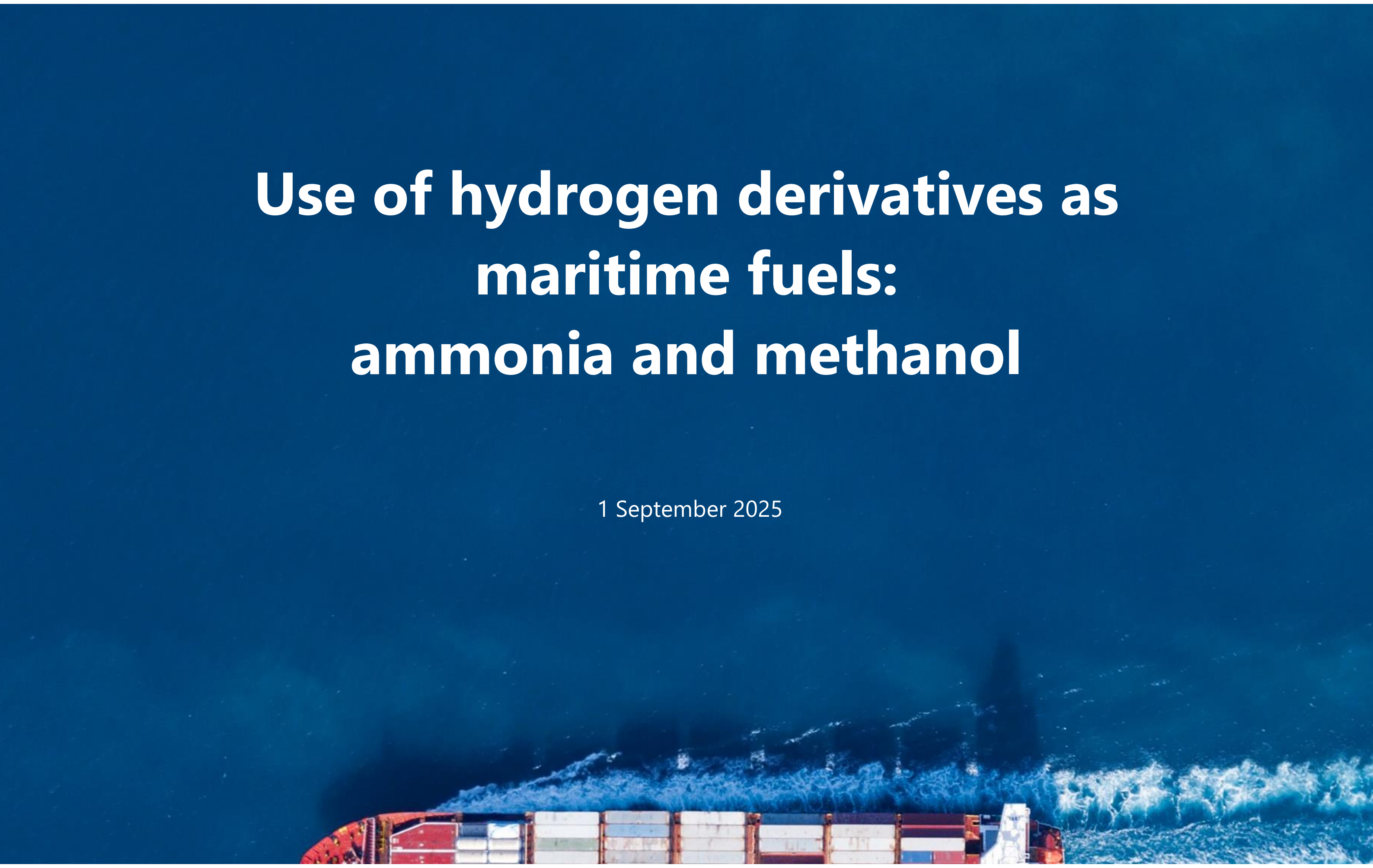
Observatorio Tecnológico del Hidrógeno



Use of hydrogen derivatives as maritime fuels: ammonia and methanol

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IN COLLABORATION

Cidaut · Centro Nacional del Hidrógeno · enagas · moeve · Politécnica

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ACRONYMS

AFC	Alkaline Fuel Cell
BLEVE	Boiling Liquid Expanding Vapour Explosion
BTX	Benzene, Toluene and Xylenes
CCC	Load and Container Transport Committee
EC	European Commission
CH_3OH	Methanol
CI	Compression Ignition
CO_2	Carbon Dioxide
CRL	Community Readiness Level
DF	Dual Fuel
DMFC	Direct Methanol Fuel Cell
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EMSA	European Maritime Safety Agency
FC	Fuel Cell
GHG	Greenhouse Gases
GT	Gross Tonnage
H_2	Hydrogen
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IRL	Investment Readiness Level
ISO	International Organisation for Standardisation
LH_2	Liquid Hydrogen
LNH_3	Liquid Ammonia
LPG	Liquefied Petroleum Gas
DMFC	Molten Carbonate Fuel Cell
CIE	Compression-Ignition Engine
ME-C	Mechanical Electronically Controlled
SIE	Spark-Ignition Engine
MGO	Marine Gas Oil

N_2	Nitrogen
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_x	Nitrogen Oxides
IMO	International Maritime Organisation
OSV	Offshore Support Vessel
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell/Polymer Electrolyte Fuel Cell
PSV	Platform Support Vessel
RORO	Roll-on/Roll-off Ship
RU	Remedial Units
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SOFC	Solid Oxide Fuel Cell
SU	Surplus Units
TRL	Technology Readiness Level
TtW	Tank-to-Wake
WtT	Well-to-Tank
WtW	Well-to-Wake

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EXECUTIVE SUMMARY

The decarbonisation of maritime transport is a strategic priority in the fight against climate change and, in turn, one of its greatest challenges. This sector, which accounts for approximately 3% of global energy-related CO_2 emissions, consumes around 5% of the world's oil.

Maritime transport is one of the most energy-efficient modes, although its aggregate impact in absolute terms is considerable. Within this context, the necessary search for sustainable solutions has led to the evaluation and implementation of **alternative fuels, including green hydrogen derivatives such as ammonia (NH_3) and methanol (CH_3OH).**

This technical report by the Hydrogen Technology Observatory, led by Enagás and drawn up in collaboration with the National Hydrogen Centre (CNH2), CIDAUT, Moeve and the Polytechnic University of Madrid (UPM), seeks to provide an analysis of the potential use of ammonia and methanol, assessing their physico-chemical and environmental properties, their level of technological maturity, the existing regulatory framework and the main current and future applications.

From a technical standpoint, both hydrogen derivatives display characteristics that make them suitable for use as maritime fuel. Methanol has a high volumetric energy density and it can be stored in a liquid state at ambient temperature and pressure, facilitating its integration into ships and port infrastructure. As for ammonia, although it has a lower energy density, it benefits from the existing global logistics infrastructure and the potential for net-zero emissions if it is produced using renewable sources (so-called green ammonia).

From a technological perspective, the document analyses the degree of maturity of the existing solutions for the two fuels. In the case of methanol, dual-stroke and four-stroke engines are already in commercial operation, as well as retrofit kits for existing vessels developed by leading manufacturers such as Everllence[1], Wärtsilä and Hyundai HiMSEN. In the case of ammonia, the initial industrial developments of engines for this fuel have already reached the market, while retrofit kits are expected by around 2027, with projects by Everllence, WinGD, J-Eng and Wärtsilä already underway. Similarly, **innovative applications in fuel cells based on pure hydrogen and its derivatives** are being explored, placing special emphasis on molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), and proton exchange membrane fuel cells (PEMFCs) in early-stage applications for small vessels, ferries and coastal

[1] Formerly MAN Energy Solutions

transport, for which hydrogen could be supplied directly or obtained from methanol or ammonia undergoing respective reforming or cracking processes.

With regard to the regulatory framework, the document outlines the normative progress within the International Maritime Organisation (IMO) and the guidelines of the classification societies. Methanol already has provisional guideline MSC.1/Circ.1621, which regulates its safe use as a maritime fuel. Ammonia is in the process of being included in the IGF (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels) and IGC (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk) codes. A regulatory proposal has already been submitted by the IMO, which is expected to obtain approval in late 2025 and enter into force in 2027. In parallel, classification societies such as DNV, ABS and Bureau Veritas have published tentative standards and specific design guides. The European Maritime Safety Agency (EMSA) and the ISO regulations are also making progress in this regard.

From a strategic and market standpoint, according to DNV's forecasts for 2050, half of the fleet is expected to operate with propulsion sources such as hydrogen, ammonia and methanol, while the other half will use conventional fuels, mainly LNG, positioning ammonia as one of the fastest-growing fuels, with a projected share of between 35%-44% of the maritime fuel mix, according to the International Energy Agency (IEA) and Everllence, a leading engine manufacturer. As for methanol, it is expected to account for between 3% and 26% of the total. Both will benefit from their potential production using renewable sources, particularly e-methanol and green ammonia, which are key to achieving the climate neutrality goals.

The document also analyses the evolution of the global shipping fleet. LNG currently constitutes the main option for reducing the intensity of emissions associated with maritime transport in the short term, with 1,239 vessels in operation. Hydrogen, methanol and ammonia are growing rapidly in the new build order book, with 173 methanol vessels, 25 ammonia vessels and 10 vessels based on hydrogen technologies. The technical challenges of onboard storage and refuelling (bunkering) are also being examined, as well as the design, safety, ventilation and compatible material requirements.

In conclusion, **methanol and ammonia, as hydrogen derivatives, constitute two complementary technological pillars in the maritime transport energy transition process for the development of ICE engines and fuel cells.** Their potential to replace fossil fuels, their scalability and their benefits in terms of sustainability and availability justify their priority consideration on the sector's decarbonisation roadmap, although both still pose operational and regulatory challenges.

1. BACKGROUND

Maritime transport is the key axis of international trade and an integral part of the **global** supply chains. In addition to being a major energy consumer (approximately **5% of annual global oil consumption**), it is one of the main sources of greenhouse gases (GHG), accounting for **3% of global energy-related CO_2 emissions** (nearly **700 million tonnes per annum**) [1] [2]. Within the sector, **international maritime transport**, including bulk carriers, oil tankers and container ships, accounts for **over 80% of total emissions** [1].

Companies in the sector have already begun to invest significantly in **reducing and optimising the efficiency of their routes** in response to the regulatory conditions, the high fuel prices, the market dynamics, the energy efficiency requirements for new vessels and the international standards limiting the sulphur content of the fuels used, as well as cutting greenhouse gases [3].

In this respect, **two factors** that are decisive in reducing emissions have been identified, namely **slow steaming** and **vessel size** [3]:

- **Slow steaming**: reducing the vessel's speed by half can reduce fuel consumption by up to eightfold. The steaming speed has undergone an average 10% reduction compared to the figure for 2008. Since that year, so-called "slow steaming" has been responsible for 67% of the efficiency improvements.
- **Vessel size**: there has been a 50% average increase. This results in a cut in the fuel consumption per tonne of load, due to the reduction in the hull's surface area and the drag of each cargo.

Throughout Europe, as indicated in the EU's **Fit for 55** Ecological Transition Plan [4], 25% of GHG emissions correspond to the transport sector, with **maritime mobility accounting for 13.5%** (**Figure 1**).

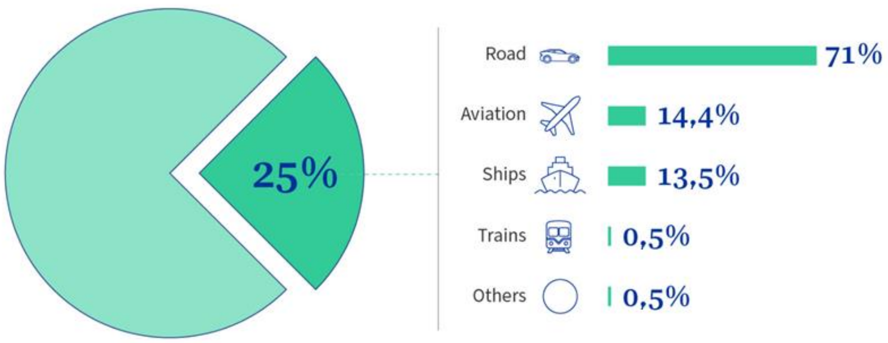


Figure 1. Transport-related GHG emissions in Europe **[4]**

The European **FuelEU Maritime** regulation, part of the Fit for 55 package of measures based on which the European Council has adopted a new [5] sanctioning regulation to decarbonise the maritime sector [4], includes the following main provisions:

(i) Achievement of a gradual reduction in **GHG emissions** from the fuels used in this sector: **from 2% in 2025 to 80% by 2050** (**Figure 2**).

(ii) A special incentive scheme to support the adoption of non-biological renewable fuels, which have significant decarbonisation potential.

(iii) Exclusion of fossil fuels from the Regulation's certification process.

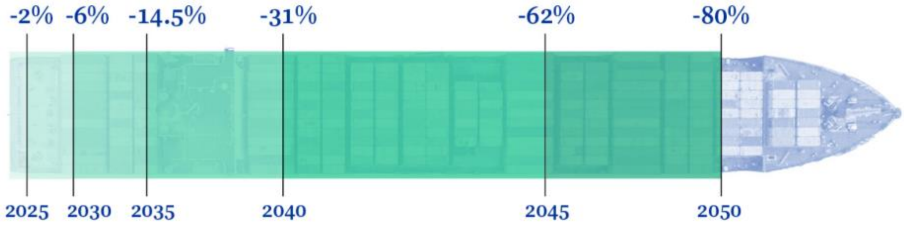


Figure 2. An average annual reduction in carbon intensity in comparison with the 2020 average. **[4]**

Furthermore, starting in January 2024, by means of the **amendment to Directive 2003/87/EC**, emissions trading in the EU will be extended to emissions from maritime transport activities, regardless of the flags of the vessels in question [6].

In July 2023, the **International Maritime Organisation (IMO)** revised its strategy for addressing GHG emissions, charting a new course towards decarbonising the sector. This new phase focuses on the development and adoption of technologies with net-zero or near-zero emissions, alternative fuels (biofuels, ammonia, methanol, hydrogen, etc.) and renewable energy sources. To drive this change, the IMO has implemented strict regulations on CO2, NOx and SOx emissions, as well as the designation of special zones or ECAs (Emission Control Areas) [7]. Its new strategy aims to achieve a **reduction in GHG emissions** of at least 20% by 2030 (compared to 2008 levels) and 100% by 2050 [8].

Different levels of technological maturity can be observed in the **technological development of alternative maritime fuels**. Biofuels such as biomethane and renewable diesel are now commercially available; however, they do not deliver as significant a carbon footprint reduction as emerging alternative fuels, including hydrogen, ammonia and methanol (using only biogenic CO_2), which have zero or near-zero carbon emissions [9].

The transport sector's transition towards the use of alternative maritime fuels **requires the involvement of the entire logistics chain**, including identifying the raw materials, developing and scaling up the production processes, developing storage, logistics and supply (bunkering) solutions that can adapt to these alternative fuels, managing the safe storage and use of the fuels on board vessels and controlling their emissions [9].

2. AMMONIA AND METHANOL AS ALTERNATIVE FUELS

2.1. Properties of the fuels

A higher volumetric energy density entails greater energy storage capacity in a smaller space, a key factor in fuel transport and storage.

Lloyd's Register [10] compared the **volumetric energy densities** of ammonia, methanol, LNG, liquid hydrogen (LH_2) and hydrogen gas at different pressures (**Table 1**).

Table 1. Comparison of volumetric energy densities **[10]**

Property	LNH_3	Methanol	LNG	LH_2	H_2 (365 bar)	H_2 (700 bar)
Density (kg/m^3)	696	790	450	70.8	23.35	38.25
Storage temperature (ºC)	-33	25	-162	-253	25	25
Storage pressure (bar)	1	1	1	1	350	700
Lower calorific power (MJ/kg)	18.8	19.9	48	119.93	119.93	119.93
Volumetric energy density (GJ/m^3)	**13.1**	**15.7**	**21.6**	**8.49**	**2.8**	**4.59**
Volumetric comparison MGO*	2.94	2.44	1.78	4.52	13.73	8.38

Note: Energy ratio of MGO (Marine Gas Oil) versus each fuel in terms of volume. The data in the table do not take into account the container/storage of each alternative.

In this comparative table it can be observed that, among the **sustainable alternatives** (methanol, ammonia and hydrogen), **methanol** is the option with the **highest energy density (GJ/m3) compared to the others**, followed by ammonia, which exceeds the different hydrogen derivative options in both gaseous and liquid states.

The MGO (Marine Gas Oil) volumetric comparison also compares the MGO energy with each alternative fuel in terms of volume. In this regard, hydrogen displays the highest value, given that it's the molecule with the highest energy in terms of mass.

As for the other properties, **gaseous hydrogen** requires compression at high pressures (350/700 bar) or liquefaction at very low temperatures (-253°C) for its transport and storage, due to its low volumetric energy density [11].

Unlike hydrogen, **ammonia** is transported and stored under less demanding conditions (-33°C and a lower atmospheric pressure), resulting in a lower cost as a maritime fuel.

2.2. Safety and environment

The Öko Institute [12] compared ammonia, hydrogen and methanol as alternative fuels with a typical fossil fuel (HFO or Heavy Fuel Oil) to determine the most suitable sustainable alternative fuel for maritime transport.

Table 2 compares ammonia with the three other fuels used in an **ICE (internal combustion engine)**, taking into account environmental criteria. Each criterion is graded, with 1 representing a high risk or low performance and 5 representing a low risk or high performance.

Table 2. Comparison of alternative fuels with fossil HFOs based on key environmental criteria **[12]**

Criterium	Ammonia	Hydrogen	Methanol	HFO
GHG reduction potential	4*	5	5**	1
Air pollutants	3	5	4	1
Aquatic ecotoxicity	2	5	5	1
Human toxicity	2	5	3	3
Flammability	2	1	2	5
Explosion risks	4	2	5	5

Note: *uncertainty regarding the N_2O emissions. **well-to-wake (WtW): a term used to assess the environmental impact of a fuel throughout its life cycle in the maritime sector, meaning Well-to-tank (WtT) + Tank-to-wake (TtW).

With respect to **GHG emissions**, **ammonia** is a molecule that doesn't emit CO_2, but it produces nitrogen oxides (NOx) upon combustion when it is used in ICEs (internal combustion engines). Selective catalytic reduction (SCR[2]) systems can reduce these emissions, in a similar way to the new fossil-fuelled vessels that meet the Tier III requirements in the ECAs (Emission Control Areas) [12]. In fact, SCR systems require ammonia or urea on board to operate, as a result of which the new vessels operating in these areas would require systems and regulations for the handling and storing of ammonia or urea [13]. **Methanol** also emits small amounts of NOx, and **green hydrogen** is expected to record near-zero emissions. **HFO** is the worst rated fuel in this parameter, since, in addition to NOx, it emits other pollutants such as SOx and carbon particles [12].

It can be concluded that hydrogen and methanol are the most suitable fuels in environmental terms, based on their overall score across the different criteria.

[2] SCR is based on a catalytic chemical reaction in which NOx is converted into nitrogen and water. For this reaction to occur, a reducing agent (such as ammonia or urea) is injected into the exhaust stream. This agent reacts with the NOx in the presence of the catalyst, transforming it into less harmful products.

2.2.1. Safety considerations related to ammonia

Ammonia is a gas under ambient conditions and it gives off a strong odour that can be detected at concentrations as low as 2-5 ppm. In the event of a leak from a refrigerated storage tank, liquid ammonia evaporates and quickly disperses into the gaseous phase, as it is lighter than air. However, if the leak comes from a pressurised tank, an aerosol is formed, generating a dense cloud that is heavier than air and larger than in the above case [14].

The industry has developed standards and codes for the safe handling of ammonia for over a century, with very few incidents reported when it is handled by trained personnel. Most of the serious accidents reported in the media have involved ammonia derivatives such as ammonium nitrate [14].

The occupational exposure limits for ammonia in Spain are [15]:

- TLV - TWA: 20 ppm (14 mg/m^3) for 8 hours
- TLV - STEL: 50 ppm (36 mg/m^3) for 15 minutes

Ammonia displays low reactivity compared to other fuels and a narrow flammability range (15%-28% by volume), which reduces the risk of fires or explosions. However, in the event of any aquatic spills, it can cause pH alterations, affecting the aquatic ecosystems [14].

Ammonia is compatible with many common materials, including carbon and stainless steels (in liquid and anhydrous states). This means that most standard pipes, fittings, and valves can be used with ammonia.

However, ammonia corrodes copper, brass and alloys containing zinc, as well as natural rubber and certain plastics [14].

The risks posed by ammonia can be managed thanks to the high maturity of storage, transportation and distribution technologies, as well as the existence of training and industrial codes, standards and regulations to ensure safety.

The development of robust regulations is a priority for shipowners, operators, technology developers, ports and classification societies, which are deeply involved in hazard identification analyses, mitigation strategies and clean energy technologies to ensure that the use of ammonia as a fuel complies with the existing safety standards [14].

2.2.2. Safety considerations related to methanol

The specific risks associated with methanol that most affect facilities largely depend on how it is stored and handled. Key considerations when handling methanol:

- Methanol is a flammable and easily ignited liquid. It burns with a non-luminous flame, which may become invisible in strong sunlight. Response teams should be equipped with infra-red devices that can remotely detect heat and relative temperature.
- The molar mass of methanol vapour is slightly greater (denser) than that of air (32 kg/kmol versus 29 kg/kmol). As a result, depending on the circumstances of the leak or spill, liquid methanol may accumulate and the vapour may migrate to ground level and concentrate in confined spaces or low-lying areas. In any event, methanol vapour, as it has almost neutral buoyancy, should easily dissipate in ventilated areas.
- Due to its toxicity, precautions should be taken when it is handled and dispensed.
- Methanol is completely miscible in water and it remains flammable, even with very high water concentrations. A solution containing 75% water and 25% methanol is regarded as a flammable liquid. This has significant implications when it comes to fire prevention. Methanol is a chemical solvent, which also affects the selection of materials and extinction strategies. It may be corrosive for some metals such as aluminium, copper, zinc, titanium and some of their alloys. It may also attack certain plastics, resins and rubbers. Compatible metallic, plastic and elastomeric materials should be chosen.
- Methanol is readily biodegradable, as a result of which it is unlikely to build up in soil or groundwater.
- Finally, methanol is stored in aboveground tanks with floating roofs and smaller tanks with internal baffles. The tanks must be grounded to prevent electrostatic discharge hazards. Ignition control can be achieved by means of inertisation with nitrogen or natural gas or by designating a controlled ignition risk area. [11]

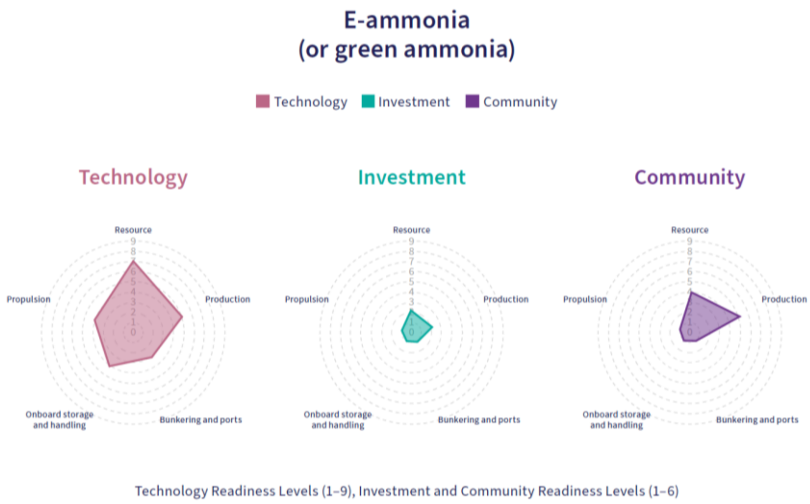
2.3. Technology readiness of the alternatives

2.3.1. Technology readiness of ammonia as a fuel

Lloyd's Register [10] analysed (**Figure 3**) the technology readiness level (TRL) of both green and blue ammonia, together with the investment readiness level (IRL[3]), indicating whether the business case is hypothetical or feasible, and the community readiness level (CRL[4]), which determines whether the necessary frameworks exist for the safe and publicly acceptable use of a technology and fuel.

With regard to technology readiness, green ammonia technology (TRL 7) is much more developed in terms of resources (validation of prototypes in a use environment) than blue ammonia technology (TRL 5), which is obtained from methane reforming with CO_2 capture systems. They have the same level of readiness in all other respects.

The IRL (investment readiness level) is the same in the two cases, while the CRL (community readiness level) is higher for green ammonia. The industry's experience of handling ammonia is expected to facilitate its regulation [10].



[3] The IRL (investment readiness level) indicates the commercial maturity of a maritime solution, from the initial business idea to the reliable financial investment. It addresses all the parameters required for commercial success, based on the work of the ARENA (Australian Renewable Energy Agency).

[4] The CRL (community readiness level) indicates the social maturity of a maritime solution in terms of its acceptability and implementation by both individuals and organisations. It is measured on the spectrum ranging from societal challenge to widespread adoption. The CRL is based on the work of the ARENA and Innovation Fund Denmark, adapted to a six-tier scale.

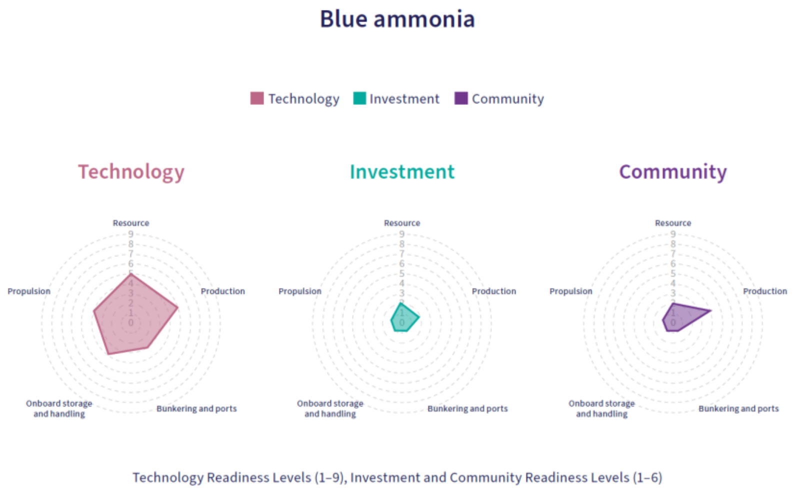


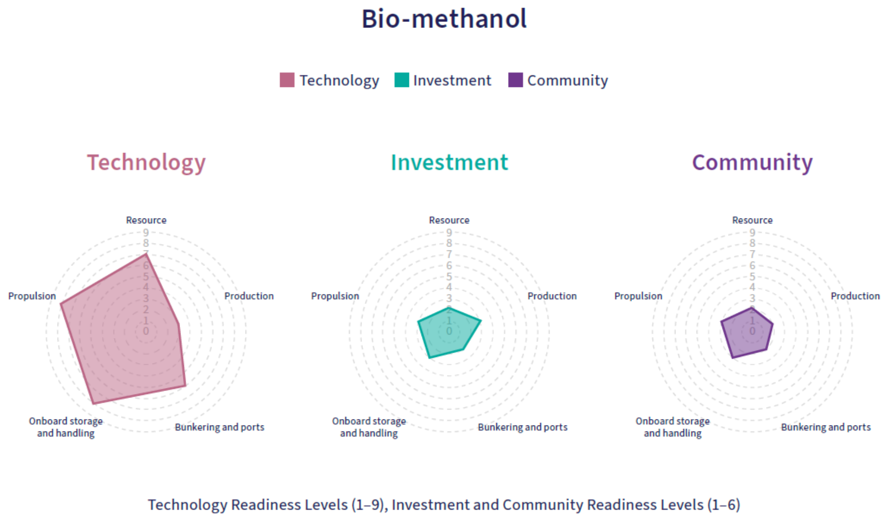
Figure 3. Level of readiness of the different areas of green and blue ammonia [10]

Note: (i) Green ammonia/e-ammonia: obtained from green hydrogen and nitrogen in the air. (ii) Blue ammonia: produced by means of steam methane reforming (SMR) with carbon capture and storage (CCS).

2.3.2. Technology readiness of methanol as a fuel

Lloyd's Register [16] conducted the same analysis with biomethanol and e-methanol (**Figure 4**), highlighting that the readiness of the two technologies is much more advanced in areas such as onboard storage and handling (TRL 8) and propulsion systems (TRL 8) than in emerging production areas such as biomethanol (TRL 3) and e-methanol (TRL 4).

The IRL (investment readiness level) is the same for both, while the CRL (community readiness level) in terms of resources is higher for e-methanol (TRL level 4) than biomethanol (TRL level 2) [16].



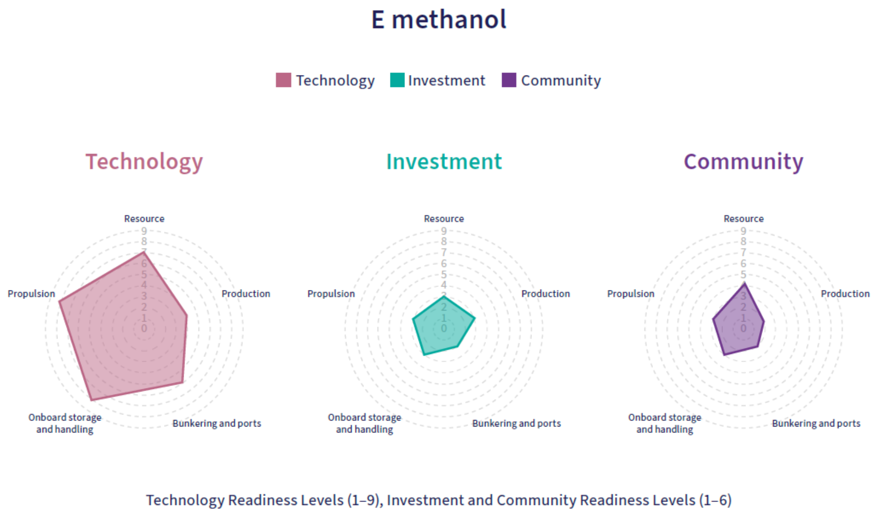


Figure 4. Level of readiness of the different areas of green biomethanol and e-methanol [16]

Note: (i) Bio-methanol: obtained from the gasification of lignocellulosic raw materials (biomass). (ii) E-methanol: produced by means of water electrolysis using renewable electricity and captured carbon dioxide.

In short, the analyses of Lloyd's Register show that, while green and blue ammonia share similar levels of investment readiness, green ammonia is more technologically advanced and more accepted in community terms. As for methanol, e-methanol is the option that is most widely accepted in community terms, and the two alternatives (biomethanol and e-methanol) are served by mature technologies for storage and onboard use, although their production processes have only reached the early stages of their development.

2.4. Existing regulations

At the Marine Environment Protection Committee (MEPC) meeting held in April 2025, the **IMO (International Maritime Organisation) established a net-zero emissions framework**, the first global legally binding framework focused on reducing emissions from vessels. This framework integrates a new standard on maritime fuels, establishing mandatory emission thresholds and a global carbon pricing mechanism for the sector [17].

The standards are expected to obtain **formal approval in October 2025 and enter into force in 2027**. The standards will be mandatory for large seagoing vessels exceeding 5,000 gross tonnes, which account for **85% of the total CO_2 emissions from international maritime transport** [17].

In order to contribute to the development of the zero-emissions framework established by the IMO, it is crucial to bear several key elements in mind. Firstly, the framework will be included in the new Chapter 5 of Annex VI (Prevention of air pollution from ships).

Furthermore, it is important to point out that Annex VI of the MARPOL Convention, which currently has 106 parties, covers 97% of the world's merchant fleet in terms of tonnage and includes mandatory energy efficiency requirements for vessels.

Moreover, **the 2023 strategy on reducing GHG emissions from ships** aims to **accelerate the introduction of zero** or near-zero **GHG-emission fuels, technologies and energy sources** [18].

The draft rules determine that ships must comply with:

- **The Global Fuel Standard.** Ships must reduce the intensity of their greenhouse gas fuels over time. Calculated using well-to-wake.
- **Global economic measures.** Ships that exceed the permitted emission threshold must acquire "remedial units" (RUs) to offset them. In addition, if ships use zero or near-zero emission technologies, they will be eligible for financial rewards.

Two levels of compliance with the targets will be established, a baseline and one requiring direct compliance. In the latter case, ships will be able to choose to earn "surplus units" (SUs). Any ship with emissions above the established thresholds must offset them by transferring surplus units between ships, using previously accumulated surplus units or remedial units acquired by means of contributions to the IMO's Net-Zero Fund.

The **IMO's Net-Zero Fund** will be established to collect the contributions to pay for emissions. The funds raised will be used for the following purposes: to reward low-emission ships, to support innovation, research, infrastructures and just transition initiatives in developing countries, to fund training, technology transfer and the development of capabilities to promote the IMO's 2023 strategy on GHG and, finally, to mitigate the negative impacts on the most vulnerable States [18]

2.4.1. Regulations related to the use of ammonia as a fuel

Ammonia is not currently approved as a fuel by the regulatory bodies and authorities in the energy sector. Although no major technological hurdles are anticipated, operational experience of the use of ammonia as a fuel is required before its widespread implementation, particularly for the development of new codes and standards.

Operational experience is essential to establish safe handling protocols, while product standards are necessary to define safe purity levels in multiple applications.

In addition, emissions tests and verifications must be performed to ensure that the ammonia's combustion does not exceed the acceptable pollutant levels. These actions must be completed before any broad regulatory approval of ammonia as a fuel can be achieved. In the meantime, its use will probably be limited to pilot and demonstration projects [19].

There are numerous standards and regulations regarding the handling and storage of ammonia, but most relate to fixed installations, process plants and non-mobile applications.

The current IGC Code of the IMO forms the basis for all the classification societies' standards related to ships carrying liquefied gas. This code pertains to LNG carriers, while the IMO's IGF Code on low-flashpoint fuels, applicable to ships such as ones capable of using ammonia as fuel, provides a regulatory framework to guarantee the safe use of these alternative fuels on board with regard to storage and supply systems and design and operational requirements.

These codes are yet to include the use of ammonia as a fuel, due to it being considered for this purpose only recently. More specifically, section 16.1 of the IGF Code establishes that methane (LNG) is the only cargo whose boil-off may be used in Category-A machinery spaces [19].

The MSC (Maritime Safety Committee) approved the interim guidelines on the safety of ships using ammonia as a fuel in December 2024, following their development and finalisation by the CCC (Load and Container Transport Committee) [20] in September 2024. The new IGC and IGF codes are expected to enter into force in January 2027 [21].

The following classification societies have drawn up tentative standards and recommendations regarding the use of ammonia as a fuel on board ships:

- ClassNK - Guidelines for ships using alternative fuels (2021)
- Bureau Veritas - Ammonia Fuelled Ships Tentative Rules NR671 (2022)
- American Bureau of Shipping (ABS) - Guide for Ammonia Fuelled Vessels (2021)
- Det Norske Veritas (DNV) - Rules for Ammonia, Part 6, Chapter 2, Section 14 (2014)
- Korean Register (KR) - Guidelines for Ships Using Ammonia as Fuel (2021)

The **main design changes with respect to ships using conventional gaseous fuels** are identified and summarised in the above-mentioned guidelines. The most important aspects include the **ventilation requirements and the layout of the living spaces**, given that the intended use of ammonia is onboard a manned platform. All the classification societies base their recommendations on the existing IGC and IGF Codes, with exceptions tailored to the properties of ammonia [19].

A study conducted by the **EMSA (European Maritime Safety Agency)** [22] concluded that **there exist several relevant standards established by the ISO (International Organisation for Standardisation) related to the handling of ammonia.** However, most are geared towards general use on land, and there is currently no specific ISO regulation on the use of ammonia as a fuel in maritime applications.

The EMSA's report indicates that the ISO 8217:2017 standard on maritime fuels is widely used for the handling of petroleum derivative products on ships, and parts of it may be applicable to ammonia.

ISO 23306:2020, which specifies LNG as a fuel for maritime applications, and the draft ISO/AWI 6583 standard on the specification of methanol as a maritime fuel, relate to examples of low-flashpoint fuels that have recently received specific standards, as a result of which ammonia is expected to follow suit.

Future versions of the IGF and IGC codes are expected to incorporate these standards and take into account the considerations of the classification societies, which maintain direct ties with the shipyards and document the design processes for the integration of ammonia on board ships [19].

2.4.2. Regulations related to the use of methanol as a fuel

The IMO developed MSC.1/Circ.1621, a guide on the safety of ships that use methanol/ethanol as a fuel [23].

As for the tank locations, methanol can be stored in structural tanks, although there are limitations on the vessel's layout and there are more safety barriers than those for conventional fuel tanks.

The regulations governing the **location of methanol tanks** can be summarised as follows [19]:

- They cannot be located adjacent to Category A machinery spaces.
- They cannot be located adjacent to accommodation spaces.
- They may not be located forward of the collision bulkhead or aft of the stern bulkhead.

- The tanks must be surrounded by 600 mm cofferdams[5] that may be inspected. These cofferdams may be removed if the methanol tank is adjacent to a tank for another fuel, an empty double hull or bottom below the vessel's minimum draft or combustion spaces for this fuel, which, in turn, will have additional protection.

As for the pipe, valve and tank **materials**, the regulation focuses on corrosion and fire prevention and establishes that:

- Stainless steel is recommended for the pipes and valves (preferably 304L or 316L stainless steel).
- The pipes must be pickled and cleaned with potable water.
- Carbon steel is compatible with methanol, but a zinc coating is recommended to prevent any corrosion caused by the presence of water.

With regard to **ventilation**, the tanks require redundant vacuum valves open to the exterior and a safety clearance of 15 m, separated from the rest of the machinery on the deck. An inert nitrogen gas system must also be available to purge the tanks. This is intended to minimise the accumulation of flammable gases and mixtures in the fuel tanks [19].

The pipes and valves outside spaces specially designed for methanol combustion and processing must have dual piping ventilated or inertised with nitrogen in the intermediate section. The inertisation spaces must be independent and ventilated.

The **refuelling spaces** must also have this inertisation system. The fire protection requires A-60 protection in the methanol tanks, bunkering spaces and fuel preparation spaces. These spaces will also require fire detection and extinction systems [19].

[5] Empty spaces between two bulkheads or watertight decks inside a ship to ensure that the contents of adjacent tanks do not leak from one to the other, thus preventing cross-contamination.

2.5. Future trends in maritime fuel use

Consumption by ships in 2022 totalled **300-320 million tonnes of conventional fuel per year, equivalent to 3,300-3,600 TWh/year.** Under the IMO's scenario, 50% of the fuel currently consumed by ships in the equivalent calorific value would need to be replaced by 2050. Under the net-zero emissions scenario in 2050, all the fuel would need to be replaced with decarbonised alternatives [24].

DNV's forecasts for the evolution of maritime fuel consumption until 2050 indicate that, under the IMO's scenario, total maritime fuel consumption would stand at around **3,300 TWh**, a similar amount to that consumed in 2022.

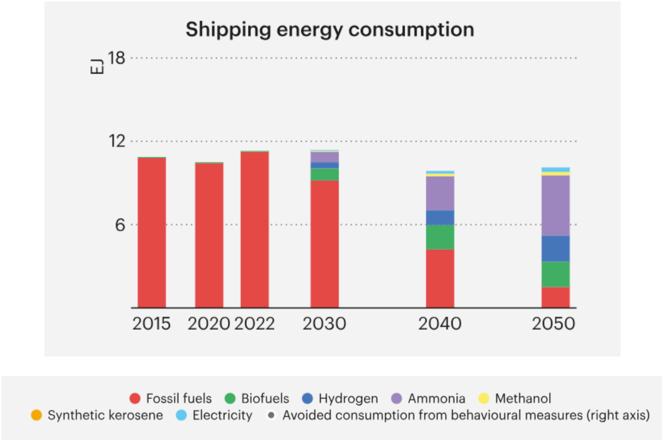
Approximately 50% of this figure would comprise **fossil fuels**, most of it (5/6) liquefied natural gas (LNG) and the remainder (1/6) fuel oil. The other **50%** would be based on **alternative propulsion sources**; **the majority (5/6) would be renewable fuels** (without any net CO_2 emissions), while the rest would be electricity (batteries or on-site production with fuel cells) and biofuels [24].

Green ammonia, as a renewable fuel, is emerging as a promising option for the maritime sector, due to the existence of a global logistics infrastructure, the lack of cryogenic storage and its flexibility, as it doesn't require any complex onboard processing. However, green ammonia production still needs to be scaled up to meet the sector's demands [13] [14].

In addition, **green methanol** is also regarded as an attractive option as a low-carbon maritime fuel, given that it can be stored in a liquid state at ambient temperature and pressure. However, this fuel is only regarded as a low-carbon fuel when it is produced from waste biomass (biomethanol) or hydrogen generated with renewable energy (e-methanol) [9]. In the short term, the greatest potential for the use of **green hydrogen** as a maritime fuel is on small vessels, which can make use of onshore hydrogen refuelling stations (HRS) [25].

Finally, it may be not be possible to scale up biofuels sufficiently to meet the maritime demand, as only a small portion of the available biomass can be affordably processed for fuel applications, and additional capacity would substantially increase costs [14].

The IEA, in its 2023 *Aviation and Shipping* report [26], estimates that methanol consumption as a maritime fuel in 2050 will only amount to 3%, compared to 44% for ammonia, as indicated in **Figure 5**.



Milestones	2022	2030	2035	2050
Shipping				
International shipping activity (trillion tonne-kilometres)	125	145	165	265
Share in final energy consumption				
Biofuels	0%	8%	13%	19%
Hydrogen	0%	4%	7%	19%
Ammonia	0%	6%	15%	44%
Methanol	0%	1%	1%	3%

Figure 5. Energy consumption in maritime transport **[26]**

Furthermore, a study by leading engine manufacturer Everllence [27] analysed the demand for alternative maritime fuels (**Figure 6**), observing that **35%** of maritime fuel is expected to be ammonia and **26%** methanol in 2050.

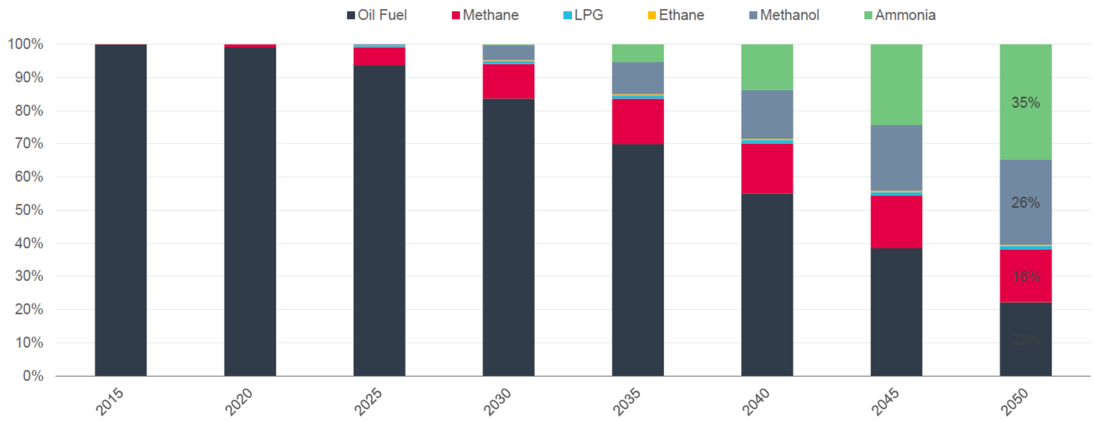


Figure 6. Demand for alternative fuels in the maritime sector **[27]**

It is concluded that the IEA and Everllence agree that **ammonia** will play a crucial role as a maritime fuel, with respective 44% and 35% market shares by 2050. In the case of **methanol**, the sources' opinions differ, with Everllence (26%) giving it much more importance than the IEA (3%).

3. APPLICATIONS

DNV, in its *Maritime Forecast to 2050* report [28], shows the different applications of alternative fuels in the maritime sector (two and four-stroke dual fuel engines, fuel cells and boilers), as well as its estimates for the year in which the technology will reach commercial status (TRL 9) and the year in which regulatory readiness for use of these fuels on board vessels will be achieved (**Figure 7**).

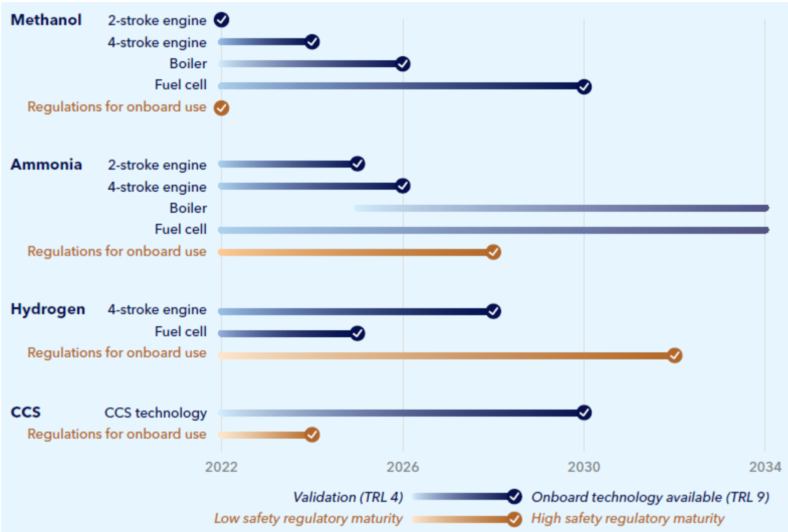


Figure 7. Applications of alternative fuels in the maritime sector **[28]**

3.1. Internal Combustion Engines (ICEs)

Most internal combustion engines are so-called **DF (dual fuel) engines**, which can run on both liquid and gaseous fuels and are available in both two and four-stroke versions. These engines are essentially "hybrids" and they have many characteristics in common with CI (Compression Ignition) and SI (Spark Ignition) engines [12].

- **CI engine or compression ignition engine (CIE):** Combustion occurs due to the compression of the air, which heats the fuel to the ignition point. This type of engine is commonly associated with the **diesel cycle** and uses diesel as its fuel.
- **SI engine or spark ignition engine (SIE):** This uses a spark plug to ignite the mixture of air and fuel. This type of engine is commonly associated with the **Otto cycle**, using petrol as its fuel.

Typically, the functioning of DF engines involves mixing the **main/primary fuel** with air in the cylinder (as in SI engines) with the subsequent compression ignition of a **pilot/secondary fuel**, usually diesel (as in CI engines [12]).

DF engines are designed to run on a conventional fuel such as HFO or MGO (primary fuel) and a complementary fuel such as LNG, methanol or other alternative fuels, and they are applicable to vessels of all sizes [12].

These engines generally operate with one of the two fuels, with the ability to easily switch from one to the other. One fuel usually serves as a pilot for the combustion of the second one [12].

Moreover, ICE engine types are typically characterised by their **combustion cycle** (two or four-stroke) and their **rotational speed** (low, medium or high), in which [29]:

- **Low-speed two-stroke** engines are used by larger cargo ships for direct or geared mechanical propulsion.
- **Medium-speed four-stroke** engines are commonly used for propulsion or auxiliary power generation and they are predominant in the maritime industry in terms of the number of engines that are installed.
- And **high-speed four-stroke** engines are typically used on smaller vessels.

Alternative fuels can be used in internal combustion engines when the engines are designed or retrofitted for them. In **Figure 8**, DNV provides information on the availability of DF engines for alternative fuels [29].

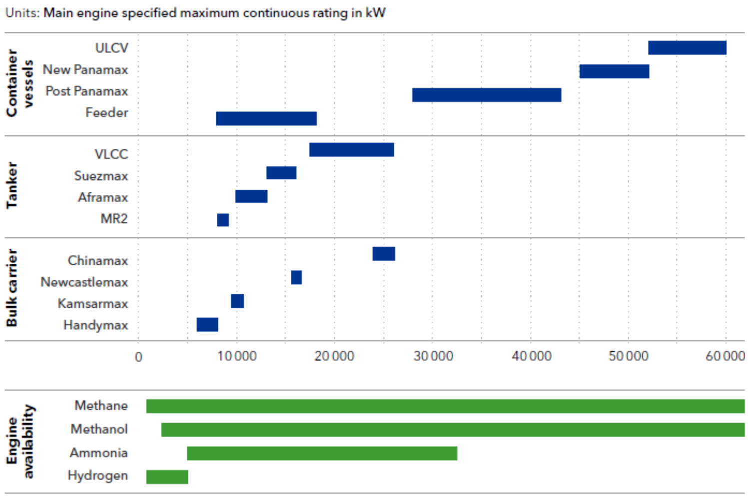


Figure 8. Availability of dual engines for alternative fuels **[29]**

Figure 8 shows (in blue) the specified maximum continuous power of the main engine in kW for commonly installed engines, according to the ship size (bulk carrier, oil tanker and container ship segments), comparing it with the engine power ranges available for use with methanol, methane, ammonia and hydrogen as the main fuel (in green).

It can be concluded that, as of today, methanol and LNG are the most widely available alternatives in any power range, followed by ammonia, which has already exceeded the 30,000 kW maximum continuous powers. Hydrogen is suitable for powers below 5,000 kW.

3.1.1. Engine manufacturers

The largest manufacturers of **two-stroke** maritime engines are **Everllence, WinGD and Japan Engine Corporation (J-Eng)**. In particular, Everllence is the global leader of two-stroke engines, with a fleet of 23,000 of the 33,000 two-stroke engines operating around the world [27].

Meanwhile, the leading manufacturers of **four-stroke** maritime engines are **Wärtsilä, Everllence, Hyundai HiMSEN, and WinGD**.

METHANOL ENGINES

Methanol used as the primary fuel **can reduce CO_2 emissions by approximately 10%**. However, it has the potential to become a carbon-neutral fuel if it is produced renewably, from biomass/biogas and/or renewable electricity [30].

TWO-STROKE

Manufacturer **Everllence**:

- New engines: it has two-stroke methanol engines operating on 20 vessels, including several methanol carriers that can use their cargo as their fuel, and a portfolio of 90 additional orders (starting in May 2023) for container ship operators such as Maersk Line, Hyundai, CMA CGM and Cosco Shipping. The vessels are built under licences from engine manufacturers in South Korea, Japan and China [16].
- Retrofit kits: Everllence is also developing a retrofit programme for its MAN B&W ME-C two-stroke engines. The company is designing its ME-C engines with the option of conversions for methanol and a range of other alternative fuels [16].

Manufacturer **WinGD**:

- New engines: WinGD has announced some of its first orders for dual two-stroke methanol engines in China. The most significant one is an order for a 90-cm bore piston engine for a container ship [16].
- Transformation kits: In parallel, it is designing an engine retrofit process to be placed on the market for vessel operators involving methanol conversions [16].

FOUR-STROKE

Manufacturer **Wärtsilä**:

- New engines: it has a four-stroke DF engine design with a 32-cm piston diameter [16].
- Transformation kits: **Wärtsilä's** first retrofit project was the LR-class Stena Germanica, in which the vessel's four ZS40 engines were converted to become DF methanol engines. The project was funded by the EU and the conversion costs amounted to €13 M, with the project's costs totalling €22 M, including an onshore methanol storage tank, the adaptation of a bunker barge and pioneering work on the project, with safety assessments and an adaptation of the rules and regulations [16]. Wärtsilä estimates that the future conversion costs could be 30%-40% lower, and Stena Line has contracted Wärtsilä to convert an undisclosed number of its other DF-powered ferries to run on methanol (June 2023) [16].

Manufacturer **Hyundai HiMSEN**:

- New engines: Hyundai claims it had orders for 74 sets of its HiMSEN H32DF-LM four-stroke methanol engines (32-cm piston diameter) in late March 2023. Hyundai's first DF HiMSEN engines will be installed on two Maersk vessels [16].

Manufacturer **Everllence**:

- New engines: for the four-stroke market, Everllence is still working on methanol injection technologies for both new builds and vessel retrofits [16].
- Transformation kits: This option will be the first to reach the market. The company believes the four-stroke vessel retrofit will be for the passenger and ROPAX (roll-on roll-off passenger) markets. Its first adaptations will be the engines on two cruise ships under a pilot project in 2025 and a RO-RO (roll-on/roll-off) vessel in 2026 [16].

In addition to Everllence, Hyundai HiMSEN, WinGD and Wärtsilä, there are other engine manufacturers developing solutions capable of running on methanol, such as Anglo Belgium Corporation (ABC), Caterpillar, China State Shipbuilding Corporation (with Hudong Heavy Industries), Rolls-Royce mtu Marine Solutions and ScandiNAOOS/Nordhaven Power Solutions [16].

AMMONIA ENGINES

Given that the shipping industry relies on the use of large diesel engines, the use of green ammonia in engines constitutes the most likely entry point for this fuel, with developments underway for engines running on ammonia. **Operating on 100% ammonia is possible**, although an additional fuel may be required in the short term to support the combustion (hydrogen, diesel, liquefied natural gas or liquefied petroleum gas), or **partial cracking of the ammonia to unlock the hydrogen** may be considered to the improve the combustion, **potentially reducing GHG emissions by 90% compared to conventional fuels** [13] [31].

TWO-STROKE

Manufacturer **Everllence**:

- New engines: Everllence is progressing with the development of ammonia-powered engines, with their completion expected in 2027. For this purpose, it has begun tests at its Copenhagen facilities and it has been working with MITSUI E&S on the construction of a test engine since 2024.
  In December 2024, Everllence announced that the company has successfully operated its ME-LGIA research engine with loads ranging from 25% to 100% at its Copenhagen research centre [32]. On 17 February 2025, MITSUI E&S announced the start of the testing of the world's first commercial MAN B&W 7S60ME-LGIA dual-stroke ammonia engine at its plant in Tamano, Japan [33].
- Transformation kits: Everllence is working on ammonia retrofit solutions for existing dual-stroke engines
  [10].

Manufacturer **WinGD**:

- New engines: In July 2023, WinGD announced that its two-stroke ammonia engines (X-DF-A model) would become available in 2025. To date, it has received orders for its use on Exmar LPG and Bocimar vessels in 2025-2027 [10].

Manufacturer **Japan Engine Corporation** (J-Eng):

- New engines: It plans to complete its first 50-cm diameter piston ammonia engine in 2025 and follow it up with a 60-cm diameter engine starting in 2026. One NYK vessel with a 2026 delivery date will use an ammonia engine from this manufacturer [29].

FOUR-STROKE

Manufacturer **Wärtsilä**:

- New engines: Wärtsilä is one of the leading manufacturers developing four-stroke engines that use ammonia as their fuel. The manufacturer launched an ammonia-fuelled engine onto the market as part of its Wärtsilä 25 platform, unveiled in September 2022. In addition, Viridis Bulk Carriers signed a letter of intent to use this engine [10].

  The company also forms part of a consortium that has received $10 M in EU funding to develop ammonia-fuelled four-stroke engines, and it has already demonstrated an engine concept running on a mixture containing 70% ammonia. In 2020, the company announced the start of its large-scale testing of ammonia engines in Norway, thanks to $2 M in funding from the Norwegian government [10], with a commercial model for ammonia engines in its portfolio.

Manufacturer **Everllence**:

- New engines: Everllence is also working on applications for four-stroke ammonia engines. In October 2024, the company announced the launch of the AmmoniaMot 2 research project, which aims to develop a medium-speed, dual-fuel and four-stroke test engine running on ammonia [34].

3.2. Hydrogen and derivative fuel cells

Fuel cells (FCs) are devices that continuously and directly transform the energy contained in a fuel into electrical energy by means of electrochemical oxidation-reduction reactions. No combustion reactions occur, so the fuel is not burnt. If the fuel is pure hydrogen, apart from the electricity and thermal energy, the only by-product is water [35].

The basic unit of a fuel cell is the single cell, which produces approximately 1 volt. Industrial applications require the accumulation of several single cells, resulting in what are known as stacks. In other words, it is necessary to combine single cells to obtain sufficient performances in industrial applications in which stacks are used [35].

The benefits of fuel cells include their zero or low emissions; since there is no combustion, no nitrogen oxides are produced, as the reactions occurring within them are of the redox kind, and the oxygen and nitrogen don't react with each other [35].

Furthermore, fuel cells have no moving parts, so they give off a low level of noise due to the ancillary equipment. As for efficiency, since they are not limited by the Carnot efficiency, higher values can be achieved than in the case of thermal engines [35].

Depending on the type of electrolyte used, fuel cells are classified as [35]:

- AFC - Alkaline Fuel Cell
- PEMFC - Proton Exchange Membrane Fuel Cell
- DMFC - Direct Methanol Fuel Cell
- PAFC - Phosphoric Acid Fuel Cell
- MCFC - Molten Carbonate Fuel Cell
- SOFC - Solid Oxide Fuel Cell

Table 3 summarises the **technical characteristics of each type of fuel cell.** One important factor is the operating temperature of the different types of fuel cells, which ranges from 65°-80°C (PEMFC, DMFC, AFC) to 1,000°C (SOFC). The most widely used types of fuel cells in the maritime industry are PEMFC (low-temperature) and SOFC (high-temperature).

Table 3. Technical characteristics of the main types of fuel cells **[36] [37, 38]**

Characteristics	AFC	PEMFC	DMFC	PAFC	MCFC	SOFC
Fuel	Hydrogen	Hydrogen	Methanol	Hydrogen	Hydrogen or methane	Hydrogen or methane
Electrolyte	KOH	Proton-exchange membrane	Proton-exchange membrane	H_3PO_4	$LiCO_3/K_2CO_3$	ZrO_2/Y_2O_3
Temperature (°C)	<100	80	80	150-200	650	500-1000
Ionic conductor	OH-	H^+	H^+	H^+	CO_3^{-2}	O^{-2}
Anode	Ni Raney	Pt/C	Pt-Ru/C	Pt/C	NiO	$Ni\text{-}ZrO_2$
Cathode	Ag	Pt/C	$Pt/Mo_2Ru_5S_5$	Pt/C	NiO	$LaMnO_3/Sr$
Matrix	Asbestos	-	-	SiC	$LiAlO_2$	-
Ignition time (h)	<0.1	<0.1	<0.1	1-4	5-10	-
Electric power density (mW/cm²)	620	420	-	250 (8 atm)	>150	120
Efficiency (%PCS)	>50	48-50 (55% peak)	30-40	36-45	43-55	43-55
Power range	5-150 kW	5-250 kW	5 kW	50 kW-11 MW	100 kW-2 MW	100-1.250 kW
TRL	8-9 TRL	TRL 9	TRL 6	TRL9	TRL 9	TRL 9
Applications	Transport, special vehicles, military applications, energy storage systems			Stationary distributed electrical power and heat generation systems		

The **PEMFC fuel cell** is one of those used most widely (**TRL 9**). This fuel cell requires high-purity hydrogen due to the use of noble metal catalysts, so it is necessary to carry out prior purification of the hydrogen (it may be affected by levels of parts per million of CO or ammonia) from the reforming of energy vectors that contain it, including methane, ammonia and methanol [39].

These fuel cells are more resistant to impurities at higher temperatures, because they don't use noble metal catalysts. In this regard, high-temperature PEMFC fuel cells have been developed, with more durable membranes capable of operating at up to 140°C [39].

Molten carbonate fuel cells (MCFCs) and **solid oxide fuel cells (SOFCs)** (both **TRL 9**) operate at such high temperatures that hydrocarbons and ammonia decompose within the fuel cell. In other words, the reforming of the fuels (ammonia, methanol, etc.) occurs within the cell itself, allowing the direct use of these compounds in these systems.

There also exists the option of using **direct methanol fuel cells (DMFCs), which directly oxidise the methanol in the anode (TRL 6).** The main benefit of this technology is its adaptability to a wide range of portable and stationary applications from mW to kW, for which the operating temperature will never be an impediment [40].

Apart from their use in short and medium-haul vessels, fuel cells can play a **key role in the hybridisation of propulsion systems in maritime transport**, integrating them into internal combustion engines and electrical storage systems to improve energy efficiency and reduce pollutant emissions.

This integration can **harness the benefits of each technology; fuel cells operate optimally with partial and base loads, while internal combustion engines can cover power peaks and offer operational flexibility.** Thanks to this hybridisation, fossil fuel consumption is reduced, CO_2 and air pollutant emissions are minimised and the overall efficiency of the propulsion system is improved, thus contributing to the sector's decarbonisation goals and helping vessels to adapt to future environmental regulations. In the field of onboard co-generation, fuel cells can simultaneously generate electricity and usable heat, improving energy efficiency during maritime operations. The waste heat produced by the cells can be used for heating spaces, sanitary water and the ship's ancillary processes, increasing the overall efficiency of the onboard energy system. This co-generation capacity is particularly significant in applications such as ferries and passenger ships, on which the thermal demands are constant and high.

The primary use of energy on board a ship is for propulsion. This is typically provided by a compression-based internal combustion system with direct transmission, on a scale sufficient to guarantee a power margin greater than that required for sailing in calm waters. Selecting the appropriate installed power for the main engine is a key component of the ship's design process. **Installing an engine that is too large increases the ship's energy efficiency design index (EEDI)**, which reduces its overall economic effectiveness (the higher the EEDI, the poorer its performance). Moreover, an engine that is too small poses a risk to the ship's manoeuvrability in extreme sea conditions [41]. **Another energy requirement, known as the auxiliary load, can reach levels similar to those of the main propulsion** in certain vessel classes such as cruise ships.

Figure 9 shows the different **alternative routes for the energy flow from the fuel to the vessel's propulsion**. A similar scheme can be developed for the auxiliary power generation by means of generator sets, although the use of fuel cells allows for a common energy system comparable to that already used by diesel-electric vessels. Although the battery storage is presented as an independent route, in practice most current systems employ hybrid solutions to stabilise the load and reduce the installed capacity of the internal combustion engine (ICE) [41].

Alternative short-term energy stores such as super-condensers can perform a similar function. A suitable energy storage system, such as a battery, will similarly complement the peak power variation limitations of the fuel cells. This will further improve the energy efficiency of the overall system. In fact, a perceived benefit of several fuel cell systems is their ability to improve onboard energy conversion efficiency [41].

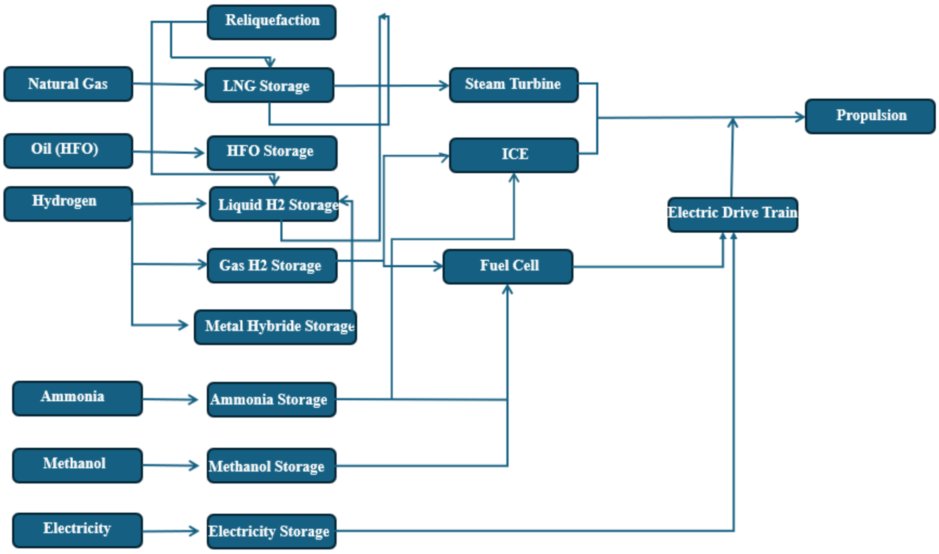


Figure 9. Energy flow paths for alternative fuels and primary engines **[41]**

The **biggest future change, if modular fuel cell systems continue to reduce their costs**, will probably occur in **electric propulsion**. Various emerging technologies in onboard electrical systems and others under development will further improve their performance [41].

One benefit of these systems will be the significant reduction in onboard maintenance infrastructure, as well as the simplification of the power distribution schemes. The ability to harness the heat generated by the fuel cells (co-generation) for other onboard functions will require careful design, but it will help to ensure the high degree of efficiency of the overall system [41].

3.3. Future forecasts for the future of the fleet of new ships

DNV, in its *Maritime Forecast to 2050* publication [29], presents the use of alternative fuels in the current and future global fleets as of June 2024, analysing the number of vessels and gross tonnage (GT).

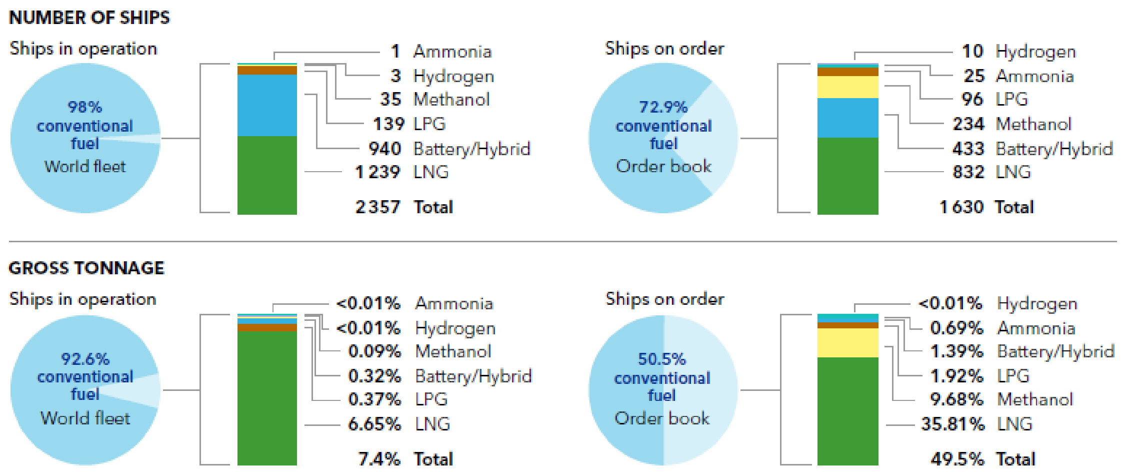


Figure 10. Current use of alternative fuels in the global fleet in terms of number of vessels (above) and gross tonnage (GT) (below). **[29]**

The main findings of the publication are as follows:

- **7.4%** of the vessels in operation, measured in **gross tonnage** (GT), use **alternative fuels**, and **49.5%**, including new orders, are expected to do so in the future. Measured in terms of **number of vessels**, the percentages are lower (**2% and 27.1%**, respectively), leading to the conclusion that larger vessels are opting for alternative fuel solutions.
- **LNG**-fuelled ships account for **6.7% of the GT** in operation, and they are expected to rise to **36% by 2050**. The orders as of June 2024 were for 171 container ships, 157 car carriers, 93 oil tankers, 16 bulk carriers and 22 cruise ships. LNG carriers that use their load of natural gas as their fuel account for 687 of the ships in service, while 339 are on order. A total of **1,239** ships capable of using LNG vessels are currently **sailing**, while **832** are **on order**.
- **Methanol**-fuelled ships account for **0.09%** of the global fleet's **GT** in operation, and this figure will increase to **9.68%** by **2050**. There are 173 container ships, 24 bulk carriers and 20 car carriers on order.
- As for **ammonia**, there is one vessel in operation and 25 on order (**0.69% of the GT**). Among them, CMB has ordered a series of eight bulk carriers with primary engines capable of using ammonia as fuel, while Exmar LPG BV has ordered two medium-sized gas carriers capable of using ammonia as a fuel and NYK has requested another.
- There are currently **940 vessels in operation** using **battery** or hybrid systems for propulsion, and **433 on order**. All-electric propulsion systems are only used on small vessels with a limited range.

Furthermore, according to DNV's Green Transport Corridors database (as of June 2024), **60 green transport corridors** with varying degrees of readiness **have been announced**. In the Baltic countries, trials for one-day-a-week operations have already been conducted [29].

Finally, regarding conversions of existing ships for them to operate with new fuels (retrofits), the number of candidates for conversion will be limited by factors such as the asset's value, the remaining service life, the design implications and the availability of fuel conversion kits for the primary engine [29].

The techno-economic analysis of a retrofit should bear in mind factors such as the length of the conversion, the downtime cost, the remaining service life, fuel prices and emissions costs, as well as the actual cost of converting the engine and ship [29].

4. STORAGE ON SHIPS AND BUNKERING

The general safety principles of the **IGC[6] and IGF[7] Codes provide the framework for the use of low-flashpoint maritime fuels** [30].

The common safety principles, such as the protected location of the fuel tanks, double barriers on the fuel supply lines, ventilation and gas detection, the classification of hazardous areas, explosion mitigation and so on are applicable to all low-flashpoint fuels. However, the specific characteristics of each of them may require particular safety measures [30].

4.1. Methanol as a hydrogen derivative

The IMO's interim guidelines on the safety of ships using methyl/ethyl alcohol as a fuel address aspects related to the ship's design and layout, the fuel containment system, the materials, the piping design, the bunkering, the power generation, fire and explosion prevention, the classification of hazardous areas, the ventilation, the electrical installations, the control systems, the crew's training and the operations [30].

Liquid fuels such as methanol are easier to handle and they more closely resemble conventional bunkering **vessels.** In addition to its marketing and transport on chemical vessels for a number of years, there is **experience of handling methanol** on fleets of Offshore Support Vessels (OSVs) and Platform Support Vessels (PSVs) for the offshore industry, which can serve as a **reference for the wider implementation of methanol as a bunkering fuel** [30].

In comparison with other alternative fuels, methanol is relatively **efficient in terms of energy storage per volume considering the physical space of the tank**, although one of its challenges lies in its low energy content and, therefore, the lower amount of energy that can be stored in a vessel's tanks [30].

That said, the **use of methanol on large vessels is more challenging**, as it would require a significant redesign, particularly since the fuel tanks would have to be enlarged to store sufficient energy for long-distance voyages in deep waters. However, the commercial and regulatory environments for short-sea vessels, which require more frequent bunkering, make methanol an ideal candidate for early implementation as a fuel [30].

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[6] IGC: International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

[7] IGF: International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels

4.1.1. Methanol bunkering

The fuel supply, infrastructure and methanol bunkering pose certain challenges for its large-scale implementation. However, **the lessons learnt from the use of LNG as a maritime fuel can be applied to the development of the methanol bunkering infrastructure** [30].

Since methanol is a liquid fuel under ambient conditions, the bunkering equipment and procedures are similar to those used with conventional fuels [30]. Historical experience and the best practices have been developed in the chemical tanker sector and on vessels subject to the IBC Code, as well as in the offshore sector, in which experience of handling methanol for drilling operations has been acquired [30].

For example, the IMO has replaced resolution A.673(16) [8] with A.1122(30)[9], which introduces the Code for the Transport and Handling of Dangerous and Noxious Liquid Substances in Bulk on Offshore Support Vessels (OSV Chemical Code) for these vessels [30].

4.1.2. Methanol storage

Methanol is suitable for storage in conventional fuel tanks, facilitating its integration into the ship's design in comparison with other low-flashpoint fuels. However, according to section 5.2.1 of MSC.1/Circ.1621, it may be limited by the vessel's hull coating when it is located below the waterline [30].

Methanol is often proposed in this location because it allows for the conversion of multiple ballast tanks into potential fuel tanks. In this case, the tanks require special coatings (such as zinc) and, due to their low flashpoint, they may require an inert nitrogen atmosphere in the tank's vapour space [30].

Regardless of the fuel or technology which is selected, the decision-making process is highly specific to each vessel. Additional safety spaces such as cofferdams and isolation compartments are also required [30].

[8] A.673(16): Guidelines for the transport and handling of limited quantities of potentially hazardous or noxious liquid substances in bulk on offshore support vessels

[9] A.1122(30): Guidelines for the transport and handling of limited quantities of potentially hazardous or noxious liquid substances in bulk on offshore support vessels (OSV chemical code)

Finally, **the methanol distribution infrastructure has been developed over decades for use in the chemical industry**, thus ensuring its availability. However, several additional terminals are expected to be required if methanol is adopted as a maritime fuel [30].

Figure 11 shows the estimated global methanol storage capacity, endorsing its mid-term logistical viability as a maritime fuel [42].

Figure 11. Estimated global methanol storage capacity **[42]**

4.2. Ammonia as a hydrogen derivative

While the **specific requirements for ammonia bunkering are still under discussion** among the players in the maritime industry, the **requirements/conditions for its transport as a cargo, including the loading and unloading operations, have been established within the industry and regulated by the IMO's** IGC Code (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk).

These requirements have also been incorporated into the ABS Rules for the Construction and Classification of Maritime Vessels, Part 5C, Chapter 8: *"Vessels Intended for the Transport of Liquefied Gases in Bulk"* [43].

4.2.1. Ammonia bunkering

It is logical to assume that ports that currently have ammonia terminals and handle its trade could become the basis for a distribution network for ammonia as a fuel for the vessels of the future [44].

In 2020, there were approximately **170 ammonia terminals around the world**, the geographical distribution of which is displayed in **Figure 12**.

Figure 12. Ammonia distribution terminals and main bunkering ports in 2020 **[45]**

The storage of ammonia at the terminals typically consists of special isothermal tanks (with capacities reaching up to 30,000 tonnes) and spherical pressure vessels (with capacities between 1,000 and 2,000 tonnes) [44]. Specific piping and valve systems in transfer booms are used for loading and unloading the liquid ammonia from the vessels [45].

While traditional fuels have a wide and complex range of properties, **ammonia is a clean fuel composed of a single substance**, which eliminates variations between types and qualities, **thus significantly simplifying the fuel sourcing, certification and analysis processes** [45].

There are currently several discussions and projects within the maritime industry seeking to develop procedures and establish guidelines for implementing ammonia bunkering.

4.2.2. Ammonia transport and storage

For ammonia, the **type of fuel tank will be selected upon the basis of which one maximises the potential storage volume** within a restricted space, taking into account the safety regulations and without compromising the vessel's design specifications. Particular attention must also be paid to aspects such as the vessel's stability, seakeeping and safety systems.

For the maritime transport of ammonia, it is common to use gas carriers designed for the transport of LPG. There are four types of independent tanks on these vessels:

- **Type A** tanks with fully refrigerated storage.
- **Type B** tanks with partially refrigerated storage.
- **Type C** tanks with pressurised or semi-pressurised storage.
- **Membrane** tanks with fully refrigerated storage.

The **type of tank chosen will determine the required safety measures**. For example, Type A, Type B and membrane storage tanks require inert gas barrier systems, which take up more space, while Type C tanks do not.

Refrigerated systems also require additional space for two-stage compression, while fully pressurised tanks do not. Refrigerated tanks also require insulation material, unlike Type C tanks, which operate at ambient temperatures.

One advantage of Type A and membrane tanks is that they generally ensure greater volumetric efficiency within a given prismatic space. These variations in the type of fuel tank are highly significant.

Depending on the ammonia's temperature and pressure conditions, several configurations for transfers between the supplying and receiving vessel should be considered [43]:

- **Transfer between similar storage conditions**: Transferring ammonia between similar temperature and pressure conditions is highly feasible. Although the operating principles for fully refrigerated and semi-refrigerated transfers are the same, unrefrigerated (or pressurised) ammonia requires a storage tank and a transfer system designed to withstand higher pressures. Unrefrigerated ammonia is stored at ambient temperature, which eliminates low-temperature operations but increases the risk of leaks due to high pressure.

- **Transfers from cooler to warmer storage:** Transferring ammonia from fully refrigerated to semi-refrigerated storage is economically viable, provided that the pumps in the former system have sufficient discharge pressure to reach the semi-refrigerated storage conditions. Transferring ammonia from fully refrigerated or semi-refrigerated storage systems to unrefrigerated systems will require booster pumps with a much higher discharge pressure to meet the pressure requirements. Although this is technically feasible, transferring ammonia from cooler to warmer conditions may pose technical and operational challenges.

- **Transfers from warmer to cooler storage:** Transferring ammonia from warmer to cooler storage conditions is not commercially viable, due to the requirements for additional cooling mechanisms to meet the conditions of the receiving tank. Therefore, transfers from unrefrigerated to fully refrigerated or semi-refrigerated storage are not considered economically viable.

5. FEATURED PROJECTS AND INITIATIVES

5.1. Renewable ammonia and methanol production

5.1.1. Ammonia production projects

Ammonia is one of the seven basic chemicals, together with ethylene, propylene, methanol and the BTX aromatics, which are used for the production of all other chemicals. It is the one with the second-highest production in terms of mass [14].

Global demand for ammonia stands at approximately 183 million tonnes, while the **global production capacity lies at around 243 million tonnes per year** [14].

Since 2000, over 130 conventional ammonia plants have been built around the world, with production capacities greater than or equal to 1,000 metric tonnes per day, based on the technology of the world's four largest licensors, with an additional daily ammonia production capacity totalling more than 230,000 tonnes.

There are currently no industrial-scale green ammonia plants operating anywhere in the world. Although **most green ammonia projects with capacities exceeding 1,000 metric tonnes per day** are still in the pre-Final Investment Decision (pre-FID) phase, their growing number reflects major interest in the sector and a clear commitment to developing large-scale decarbonisation solutions.

5.1.2. Methanol production projects

Methanol is another of the seven basic chemicals that are used for the production of all other chemicals. Approximately 110 million tonnes (Mt) are produced each year, with the **global production capacity amounting to approximately 170 million tonnes** [46].

Over the past 15 years, over 76 conventional methanol plants have been built around the world, based on the technology of the leading licensors, with the additional daily methanol production capacity totalling nearly 23,000 tonnes.

Taking into account the major licensors of green methanol technologies worldwide, only **three methanol production plants** (two in China and one in Denmark) [47] **can be regarded as industrial-scale plants**. There are also six other plants operating at the demonstrator level and one pilot plant. Two other projects are scheduled to be launched this year (an industrial-scale one and a demonstrator) and a third industrial-scale project has reached the early stages of construction. In addition, there are 16 other industrial-scale projects under development in the pre-FID phase.

5.2. Uses of ammonia and methanol in the maritime sector

5.2.1. Ammonia ship projects

Since 2019, **most ammonia-related projects** in the maritime sector have focused on the **design of ships powered by this fuel**. These projects cover all the major vessel types, including oil tankers, gas carriers, bulk carriers, container ships, RORO cruise ships and tugboats. [45]

Ammonia carriers have been identified **as the first type of vessel to adopt this fuel as a bunkering energy source**. The ammonia and liquefied petroleum gas (LPG) carrier segment of the global fleet accounts for approximately 2% of maritime fuel consumption, and these transformations will be necessary throughout this decade, as the ships typically have a lifespan ranging from 20 to 25 years [14].

As regards the design and construction of these vessels, most of the projects (**Table 4**) are being developed in Asia and Europe, in countries such as China, South Korea, Japan, Norway, Finland and Denmark [48].

Table 4. Ammonia ship and bunkering projects **[48]**

Category	Location	Main Partners	Project Description
Ammonia Bunkering	Singapore	Nanyang Technological University, American Bureau of Shipping, Ammonia Safety and Training Institute, ExxonMobil, EPS, Everllence, Jurong Port, PSA International, Hoegh LNG	Ammonia as the maritime fuel in Singapore - supply chain, bunker safety and potential issues
	Singapore	Itochu group, Itochu Enex, Itochu Corporation, Vopak terminal	Memorandum of Understanding to study the ammonia maritime fuel supply chain in Singapore
	Singapore	A. P. Moller - Maersk A/S, Fleet Management Limited, Keppel Offshore & Maritime, Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, Sumitomo Corporation, Yara	Ammonia as maritime fuel in Singapore
	Singapore	Global Centre for Maritime Decarbonisation	Ammonia bunkering study
Bunker Tanker / Gas Carrier	South Korea	MISC Berhad, Samsung Heavy Industries, Lloyd's Register, Everllence, Yara, Maritime and Port Authority of Singapore	The Castor Initiative: design an ammonia-fuelled tanker, establish the design, concepts and identify the regulatory requirements
	Finland	Wärtsilä, Aker Solutions, DFDS, Equinor, Grieg Star	Zeeds (Zero Emission Energy Distribution at Sea initiative): Onshore and offshore green NH3 production and distribution
	Japan	NYK Line, Japan Marine United Corporation, Nippon Kaiji Kyokai (ClassNK)	Ammonia fuelled ammonia gas carrier and ammonia floating storage and regasification barge
	Norway	Grieg Edge, Wärtsilä	120 m long ammonia fuelled tanker with a cargo capacity of 7,500 m3 of ammonia
	South Korea	Hyundai Mipo Dockyard, Lloyd's Register, Everllence	50,000 DWT MR tanker design
	China/ Greece	Avin International, China's New Times Shipbuilding	Suezmax series tanker
	South Korea	Lloyd's Register, Samsung Heavy Industries, MISC Berhad	Ammonia fuelled very large crude carriers (VLCCs)
Bulk Carrier	China	Shanghai Merchant Ship Design & Research Institute (SDARI), Lloyd's Register	180,000 tons bulk carrier design
	Japan	Japan Shipping Zero Emission Project by industry consortium	80,000 DWT bulk carrier concept design
	China	Shanghai Merchant Ship Design	Ammonia fuelled 7,000-unit capacity

		& Research Institute, China State Shipbuilding Corporation	car carrier
Container Ship	China	Dalian Shipbuilding Industry Co., Lloyd's Register, Everllence	23,000 TEU ultra-large container ship concept design
	China	American Bureau of Shipping, Everllence Shanghai Merchant Ship Design & Research Institute	2,700 TEU container ship design (Chittagongmax Container)
	South Korea	Lloyd's Register, Daewoo Shipbuilding & Marine Engineering, Everllence	23,000 TEU ultra-large container ship design
Other Types of Vessels	Norway	Colour Fantasy	The world's largest RORO cruise liner
	Japan	NYK Line, IHI Power Systems Co., Ltd., Nippon Kaiji Kyokai (ClassNK)	Tugboat design
	Denmark	Global Maritime Forum, Lauritzen-Kosan, Yara, Ørsted, Wärtsilä, Everllence, DNV, Danish Ship Finance, DNB, Fürstenberg Maritime Advisory	The construction of the world's first ammonia-powered deep-sea vessel
	Norway	Ship FC Consortium, Equinor, Eidesvik Offshore, Wärtsilä, Prototech, Yara, FraunhoferIMM, SME Persee, The University of Strathclyde, National Centre for Scientific Research, Demokritis, North Sea Shipping, CapitalExecutive Ship Management, Star Bulk Ship Management, Sustaina	Offshore vessel Viking Energy: 2 MW ammonia fuel cell to be retrofitted

5.2.2. Hydrogen and derivative fuel cell (FC) projects

Hydrogen and fuel cell technology has already been applied to submarines and small inland and coastal vessels and as an auxiliary power source, demonstrating its viability on a small scale. In addition, several demonstration projects are underway on ferries and small transporters. Some projects for larger cargo vessels have recently been funded, but commercial-scale vessels are generally in the design study stage, and a variety of fuels and fuel cell types are currently being tested.

Multi-fuel combustion engines (capable of running on a variety of gaseous and liquid fuels) are already on the market. **The European hydrogen and fuel cell supply chain is becoming increasingly interested in maritime and riverine transport**, with formal partnerships and joint ventures between FC manufacturers and some maritime engine and propulsion system suppliers and system integrators.

According to a study by the University of La Coruña [36], fuel cells have great potential for use on board ships, especially in the generation of auxiliary electrical power in waters and ports with strict environmental regulations. Furthermore, another analysis by the Polytechnic University of Catalonia [49] [49] highlights the increasing implementation of fuel cells in maritime transport as a measure to reduce emissions.

In addition, **the direct methanol fuel cell (DMFC) has been identified as a promising technology due to its efficiency and simplicity**, making it suitable for both stationary and portable applications [40].

These studies endorse the idea that fuel cell technology is under development in Spain, although its current use on ships is mainly limited to auxiliary systems and methanol as a fuel [36] [40].

For certain types of use (inland waters and small vessels sailing and staying close to the coast) and possibly **for cruise ships, hydrogen fuel cells are regarded as a promising zero-emission option.** Several projects have already been launched in Europe, as listed in **Table 5**.

Table 5. Examples of maritime projects that use fuel cells

Project/Company	Type of cell	Fuel	Scale	Description	Source
Hydra/NORLED	PEMFC (Ballard FCwave™)	Hydrogen	RoPax ferry, 82 m, 295 pax, 80 vehicles	It uses liquid hydrogen as a zero-emission fuel for the ferry's propulsion. It is equipped with an 80-cubic-metre hydrogen storage tank. It can reduce annual carbon emissions by up to 95%	[50]
HySeas III (H2020)	PEMFC	Hydrogen	40m ferry, 120 pax + 16 cars (or 2 lorries)	The project successfully demonstrated the integration of fuel cells into a proven maritime hybrid electric propulsion system	[51]
HySHIP (FCH JU)	PEMFC (~3 MW)	Hydrogen	Hydrogen bunkering ship	The vessel runs on liquid green hydrogen and distributes LH2 to the hydrogen hubs along the Norwegian coast	[52]
Flagships (FCH JU)	PEMFC (~1.6 MW)	Hydrogen	NORLED and CFT shipowners	The two vessels run on liquid hydrogen produced on-site with electrolysers powered by renewable electricity	[53]
eSHyIPS (FCH JU)	N/A	Hydrogen	N/A	Define the new guidelines for the effective introduction of hydrogen into the maritime passenger sector and promote its implementation within the global and EU strategy for a clean and sustainable environment, geared towards achieving a zero-emission shipping scenario.	[54]
HIDRAM	PEM/SOFC	Ammonia	Small	Develop a pioneering demonstrator in Europe for hydrogen storage in the form of green ammonia, including the synthesis of ammonia based on green hydrogen and two technologies for its conversion into electricity (PEM fuel cells and SOFC), applying it to the maritime sector as a multi-purpose fuel.	[55]
ShipFC (FCH JU)	SOFC (~2 MW)	Ammonia	Viking Energy" (PSV refitted), ≈95 m	The vessel uses a large ammonia fuel cell, allowing it to operate solely on clean fuel for up to 3,000 hours per year. Its operational efficiency is also being studied on three other types of vessels to illustrate the technology's transferability to other segments of the shipping industry.	[56]
HyMethShip	SOFC	Methanol	Commercial media	It combines a membrane reactor, a CO_2 capture system, a CO_2 and methanol storage system and a hydrogen-powered combustion engine in a single system	[57]
GreenPilot (Sweden)	PEMFC	Methanol	Small	The project included the conversion and testing of three different engines for them to run on methanol, two of which were installed and operated on the refitted pilot boat.	[58]
E1 Marine	PEMFC	Methanol	Tugboats	The system converts methanol into hydrogen onboard the tugboat, and it is then used in a fuel cell to generate power cleanly and efficiently	[59]
Fraunhofer IMM	PEMFC	Methanol	Small/Medium-sized	They have developed a highly compact reformer with several benefits with respect to conventional technology, including the catalyst's robustness,	[60]

				higher activity (reducing the demands on the catalyst) and optimal heat integration	
SerEnergy	PEMFC	Methanol	Auxiliary	These fuel cells can supply power without any energy loss from additional converters, providing a highly efficient energy supply	[61]

To date, the scale of the demonstrations remains significantly lower than what is required for a fuel cell to become the primary power source on an intercontinental vessel or cruise ship. However, several design projects are underway to test the applicability of the integration of FCs into these types of vessels.

To date, no consensus has been reached on the optimal strategy for fuel and propulsion technology, due to the diversity of maritime transport, such as the magnitude of the energy storage and the power required for several cases (taking into account factors such as the vessel type and size, the maximum cargo to be carried, the distances to be covered, the route types, etc.), as well as the implications for the ship's design, integration, fuel storage and regulation.

CONCLUSIONS

The need to decarbonise maritime transport positions **hydrogen derivatives such as ammonia and methanol as technological pillars in the sector's energy transition**, given their properties, technological readiness levels, applications and market prospects.

- **Properties of alternative fuels**

Methanol is the hydrogen derivative with the highest volumetric energy density and it can be stored in a liquid state at ambient temperature and pressure, facilitating its integration into ships and port infrastructure. Its lower calorific value compared to traditional fuels will entail greater space requirements to maintain autonomy on long-distance routes. Using methanol as the primary fuel can reduce GHG emissions by approximately 10%. Its potential as a carbon-neutral fuel will depend on the availability of renewable electricity and biogenic CO_2.

Ammonia, on the other hand, while having a lower energy density than methanol, can benefit from the existing global logistics infrastructure for its transport, storage and handling, and it has lower storage costs than hydrogen. However, it will require adaptations to the design of ships to produce it safely and efficiently. Green ammonia is capable of reducing GHG emissions by 90% compared to the conventional fuels used to date.

Both ammonia and methanol will entail space limitations on board, and these must be taken into account in the ship's design and conversion.

- **Safety and risk management**

Methanol requires inertisation and ventilation systems, fire protection and anti-corrosion materials, while ammonia, which is less flammable, can be managed with well-established industrial safety standards.

The industry's experience of handling ammonia can contribute to the development of safety protocols for its use as a fuel, while methanol is compatible with existing ship systems and materials, thus lowering the barriers to its implementation.

- **International and European regulations**

The current regulatory framework establishes targets for reducing emissions in maritime transport, including the IMO Strategy, which calls for a 20% reduction by 2030 and neutrality by 2050, and the FuelEU Maritime regulation, which establishes progressive GHG emission reductions and certification mechanisms. The two regulations are expected to converge to prevent a loss of competitiveness in Europe.

With regard to fuels, regulations on the use of methanol as a fuel have already been developed (MSC.1/Circ.1621) and applied. As for the use of ammonia, amendments to the IGF and IGC Codes are being developed and they are expected to enter into force in 2027. Their formal approval is expected to take place in October 2025, consolidating a regulatory framework to ensure its safe use on board ships.

- **Availability of engines and propulsion technologies**

Both methanol and ammonia have been industrially developed in two and four-stroke Dual Fuel (DF) engines (TRL 9), as well as retrofit kits for existing vessels. Manufacturers such as Everllence, Wärtsilä, WinGD and Hyundai HiMSEN lead this sector. Methanol is already commercially used on 35 vessels in operation and retrofit kits have been developed. Regarding ammonia, one vessel is in operation as of today, in addition to 25 new orders, and the retrofit kits for the vessels are expected to be developed by 2027.

As for fuel cells, there is growing interest in the use of MCFC and SOFC technologies (TRL 9), which are capable of using ammonia and methanol as hydrogen carriers, for auxiliary power generation applications and in onboard hybrid systems. Meanwhile, PEMFCs integrated into methanol reforming systems are planned for small vessels and coastal transport, for which the refuelling is simplified and the operational advantages of these technologies are maximised.

- **Market prospects and future demand**

Analyses by the International Energy Agency (IEA) and Everllence predict that ammonia will become one of the main alternative fuels by 2050, securing a 35%-44% share of the maritime mix, while methanol is envisaged as a transition fuel in the short and mid terms, with shares lying between 3% and 26%, depending on the scenarios.

Methanol is becoming established as a short-term option, driven by the availability of biogenic CO_2, on short and medium-haul routes, due to its ease of integration. Meanwhile, ammonia is emerging as a long-term solution, especially for transoceanic routes, with the development of green ammonia value chains proving key to ensuring net-zero emissions.

Hydrogen, primarily in fuel cells, is envisaged for applications in small vessels, ferries and coastal shipping in the early stages. This hydrogen could be obtained on board from methanol or ammonia by means of respective reforming and cracking processes.

- **Logistics and bunkering**

Ammonia as a fuel will leverage the existing port infrastructure, with more than 170 terminals in operation worldwide serving as future logistics hubs. As for methanol, its bunkering and storage infrastructure is already available, thanks to its use in the chemical industry and offshore operations, which will facilitate its expansion.

Vessels already transporting ammonia or methanol are prime candidates for conversion into vessels powered by these fuels, harnessing their operational experience and reducing logistical barriers.

- **Strategic conclusion**

Hydrogen derivatives (both methanol and ammonia) offer viable and complementary solutions on the maritime transport decarbonisation roadmap, with scalability, technological readiness and the capacity for integration into the existing systems. Maximising their potential will require:

- Furthering the development of specific regulations, especially ones for ammonia.
- Promoting the renewable production of the two fuels to ensure their true climate sustainability.
- Adapting the port and bunkering infrastructure to facilitate their safe and competitive supply.
- Boosting investment in propulsion technologies and safe onboard storage and handling systems.

Ammonia and methanol can thus play a fundamental role in the maritime sector’s transition to net-zero emissions, while ensuring the competitiveness and sustainability of the global logistics chains.

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