Fuel for thought

Hydrogen

Expert insights into the future of alternative fuels

Your trusted adviser in alternative and low carbon maritime fuel

Contents

Introduction

The challenge of maritime decarbonisation is not that it is happening, but that it needs to happen so quickly.

The evolution of sail to its heyday of the great tea clippers took centuries, and the transition to coal-powered steam ships was driven by greater supply chain mobility and speed. The arrival of diesel-fuelled engines led to a new type of ship propulsion and power generation, but this has taken close to one hundred years to evolve to where they are today.

Each shift had a dramatic impact on the cost, speed and efficiency of shipping. The energy transition that the maritime industry faces today is distinct from those earlier evolutions. It is not driven solely by technological advances or economics, but by an environmental imperative, increasingly underscored by social pressure, policy, and regulatory demands to reduce emissions.

Decisions are being made today with some commercial uncertainty, but in the knowledge that regulations, rather than economics, will push forward change. In this context, shipowners, charterers, insurers, financial markets and technology suppliers are seeking a better understanding of where the industry is heading.

Lloyd’s Register (LR) is committed to providing trusted advice and to leading the maritime industry safely and sustainably through the energy transition. Our new Fuel for Thought series puts decarbonisation options under the spotlight, analysing policy developments, market trends, supply and demand mechanics and safety implications. Each edition focuses on a specific fuel or technology, creating a reference point for the industry to overcome upcoming challenges as it faces the next great shift in ship propulsion.

This edition of Fuel for Thought focuses on hydrogen, a regularly produced chemical element and fuel with near-zero greenhouse gas emissions potential that is moving towards green production at scale, providing one possible answer to the challenges faced by owners and operators.

Other editions of Fuel for Thought, dedicated to methanol, nuclear, ammonia, LNG, biofuel, and other alternative fuels, can be found on the Fuel for Thought hub: www.lr.org/fuelforthought

1.1

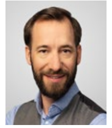
Chapter 1: Foreword

The maritime sector continues on its journey towards decarbonisation, with a number of regional and national schemes in place and the global mechanisms and frameworks still being worked out. As the urgency to reduce greenhouse gas emissions intensifies, hydrogen emerges not merely as a promising alternative, but as a cornerstone of the clean energy transition. This report, “Fuel for Thought: Hydrogen,” offers a comprehensive exploration of hydrogen’s potential to transform shipping into a zero-emissions industry.

At Hydrogen Europe, we believe that hydrogen is more than a fuel, it is one of the main vectors for systemic change. Its versatility, scalability, and compatibility with renewable energy sources make it uniquely positioned to address the complex challenges of maritime decarbonisation. Yet, the path forward is not without obstacles: Infrastructure, regulation, safety, and cost remain critical hurdles. This report does not shy away from these realities. Instead, it provides a clear-eyed assessment of the current landscape, while charting a course for innovation, investment, and international collaboration.

I commend Lloyd’s Register for its leadership in producing this in-depth analysis. By combining technical insight with policy context and market intelligence, this publication equips stakeholders across the maritime value chain with the knowledge needed to make informed, forward-looking decisions.

Hydrogen is not a distant solution: It is here, and it is evolving rapidly. With the right frameworks and shared commitment, we can accelerate its adoption and unlock a cleaner, more resilient future for global shipping.



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1.2

Hydrogen fact file

What is it? H_2

Hydrogen is the lightest chemical element. At ambient temperature, hydrogen is a clear, colourless, odourless gas that is lighter than air. Hydrogen is an extremely flammable gas with a wide flammability range and very low minimum ignition energy.

The unique characteristics of the simplest element in the periodic table introduce great potential for its use as a sustainable alternative to fossil fuels in shipping, along with a range of technical and safety challenges.

The sole byproduct from the combustion of hydrogen in air is water, eliminating greenhouse gas (GHG) emissions and many other common pollutants. However, the high temperature of a hydrogen flame can lead to the formation of oxides of Nitrogen (NOx) from the air, which must be controlled.

Hydrogen can be produced from water by electrolysis, bringing the potential for sustainable fuel production through the use of electrolysers powered by renewable energy. In 2023, low emissions* hydrogen represented less than 1% of global hydrogen production, with the remainder produced from natural gas, coal, and as a by-product from other industrial processes.

*The IEA Global Hydrogen Review 2024 considered low emissions hydrogen sources to be electrolysis powered by renewable energy, and biomass and fossil fuel production with sufficiently low emissions through high carbon capture and permanent storage.

Types of hydrogen

Hydrogen can be supplied as a compressed gas (CH_2) or in a liquid state (LH_2). Colours are often used to denote hydrogen created by particular processes, a shorthand for the carbon intensity of its source.

Green hydrogen
Produced by electrolysis of water using surplus renewable energy sources

Pink hydrogen
Produced by electrolysis of water using nuclear power, sometimes called purple or red hydrogen

Blue hydrogen
Produced by steam reforming of natural gas with carbon capture and storage

Grey hydrogen
Produced by steam reforming of natural gas without carbon capture

Black and brown hydrogen
Produced from black coal or brown coal (also known as lignite)

White/gold hydrogen
Naturally-occurring hydrogen produced by organic and other natural processes in the earth's mantle and crust

Turquoise Hydrogen
Produced by methane pyrolysis, yielding hydrogen and solid carbon – can be low emission if powered by renewables with carbon capture/usage

Hydrogen production is explored in Chapter 4.

Despite having the highest energy density of any fuel by mass, hydrogen-powered ships will require larger fuel tanks than those using conventional fuels as hydrogen has the lowest energy density by volume of the fuels being considered by the maritime sector (see energy density comparison table, page 8).

Indirect global warming potential

Hydrogen is not a GHG, but studies have shown that when emitted into the atmosphere, hydrogen reacts with other GHGs like methane, ozone, and water vapour, increasing their amounts by extending their lifetime in the troposphere and stratosphere, contributing to global warming.

A 2023 multi-model assessment of the Global Warming Potential (GWP) of hydrogen estimated the figure at 11.6±2.8 times the GWP of CO_2 over a 100 year horizon, and 37.3±15.1 over 20 years.

There is broad consensus that adopting green hydrogen as a fuel will provide a significant net benefit to GHG emissions and reduce global warming by replacing fossil fuel energy sources, preventing the release of GHGs such as methane and CO_2. Hydrogen slip is expected to be much lower in a closed fuel cell system compared to combustion.

To reach a useful energy density for transportation and use as a fuel, hydrogen is commonly liquefied and must be kept at extremely low temperatures to remain liquid. The maritime industry has experience with cryogenic fuels through LNG, which boils at -162°C, but hydrogen's lower boiling point of -253°C introduces further safety considerations for storage and bunkering.

The thermal insulation requirements for LH_2 storage tanks reduces hydrogen's effective volumetric energy density to around 13% of HFO and its equivalent storage tank, placing limitations on the commercially practical voyage distance for hydrogen-powered ships. Development of hydrogen technologies in shipping is currently focused on short-sea routes and deployments with regular bunkering opportunities to avoid the need for more and larger expensive fuel tanks, potentially at the expense of cargo space, or adding port calls for bunkering.

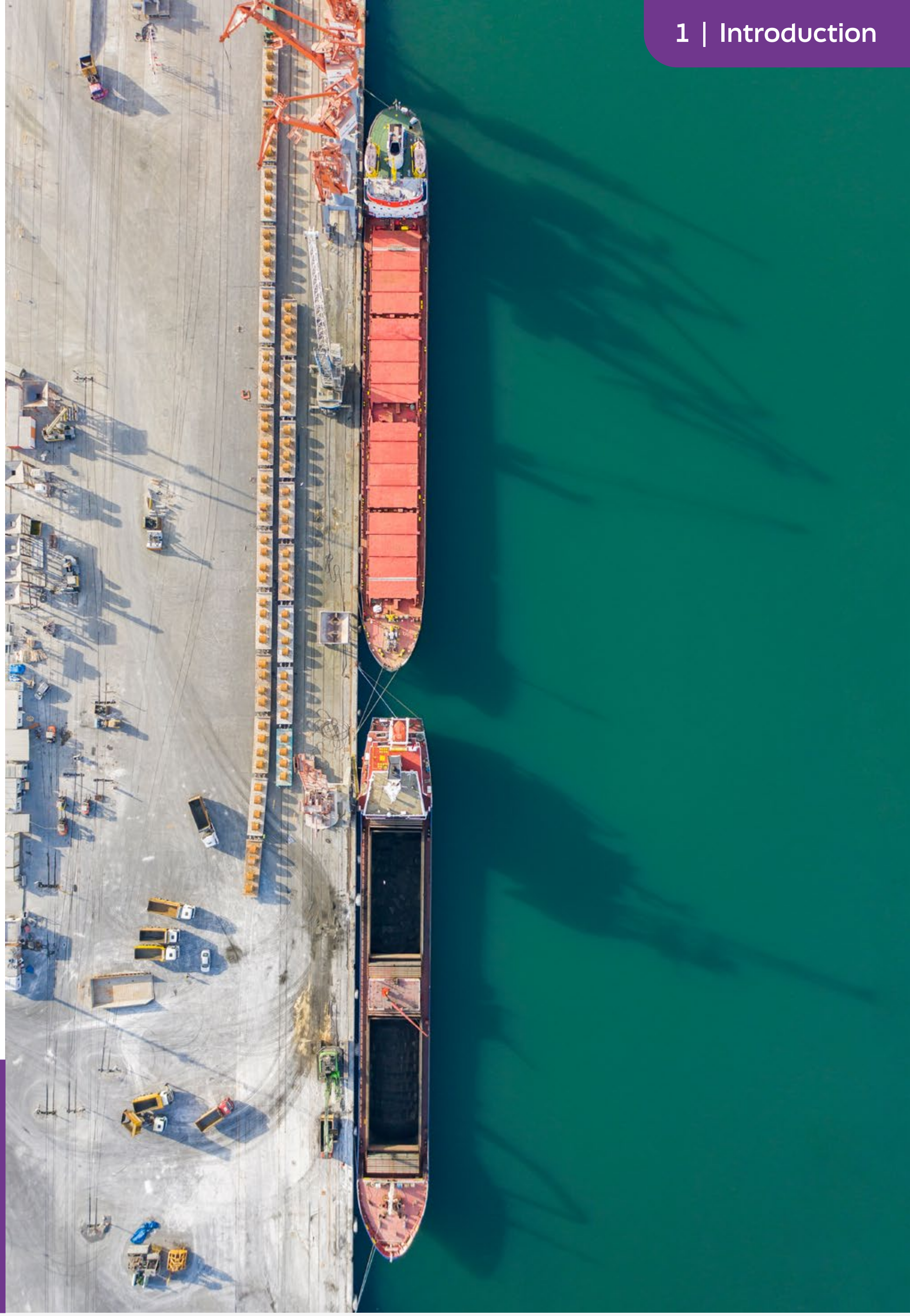
Beyond its use as a standalone fuel, hydrogen is a component of other alternative fuels for shipping including ammonia (NH_3), and methanol (CH_3OH). Ammonia is viewed as a useful hydrogen carrier in some industries, owing to its high hydrogen content and the relative simplicity of its storage and transportation. Promising technologies are reaching the market to crack ammonia into hydrogen onboard ships, increasing the energy density of stored fuel.

There are two main hydrogen propulsion technologies in shipping. The first is burning the fuel in an internal combustion engine to generate mechanical energy. The second is the use of hydrogen fuel cells which split hydrogen molecules to generate electricity to power electric motors. Both approaches are explored in more detail in section 5 – Technology readiness.

Hydrogen combustion formula:

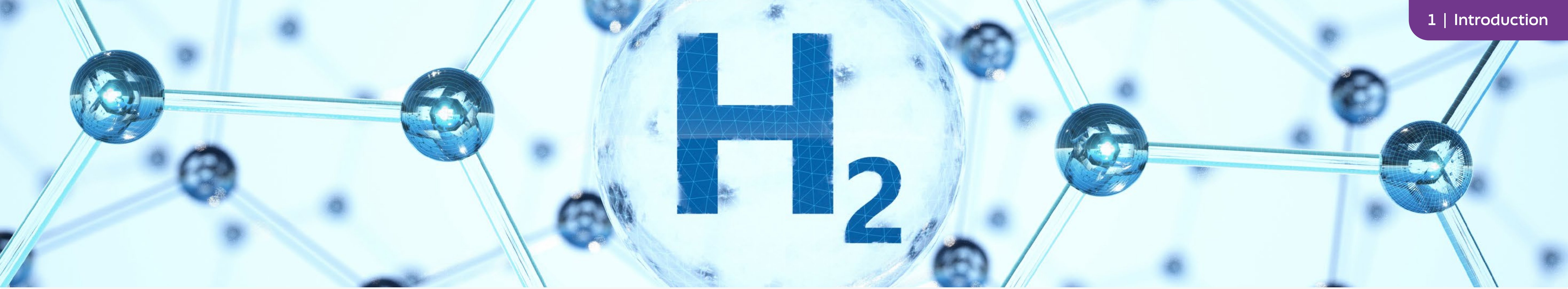
$$2H_2 + O_2 \rightarrow 2H_2O$$

In an internal combustion engine, hydrogen reacts with oxygen in the air to create water and heat/energy.



Properties table

Property	Value
Boiling temperature	-252.9 °C
Density	Liquid 70.8 kg/m3 at -252.9 °C, 1 bar Gas: 0.0827 kg/m3 at 20 °C, 1 bar
Lower flammability limit (by volume in air)	4%
Upper flammability limit (by volume in air)	77%
Auto-ignition temperature	584.85°C
Minimum ignition energy	0.017mJ
No sulphur	
No carbon	
Molecular weight	2.01594 g mole^{-1}



Energy density comparison table

Property	Liquid hydrogen	Gaseous hydrogen (350 barA)	Gaseous hydrogen (700 barA)	Liquid ammonia	Methanol	LNG
Density (kg/m^3)	70.8	23.315	39.223	696	790	450
Storage temp (°C)	-253	25	25	-33	25	-162
Storage pressure (barA)	1	350	700	1	1	1
Lower heating value (MJ/kg)	119.93	119.93	119.93	18.8	19.9	48
Volumetric energy density (MJ/lt)	8.49	2.79	4.7	13.1	15.7	21.6
Volumetric comparison vs MGO	4.52	13.73	8.16	2.94	2.44	1.78

Advantages/disadvantages of hydrogen

The following table offers a brief insight into the benefits of using hydrogen as a marine fuel along with challenges and issues.

Advantages and potential
If produced from renewable energy, hydrogen enables near to 100% reduction of Well-to-Wake GHG emissions
Hydrogen produced with carbon capture has the potential for net-zero GHG emissions
Carbon free, with no particulate matter, SOx, or NOx when used in a fuel cell
Useful as a standalone fuel or as a blend component in other fuels to reduce carbon footprint and GHG emissions
Essential for producing all zero-emission e-fuels (such as ammonia, e-LNG, e-diesel, e-methanol) to enable compliance with IMO GHG targets
A future-proof fuel in carbon-priced markets
Non-toxic, only asphyxiation risk
High diffusivity lowers risk of accumulation in ventilated spaces as hydrogen disperses rapidly
Aligns with decarbonisation goals in many national strategies
Enables compliance with future IMO GHG regulations
Wide potential applicability: usable in internal combustion engines, fuel cells, or hybrid systems

Challenges and issues
Very high fire and explosion risks
Lower energy density on volumetric basis than existing fuels
LH_2 requires very low cryogenic storage temperatures, expensive storage systems
Current high commodity prices for hydrogen, and technology prices for ICE and fuel cells
Requires significant infrastructure investment for green hydrogen production, distribution and bunkering
Requires careful selection of containment materials due to Hydrogen embrittlement
Regulations/standards for hydrogen as marine fuel are still under development
Current onshore experience is minimal, and the application is confined to organisations operating under strict confidentiality. As the fuel type is unfamiliar within the shipping sector, comprehensive training will be essential to ensure safe and compliant operations
Could produce NOx during high-temperature combustion, requiring mitigation techniques
Potential as indirect GHG, leaks and slips must be controlled

1.3

Readiness of hydrogen as a marine fuel

LR has collaborated with industry stakeholders to build a comprehensive assessment of different aspects of the fuel supply chain from production to delivery onboard, and the technologies for use as a fuel onboard for power generation.

LR's Maritime Decarbonisation Hub has developed a framework to measure the current readiness of several fuels in its Zero-Carbon Fuel Monitor publication.

A lot of focus is often put on the technology readiness level (TRL) of a new fuel solution, but this is just one element to consider. The industry's willingness to adopt a new solution is also based on its investment readiness (IRL) which signifies whether its business case is hypothetical or well proven. In addition, community readiness (CRL) is crucial; this identifies whether the frameworks for safe and publicly acceptable use of a technology and fuel are in place. TRL is assessed on a scale of one to nine, whilst the scales for IRL and CRL are from one to six.

LR uses the outputs of the monitor to identify research, development and deployment projects that will advance solution readiness and accelerate a safe and sustainable transition to net-zero greenhouse gas (GHG) emissions. The charts below show the relative maturity of the technologies necessary for the use of blue and green hydrogen across key areas including propulsion, onboard storage and handling, production, and bunkering.

The data also shows the challenges facing wider hydrogen adoption as community readiness requires better education and regulation around the use of hydrogen as a marine fuel, and investors require stronger demand signals to support low emissions hydrogen production facilities and larger scale commercial trials of technologies along the supply chain. Examples of supportive demand signals include policy incentives, carbon pricing, mechanisms, and fuel subsidies as drivers for investment in hydrogen infrastructure.

These themes are explored in further detail throughout this report.

Definitions of the IRL, TRL and CRL levels can be found in Annex 1.

E-hydrogen Technology, Investment and Community Readiness

Technology Readiness Levels (1–9), Investment and Community Readiness Levels (1–6)

Blue hydrogen Technology, Investment and Community Readiness

Technology Readiness Levels (1–9), Investment and Community Readiness Levels (1–6)

2.1

Chapter 2:
General Safety and Flammability issues

Hydrogen is non-toxic and with a density of just 7% of air (at 0°C, 1 atm), the gas disperses quickly in the event of a release but can accumulate in confined or poorly ventilated areas. There are multiple hazards in the storage, use and transport of hydrogen that must be mitigated in industrial use:

Hydrogen's flammability range of 4% to 75% by volume in air is wider than most common fuels, increasing the risk of ignition in the event of a leak, resulting in fire or explosion.

Hydrogen's detonation range by volume in air of 18.3% to 59% increases the risk of explosion when a mixture of hydrogen and air meets an ignition source within a confined space.

Hydrogen's low minimum ignition energy of 0.017mJ, around a tenth of many fossil fuels, requires tight control of ignition sources including static electricity.

Hydrogen burns with a pale to clear blue flame that is nearly invisible in many lighting conditions, including daylight, and fires require specialist equipment to detect.

As with all cryogenic liquids, LH_2 presents a risk of cold burns should human skin contact the material itself or very cold machinery components such as uninsulated pipes.

LH_2 leaks can freeze the air leading to oxygen enrichment, raising the risk of explosion. All gases are solid at LH_2 temperatures except helium.

When LH_2 leaks, the cold hydrogen vapours it produces can initially stay low to the ground, behaving like heavier-than-air gases, potentially creating flammable mixtures. As these vapours absorb heat from the surrounding air and warm up, they become much less dense and start rising quickly.

Hydrogen can make common materials, including some steels, much less ductile and strong through hydrogen embrittlement. Cold embrittlement (ductile to brittle transition) is a consideration for components in contact with LH_2. Materials exposed to hydrogen must be carefully chosen to avoid cracking and failure.

Due to these hazards, the use of hydrogen as a marine fuel requires safeguards relating to ship design and construction, machinery and technology arrangements, bunkering technologies, onboard procedures, and crew training.

In March 2023, LR released its Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels Notice No.3, containing general and specific rules on the design and operation of vessels using hydrogen as a fuel in the new LR 3 appendix. Topics addressed include fuel containment, preparation and supply, limiting the impact of an explosion, material selection, power generation and prime movers, and fire safety.

2.2

Maritime safety regulations

The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) covers the construction and equipment of ships carrying liquified gases as bulk cargoes, including the use of such cargoes as fuel, but currently lacks detailed requirements for liquefied hydrogen.

In May 2024, the IMO's Maritime Safety Committee adopted MSC.565(108) 'Revised Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk' which will be the basis of which will support the safe implementation for transporting hydrogen. IMO has finalised draft amendments to the Revised Interim Recommendations for the Carriage of Liquefied Hydrogen in Bulk which will be expected to be adopted at MSC 111 in May 2026.

For non-gas carriers using low-flashpoint fuels like hydrogen as fuel, the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) applies. The IGF Code also lacks specific requirements for vessels fuelled by hydrogen, but allows for alternative designs that meet the intent of the relevant goals and functional requirements within the code while providing equivalent safety levels. The IMO has finalised its work on draft interim guidelines for the Safety of Ships using Hydrogen as Fuel which will now be expected to be approved at MSC 111 in May 2026, after which they will come into effect and support the alternative design process.

LR's 'Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels' aim to ensure ships being built with a view to classification with LR also meet IGF Code requirements. Appendix LR3 contains general and specific requirements for ships using hydrogen as a fuel in order to achieve IGF Code goals and functional requirements. The document is available for free at OneOcean's Regs4ships.

The goal of the codes, interim guidelines and rules and regulations is to consider the specific nature of hydrogen as a cargo and as a marine fuel, and indicate the necessary prerequisites for the equipment, machinery, and other systems as well as their arrangement on board in order for the vessel to use hydrogen safely in a way that minimises the risk to the ship, its crew and the environment.

The Interim Guidelines for Ships Using Fuel Cell Power Installations were incorporated into LR Ship Rules Pt 5 Ch 26 Fuel Cell power installations and became effective on January 1, 2022. In April 2023, LR published Guidance Notes on the Installation of Fuel Cells on Ships, which was updated in July 2025. These Guidance Notes are particularly intended for shipbuilders and shipowners considering the use of fuel cell technology in new ship designs or considering the retrofitting of fuel cell technology on board existing ships. Mandatory instruments for fuel cell power installations are expected to be developed by IMO in the upcoming years

LR has also published Guidance Notes for Liquid Hydrogen Systems, containing guidance related to material suitability, design, qualification and maintenance aspects of piping components, safety devices, containment systems, and layout of liquid hydrogen systems. LR's Guidance Notes on Composite Cylinder Systems for Gaseous Hydrogen Containment was published in January 2024 and provides guidance for composite cylinders of Type 2 (metal cylinder with hoop wrapped in composite), Type 3 (fully wrapped with metallic liner) and Type 4 (fully wrapped with polymeric liner) configurations.

LR's notation for hydrogen-fuelled vessels HY is a low-flashpoint fuels (LFPF) notation, accompanied by GC for gas carriers, and GF for ships other than gas carriers using low-flashpoint fuels. Gas ready (GR) notations available for hydrogen include approval in principle of the basic design (A), necessary structural reinforcement (S), gas storage tank in place (T), gas fuel piping installed (P), and a list of gas-fuelled engineering systems (E).

Crew training

High levels of crew competency and familiarity with hydrogen as a fuel will be central to its safe adoption as a low emissions fuel for shipping.

In February 2025, the IMO's [Sub-Committee on Human Element, Training and Watchkeeping (HTW)](#) agreed draft generic interim guidelines on training for seafarers on ships using alternative fuels and new technologies, and submitted to the Maritime Safety Committee (MSC) meeting in June 2025, with a view to approval as an STCW.7 circular.

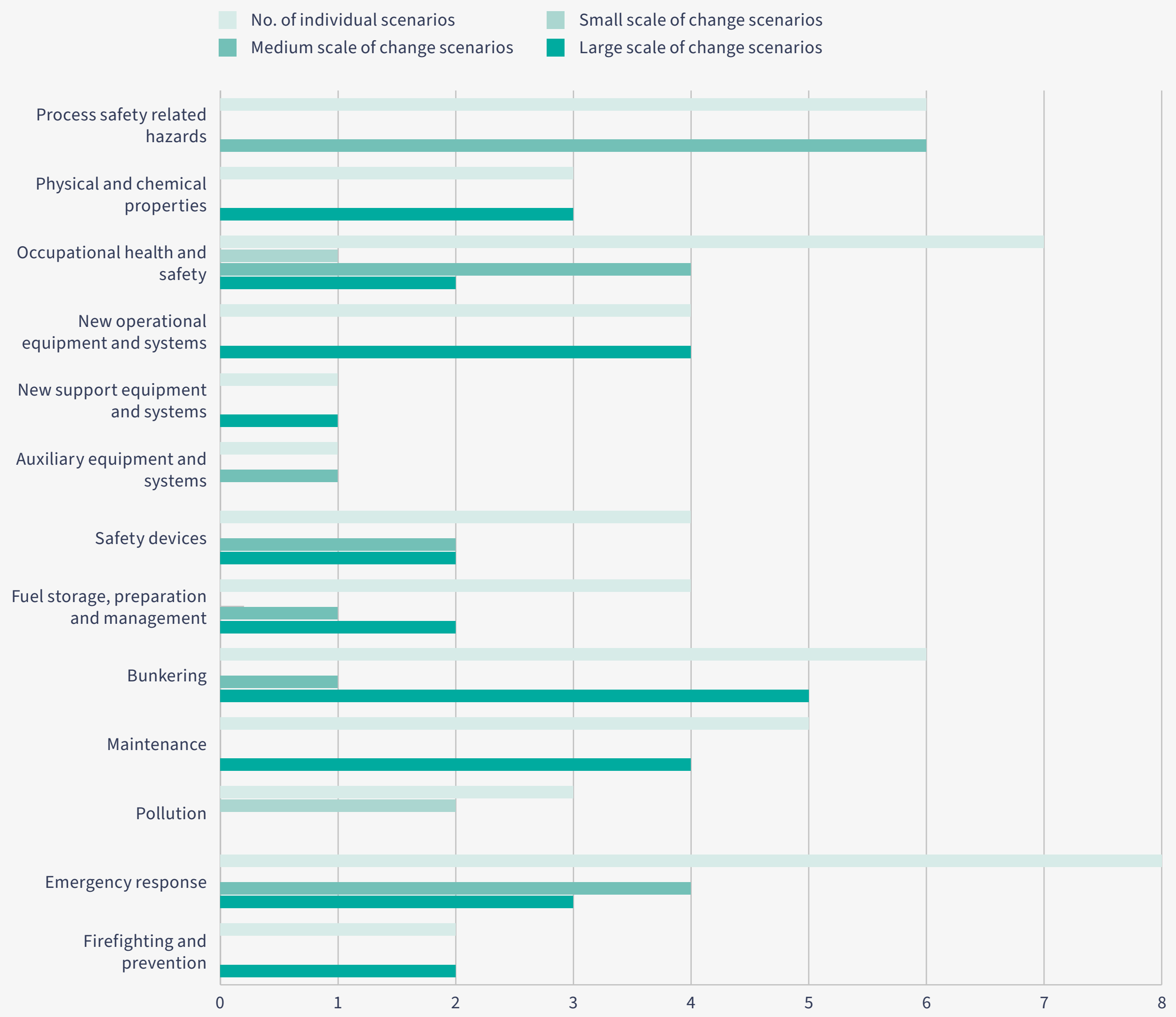
A Correspondence Group was established to develop the interim guidelines on seafarer training, including on hydrogen fuel cell powered ships and the use of hydrogen as a fuel.

The group is scheduled to submit a report to HTW 12 in February 2026.

The work on seafarer training for ships using alternative fuels at HTW is separate from the ongoing review of the Seafarers' Training, Certification and Watchkeeping (STCW) Convention. Phase 1 of the review identified over 500 amendments or gaps in the convention that need to be resolved, including the emergence of new technologies on ships and ship operations, which includes new energy sources. The revised roadmap predicts entry into force of the revised STCW Convention in around 2032.

In addition the Maritime Just Transition Task Force (which include the IMO, The UN and LR as key contributors) has launched an Advanced training framework and instructor handbook for "Hydrogen as a marine fuel" available [here](#).

Hydrogen Perceived scale of change by theme, level and number of related scenarios



Totals

54
No. of individual scenarios

3
Small scale of change scenarios

13
Medium scale of change scenarios

34
Large scale of change scenarios

Source: Maritime Just Transition Taskforce – Considerations of Training Aspects for Seafarers on Ships Powered by Ammonia, Methanol, and Hydrogen

With the support of the LR Foundation, the Maritime Just Transition Taskforce (MJTT) investigated the training needs for seafarers to safely operate ships fuelled by hydrogen, ammonia, and methanol, and published its findings in Considerations of Training Aspects for Seafarers on Ships Powered by Ammonia, Methanol, and Hydrogen.

The report gathers the findings from workshops conducted with the aim of informing the Baseline Training Framework for Seafarers in Decarbonization project launched by the IMO and MJTTF with support from the LR Foundation. The project's outputs include training materials necessary for seafarers to safely use new zero and near-zero GHG emission fuels and draft associated competency standards to fill subjects not yet covered by the STCW Code.

The chart below shows the number and severity of changes necessary in areas of seafarer competency contained in STCW, as perceived by workshop participants. The accompanying table shows the required knowledge and proficiency by competency area.

Competency	Knowledge Understanding and Proficiency
Familiarity with physical and chemical properties, including hazards of fuels	Physical, chemical and hazardous properties of compressed (CH_2) and liquid hydrogen (LH_2) properties
Application of occupational health, safety precautions and measures, including prevention of hazards	Function and calibration of gas measuring instruments, leak and flame detection devices
Knowledge of the prevention, control, fire-fighting and extinguishing systems	Fire organisation, the unique hazards of hydrogen fuel systems, fuel handling, ventilation and vapour ignition
Undertake precautions to prevent pollution of the environment from the release of fuels	Shipboard spill/leakage/venting response procedures, PPE to use when dealing with CH_2 and LH_2 incidents
Response to other emergencies	Ship-specific response to emergencies that may impact CH_2 and LH_2 systems
Operation of fuel controls related to the propulsion plant	Operating principles of main and auxiliary machinery
Operation of engineering systems, services and safety devices	Automation for cryogenic fuel systems, fuel preparation rooms, ventilation systems
Ability to safely perform and monitor all operations related to the fuels used	Fuel handling systems, materials of construction and insulation and difference between CH_2 and LH_2 systems
Safe management and planning of bunkering, stowage and securing of fuel	Fuel storage systems, Quick Connect Disconnect Couplings and Vessel Separation Devices, Emergency Shutdown (ESD) procedures
Compliance with legislative requirements	Relevant IMO instruments including non-mandatory guidelines and industry guidance

Source: Maritime Just Transition Taskforce – Considerations of Training Aspects for Seafarers on Ships Powered by Ammonia, Methanol, and Hydrogen

2.3

Specific bunkering considerations

The maritime industry has limited experience with compressed and liquid hydrogen, both as a fuel and as a cargo. While the industry has gained a great deal of experience handling cryogenic liquids through the bunkering of LNG, the characteristics of liquid hydrogen and its lower storage temperature will require bunkering processes that address the unique hazards of hydrogen, and the use of suitable materials.

There are no international standards for bunkering liquid hydrogen, although limited experience is being built through the bunkering of ferry MF Hydra by truck in Norway. Small-scale bunkering of compressed hydrogen has been carried out on ships using technologies adapted from the automotive sector.

LH_2 is stored at below -253°C. As nitrogen and oxygen—which together make up 99% of air—are solids at such low temperatures, there is a risk of pipe blockage, valve obstruction and filter clogging from frozen nitrogen and oxygen should an LH_2 system be contaminated with air. Nitrogen is commonly used to purge and inert LNG gas tanks, but it's freezing point means the use of nitrogen for purging should be succeeded by nitrogen-freeing with gaseous hydrogen before being exposed to LH_2. Alternatively, helium could be used for purging as it is the only substance that remains a gas at LH2 temperatures.

Hydrogen's wide flammability range of 4-75% in air brings higher risk of fire in the event of small leaks, compared to other gas fuels. Hydrogen has the lowest minimum ignition energy of any fuel, a level that can be reached by the discharge of static electricity generated by a person without them being aware of it. Control of ignition sources in hazardous areas is a key safety consideration, measures include electrostatic grounding, use of spark free tools, anti-static clothing and footwear, and controlling exposed surface temperatures. Further risk of fire or explosion may come from air condensing around LH_2 leaks and on low temperature surfaces, creating a localised high oxygen environment. Vacuum insulation of LH_2 bunkering system components is used to limit condensation and freezing.

Gas and flame detection systems will be necessary at hydrogen bunkering stations as the gas is odourless, colourless, and burns with a pale blue flame that can be difficult to see.

As the lightest gas, hydrogen disperses quickly in air, a characteristic which has mixed safety implications. In an open or ventilated space, hydrogen gas disperses quickly and as a non-toxic substance poses very limited risk to human health and the environment. However, liquid hydrogen expands to 848 times its volume on boiling and in the event of a leak, this expansion and dispersal can quickly create a large flammable cloud of gas, owing to hydrogen's high flammability range. Open air bunkering stations will reduce the risk of fire in the event of a leak, and ventilation may limit fire risk in enclosed areas so long as potential ignition sources from fans and ductwork are controlled.

Another of hydrogen's extremes is the small size of its molecule, which makes many non-metallic materials suitable for containment of other fuels permeable to hydrogen gas. Materials for ship- and shore-side bunkering facilities must also withstand hydrogen embrittlement, and low temperatures for LH_2 bunkering.

Due to the hazards of LH_2 bunkering operations, more of process may be automated in order to remove personnel from high-risk areas and reduce scope for human error.

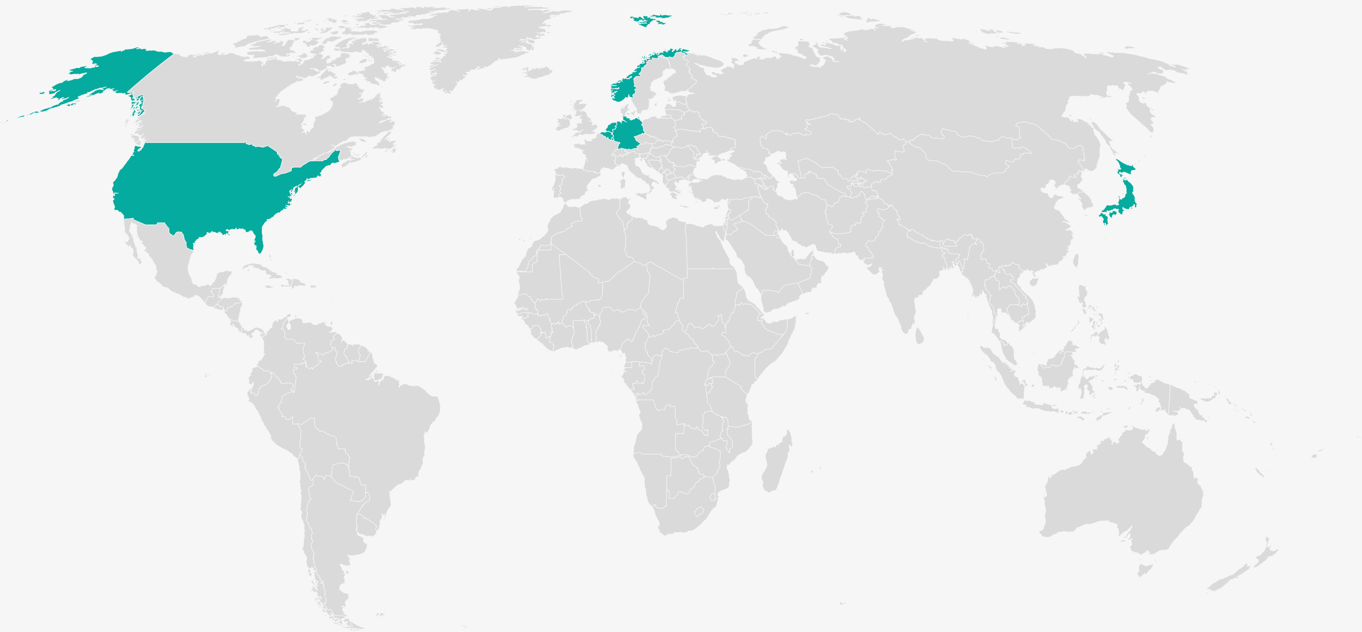
The development of a supply chain for the use of hydrogen as a marine fuel, including bunkering locations and operations, will require thorough examination of the related risks and preparation of international regulations and relevant guidelines. Standards for hydrogen bunkering are necessary both to reduce risks to human health and the environment, and to remove a barrier on an important path to decarbonisation for the shipping industry.

In August 2024, the Maritime Technologies Forum (MTF), of which LR is a member, released its report Guidelines for the Development of Liquefied Hydrogen Bunkering Systems and Procedures. The document provides a framework for the development of LH_2 bunkering guidelines, and invites further industry development and discussion on its proposals to supplement CCC's work on hydrogen as a fuel, the scope of which ends at the bunkering manifold.

Other relevant regulatory work on hydrogen bunkering includes the ISO 24132 *Ships and marine technology — Design and testing of marine transfer arms for liquefied hydrogen*, published in June 2024, ISO 11326:2024 *Ships and marine technology — Test procedures for liquid hydrogen storage tank of hydrogen ships*, published in November 2024, and the currently under development ISO/AWI 21341 *Ships and marine technology — Test procedures for liquid hydrogen valve of hydrogen ships*.

Hydrogen bunkering locations

Hydrogen bunkering facilities are in operation or under construction in Belgium, Germany, Japan, Luxemburg, the Netherlands, Norway, and the United States. Further ports in those same nations and beyond have studies underway to assess the commercial and practical feasibility of hydrogen bunkering installations as a first step towards offering hydrogen to vessels.



2.4

Fuel quality/ specifications

International standards for hydrogen fuel quality for vehicle and stationary applications are set out in ISO 14687:2025 ‘Hydrogen fuel quality — Product specification’. For shipping, a similar process will need to be undertaken to develop an international standard for hydrogen as a fuel for marine applications.

Marine applications are not within scope of the ISO 14687 standard, but it serves as an example of hydrogen fuel standards and the purity requirements of different technologies. The ISO standard classifies gaseous hydrogen and hydrogen-based fuels as Type I, with grades from A to E. LH_2 is classified as Type II, with grade C suitable for use in off-road vehicles, aircraft and space-vehicle onboard propulsion and electrical energy requirements, and grade D for use in fuel cell applications in road vehicles.

Hydrogen purity requirements vary depending on the end use, with fuel cells typically requiring higher purity fuels than internal combustion engines.

Type II Grade C liquid hydrogen and Type I Grade C hydrogen gas share a minimum standard of 99.995% hydrogen, Type I Grade B hydrogen gas has a 99.90% purity standard, and all have defined maximum total gas impurities of 50 µmol/mol along with specific limits for impurities including water, oxygen, argon, nitrogen, and helium.

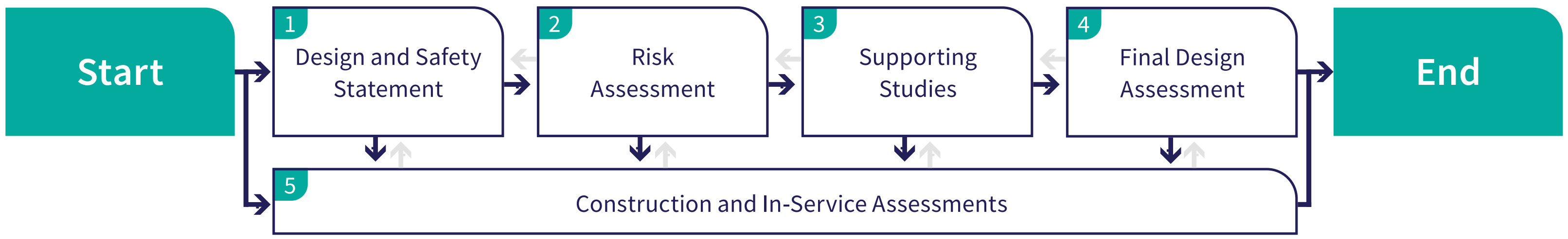
2.5

LR Risk Based Certification Process

New, novel and alternative designs

LR's requirements for ships using hydrogen as a fuel are contained within Appendix LR3 to the Rules and Regulation for the Classification of Ships Using Gases or Other Low-flashpoint Fuels. These requirements follow a risk-based approach where the fundamental requirement is to demonstrate an equivalent level of safety to that achieved with conventional oil-fuelled systems.

The Risk Based Certification process from LR's ShipRight Procedure for Risk Based Certification (RBC)



The risk-based process is to be undertaken in accordance with LR's ShipRight Procedure for Risk Based Certification (RBC). It is based on IMO guidance and LR's experience of how a safety justification can inform the normal rigors of ship classification.

Importantly, the process is scalable, meaning the amount of work required in each step is proportionate to the risk presented.

3.1

Chapter 3: Drivers for Hydrogen

EU decarbonisation regulations for shipping are covered in more detail in LR's report Fit for 55: Managing compliance and optimising operations under the EU's new regime, along with key strategic considerations for optimising exposure to Fit for 55 regulations.

Regulations

The following discussion focuses on the regulatory drivers increasing shipowner interest in the use of low- and zero-carbon fuels for ship power and propulsion, including hydrogen. For safety regulations, see chapter 2.

National, regional, and international regulations are driving the maritime industry towards decarbonisation, reducing GHG emissions to limit the effects of global warming on society and the environment. While these regulations do not specifically promote the use of hydrogen as a marine fuel, the potential to produce hydrogen using renewable energy, and the lack of GHG emissions from its use in internal combustion engines and fuel cells make hydrogen a strong candidate fuel for a net zero future.

EU Regulations

Some of the most advanced regulations driving decarbonisation in shipping are from the European Union (EU). The Fit for 55 package is the bloc's overarching decarbonisation strategy across society and business. It aims to reduce EU GHG emissions by at least 55% by 2030, compared to 1990 levels. Shipping companies need to be aware of five elements of the EU Fit for 55 package that impact shipping:

- A revised Monitoring, Reporting and Verification of greenhouse gas emissions from maritime transport regulation (EU MRV)
- A revised Directive on the EU emissions trading system (EU ETS)
- A new FuelEU Maritime Regulation
- Revised Alternative Fuels Infrastructure Regulation (AFIR)
- A revised Renewable Energy Directive (RED III)

Together, these interlocking requirements will drive ship owners to adopt more stringent ship efficiency strategies, as well as low-carbon fuels such as hydrogen for newbuilds and as retrofit solutions.

EU Emissions Trading System

As of 1 January 2024, passenger and cargo ships of 5,000 GT and over calling at European Economic Area (EEA) ports became subject to the region's emission trading scheme (ETS). Additional ship types and sizes will fall into scope of the scheme in future years.

Shipping companies with responsibility for affected ships will need to buy allowances to cover tank-to-wake (TtW) greenhouse gas (GHG) emissions (CO_2, CH_4 and N_2O) reported under EU MRV for intra-EEA (EU plus Norway and Iceland) voyages, in EEA ports, and for half of the GHG emissions created during voyages to and from the EEA. From 1 January 2024, EU allowances for CO_2 emissions had to be surrendered under EU ETS, with CH_4 and N_2O emissions falling into the scope of ETS from 2026.

There are no free allowances for shipping as there were for other sectors in the early stages of EU ETS, but there will be a phase-in period where shipping companies will only surrender allowances covering only a percentage of the verified emissions for a particular year.

Surrender of allowances for each reported year will be required by 30 September of the following year. Failure to surrender sufficient allowances will result in the accrual of penalties.

A review of ETS in 2026 will consider whether emissions should be measured on a well-to-wake (WtW) basis.

40% of verified emissions reported for 2024

70% of verified emissions reported for 2025

100% of verified emissions reported for 2026 (and each year thereafter)

FuelEU Maritime

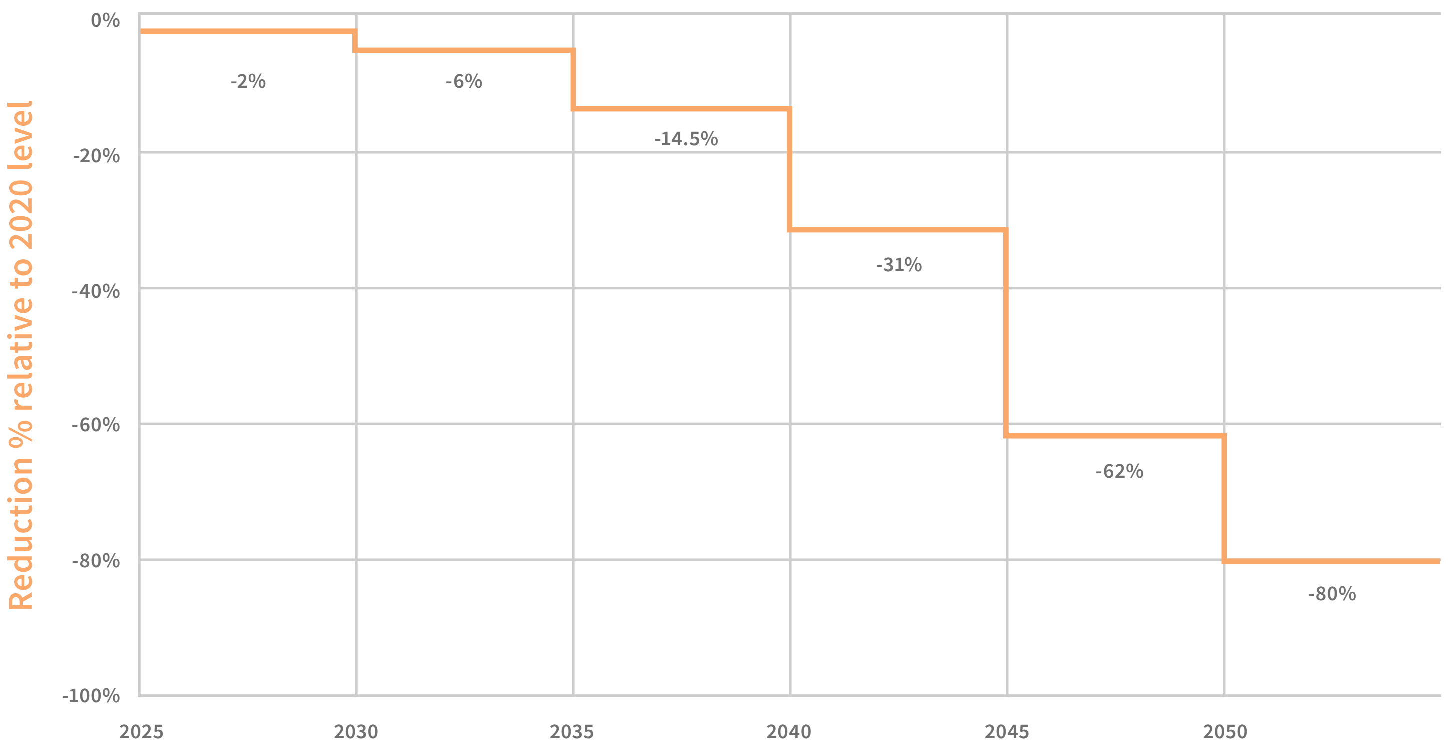
Operating alongside EU ETS, Fuel EU Maritime aims to promote the adoption of low- and zero-carbon fuels in shipping as carbon pricing alone (through ETS) will not be sufficient to meet the bloc's goal of reaching carbon neutrality by 2050.

From 1 January 2025, shipping companies operating ships over 5,000 GT calling at EEA ports (but currently excluding Norway and Iceland who are yet to implement FuelEU into national law) are required to meet stepped reductions in the GHG intensity of energy used onboard as shown in the table to the right. An additional requirement to have zero at-berth emissions (for container and passenger ships) comes into effect from 2030, posing an opportunity for adoption of green hydrogen as a fuel. Firm orders have been placed for cruise ships with hydrogen fuel cells in order to meet hotel demand at berth with zero GHG emissions.

The FuelEU Maritime Regulation requires submission of a monitoring plan, separate to the MRV monitoring plan. Assessment for each ship should indicate the chosen method used to monitor and report the amount, type and emission factor of energy used on board. From 1 January 2025, each ship must implement the FuelEU monitoring plan to collect the required data. The full year's data will then be submitted for verification by 30 March of the following year.

FuelEU Maritime incentivises the use of renewable fuels from non-biological origin (RFNBOs) in ships by rewarding early adopters of such fuels, including green hydrogen. RFNBOs will be eligible for a 2x multiplier under FuelEU Maritime until 2033, applying their GHG emissions savings twice. A sunrise clause will mandate the use of RFNBO and advanced biofuels for 2% of shipping's energy needs from 2034 should the market fail to reach 1% adoption of green e-fuels by 2031.

FuelEU Maritime reduction factors



Above: Reduction in GHG intensity of energy used on board from 2020 levels (%).

Pooling

Included in the provision of each ship's FuelEU data is the optional notification of the decision to pool ships. Pooling allows the responsible owners and managers to bring together ships that have been operated within a fleet, within a company or among companies.

Pooling allows the benefits of a ship's low GHG intensity to be shared among other vessels to reduce the GHG intensity of those vessels under FuelEU Maritime. The objective of pooling is to enable and support early investment in new ships using low- and zero-GHG-emission solutions as well as investment in more costly retrofit solutions with greater emissions benefits. Owners of low-carbon ships have the option to reduce their own fleet exposure through pooling, and to seek commercial benefits through pooling with owners of non-compliant ships.

As noted in this LR article, the ability to pool emissions surpluses has far-reaching significance. For example, a pool of ten boxships could avoid around €277 million in FuelEU Maritime penalties in five years (2030–2034) if they are joined by a single ship fuelled with e-methanol. That saving far outweighs the likely cost of building the methanol-fuelled containership.

GHG emission factors for fuels under Fuel EU Maritime

FuelEU Maritime provides a methodology for establishing the GHG intensity of the energy used onboard ships, with calculations for well-to-tank (WtT) emissions (those associated with the production and supply of a marine fuel) as well as well-to-wake (WtW) emissions (also adding in emissions as a result of the fuel's use on the ship). Hydrogen's TtW GHG emissions are zero when used in fuel cells, and when burned in internal combustion engines there is only the potential NOx emissions related to high temperatures to control.

Hydrogen derived from natural gas by steam reforming is given a WtT emissions factor of 132 gCO_2eq/MJ, around 10 times the level for heavy fuel oils. The WtT GHG intensity of hydrogen produced by electrolysis is highly dependent on the electricity source used to power the process, and will approach 0 for electrolysers powered by surplus renewable energy.

International regulations (International Maritime Organization)

In 2018, following the 2015 Paris Climate Agreement, the IMO agreed an initial GHG strategy to outline a pathway to reduce shipping emissions by focusing on CO_2 reductions from ships, to keep global warming to within 1.5 degrees. The initial strategy led to the development of short-term measures including the Energy Efficiency Existing Ship Index (EEXI) and the Operational Carbon Intensity Indicator (CII).

At the 80th meeting of its Marine Environment Protection Committee (MEPC80), IMO adopted a revised GHG reduction strategy. This aims to achieve net-zero CO_2 equivalent emissions by, or around, 2050. There are indicative checkpoints along the way for shipping to aim for, including:

- Total GHG emissions to reduce by 20–30% by 2030
- Total GHG emissions to reduce by 70–80% by 2040

Both compared to 2008 levels.

There is also a target for low- or zero-carbon fuel uptake of at least 5%, striving for 10%, as well as a reduction of carbon intensity of international shipping by at least 40% by 2030 compared to 2008 levels.

The revised GHG reduction strategy sets a timeline for the adoption of mid- and long- term measures to reduce emissions from shipping. Mid-term measures in the form of a technical GHG energy intensity standard and an associated economic element were agreed at MEPC 83 in spring 2025. However, the proposed draft regulations have not been adopted by IMO as was expected in October 2025. Accordingly, any entry into force and application dates remain unknown.

GHG Fuel Intensity (GFI)

Should the IMO adopt its draft 'IMO Net-Zero Framework' which includes a GHG Fuel Intensity Standard (GFI), this would assess the GHG energy intensity of a ship based on the fuel and other energy choices it makes, as well as the use of energy from other zero emission sources.

A ship's attained GFI will be calculated by multiplying the amount of energy provided by each of its fuels and energy sources by the GHG intensity of those energy sources, then dividing by the total amount of energy used by the ship.

The GHG intensity of a given fuel or energy source will be certified by an IMO-recognised Sustainable Fuel Certification Scheme to verify the fuel or energy source's GHG emissions on a WtW basis.

The ship's attained GFI will be compared to annual GFI targets starting at 93.3gCO_2eq/MJ (the fleet average for 2008) and be lowered each year, as shown in the chart to the right. It is unclear at this stage if the existing dates will be retained or modified.

Economic implications

Under the proposed IMO framework, ships over or under performing against the technical GFI standard will face economic impacts.

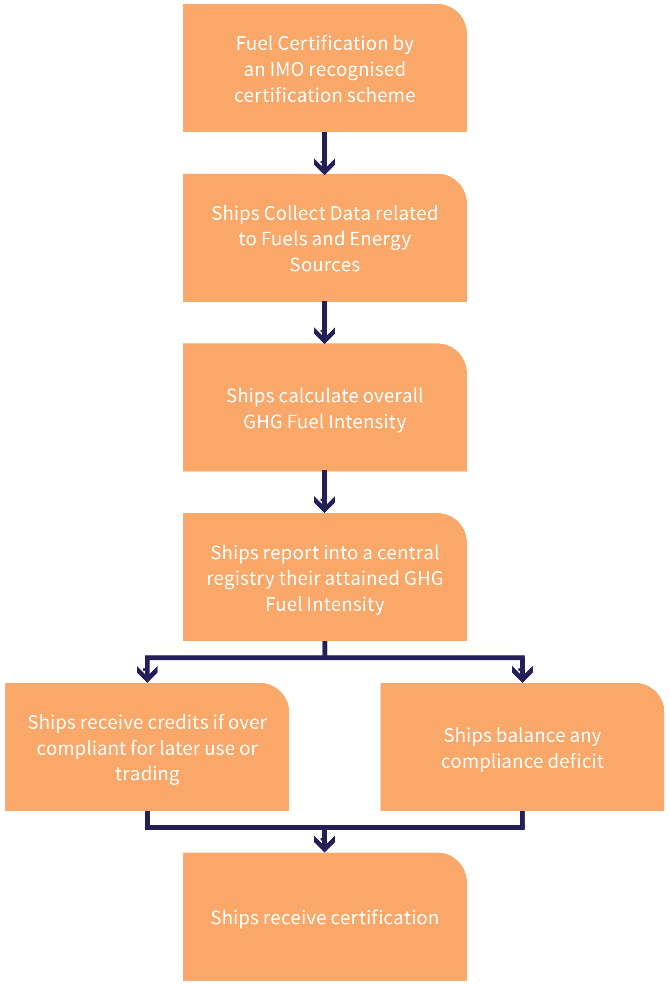
A ship with a GFI below the Direct Compliance Target will receive Surplus Units equal to its compliance surplus, effectively credits which can be banked for later use or sold on to other ships with a deficit within 2 years.

A ship with a GFI above the Direct Compliance Target will need to balance its compliance deficit through the purchase of Tier 1 Remedial Units priced at $100/tonne CO_2eq until the price is reviewed.

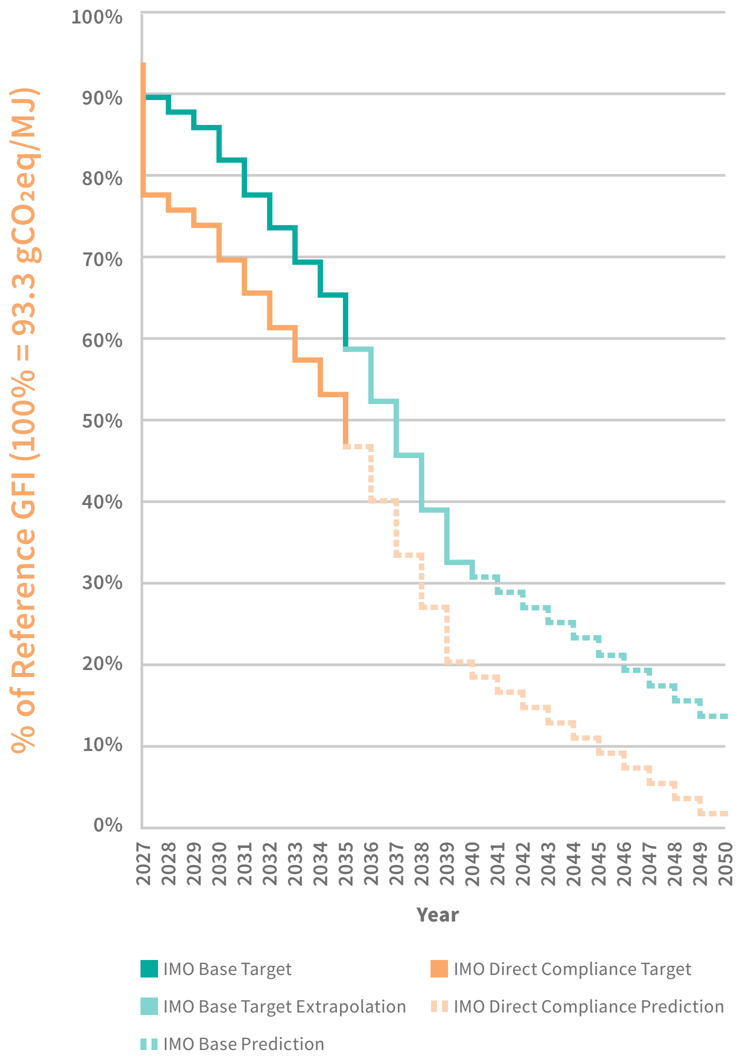
In addition to balancing its Tier 1 compliance deficit, a ship with a GFI above the base target will need to balance its Tier 2 deficit by either using surplus units banked from the previous two years, acquiring surplus units from another ship, or by purchasing Tier 2 Remedial Units, initially priced at $380/tonne CO_2eq.

Funds generated by the purchase of Remedial Units will be paid to the IMO Net-Zero Fund.

An overview of the proposed GFI regulatory framework



Proposed GFI reduction trajectories



Zero and Near Zero GHG emissions

The GFI framework includes provision to financially reward ships with Zero or Near Zero GHG emissions fuels and technologies (ZNZ) based on GFI. The reward amount to be paid by the IMO NetZero Fund is yet to be agreed, but will apply to ships achieving a GFI below the ZNZ threshold, currently set at 19.0 gCO_2eq/ MJ until the end of 2034 and 14.0 gCO_2eq/MJ from 2035 if the scheme was to begin in 2027, but there is not yet a confirmed start date.

Lifecycle Assessment

Lifecycle analyses of hydrogen as a marine fuel underline the critical importance of renewable energy to achieving the full decarbonisation potential of hydrogen in the shipping industry. The TtW emissions from hydrogen will be identical regardless of how it was produced—zero CO_2, CH_4, and N_2O emissions when used in a fuel cell, with potential for minor N_2O emissions when burned in an internal combustion engine.

WtT emissions for hydrogen pathways vary greatly depending on the feedstock, the method used to extract hydrogen from the feedstock, and the source of the energy used to power the process. Generating hydrogen by electrolysis using renewable energy sources such as photovoltaic and wind turbines holds the potential for near-zero WtT emissions. Hydrogen production methods are explored in more detail in section 4 of this report.

The IMO has adopted Guidelines on the life-cycle analysis of marine fuels (LCA Guidelines) to assess the GHG intensity of current and future fuels for shipping, and continues to review them. These will support the technical and economic measures by enabling calculations of WtT and WtW emissions.

Appendix 1 of the LCA guidelines contains 10 distinct fuel pathways for the production of hydrogen, including steam methane reforming of natural gas, gasification of coal, gasification of biomass, and entries for electrolysis powered by renewable energy, grid mix electricity, and nuclear power.

Once populated, the well-to-wake and tank-to-wake emissions factors attributed to each fuel pathway and energy converter in the guidelines are expected to be used in future IMO regulations supporting the reduction of GHG emissions in shipping. Member States have been invited to prepare default emissions factors proposals for review by IMO in the future.

3.2

Ship operator demand and interest

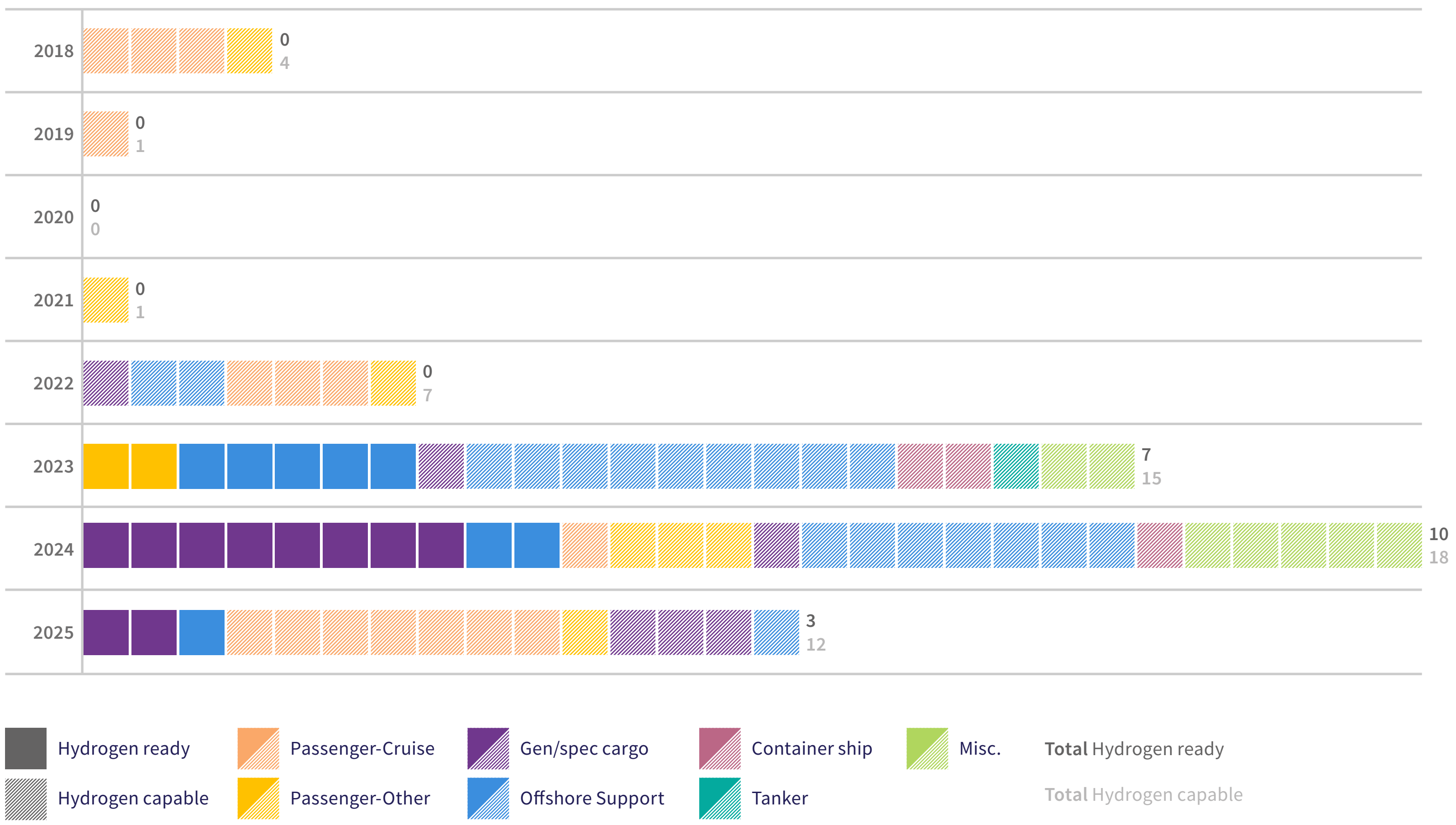
Sustainably produced hydrogen is a core component of many visions of a net zero future, both as a standalone fuel for industrial uses and as a feedstock for other green fuels such as ammonia and methanol. Identifying the potential for broad commercial and industrial use of hydrogen, and its clear path to zero operational emissions when used as a marine fuel, shipowners have shown keen interest in assessing its suitability for a range of trades and vessel types.

Initial developments in hydrogen-powered ships have been in the short-sea and coastal segments, where regular refuelling opportunities and shorter voyages allow for the use of less energy dense fuels without the need for large fuel tanks.

Hydrogen-powered ships currently account for 0.01% of the fleet in operation, and less than 0.5% of the orderbook, totalling 40 vessels. Hydrogen capable vessels, those currently able to run on hydrogen, are represented in the car/passenger ferry segment, container ships, cruise ships, ro-ro cargo ships, and tugs. Hydrogen applications across the fleet include the use of hydrogen as the main fuel in dual-fuel ICEs, as a fuel for power cells supplying energy for main propulsion, and the use of fuel cells to meet auxiliary energy demands such as hotel loads in port.

In 2024, Clarksons reported 12 new orders for vessels capable of using hydrogen as a fuel on delivery.

Orderbook fleet , Hydrogen uptake over time



3.3

Techno-economic drivers

Economic modelling for hydrogen as a marine fuel is made difficult by the forecasting of sustainable hydrogen production and demand over the medium- and long-term, which will ultimately dictate the fuel's cost. As with other alternative fuels, competition from other industries will also be a factor in hydrogen pricing and availability.

The price of carbon emissions under environmental regulations taxing GHG emissions will heavily affect the commercial viability of hydrogen against standard marine fuels and other alternative fuels. As carbon taxes increase, green hydrogen becomes more commercially viable. Regulatory compliance benefits and the avoidance of carbon taxes and other emissions-related penalties contribute to the commercial case for green hydrogen as a fuel; the social and economic benefits alike are substantially reduced for grey, black, and brown hydrogen.

Dual-fuel, retrofit, and ready notations

In the current absence of readily available green hydrogen bunkering at scale, options are available and under development for shipowners anticipating the use of hydrogen as a fuel for their fleet in the future.

Dual- and multi-fuel engines are available from multiple engine manufacturers, enabling a ship to use a more readily available fuel before switching to hydrogen, or to balance the fuel costs and regulatory compliance benefits by switching between fuels. Engine options are generally limited to those suitable for smaller vessels, with ongoing development of hydrogen ICEs. Engine technologies are explored further in Section 5.

Hydrogen fuel cells offer a retrofit path to zero emissions operation for vessels with electric propulsion by replacing generators powered by fossil fuels.

Hydrogen-ready recognitions are available and by offering a path to cheaper future retrofits help break the 'wait and see' approach that leads to delays in committing to new ship orders as shipowners await greater clarity on fuel availability and preferred technologies. Where a future fuel pathway is unclear, ships can be designed to make future retrofits of alternative fuels both easier and more cost efficient.

Techno-economic modelling

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping's (MMMCZCS) May 2024 report 'Fuel Cell Technologies and Applications for Deep-Sea Shipping' contains aggregated fuel cell price development forecasts from technology providers for different marine fuel cell technologies, showing initial cost expectations between $3,800/kWel and $5,400/kWel, declining steeply between 2025-2030, and continuing to fall before converging at just over $1,000/kWel from around 2038.

The report notes high replacement costs for fuel cells, with expectations that 30-40% of the system will need to be replaced every three to four years, adding an annual cost per installed kW that will fall over time in line with initial costs.

The report compares various fuel cell technologies using a range of fuels, including blue hydrogen, across three case studies: a 6,300 kW fuel cell for a 14,000 teu containership, 2,000kW for a LR2 tanker, and 800kW for an 82,000 DWT bulk carrier.

The current very high cost of liquid hydrogen storage systems for ships resulted in high capital expenditure cost forecasts of up to 20 times that of the low sulphur fuel oil equivalent. These high capex costs contributed to the hydrogen-powered fuel cell having the least competitive TCO in most scenarios, and only outperforming LSFO for a containership with reefers.

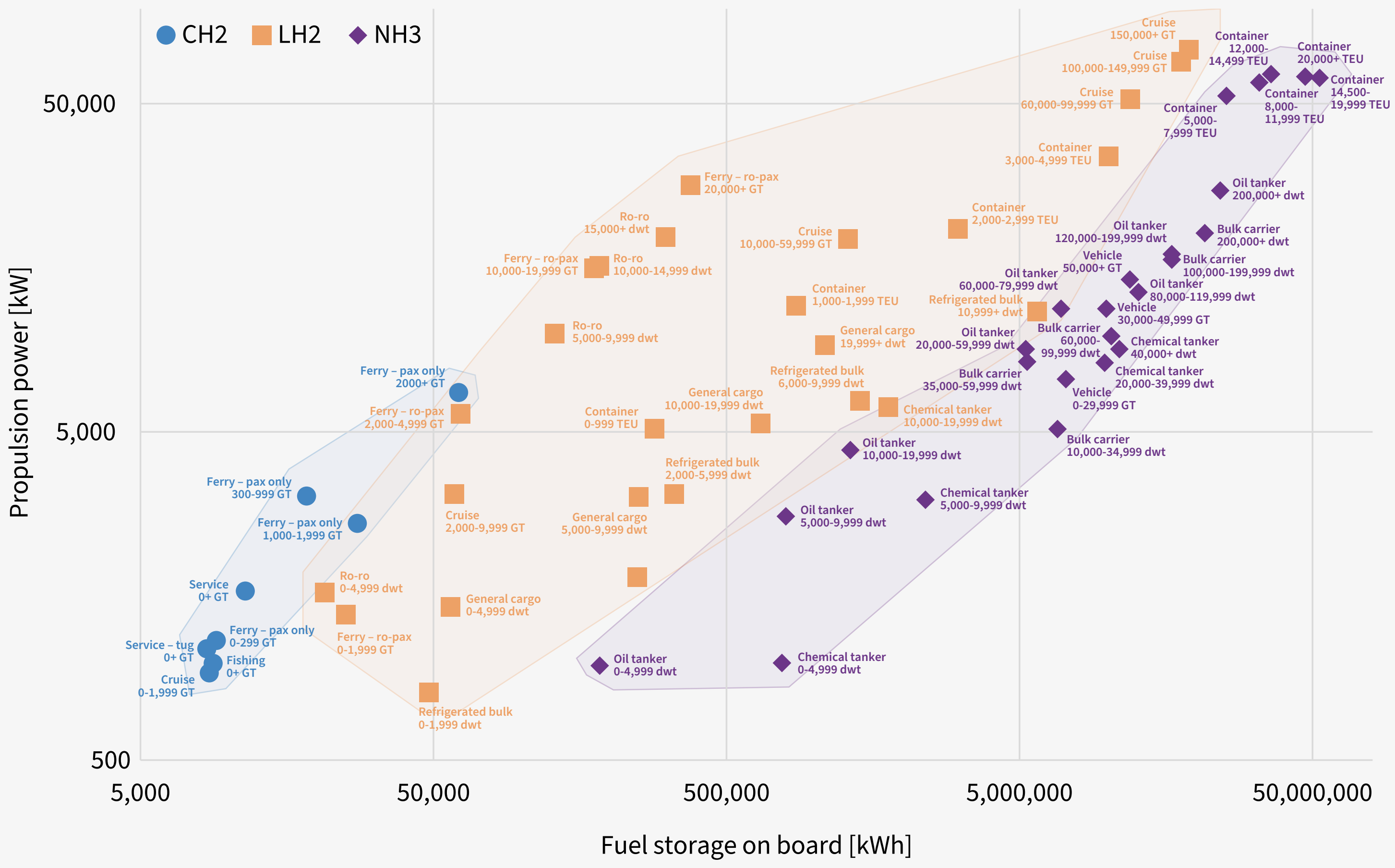
Highlighting the difference in fuel storage costs, The European Maritime Safety Administration's (EMSA) November 2023 report [‘Potential of Hydrogen as Fuel for Shipping’] put liquefied hydrogen storage and fuel supply costs at €50,310 per tonne bunker, compared to €1,000 for fuel oil.

The EMSA report shows capex costs for hydrogen dual-fuel engines at more than double those for fuel oil ICEs on a per kW basis across all power capacities. On a TCO basis, the report's example cases for a ro-pax ferry and a ro-ro cargo vessel powered by green hydrogen both predict TCO around three times that of an equivalent conventionally fuelled ship, with cost parity by 2050 for ships using blue hydrogen.

Hydrogen Europe's 2021 Techno-Economic Assessment of Low-Carbon Hydrogen Technologies for the Decarbonisation of Shipping compared the cost efficiency of hydrogen and other e-fuel technologies across 61 ship types, finding LH_2 to be the optimal solution for most vessels based on fuel storage requirements and propulsion power, with some smaller vessels better suited to compressed hydrogen, and the largest to an ammonia-powered fuel cell.

TCO analyses help to identify the areas most in need of attention for hydrogen to be commercially competitive with fossil fuels and other alternative fuels in the medium and long term. Capex costs for engines, fuel cells, and storage systems are clear priorities for further development to bring down costs more quickly than the timeline currently forecast. Government support may be necessary to help overcome the supply and demand dilemma for nascent hydrogen technologies.

Optimum zero-emission option for various ship types



Source: Techno-Economic Assessment of Low-Carbon Hydrogen Technologies for the Decarbonisation of Shipping, Hydrogen Europe, 2021.

3.4

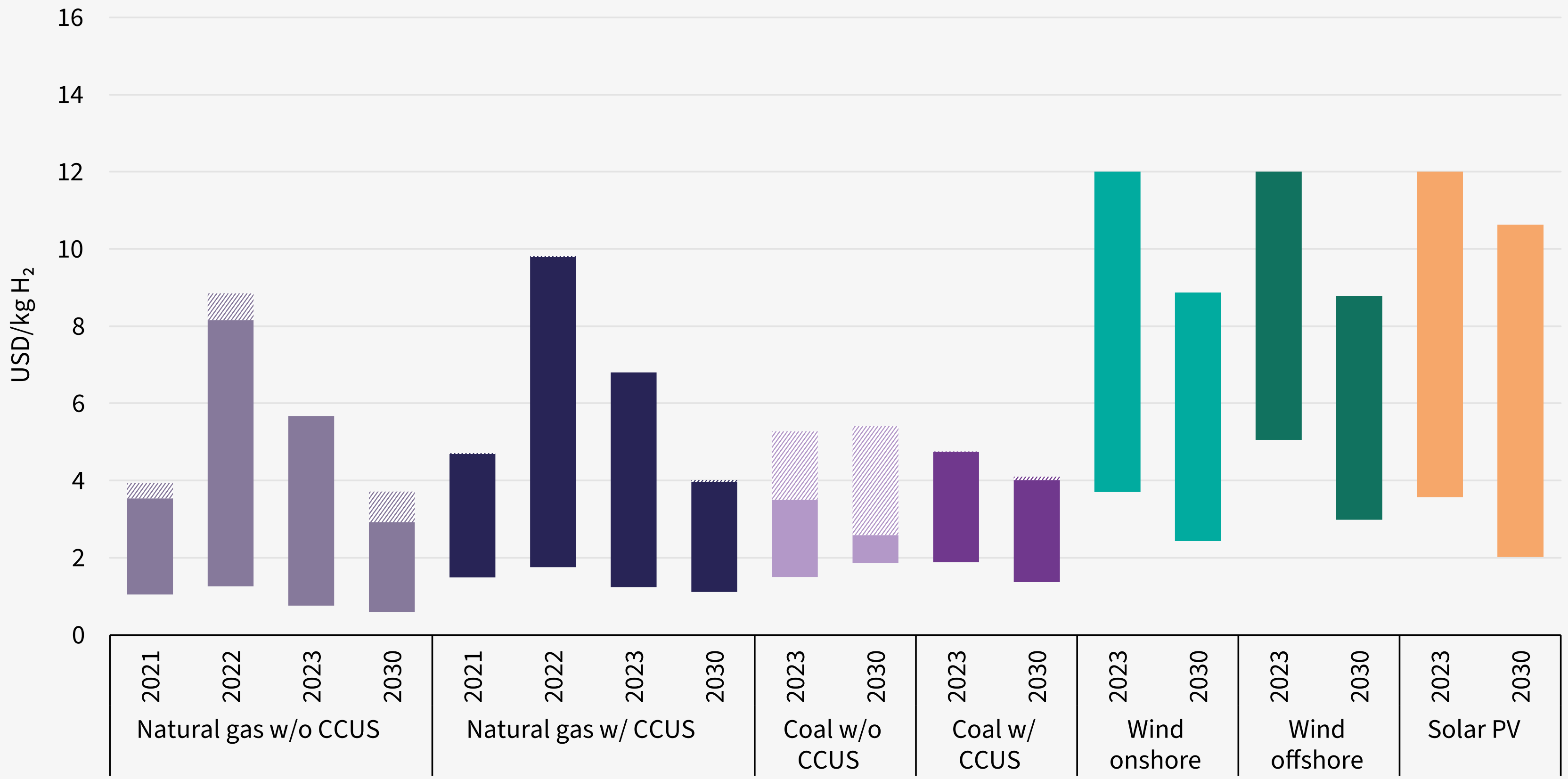
Fuel price forecasts

Hydrogen production costs serve as an indicator of hydrogen fuel prices, although delivered costs will be higher after adding a margin for processing and distribution.

The IEA's Global Hydrogen Review 2024 shows production cost forecasts for various hydrogen production methods, with a clear downward trend for blue and green hydrogen.

In December 2024, BloombergNEF substantially increased its US and Europe hydrogen production costs forecast for 2050 to a range of $1.60/kg to $5.09/kg, compared to current costs of between $3.74/kg to $11.70/kg. Analysts cited higher electrolyser costs as the cause for the 55% increase in the 2050 figures from its 2022 forecast.

Hydrogen production cost ranges by pathway, 2023, and in the Net Zero Emissions by 2050 Scenario, 2030



Source: IEA Global Hydrogen Review 2024. Shaded areas for natural gas and coal without CCUS represent the CO2 price impact, based on USD15-140/t CO_2.

4.1

Chapter 4:
Hydrogen production and supply

Introduction

The scaling up of sustainable hydrogen production is key to the adoption of hydrogen in the maritime industry, as the emissions profile of hydrogen as a fuel source is mostly dependent on its production method. Robust certification schemes will be necessary to verify the GHG credentials of supplied fuels. A full supply chain including bunkering facilities will need to be developed to serve ships powered by liquid hydrogen and compressed hydrogen gas, a challenge made more capital intensive by the specific requirements of safe hydrogen storage and transportation, particularly in a liquid state.

Hydrogen demand is typically met by facilities located close to consumers, and international trade is limited due to the cost and difficulty of transporting hydrogen in bulk.

Development of green hydrogen production capabilities will be supported by demand for e-fuels for transportation and other industries, as sustainable hydrogen is essential to the production of synthetic fuels including green ammonia and green methanol. Growth of hydrogen economies will support demand, investment, and broader technological progress, but may also see shipping compete with other industries for limited green hydrogen supplies both as a fuel and a component of other fuels.

Global hydrogen demand in 2023 was 97 Mt, according to IEA figures, with low-emissions hydrogen representing less than 1 Mt. Low-emissions hydrogen production could reach 49 Mt per year by 2030 based on announced projects as of late 2024, a 30% increase over the prior year. While the number of projects reaching final investment decisions (FID) doubled between the IEA's annual reports, most potential hydrogen production capacity is in the early project stages and the sector would require a 90% compound annual growth rate to realise the full low-emissions pipeline to 2030.

Projects with FID comprise 1.9Mtpa of electrolysis capacity and 1.5Mtpa of capacity using carbon capture, utilisation and storage (CCUS).

Global hydrogen production emitted 920 Mt of CO_2 in 2023, according to the IEA, reflecting the dominance of carbon intensive grey hydrogen production. To align with the agency's own net zero scenario in 2030, total emissions will need to fall by roughly 10% while production increases by over 50%.

4.2

Production pathways

Steam Methane Reforming (SMR) is the most common production method for hydrogen, accounting for over 60% of global production. In SMR, High temperature steam reacts with methane under high pressure to produce hydrogen and carbon monoxide, with some CO_2. A further process, the water-gas shift reaction, uses a catalyst to react carbon monoxide and steam to produce CO_2 and more hydrogen.

Steam-methane reforming reaction
$CH_4 + H_2O$ (+ heat) → $CO + 3H_2$

Water-gas shift reaction
$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

Around 60% of the CO_2 emitted by SMR is from the reformer, with 40% from the burning of natural gas to heat the furnace providing heat for the reaction.

Low emissions or blue hydrogen can be created with SMR by employing CCUS to capture CO_2 emissions contained in flue gases. Carbon capture technologies are under development to increase the capture rate and reduce the emissions of the overall process. Large-scale hydrogen production projects with CCUS projects are under construction in North America and Europe.

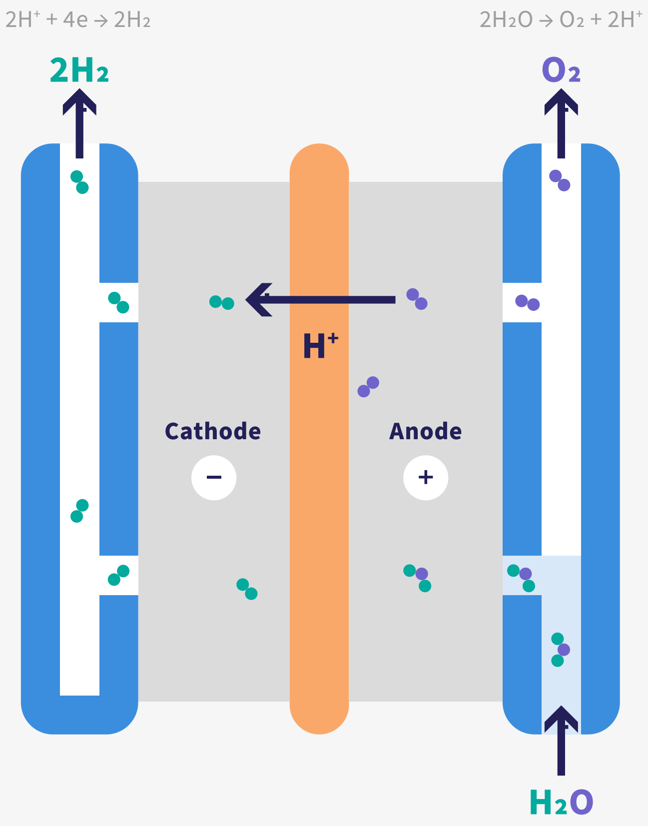
Coal gasification accounts for around 20% of global hydrogen production, predominantly in China. Its 18-20kg of CO_2 emissions per kg of hydrogen make it the most carbon intensive method of production, compared to SMR's 8-12kg.

Crushed coal is exposed to oxygen and steam to create a synthesis gas (syngas) of carbon monoxide, hydrogen, CO_2, and water. Syngas has multiple uses; for hydrogen production the water-gas shift reaction is used to create more hydrogen and CO_2 from carbon monoxide and water.

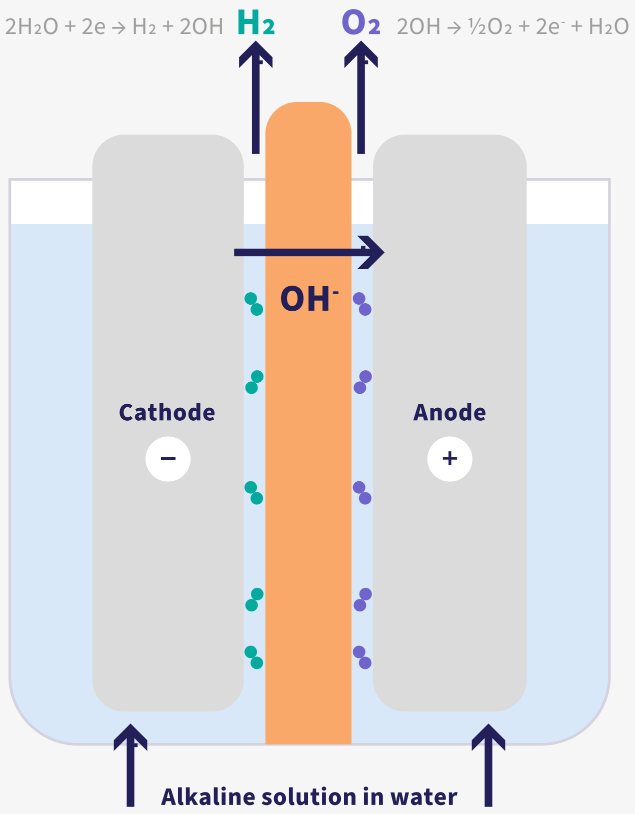
High CO_2 emissions from unabated coal gasification plants and the potential for carbon capture rates of over 90% using existing technologies make the facilities prime candidates for the use of CCUS to produce blue hydrogen. Hydrogen from unabated coal gasification has more than double the emissions intensity of unabated SMR, but the pathways have similar intensities when both are equipped with CCUS.

Autothermal Reforming (ATR) is an alternative production pathway that is gaining popularity due to its high energy efficiency and CO_2 capture rate potential. By combining hydrogen production and process heating in one reactor, the CO_2 stream is concentrated, capture costs decrease, and potential capture rates exceed 90%. Many ATR projects have a CO_2 capture target of 95%.

Proton exchange membrane electrolysis



Alkaline water electrolysis



Electrolysis is a method of creating hydrogen from water using electricity to separate the hydrogen and water that make up H_2O.

Electrolysis is the leading candidate for future green hydrogen production, although its GHG emissions profile is highly dependent on the energy source powering the electrolyser. Hydrogen produced from grid mix electricity can be more carbon intensive than even coal gasification, depending on the local energy mix, whereas electrolysers powered by renewable energy or nuclear power can produce hydrogen with a carbon intensity approaching zero.

Installed electrolyser capacity of 1.4GW at the end of 2023 was expected to approach 5GW at the end of 2024, according to IEA. China accounted for 80% of capacity that came online in 2023, and 75% of new capacity slated for 2024. Electrolyser manufacturing capacity is expanding and is not currently considered a limiting factor for electrolyser projects.

Increased renewable energy capacity is necessary for electrolysers to produce green hydrogen.

Electrolysers require pure, de-ionised water to optimise performance, maintain output quality, and reduce operating costs by extending component lifespans. Filtration, deionisation, and reverse osmosis technologies exist at scales suitable for electrolysers and can be fed with freshwater and desalinated seawater. IEA says water desalination and purification costs are under 2% of the total hydrogen production costs. It should be noted that many hydrogen production cost forecasts exclude water costs.

Electrolyser projects commonly incorporate and are co-located with renewable electricity sources in order to control costs and to keep carbon intensity of the end product low.

4.3

Transportation and storage

Logistics costs for hydrogen are high across transportation and storage. Such costs for compressed gas are around six times those for LNG, and for LH_2 costs are roughly double those for LNG, according to Hydrogen Europe's 2021 technical paper Techno-Economic Assessment of Low-Carbon Hydrogen Technologies for the Decarbonisation of Shipping.

Due to the range in energy density of hydrogen's various forms and their related processing and infrastructure costs, the most cost effective method of transporting hydrogen over land depends on the distance to be travelled and the volume of hydrogen to be transported, as shown for North-West Europe in the chart to the right. As industrial areas with proximity to the sea, port areas are considered a strong candidate for locating green hydrogen production facilities using green electricity from wind turbines to power electrolysers.

Another method for transporting hydrogen is as ammonia, taking advantage of the cheaper transport costs and higher energy density of the hydrogen-rich chemical. To meet large scale demand for hydrogen in port, green ammonia could be imported by pipeline for conversion to liquid hydrogen for bunkering. While each stage of the process would have energy costs and related emissions, the process may prove more efficient than transporting liquid hydrogen, depending on distances travelled and other factors. According to EMSA's 'Potential of Hydrogen as a Fuel for Shipping', total production costs for green hydrogen are lowest when ammonia is used as a carrier.

The most cost effective form of hydrogen for a given shipping project will depend on the ship's range and power demands.

Distance in km

Quantity in kg per year	10	50	100	200	300	400	500	600	700	800	900	1,000	1,250	2,000	2,500
100,000	CH2	CH2	CH2	CH2	CH2	CH2	CH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
200,000	CH2	CH2	CH2	CH2	CH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
500,000	CH2	CH2	CH2	CH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
1,000,000	CH2	CH2	CH2	CH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
2,000,000	CH2	CH2	CH2	CH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
3,000,000	CH2	CH2	CH2	CH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
4,000,000	CH2	CH2	CH2	CH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
5,000,000	CH2	P	P	P	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
10,000,000	CH2	P	P	P	P	P	P	LH2	LH2	LH2	LH2	LH2	LH2	LH2	LH2
15,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	LH2	LH2	LH2
20,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	LH2
25,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P
30,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P
50,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P
100,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P
250,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P
500,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P
1,000,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P
2,000,000,000	CH2	P	P	P	P	P	P	P	P	P	P	P	P	P	P

CH2 – Road transport of gaseous Hydrogen

LH2 – Road transport of liquid hydrogen

P – Pipeline

Source: Interreg NorthWest Europe System-Based Solutions for H2-Fuelled Water Transport in North-West Europe, Comparative report on alternative fuels for ship propulsion

Hydrogen as a cargo

There is one LH_2 tanker in operation in the world. Suiso Frontier was launched in 2020 to transport hydrogen from Australia to Japan in its 1,250 m^3 Type C containment tank and completed its first shipment in 2022.

Since liquefied hydrogen was not explicitly covered under the IGC Code, a CCC working group drafted interim recommendations to facilitate the approval and classification of the Suiso Frontier. The initial version of the 'Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk (MSC.420(97))' were adopted in November 2016 to address requirements for vacuum insulated containment systems. Since then, the interim recommendations are being revisited to include other types of containment systems such as novel non-vacuum insulated tanks (adopted by MSC.565 (108)) and membrane type containment systems (completed during CCC11 and expected to be approved during MSC 111 in May 2026).

In July 2025, Japan submitted test results from its experience with Suiso Frontier to CCC (CCC 11/INF.5). The ship's cargo containment system was tested on three round trips between Japan and Australia, and the findings compared with the special requirements in the Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk. The demonstration tests confirmed the effectiveness of the multi-layer vacuum insulation system, the submission states.

Research and development is ongoing for LH_2 ship designs, pushing their size and capacity well beyond that of Suiso Frontier. Cargo storage tanks and containment systems are crucial technologies for LH_2 ships, along with their integration with ship designs and operations.

Demand for hydrogen transportation is expected to increase as economies turn to hydrogen as an energy source for more industries.

Infrastructure costs

There are opportunities for cost savings in the development of hydrogen infrastructure through the retrofit of LNG terminals, according to a 2024 Poten & Partners report. Some planned LNG terminals are being designed 'hydrogen ready' to reduce future upgrade and retrofit costs to accommodate hydrogen and/or ammonia as a hydrogen carrier.

Lowering infrastructure development costs will support the adoption of hydrogen projects and reduce their contribution to delivered hydrogen prices.

5.1

Chapter 5: Technology readiness

Internal combustion engines using up to 100% hydrogen are available on the market along with hydrogen fuel cells, but both technologies are in need of greater demand to drive development of wider product offerings and scale up production to reduce costs.

Fuel cells generate electrical energy and are generally more efficient than internal combustion engines.

5.2

Hydrogen Internal Combustion Engines

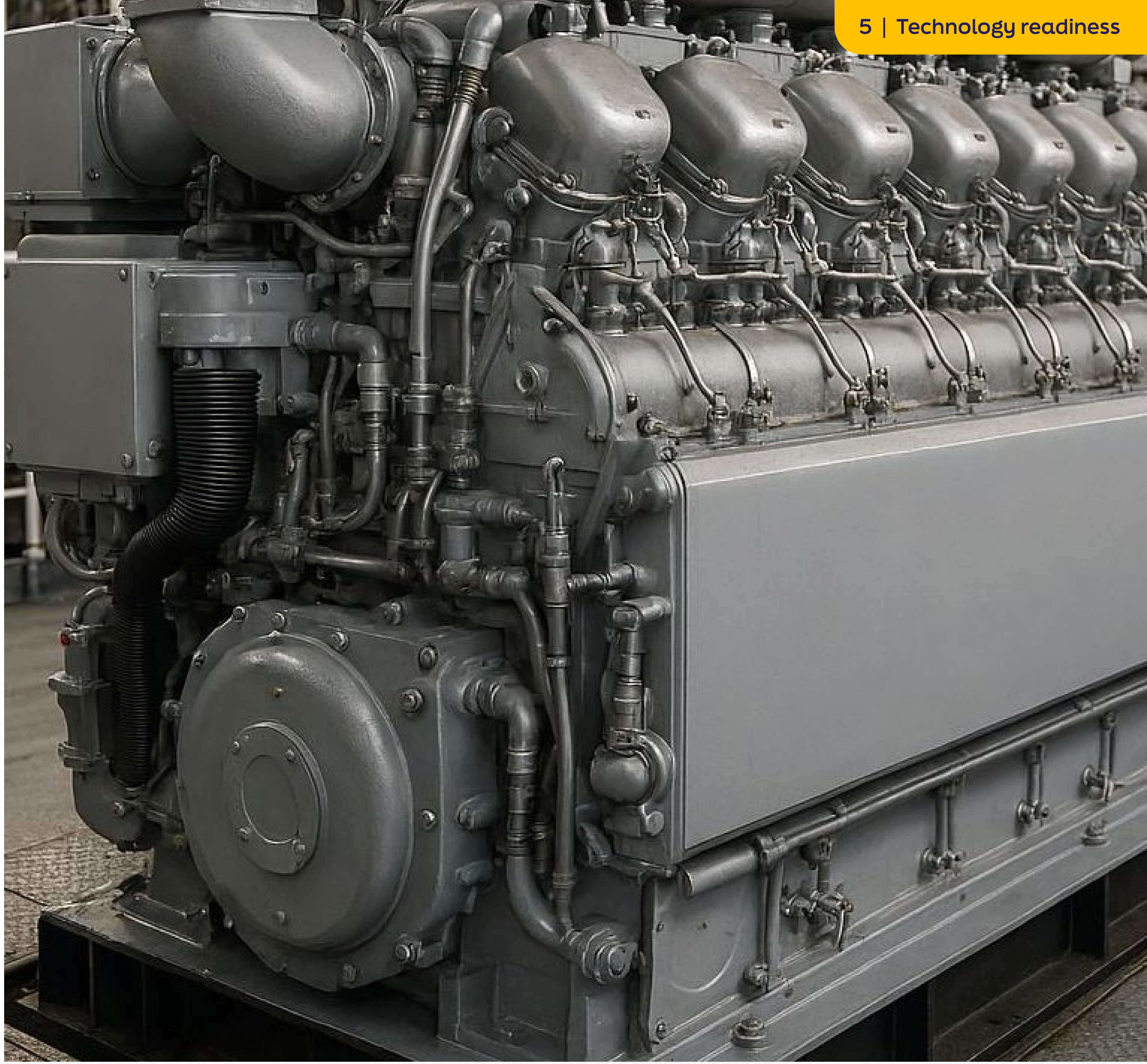
Hydrogen can be used in ICEs either as a standalone fuel, a blend component to improve characteristics of other fuels, or as a main fuel along with a pilot fuel. Dual-fuel ICEs offer the flexibility to adopt hydrogen as a fuel before a completely reliable supply is available, switching to use of the conventional fuel oil when hydrogen is unavailable, and ICEs are able to use lower purity hydrogen sources than fuel cells.

Fuel blending tests have shown diesel and dual-fuel ICEs as capable of accommodating fuel mixes containing up to around 25% hydrogen by volume with minimal operational changes and impacts. Design criteria for hazardous areas must be considered for engines using hydrogen, owing to standards on the use of equipment in potentially explosive environments.

Available hydrogen engines are currently limited to smaller power outputs suitable for harbour craft, ferries, and work boats, and for use as generators for auxiliary loads.

The challenges for marine hydrogen ICEs development include:

- Design changes to optimise for hydrogen blends
- Complete redesign necessary for fully optimised 100% hydrogen engines
- Pre-ignition risk from component hotspots and lubricant formulations
- High flame heat and NOx generation
- Exhaust explosions and indirect Global Warming Potential from fuel slip
- Presence of water in the crankcase, causing corrosion and affecting lubricants
- Lower power output by volume may require larger engine sizes



Dual fuel hydrogen

Compression ignition ICEs compress the fuel-air mix to reach high enough pressures and temperatures to cause the fuel to autoignite. Hydrogen's autoignition temperature of 584 °C compares to around 250 °C for diesel, making ignition by compression impractical for pure hydrogen.

To use hydrogen in compression ignition engines, a pilot spray of diesel is injected to ignite the hydrogen-air mixture. Reduction in GHG and other emissions can be achieved by replacing most of the fuel used by the engine with sustainably-produced hydrogen. The necessary volume of pilot fuel depends on engine design and load. Further WtW GHG emissions reductions can be achieved by using a sustainable pilot fuel, such as biodiesel or HVO, bringing WtW GHG emissions to near zero.

Among the considerations for designing compression ignition engines are the precise control of ignition timing, fuel injection volume and timing, and air intake. NOx emissions must also be controlled.

There is significant global activity in the development of ICEs for shipping by researchers and manufacturers, as well as related work in the heavy and light automotive sectors and in land-based engines for electrical power generation.

Recent and significant developments in hydrogen ICEs

CMB.TECH and Anglo Belgian Corporation joint venture BeHydro offer a series of dual-fuel four-stroke engines that operate on fuel mixes up to 85% hydrogen and range in output from 600 kW to 2.7 MW. LR granted approval in principle to BeHydro's engine design in 2020, followed by the award of the first Type Approval for a hydrogen-powered dual fuel engine in 2023. ABC engines have also developed a 100% hydrogen engine variant for marine applications.

A pair of 749 kW MAN D2862 LE448 dual-fuel hydrogen power engines were fitted with CMB.TECH hydrogen injection systems for LR-classed crew transfer vessel (CTV) Hydrocat 48. The V12 engines use around 5% diesel pilot fuel in hydrogen mode, and are capable of operating on pure diesel when hydrogen supply is not available. The CTV has since been joined by another hydrogen-powered ship of the same design, as well as Windcat 57, the first in a series of six hydrogen dual-fuel vessels with 2.1 MW of installed power from a pair of MAN D2862 engines.

LR issued type approval for the hydrogen solution to be installed on four 80-tonnes bollard pull dual-fuel hydrogen ASD Tugs 2812 FF-H2 from Damen, under construction for CMB.TECH. Damen and CMB.TECH have collaborated on the Elevation series of Commissioning Service Operation vessels (CSOV); the six ships will feature dual fuel hydrogen engines and hybrid battery systems. The first in the series, Windcat Rotterdam, was launched in October 2024 and is due for delivery in 2025.

CMB.TECH also worked with Volvo Penta on the prototype D4-300 engines on Hydroville, and the dual fuel D13-1000 engine for the ferry Hydrobingo.

Yanmar announced in 2024 that it had completed land-based testing of a hydrogen-powered four-stroke high-speed engine for use in Japanese coastal vessels as part of the Nippon Foundation's Zero-Emission Ship Project.

In larger engine developments, MITSUI completed a successful test running a 50 cm bore MAN B&W ME-GI two-stroke engine on hydrogen in 2024. A single cylinder was converted to run on hydrogen, recording up to 95% GHG emissions reduction in operations up to 100% load.

Japan Engine Corporation announced in 2023 that it had begun a one year test of a hydrogen fuel injection device for a large low-speed two-stroke engine. The tests will be followed by the development, design and manufacturing of a full-scale hydrogen direct injection engine for demonstration purposes, said J-ENG, for completion in 2027 after one year of operation for testing and verification.

Pure hydrogen

Spark or electrical ignition allows for the use of 100% hydrogen as a fuel in ICEs by eliminating the need for a pilot fuel; the fuel-air mix is ignited by an electric spark generated by a spark plug, rather than by pressure and heat.

While spark ignition (SI) ICEs are an established land-based technology, marine applications are so far limited. The established four-stroke marine engines may have many components compatible for use with hydrogen, however adjustments are necessary to account for hydrogen's low ignition energy and low power density. Ignition timing and fuel injection must be precisely controlled to prevent pre-ignition, and consideration given to hotspots that could cause ignition.

Turbochargers are an important technology for hydrogen engines, forcing more air into the engine to boost power density and increase overall efficiency. Hydrogen ICEs have higher airflow demands than diesel engines, and may require more complex turbocharging solutions to optimise efficiency – a key consideration for expensive green fuels.

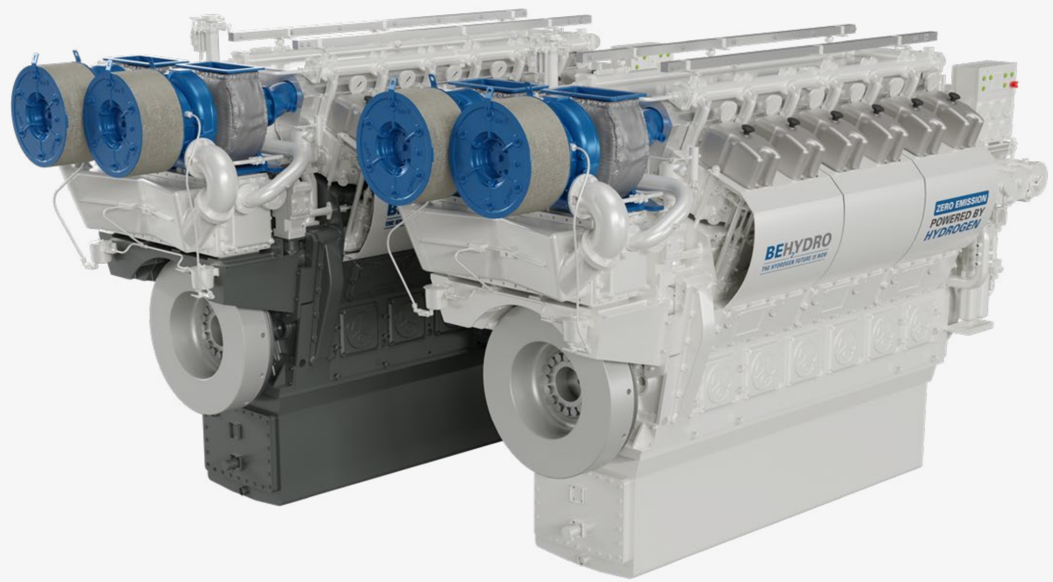
As 100% hydrogen users, hydrogen-only engines face competition from hydrogen fuel cells in some applications, units which are more energy efficient than ICEs. ICEs have some advantages over fuel cells, such as greater efficiency at high loads and the ability to operate using lower-purity hydrogen.

Fuels cells have no NOx emissions, but NOx can be emitted during high-heat combustion in ICEs. NOx management and mitigation strategies for hydrogen ICEs include load management, lean burn techniques, water or steam injection, and exhaust gas recirculation.

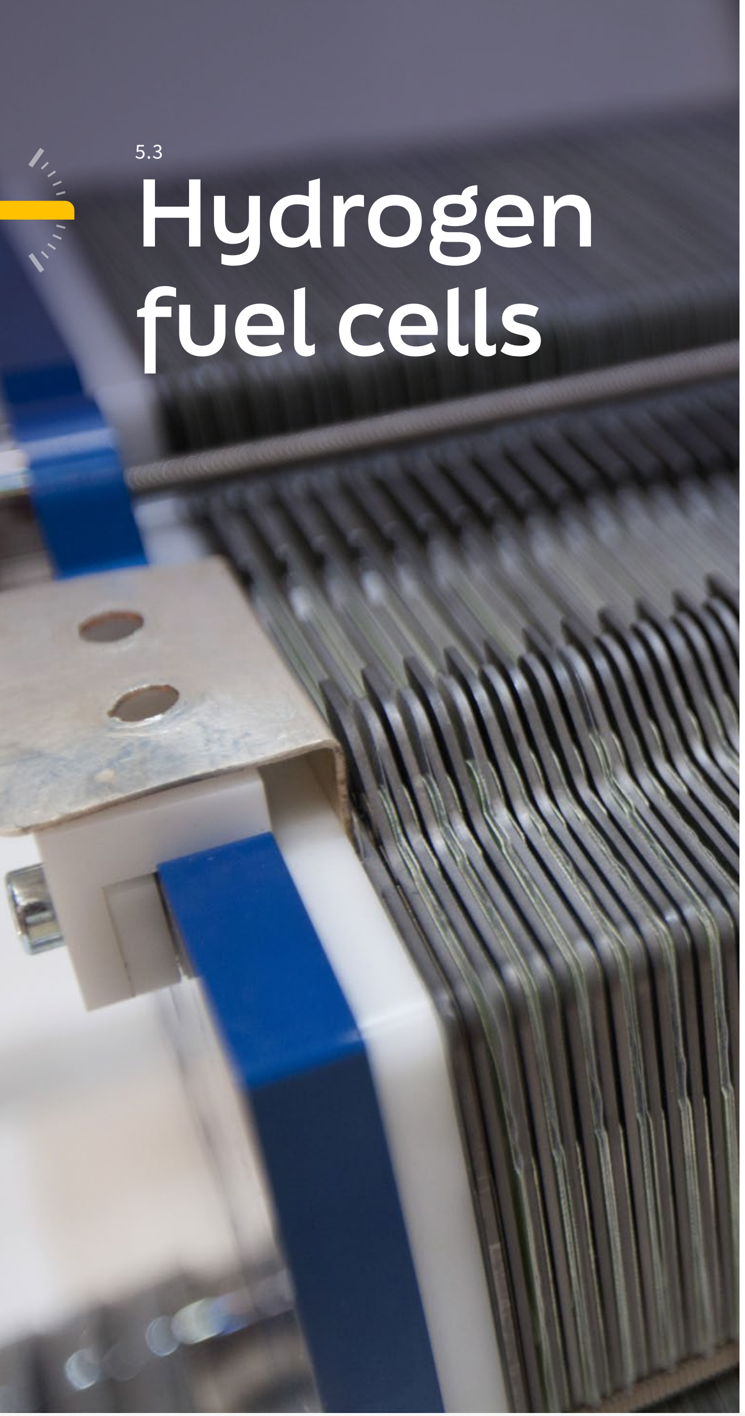
Pure hydrogen ICE projects

BeHydro has a series of 100% hydrogen engines ranging from 1MW to 2.7MW, while J-ENG has stated its aim of commercialising a hydrogen engine with an electric ignition system to reach even higher environmental performance levels. Yanmar is also developing a 100% SI hydrogen engine.

Wärtsilä launched a 100% hydrogen-ready power plant engine based on one of its marine engine designs. The product will be open for orders in 2025 for delivery from 2026, and while it is not itself a marine product, shows relevant development activity and experience-building. A further example is Rolls-Royce's successful test of a 12-cylinder gas variant of its mtu Series 4000 L64 engine running on 100% hydrogen fuel.



© BeHydro 12-cylinder Dual Fuel /Spark-ignited hydrogen engines



5.3

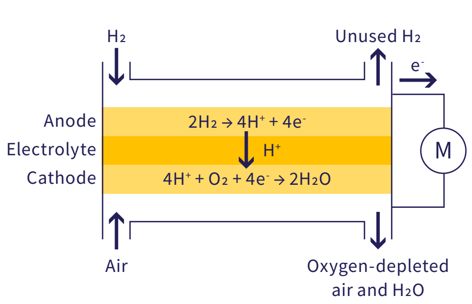
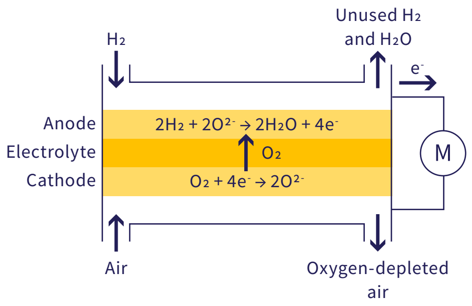
Hydrogen fuel cells

Fuel cells are increasingly seen as an option for propulsion and auxiliary power generation in certain shipping sectors, providing a reliable source of zero carbon electricity with high efficiency. Fuel cells generate DC electrical power by converting a fuel, often hydrogen, into power through an electrochemical reaction with an oxidant, commonly air.

One of the most attractive characteristics of hydrogen fuel cells for shipping is their zero TtW emissions, eliminating emissions of pollutants and GHGs, and bringing significant compliance benefits under emissions regulations. Fuel cells using green hydrogen can achieve zero WtW emissions, offering one-step compliance with 2050 emissions targets where sustainable hydrogen is available. Fuel cells are highly efficient, with efficiencies between 45% and 63% at rated power, depending on technology, although efficiency deteriorates over time.

Fuel cells are been increasingly adopted for medium- and heavy-duty automotive use and are available at commercial scale in those sectors, with lesser adoption within shipping.

Various fuel cell technologies have been developed. The most common type of commercial fuel cell power systems available are Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC). Their characteristics are detailed in the table on the right.

Characteristic	Proton Exchange Membrane Fuel Cell (PEMFC)	Solid Oxide Fuel Cell (SOFC)
MEA schematic		
Operation temperature	60 to 80°C	600 to 800°C
Fuel	Hydrogen	Hydrogen and methane
Water generation	At the cathode (air side)	At the anode (fuel side)
Start-up and load changes	Fast	Slow
Main applications	Automotive	Stationary power generation

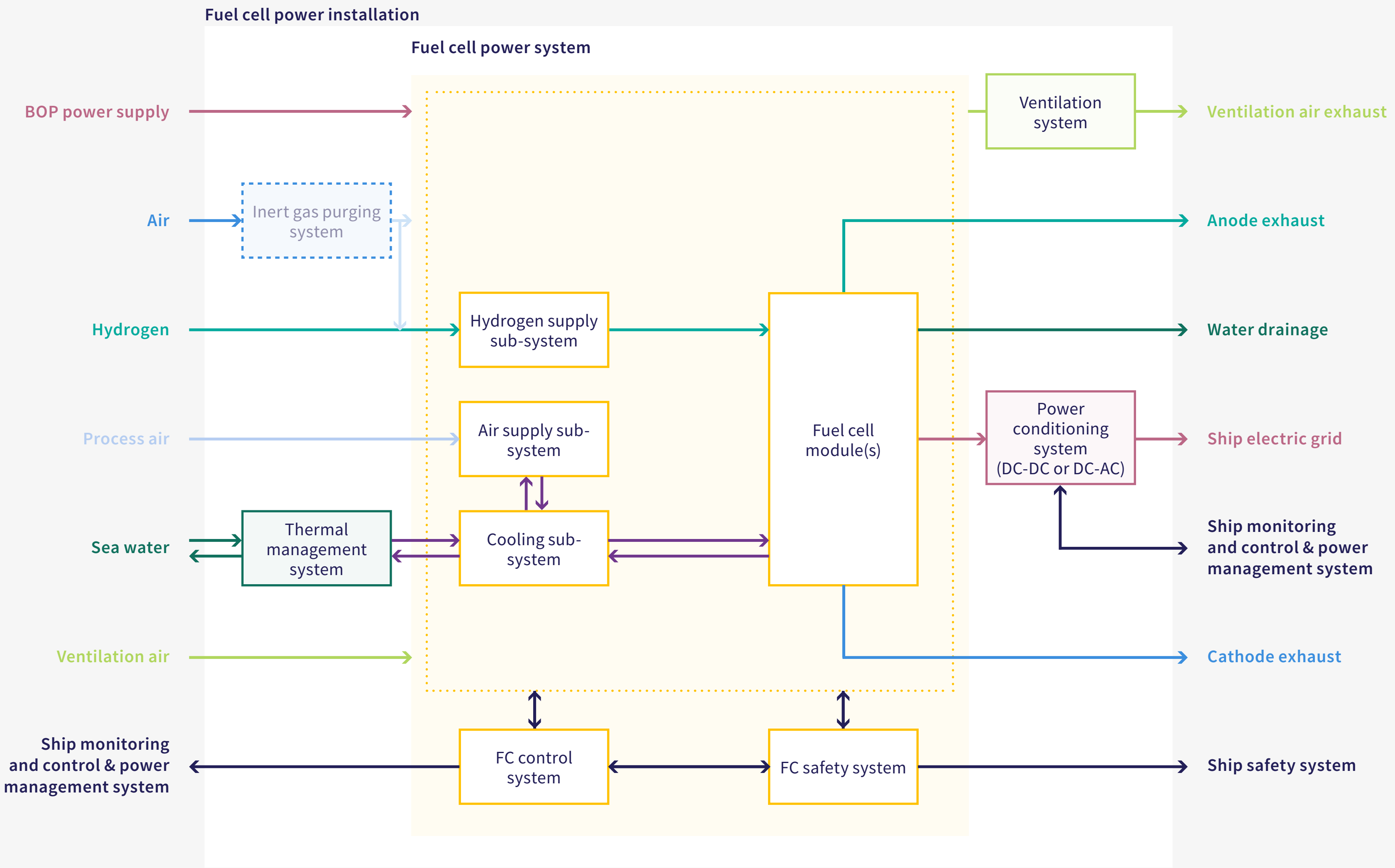
Source: LR Guidance Notes on the Installation of Fuel Cells on Ships, July 2025

Fuel cells are scalable in power with the addition of additional membrane electrode assemblies (MEA), the basic unit of a fuel cell. Various additional systems are required beyond the fuel cell module, including ventilation and cooling, as detailed to the right for a PEMFC.

Fuel cells typically are paired with batteries as a hybrid system in order to manage changes in demand.

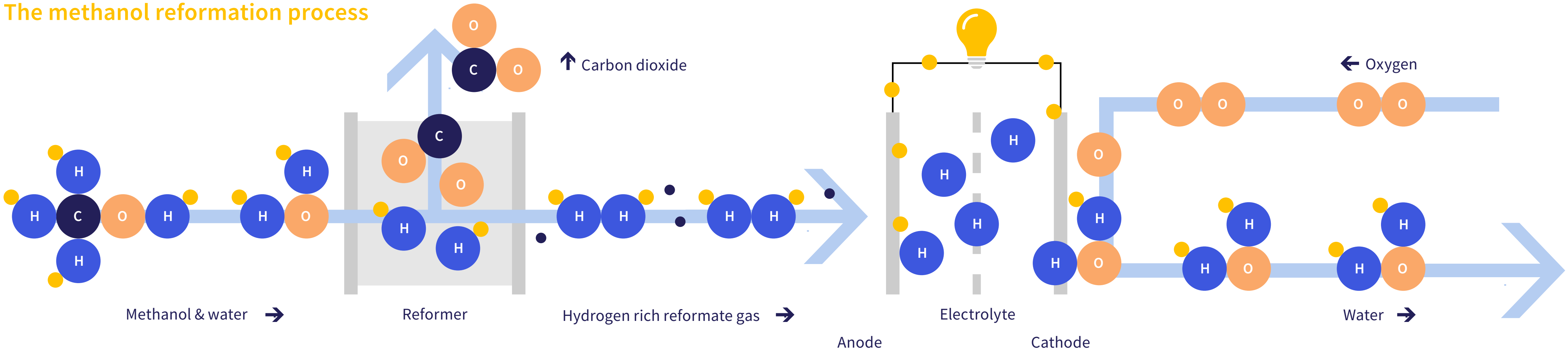
Commercially available compact design PEMFC marine fuel cell power systems require about 5 to 10 m² of installation space per megawatt of power output.

Fuel cells have their own maintenance requirements such as sensor check, filter replacements, and coolant replacement, but are viewed favourably from a maintenance perspective due to having fewer moving parts compared to ICEs.

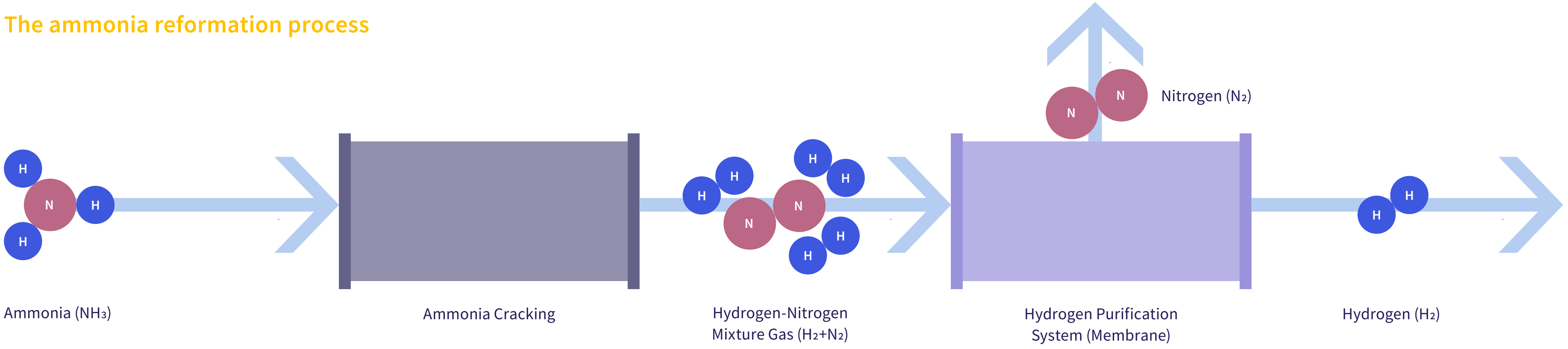


To address the challenges related to onboard hydrogen storage due to its low energy density, converters and reformers are under development to enable onboard generation of hydrogen from a more energy dense fuel such as ammonia or methanol. Carbon capture and storage would be necessary to limit GHG emissions from methanol reformers.

The methanol reformation process



The ammonia reformation process



Fuel cell projects

LR awarded Approval in Principle to ship owner Torghatten Nord in 2022 for two hydrogen-powered vessels operating on Norway's longest ferry route, and will class the two ships for arctic sailings. On delivery in 2026, the ships are expected to be the largest hydrogen-powered vessels in the world, each with 6.4 MW of fuel cells from PowerCell, with backup from HVO-fuelled gensets from Bergen Engines.

Two Shiptec hydrogen passenger ferries using zero-emissions compressed hydrogen powered fuel cells were granted LR AiP in 2024. The 300-passenger *Saphir* and 12-passenger catamaran *Quinten Lebt* will operate on Lake Lucerne and Lake Walen, respectively.

LR granted AiP to HD Hyundai Mipo & Korea Shipbuilding and Offshore Engineering's (KSOE) design for a 1,300 teu ammonia fuel cell feeder ship using Amogy's onboard ammonia-to-hydrogen technology to provide hydrogen to the fuel cell. The ship has a power output of 8 MW and was the result of a joint development project between LR, HD HMD, HD KSOE and Amogy.

H2SITE's containerised ammonia to hydrogen onboard cracking technology received LR AiP after demonstrating its performance at kW scale in offshore conditions on OSV *Bertha B*. The company is working on upscaling its technology to the MW scale.

Furthering industry understanding of such cracking technology, LR has partnered with energy companies ROTOBOOST and Amogy on a fuel cell and pre-combustion Carbon Capture Storage System (CCS) to evaluate the use of hydrogen fuel cells, ammonia and methane cracking technology and CCS from a technical readiness, financial and regulatory perspective.

PowerCell's Marine System 200 fuel cell, as featured in the Torghatten Nord ferries, will be central to the research project.

MF Hydra is the world's first LH_2-powered ship and is powered by two Ballard 200kW fuel cell modules.

H2 Barge 1, a 110-metre 208 teu containership formerly named *MSC Maas*, was launched in the Netherlands in 2023 to serve the route between Rotterdam and an inland terminal in Belgium.

Newbuild river vessel *ZULU 06* was delivered in late 2024 with a pair of 200 kW Ballard fuel cells, and was part of the FLAGSHIPS project alongside Future Proof Shipping's *H2Barge2*, a 190 teu container vessel retrofitted with six fuel cells totalling 1.2 MW. Future Proof Shipping's LR-classed *H2 Barge 1* was retrofitted with triple redundant fuel cell capacity totalling 900 kW paired with a 1MWh battery.

Sea Change was delivered in 2021 and was the first hydrogen fuel cell vessel in the US. The ferry is equipped with 360 kW of Cummins fuel cells for its operations for San Francisco Bay Ferry.

The hull of river vessel *Dong Fang Qing Gang* was launched in China in 2024, and is due to be equipped with a pair of 240 kW fuel cells from Sinosynergy, giving the 64 teu barge a range of around 235 miles.

Samskip will operate two 500 teu hydrogen-powered shortsea container vessels with 3.2 MW hydrogen fuel cells in North West Europe as part of a collaboration with Ocean Infinity. The vessels will be remotely controlled and autonomous ready, serving a route between Oslo and Rotterdam.

Torghatten Nord Hydrogen-powered vessels © Torghatten and Norwegian ship design

Chapter 6
Summary and conclusions

Hydrogen is widely considered as essential to the global ambition of a net zero society. As a fuel for ships, hydrogen has the potential to deliver the ultimate goal of net zero emissions shipping by 2050, eliminating the industry's GHG emissions and increasing air quality.

As with other zero-emissions solutions, there are technical, commercial and regulatory challenges to be overcome, but there are no roadblocks to hydrogen's broad adoption in the shipping industry.

As a necessary component of other e-fuels such as e-ammonia, e-methanol, and e-LNG, adoption of those other fuel pathways will bring benefits through incentivising investment in green hydrogen production and research into hydrogen technologies.

On the regulatory front, global awareness of hydrogen's role in decarbonisation is supporting work on national hydrogen policies and relevant technical standards. Within shipping, regulations for hydrogen are currently incomplete, but interim guidelines for the safe adoption of hydrogen are in active development at the IMO and are on course to bring greater clarity to support adoption. Such work is vital to understanding and managing fire and explosion risks as well as others arising from the use of hydrogen onboard.

The establishment of hydrogen infrastructure will require significant capital investment due to the lack of existing facilities and the specific requirements of hydrogen storage and transportation.

The energy density of hydrogen presents integration challenges for larger vessels, requiring efficient propulsion systems and appropriate operating profiles to be viable. Broader challenges include the high price for prime movers, storage, and handling equipment, and the space requirements for LH_2 tanks. As production of relevant technologies scale up, equipment costs will fall, and innovations such as onboard ammonia cracking will expand the fleet for which hydrogen is a viable fuel choice. Technological development is moving at a rapid pace and early experience with hydrogen in shipping is building, often in projects with state support.

The greatest challenge for hydrogen in shipping is its commercial viability, which will ultimately be dictated by the world's commitment to decarbonisation. Higher carbon pricing under market-based measures will improve the competitiveness of hydrogen as a marine fuel, and drive increases in green hydrogen production capacity, improving availability.

Lloyd's Register will closely follow developments across these areas and cover them in future updates to this guide.

Chapter 7
Other resources and annexes

Hydrogen Europe Techno-Economic Assessment of Low-Carbon Hydrogen Technologies for the Decarbonisation of Shipping https://hydrogeneurope.eu/in-a-nutshell/reports/

EMSA – Potential of Hydrogen as Fuel for Shipping

ISO/CD 21341 Ships and marine technology — Test procedures for liquid hydrogen valve of hydrogen ships

ISO 24132 Design and testing of marine transfer arms for liquefied hydrogen

ISO 11326:2024 Ships and marine technology — Test procedures for liquid hydrogen storage tank of hydrogen ship

CIMAC WG17 | Guideline – Hydrogen in Stationary 4-Stroke Gas Engines for Power Generation

Zemo Partnership Low Carbon Hydrogen Well-to-Tank Pathways Study

LR Engine Retrofit Report 2023: Applying alternative fuels to existing ships

LR Guidance Notes on Composite Cylinder Systems for Gaseous Hydrogen Containment

LR Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels

LR Guidance Notes on the Installation of Fuel Cells on Ships

LR Guidance Notes for Liquid Hydrogen Systems

LR ShipRight Procedure for Risk Based Certification (RBC).

Lloyd’s Register Maritime Decarbonisation Hub The future of maritime fuels What you need to know

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping’s (MMMCZCS) Fuel Cell Technologies and Applications for Deep-Sea Shipping

EU – FuelEU Maritime

EU – Guidance on the targets for the consumption of renewable fuels of non-biological origin in the industry and transport sectors

IMO – Guidelines on the life-cycle analysis of marine fuels (LCA Guidelines)

Lloyd’s Register Maritime Decarbonisation Hub – Zero Carbon Fuel Monitor Hydrogen

Interreg NorthWest Europe System-Based Solutions for H2-Fuelled Water Transport in North-West Europe, Comparative report on alternative fuels for ship propulsion

Maritime Just Transition Taskforce – Considerations of Training Aspects for Seafarers on Ships Powered by Ammonia, Methanol, and Hydrogen

IEA – Hydrogen Production and Infrastructure Projects Database

IEA – Energy Technology Perspectives 2024

IEA – Global Hydrogen Review 2024

T&E – e-Fuels observatory for shipping, May 2024

Annex 1: Technology, Investment and Community readiness levels (TRL, IRL, CRL) and definitions

There are three readiness levels used in this report: technology, investment and community. All are on a scale, with TRL on a scale of one to nine, and CRL and IRL on a scale of one to six.

Technology readiness (TRL)

The technology readiness level indicates the maturity of a solution within the research spectrum from the conceptual stage to being marine application ready. It is based on the established model used by NASA and other agencies and institutes, using a nine-level scale.

Level	Technology Readiness Level (TRL)	
1	Idea	Basic principle observed
2	Concept	Technology concept formulated
3	Feasibility	First assessment feasibility concept and technologies
4	Validation	Validation of integrated prototype in test environment
5	Prototype	Testing prototype in user environment
6	Product	Pre-production product
7	Pilot	Low-scale pilot production demonstrated
8	Market introduction	Manufacturing fully tested, validated and qualified
9	Market growth	Production and product fully operational

Investment readiness level (IRL)

The investment readiness level indicates the commercial maturity of a marine solution on the spectrum from the initial business idea through to reliable financial investment. It addresses all the parameters required for commercial success, based on work by the Australian Renewable Energy Agency (ARENA). The six-level scale used summarises the commercial status of the solution and is determined by the available evidence in the market.

Community readiness level (CRL)

The community readiness level indicates the societal maturity of a marine solution in terms of acceptability and adoption by both people and organisations. It is gauged on the spectrum from societal challenge through to widespread adoption. CRL is based on the work by ARENA and Innovation Fund Denmark adapted to a six-level scale.

	INVESTMENT READINESS LEVEL (IRL)	
1	Idea	Hypothetical commercial proposition
2	Trial	Small-scale commercial trial
3	Scale up	Commercial scale up
4	Adoption	Multiple commercial applications
5	Growth	Market competition driving widespread development
6	Bankable asset	Bankable asset class

	COMMUNITY READINESS LEVEL (CRL)	
1	Challenge	Identifying problems and expected societal readiness, formulation of possible solution(s) and potential impact
2	Testing	Initial testing of proposed solution(s) together with relevant stakeholders
3	Validation	Proposed solution(s) validated, now by relevant stakeholders in the area
4	Piloting	Solution(s) demonstrated in relevant environment and in cooperation with relevant stakeholders to gain initial feedback on potential impact
5	Planning	Proposed solution(s) as well as a plan for societal adaptation completed and qualified
6	Proven solution	Actual project solution(s) proven in relevant environment

More details on the readiness levels adopted by Lloyd's Register can be found on the LR Maritime Decarbonisation Hub zero carbon fuel monitor.

Nuclear
Hydrogen
LPG
Methanol
Ammonia
LNG
Biofuel
Electric