolidation, infrastructure availability, and commercially viable business models, which are not captured by TRL metrics alone. Consequently, while EU policies are demonstrably effective in advancing targeted aspects of technology maturity, the database confirms that such advancements should not be conflated with large-scale adoption or real-environment implementation. A more balanced assessment of impact therefore requires simultaneous consideration of TRL, CRL and SRL evolution, explicitly recognising that increases reported within EU-funded projects represent necessary but not sufficient conditions for systemic deployment across the maritime sector.

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