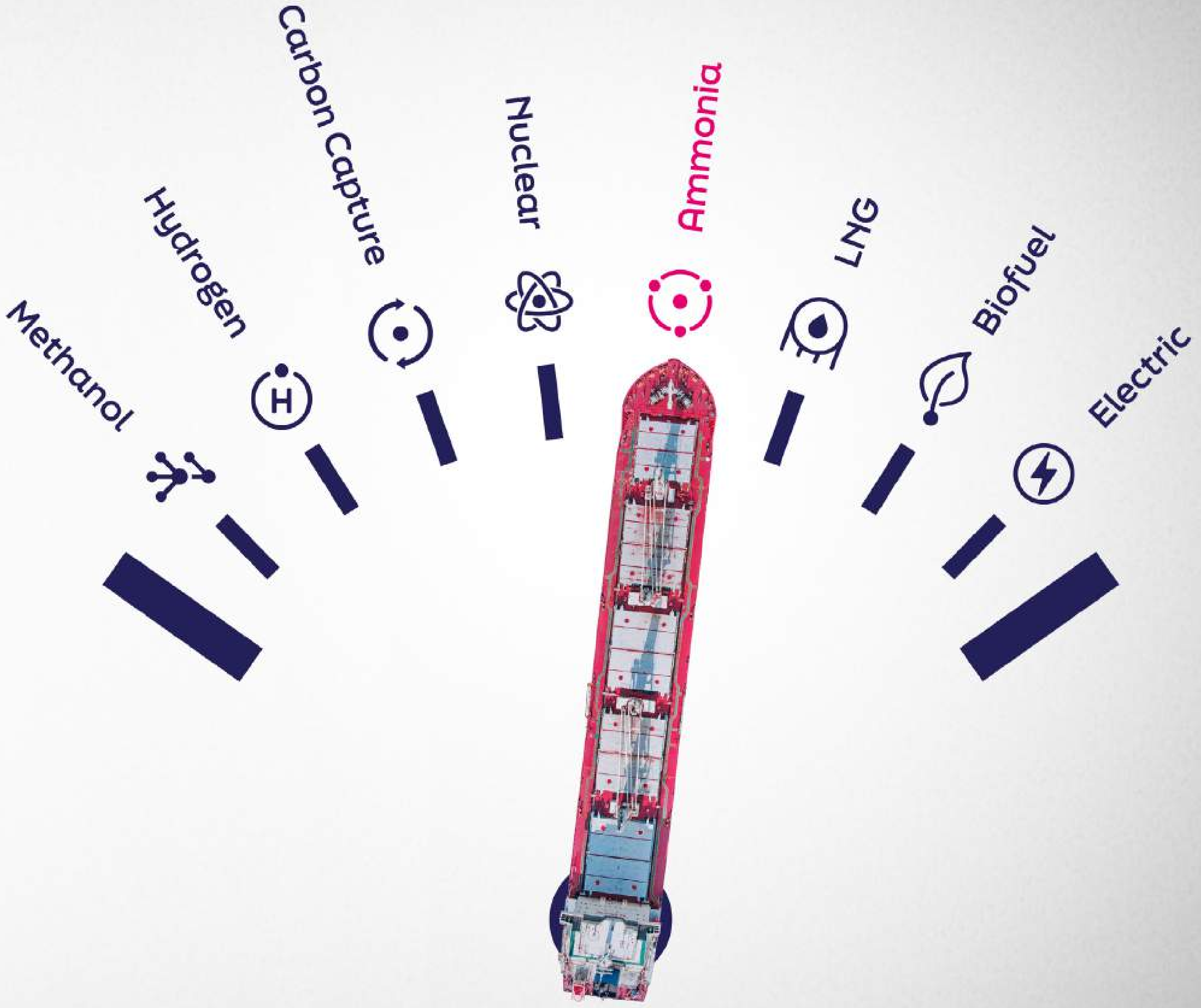
FUEL FOR THOUGHT
Ammonia



Expert insights into the future of alternative fuels

Your trusted adviser in alternative and low carbon maritime fuel

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Preface

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 vessel propulsion, but this took close to one hundred years to emerge. Each shift had a dramatic impact on the cost, speed and efficiency of shipping. The energy transition 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 without commercial certainty, 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 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 ammonia, a regularly produced chemical and potential maritime fuel that is moving towards green production. Its properties, such as the absence of carbon atoms in its molecular structure, make it one of the main candidates for a zero CO_2 emission future fuel.

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

1.1

Chapter 1: Introduction

Introduction from the Ammonia Energy Association – Trevor Brown, Executive Director, Ammonia Energy Association (AEA)

As momentum builds for the global shipping industry to decarbonise, stakeholders are turning to a suite of lower-carbon pathways.

Where combustion fuel is concerned, ammonia is rising to prominence as a long-term choice. Challenges are still being worked through but supposed 'deal-breakers' are quickly being surmounted, with the first ammonia-powered ships due to hit the water in 2025.

In terms of technology, engine-makers such as Wärtsilä, MAN Energy Solutions and WinGD have all reported significant progress in ammonia-capable marine engines in the past year. Bolstered by successful testing programmes and the concurrent development of fuel supply and safety mitigation systems, newbuild engines and retrofits (enabling existing engines to run on ammonia fuel) look set for commercial availability from 2025. Some pilot projects are already in operation.

Turning to supply, global ammonia production currently sits at around 180 million tonnes (Mt) per year, with the vast bulk used immediately for fertiliser manufacturing. 20 Mt of this production volume is traded across oceans each year, resulting in a sprawling global network of ammonia terminals and handling facilities, much of it located close to key bunkering locations.

Industrial decarbonisation accelerator, Mission Possible Partnership, forecasts that by 2050, marine fuel demand alone could amount to as much as 688 Mt of ammonia per year, supplied by a worldwide, thousand-strong fleet of production plants. New and existing ammonia producers are already making their intentions known, announcing mega-scale fuel production plants in key shipping locations like the US Gulf Coast and the Gulf of Suez. Many are targeting the emerging marine fuel market.

Demand for ammonia will continue to grow in the fertiliser sector and in emerging applications like power generation. This will accelerate production growth, with the marine fuel sector another major driver of future ammonia demand. The remaining years of this decade are not only crucial for decarbonising global shipping, but also for implementing ammonia safely as a marine fuel.

1.2

Ammonia fact file

What is it? NH_3

Ammonia is a commonly produced industrial chemical. At ambient temperature and pressure, ammonia is a clear, colourless gas that is lighter than air. It can be absorbed in water and is corrosive, with potential for serious injury to eyes, throat and lungs. It has a distinctive pungent odour.

About 70% of current ammonia production is for the fertiliser industry (World Economic Forum, 2022) and it is seen as a critical resource for global food security. More than half of currently available ammonia is produced in four countries (China, the US, India and Russia), using hydrogen formed from natural gas and coal, then combined with nitrogen separated from the air using electricity. The hydrogen production processes, coal gasification (26%) and steam methane reforming (73%), account for the majority of the CO_2 emitted during ammonia production today.

Production of ammonia currently emits 450 Mt of CO_2 per year, representing 1.3% of man-made emissions, the largest source of emissions in the chemical sector.

While its demand from existing uses of ammonia continues to grow, new applications of ammonia as an efficient hydrogen carrier and a carbon-free fuel are set to make the most impact on demand. Global demand is expected to increase from 183 Mt in 2020 to 688 Mt in 2050. Of this new demand, less than half will be from existing uses, with 197 Mt expected from the maritime sector alone. A further 127 Mt will come the use of ammonia as a hydrogen carrier, supplying decarbonised feedstock and fuel for the chemical and industrial sectors (IRENA, 2022).

Decarbonisation efforts in sectors that already use ammonia products are adding pressure for production to become greener. There are two methods for producing the hydrogen used in the creation of clean ammonia. The first involves the use of fossil feedstocks and applying carbon capture and utilisation techniques. The second method involves using electrolysis to extract hydrogen from water, which is a cleaner alternative to reforming or gasifying hydrogen from coal or natural gas. Hydrogen from either source is combined with nitrogen extracted from the air, using the Haber-Bosch process. To produce green ammonia, renewable electricity is required for both electrolysis and for combining hydrogen with nitrogen (see Annex 2 for definitions of different types and colours of ammonia).

Ammonia production formula

$$N_2 + 3H_2 = 2NH_3$$

Properties table

No sulphur

Density
Liquid: 680kg/m³ at -33C
and I bar pressure

No carbon

Boiling point
-33.3C
(at 1 bar pressure)

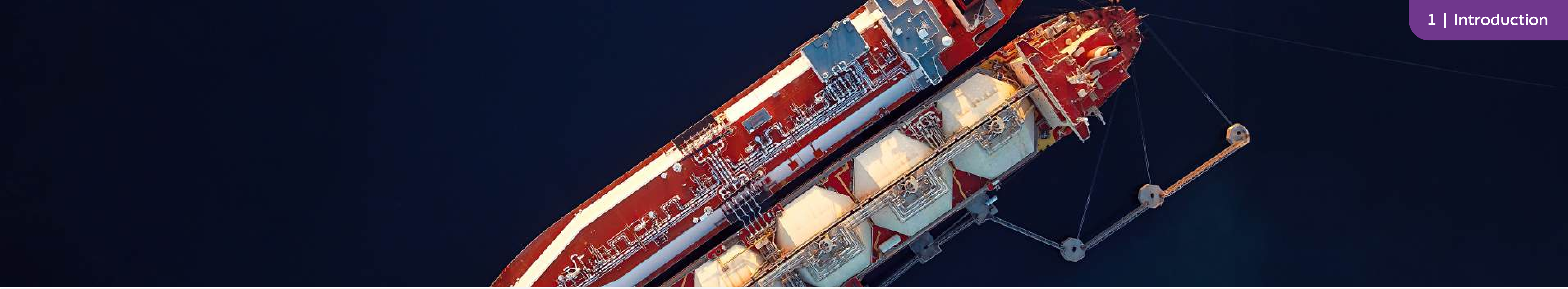
Autoignition
651°C

Energy density
18.8 MJ/kg

Molecular weight
17.0 g mol^{-1}

Upper explosive limit
28%

Lower explosive limit
15%



Energy density comparison table

Property	Liquefied ammonia	Methanol	LNG	Liquefied hydrogen (LH_2)	Gaseous hydrogen (350 bar)	Gaseous hydrogen (700 bar)
Density (kg/m^3)	696	790	450	70.8	23.35	38.25
Storage temp (°C)	-33	Ambient	-162	-253	25	25
Storage pressure (barg)	1	1	1	1	350	700
Lower heating value (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

Factors to consider for ammonia as marine fuel

Social acceptance	Safe handling/infrastructure	Ammonia scalability
↑ Potential to reduce the environmental impact of the marine industry	↑ Industrial and maritime cargo experience to draw on	↑ Better energy carrier than liquefied hydrogen
↑↓ Lifecycle analysis: 'Actual' environmental reduction, only if supply is from green production	↑ Ability to regulate and reduce risk	↑ Existing production (although requiring large transformation to produce and supply near-zero or net-zero ammonia)
↓ Stranded assets if social acceptance were to change	↓ Impact on aquatic, human, and environmental health	↑ Technology maturity demonstrated upstream
↓ Impact/harm beyond boundary of ship and port	↓ Lack of existing bunkering infrastructure	↑ Transportation and opportunity to consume ammonia cargo as fuel
↓ Social demand for reduction in environmental impact increases safety risks	↓ Skills and training requirements, including onboard, port, shipyard and shoreside crews	↓ Capability of achieving near-zero GHG fuel at scale
↑↓ Lobbying creating conflicting and confusing information environment	↓ Regulatory landscape currently inadequate for ammonia use as fuel	↓ Competition from other sectors
		↓ Shipyard capacity and competence
		↓ Technology immaturity downstream

1.3

Readiness of ammonia as a marine fuel

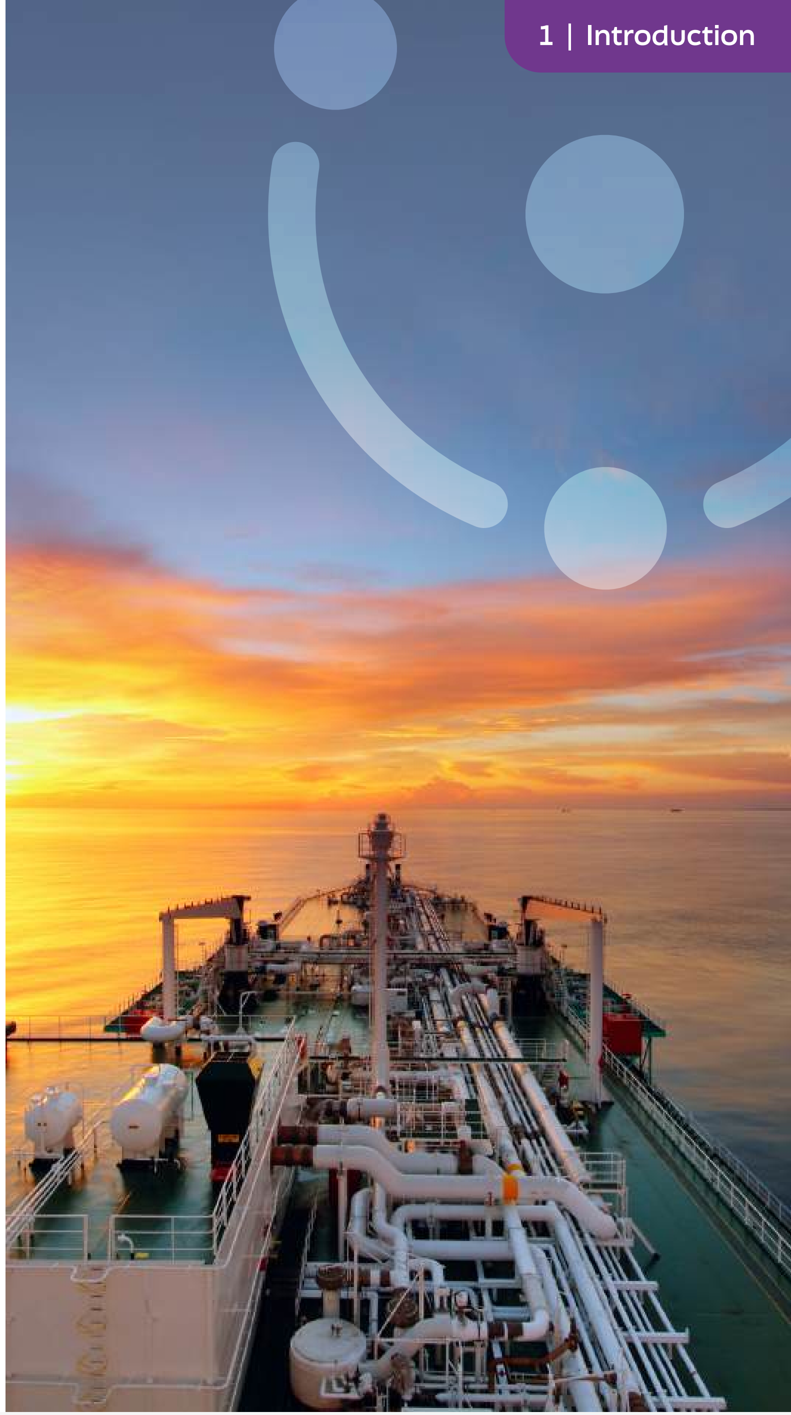
Lloyd's Register has collaborated with industry stakeholders to build a comprehensive assessment of different aspects of the fuel supply chain from production to delivery onboard, and the technologies for use as a fuel onboard for power generation.

Lloyd's Register'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 GHG emissions. The table and more detailed information that follow reveal how, although the technologies for producing, delivering, and combusting blue or e-ammonia are becoming more advanced, the investment outlook is in most cases is not yet favourable. Additionally, community acceptance is still lacking due to persistent safety concerns.

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

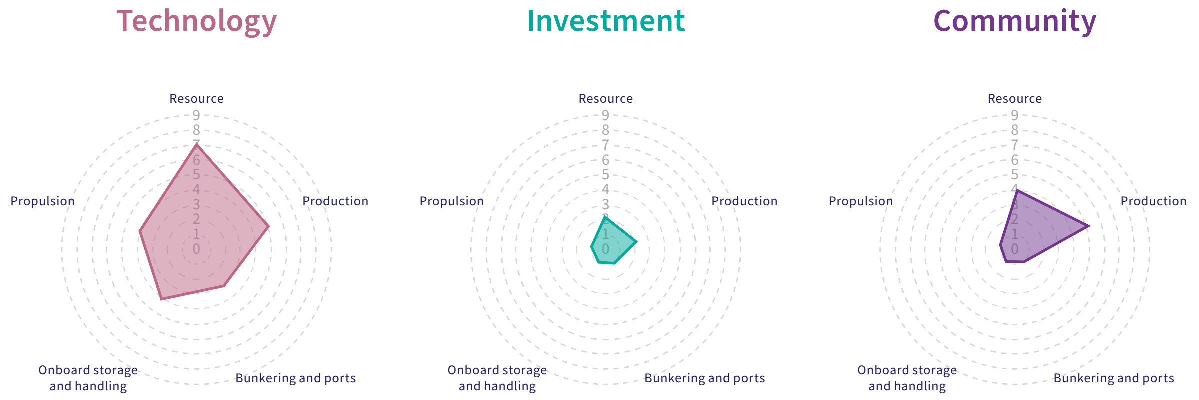


Ammonia readiness levels

Source: Maritime Decarbonisation Hub

E-ammonia (or green ammonia)

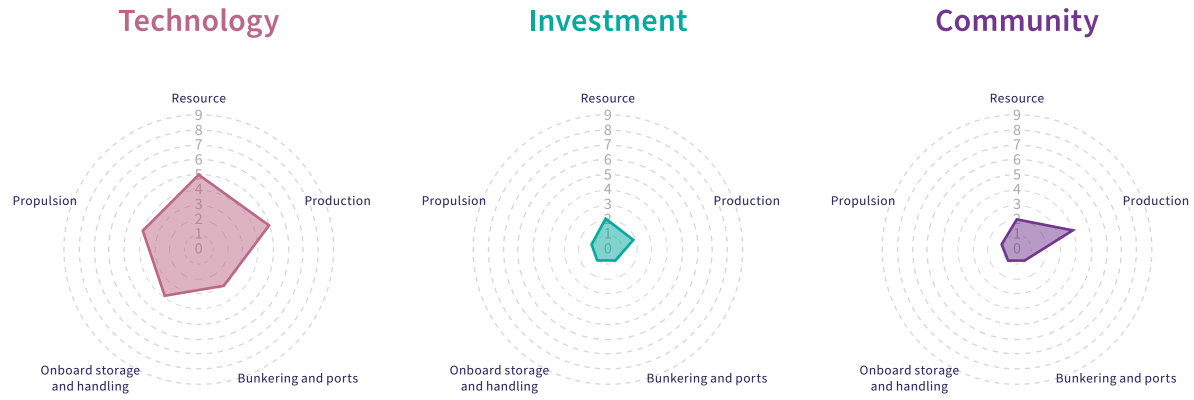
Technology | Investment | Community



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

Blue ammonia

Technology | Investment | Community

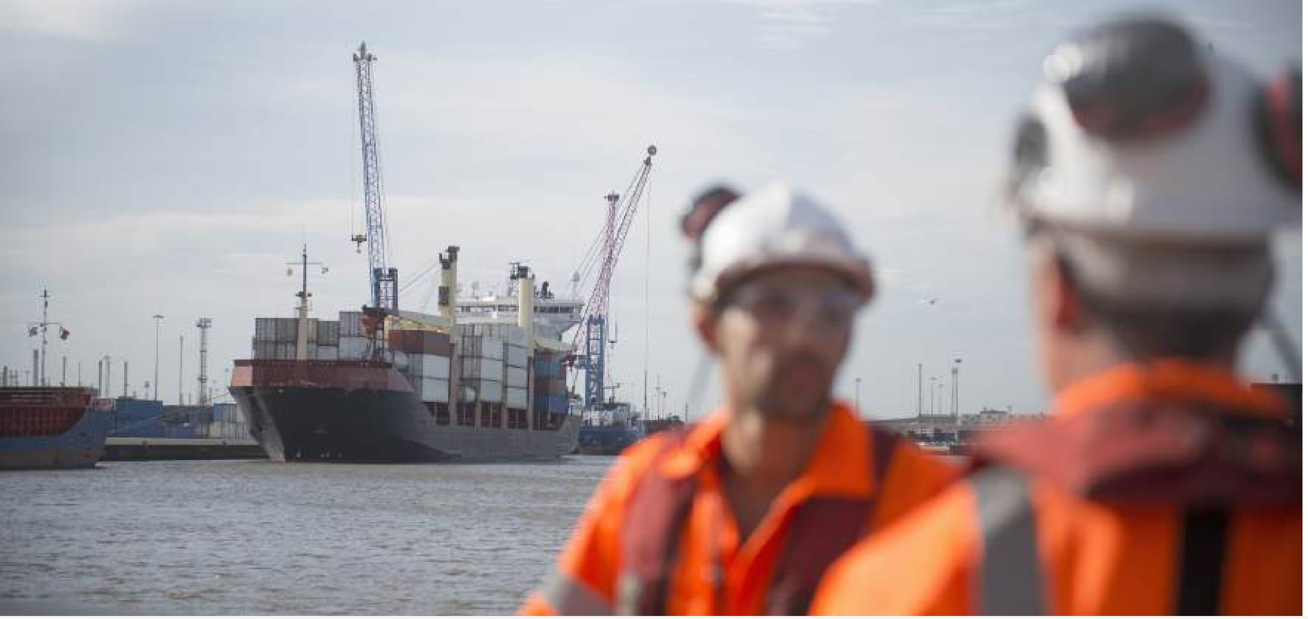


Technology Readiness Levels (1–9), Investment and Community Readiness Levels (1–6)

2.1

Chapter 2: General safety and toxicity issues

A recently published joint study, *Recommendations for Design and Operation of Ammonia-fuelled Vessels*, by LR Maritime Decarbonisation Hub and Maersk McKinney Moller Centre for Zero Carbon Shipping includes advanced safety knowledge and understanding concerning ammonia handling and storage on board vessels.



High-priority recommendations from the joint study include:

- Lowering storage temperature to reduce the safety risk from ammonia fuel
- Dividing the fuel preparation room into two or more separate spaces containing different groups of equipment that could leak ammonia
- Minimising, monitoring, and controlling access to, and length of time spent, in spaces containing ammonia equipment
- Placing ventilation outlets from spaces containing ammonia equipment in a safe location, adequately separated from areas accessed by crew, to avoid accidental release of toxic concentrations of ammonia affecting personnel
- Installation of multiple sensors of different types to detect ammonia leaks

A supporting document to this study, *Human Factors Considerations: Ammonia Fuel End-of-Stage Report*, published by LR, provides a preliminary account of the human factors that should be addressed to prepare for ammonia fuel use. The results of this analysis point to the need for companies, and the marine industry as a whole, to apply human factors engineering principles, such as ergonomics, within the design of ammonia-fuelled vessels. Ensuring enhancements conform to a company's safety (and environmental) management system and approach will also be required.

For example, procedures must outline any new or modified planning, communication, competency/training and emergency response requirements related to ammonia. Other areas where modification, changes or new enhancement would be needed include (but are not limited to):

- Managing changes to operational and maintenance procedures and practices
- Personnel-related matters, including roles, responsibilities, staffing and interfaces with other organisations

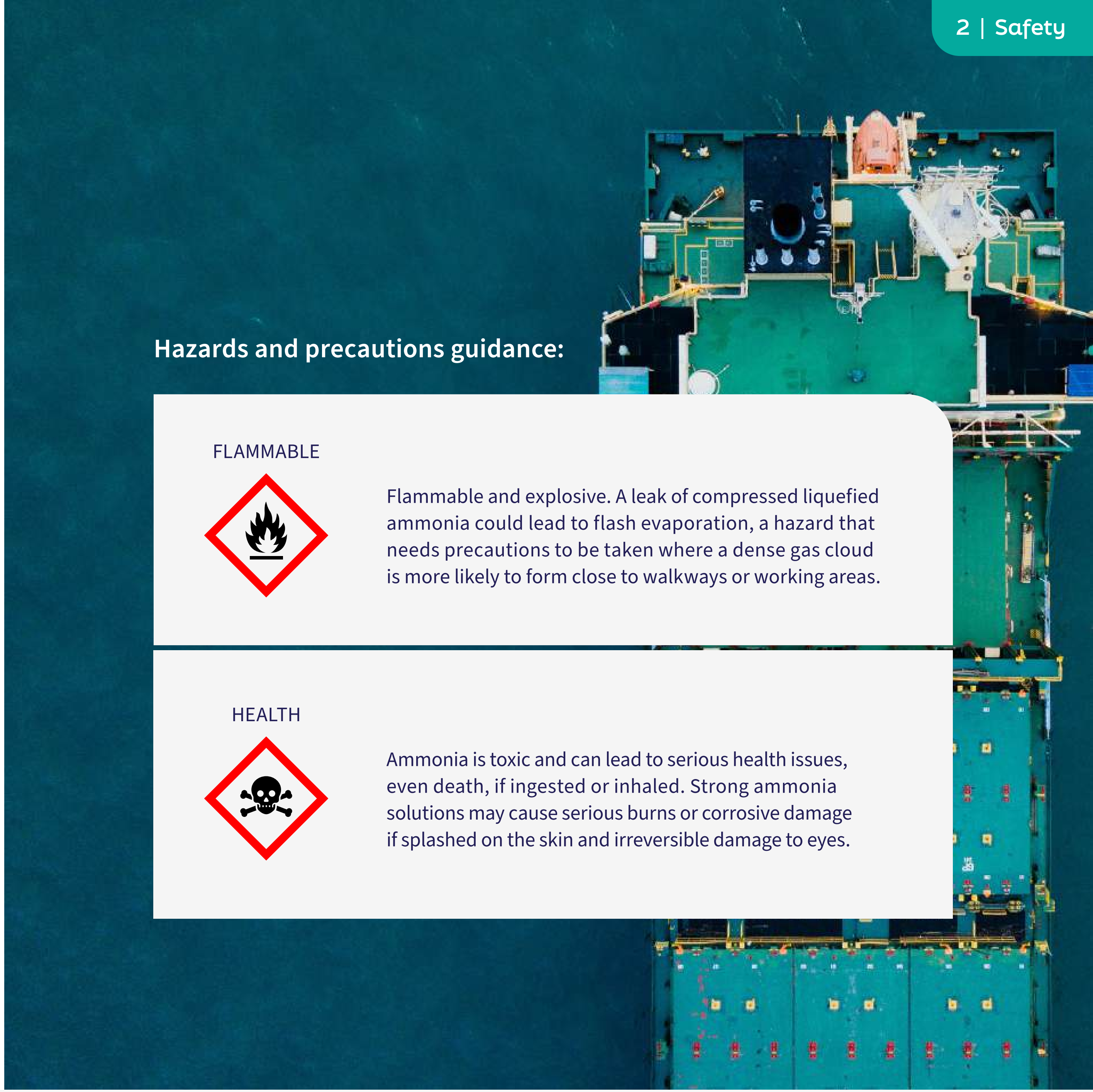
2.2

General safety

Ammonia can be found naturally in the air, soil, water and in our bodies. It is also an ingredient in household cleaners and other household products. However, it can cause irritation and burning of the skin, mouth, throat, lungs and eyes. High levels can severely damage the lungs and lead to death. The level of harm depends on concentration and duration of exposure. Ambient ammonia vapour is lighter than air, however when compressed ammonia is released, the liquid flash evaporates, causing a heavier-than-air vapour cloud.

Anhydrous ammonia

Liquefied ammonia can be referred to as anhydrous ammonia when it does not contain any water. Ammonia is highly miscible in water and will form an ammonia hydroxide solution. Ammonia solution can form toxic atmospheres and under certain conditions can be flammable. This solution remains flammable and toxic.



Hazards and precautions guidance:

FLAMMABLE

Flammable and explosive. A leak of compressed liquefied ammonia could lead to flash evaporation, a hazard that needs precautions to be taken where a dense gas cloud is more likely to form close to walkways or working areas.

HEALTH

Ammonia is toxic and can lead to serious health issues, even death, if ingested or inhaled. Strong ammonia solutions may cause serious burns or corrosive damage if splashed on the skin and irreversible damage to eyes.

IGF Code Hazardous Zone Areas

Hazardous Zone Area 0:	Hazardous Zone Area 1:	Hazardous Zone Area 2:
Interior of fuel tanks, pipework for pressure relief or venting, pipes and equipment	Tank connection spaces, fuel preparation rooms, fuel storage hold space, cofferdams and any enclosed or semi-enclosed space where leakage may occur	Areas within 1.5 m surrounding open or semi-enclosed Zone 1 spaces

Ammonia compatibility with materials

LR's *Guidance notes for fuel system risk assessments, hazard identification – hydrogen and ammonia* identify several compatibility considerations for the use of ammonia as a marine fuel.

Metals have varying degrees of compatibility with ammonia and ammonium hydroxide (Section 2.2.5). Mercury, copper, copper alloys, and zinc should not be used in tanks and associated pipelines, valves, fittings and other equipment in direct contact with ammonia. Under certain conditions, ammonia and water in contact with carbon dioxide could form ammonium carbonate or ammonium bicarbonate. This has the potential to block, damage and degrade equipment, components and pipelines.

Stress Corrosion Cracking (SCC) can occur in components exposed to a corrosive medium such as ammonia and subject to tensile stress. In ammonia fuel systems, there is potential for cracking of carbon and high nickel content steels susceptible to SCC in anhydrous ammonia, and cracking of copper and some of its alloys susceptible to SCC in ammonia solution. The resulting damage may lead to sudden catastrophic failure.

Consequently, the design and arrangements of the ammonia fuel bunkering system, fuel containment system, fuel supply system, and power generation system all need to consider the potential for SCC. The risk of SCC is controlled under the IMO International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) Article 17.12. This allows use of carbon steels provided a small quantity of water is present in the ammonia. Ammonia also has varying degrees of compatibility with plastics, elastomers and sealants (Section 3.2.3). It is essential that the manufacturer is consulted to check compatibility between their specific product and the anticipated conditions of use.

2.3

Maritime safety regulations

The development of safety regulations for the use of ammonia as a fuel at IMO is on a twin track, with separate prescriptive guidelines being drafted for:

- Vessels using ammonia cargo as fuel
- Vessels bunkering ammonia specifically for use as fuel

Gas-carrying vessels using ammonia cargo as fuel

The IMO is in the process of developing interim guidelines for the use of ammonia as fuel to support the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), with a draft due to be agreed by the Sub-Committee on Carriage of Cargoes and Containers (CCC) in its tenth meeting, in September 2024.

At the same time, draft revisions have been agreed to Section 16.9.2 of the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) to allow the use of toxic products, including ammonia, as fuel by gas carriers transporting ammonia provided a level of safety equal to natural gas is provided. The IGC Code currently states that toxic cargoes shall not be used as fuels on gas-carrying vessels. This currently prevents the use of ammonia. At CCC9 in September 2023, the sub-committee acknowledged that the current wording of Section 16.9.2 represents an impediment to the uptake of ammonia as a marine fuel on gas-carrying vessels. The agreed draft text to amend 16.9.2 of the Code should be finalised at CCC10.

At CCC9 it was agreed to develop Guidelines to ensure ships using ammonia and other toxic cargoes as fuel are designed and operated to the same level of safety as a ship carrying and using natural gas as fuel. This means that, unlike for ammonia-fuelled vessels regulated under the IGF Code, the sole approach of risk-based designs will not be accepted until guidelines are in place. In effect, the two sets of guidelines will be relatively similar, with one of the key differences likely to be around the use of double-walled piping which may be required throughout non-gas-carriers using ammonia, but only outside cargo areas on gas carriers.

Vessels bunkering Ammonia for use as a fuel only

Lloyd’s Register published rules for ammonia-fuelled non-gas carrier vessels in July 2023, based on the alternative risk-based design pathway allowed for under the IGF Code, and hopes to publish Rules for Ammonia Gas Carriers consuming its own cargo in July 2024. Rules for gas carriers using ammonia as fuel will be published once IMO requirements and any interim prescriptive requirements become clear.

Safety regulations for ammonia on ships when used as a fuel are based on risk assessments and risk-based certification needs. These are therefore high level and more goal-based in nature than prescriptive. International maritime safety regulation on ammonia fuel-handling is under discussion at the IMO and within IACS and other safety forums, with classification issuing guidance on fuel system design, handling and other critical safety considerations. The approval process is outlined in the IMO Guidelines for Approval of Alternatives and Equivalents (MSC.1/Circ.1455).

Lloyd’s Register has developed a Risk-Based Certification (RBC) process which is consistent with and based upon MSC.1/Circ.1455 and other related IMO guidelines, yet equally applies to non-SOLAS projects. RBC is used where risk assessment is required to inform certification and provide confidence in new, novel and alternative designs.

For an alternative fuel project, the risk-based process needs to meet the mandatory requirements in SOLAS Reg II-1/55 (including the IGF Code), the guidance in MSC.1/Circ.1455, and be undertaken in accordance with the LR RBC process. Refer to Section 5 Classification Rules for further information on the application of RBC.

2.4

Specific bunkering considerations

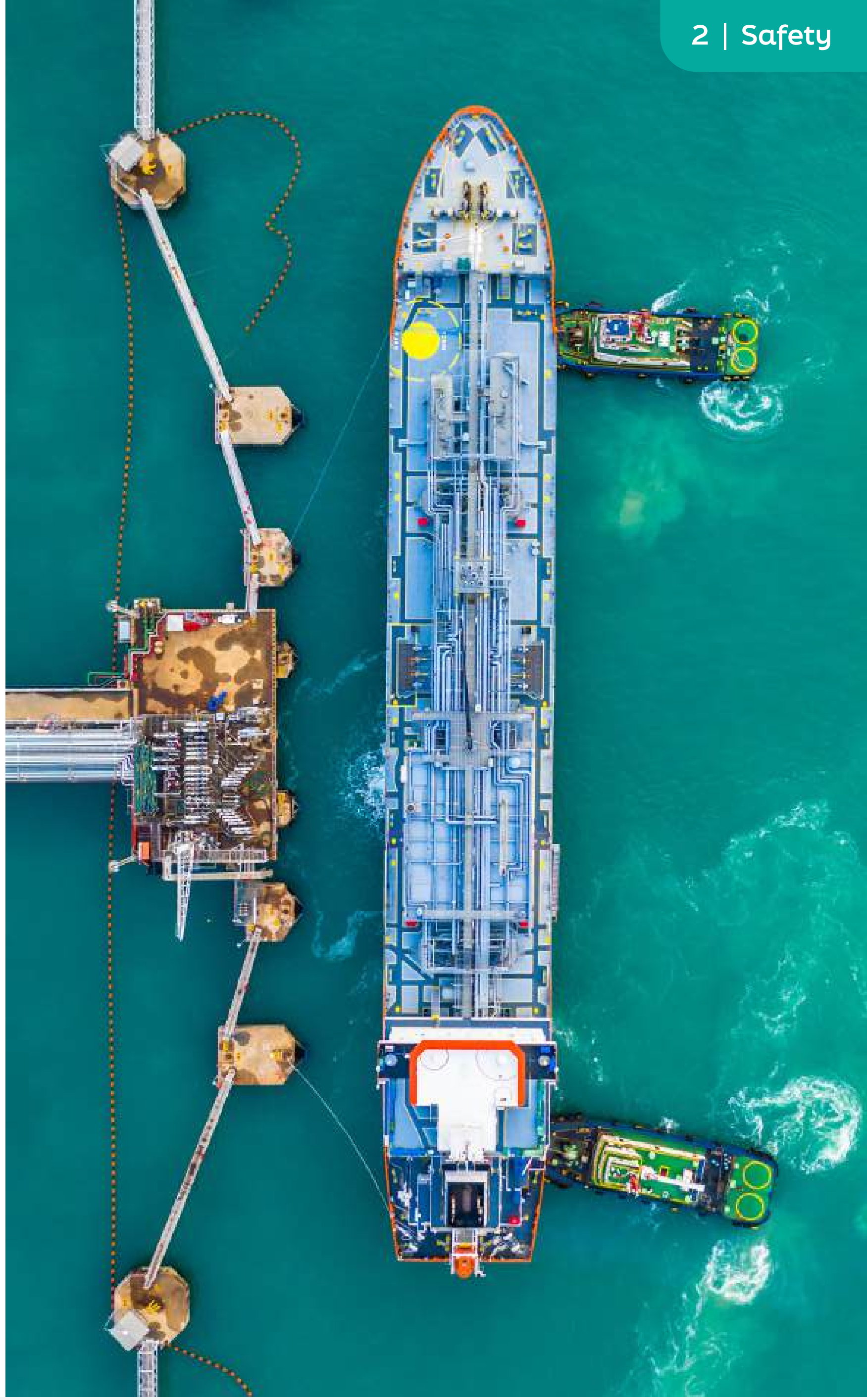
Ammonia will be delivered to a vessel as a fully refrigerated, semi-refrigerated or compressed liquefied. The hazardous nature of the fuel leads to specific handling precautions and requirements on bunkering and fuel storage systems. Experience of handling ammonia as a cargo will help with the development of bunkering regulations, as will relevant experience in other industries where liquid ammonia is used regularly.

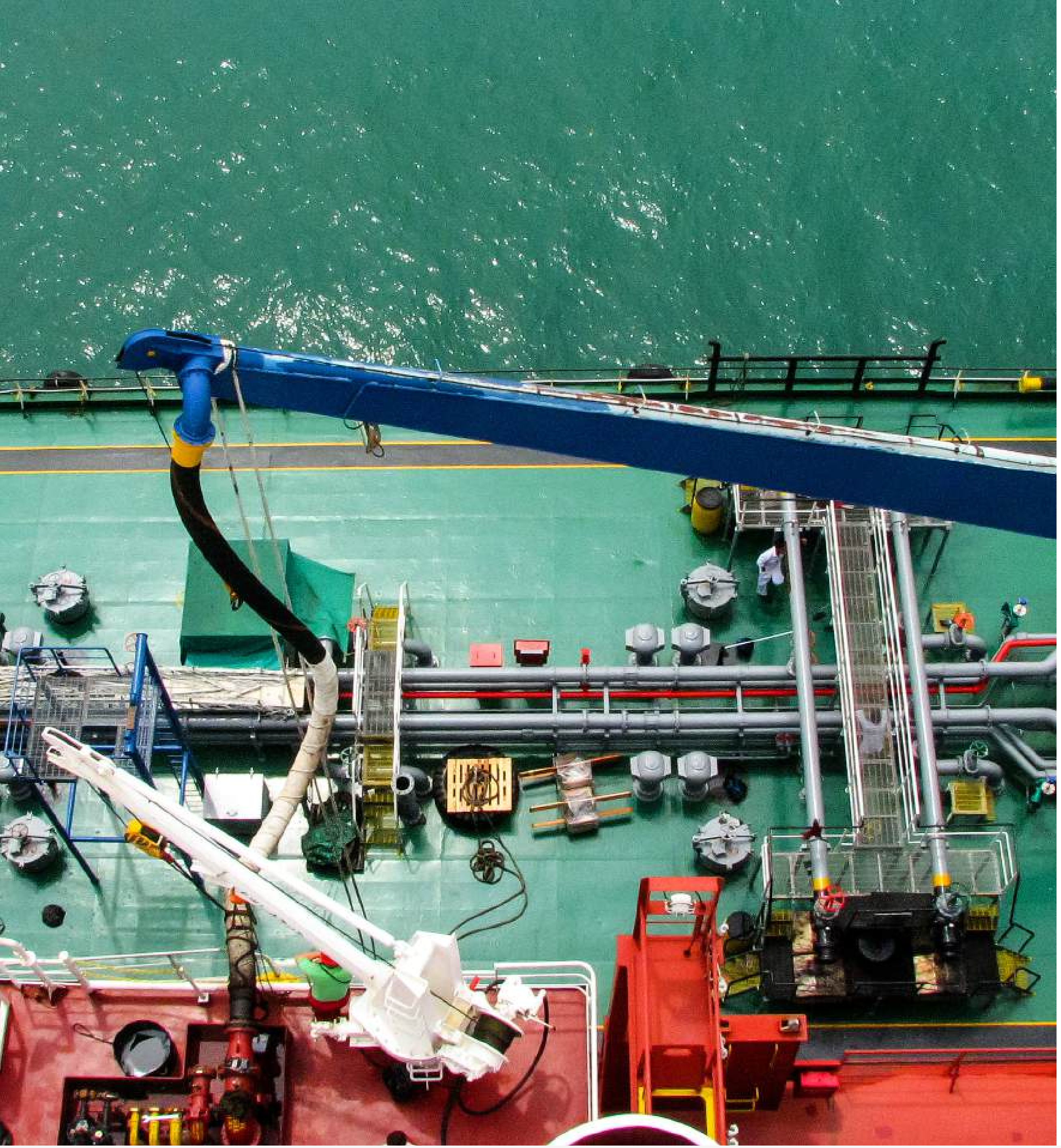
The design of bunkering stations for ammonia-fuelled vessels is covered in LR's *Requirements for Ships Using Ammonia as Fuel*. Alongside the requirements common to all vessels using gas or low-flashpoint fuels, special consideration in risk assessments should be given to the 'reasonably foreseeable worst case' leakage scenario, the ship's toxic area plan, and access through airlocks from non-toxic areas.

Bunkering stations should be arranged to safely contain and manage leakage and can be open, semi-enclosed or closed by design. Closed or semi-enclosed bunkering stations should be gas-tight towards adjacent spaces. Drip trays should not drain overboard. Bunkering systems should allow for closure of automatic shutdown valves (with remote operation functionality) without delay and without creating transient overpressures.

In September 2023, Lloyd's Register concluded a Hazard Identification (HAZID) study and a Quantitative Risk Analysis (QRA) for Yara Clean Ammonia Australia and Pilbara Ports. Key results of the study showed that ship-to-ship ammonia bunkering operations could be performed within acceptable risk levels at anchorages in Dampier and Port Hedland.

The project identified hazards related to various ammonia bunkering modalities. The hazards were ranked as high, medium or low risk during the HAZID workshop, with loss of containment scenarios further assessed in the QRA. As part of the HAZID study, several recommendations were recorded for further action to manage the risk associated with the bunkering modalities. The HAZID workshop was attended by personnel and subject matter experts from ports currently handling ammonia or carrying out loading operations to gas carriers. It also drew on the experience of Yara which has been safely managing supply and delivery of ammonia for decades.





The HAZID process identified a number of high- and medium-risk scenarios which should further be addressed and evaluated as a part of the compatibility assessment for actual ship designs that will be involved in bunkering operations.

Recommendations included consideration for provision of:

- Additional overpressure protection and gas detectors
- Compatibility assessments carried out between the bunker vessel and the receiving vessel

The following uncertainty factors were identified, although the influence of these on the risk outcomes is expected to be within the available risk margin:

- Uncertainty of the bunkering locations
- Uncertainty in the receiving vessel design
- Compatibility-related additional findings
- Anticipated knowledge gaps in ammonia
- Toxic dispersion of ammonia whereby a combination of different consequence modelling software was used to make up for modelling gaps related to simulating ammonia spill onto water

The assumptions applied and risks identified are specific to this project and the ammonia bunkering scenarios considered. They may not be fully applicable to other projects. Individual projects will need to address risks specific to their own cases.

2.5

Fuel quality and specifications

There are industry discussions on draft standards or grades of ammonia for use as an energy source – a fuel grade. For anhydrous ammonia, there are three existing grades (commercial grade, refrigeration grade and premium grade). These range from 99.5% to 99.995% purity, with the lower, commercial 99.5% purity in the majority.

Ammonia absorbs water easily and when water is in the ammonia it is difficult to remove. A small amount of water in ammonia (up to 0.5%) is needed to improve the safety of storage by reducing the risk of stress corrosion cracking (SCC). Commercial-grade ammonia is likely to be suitable for ammonia dual-fuel engines.

Any fuel standard must address the questions of ammonia storage on board ships as fuel tanks can be pressurised or refrigerated.

There will also be the issue of emissions after combustion, notably NOx emissions. Poor combustion of ammonia will not only leave unburned ammonia in the exhaust (ammonia slip), but also NOx and N_2O.

MAN Energy Solutions has developed its own preliminary guidance for ammonia going into its dual-fuel ammonia engines once these reach the market. It notes that particles in the fuel could come from particles breaking free from catalyst used in NH_3 production (catfines) and from the transportation of the ammonia. This raises a consideration about ammonia bunker logistics, the need for the ammonia fuel standard to control debris (particles), and the required specifications for onboard fuel filtering between fuel tank and engine.

MAN ES preliminary fuel specification guidance

Property	Unit	Limit	Value	Test Method Reference[1]	
Ammonia	% mass	Min.	99.5	TBD	- Energy content
Water	% mass	Min. Max.	0.1 0.5	ISO 7105	- Inhibit SCC
Oil	% mass	Max.	0.4	ISO 7106	- Control amount
Oxygen	% mass	Max.	TBD	TBD	- Inhibit SCC
Nitrogen	% mass	Max.	0.3	TBD	- Control air amount
Sulphur	% mass	Max.	TBD[2]	TBD	- MARPOL regulation
Particles	-	Max.	Note[3]	-	- Reduce wear

1 Latest edition to be applied. ISO standard methods are the highest level of international methods and are therefore recommended. Equivalent methods from ASTM, GPA and IP can also be used.
2 Compliant with statutory requirements.
3 Most particles are expected to end up in the NH_3 due to transport of the NH_3, not during NH_3 production. Particle sizes and amounts are therefore dependent on the actual NH_3 logistics involved between NH_3 production and vessel fuel tank. Filtering to 10 µm between vessel tanks and engine is therefore considered the best way to avoid engine problems due to particles. Particles breaking free from the NH_3 production catalyst may be an issue with respect to wear of the engine and this topic is subject to further evaluation.

NH_3 reported as liquid

- Atmospheric pressure, -33°C
- High pressure, atmospheric temp.

Commercial grade ammonia specification sheet from ammonia producer, CF Industries.

Property	Ammonia specification
Physical state	Gas
Appearance	Colourless gas Liquid under pressure
Colour	Colourless
Odour and odour threshold	Pungent 5 ppm
pH	> 12 (conc 100% v/v)
Melting point	-78°C @ 1013 hPa
Boiling point	-33°C @ 1013 hPa
Flash point	The endpoint is not applicable as the substance is an inorganic gas. Aqueous solutions of ammonia do not show any flash point.
Critical temperature*	132.41°C @ 1013hPa
Auto-ignition temperature	651.1°C
Decomposition temperature	450°C
Flammability (solid, liquid, gas)	Flammable gas Explosion limits: 16% to 25% (Anhydrous ammonia is listed on Annex I of Directive 67/548/EEC with classification as (R10) 'Flammable'.)
Vapour pressure	861 hPa @ 20°C

*Critical temperature is the temperature at and above which ammonia vapour cannot be liquefied regardless of pressure applied.

3.1

Chapter 3: Drivers for ammonia

Regulations

The following discussion focuses on various regulatory drivers behind the interest in ammonia as a fuel. For safety regulations, see Chapter 2 of this report. The regulatory drivers for ammonia as a fuel are not specific to ammonia. They do however encourage owners and operators to switch their ships to less carbon-intensive operations, where ammonia is one fuel option.

EU Regulations

Some of the most advanced regulations are from the European Union. Shipping companies need to be aware of five elements of the EU *Fit for 55* package that impact shipping. The *Fit for 55* package is the bloc's overarching decarbonisation strategy across society and business. It includes:

- 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)

Initial analysis highlights how these interlocking requirements will drive ship owners to adopt more stringent vessel efficiency strategies, as well as new low-carbon fuels.

EU Emissions Trading System

As of 1 January 2024, passenger and cargo ships of 5,000GT and over calling at EEA ports became subject to the region's emission trading scheme. (Additional ship types and sizes will fall into scope of the scheme in future years). Shipping companies with responsibility for such ships will need to buy allowances to cover greenhouse gas (GHG) emissions (CO_2, CH_4 and N_2O) for intra-EEA (EU plus Norway and Iceland), in EEA ports and for half of the GHG emissions created during voyages to and from the EEA. GHG emissions to be recorded under EU MRV include CO_2, CH_4 and N_2O. From 1 January EU allowances for CO_2 emissions will have to be surrendered under EU ETS, with CH_4 and N_2O emissions falling into scope of ETS from 2026.

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

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)

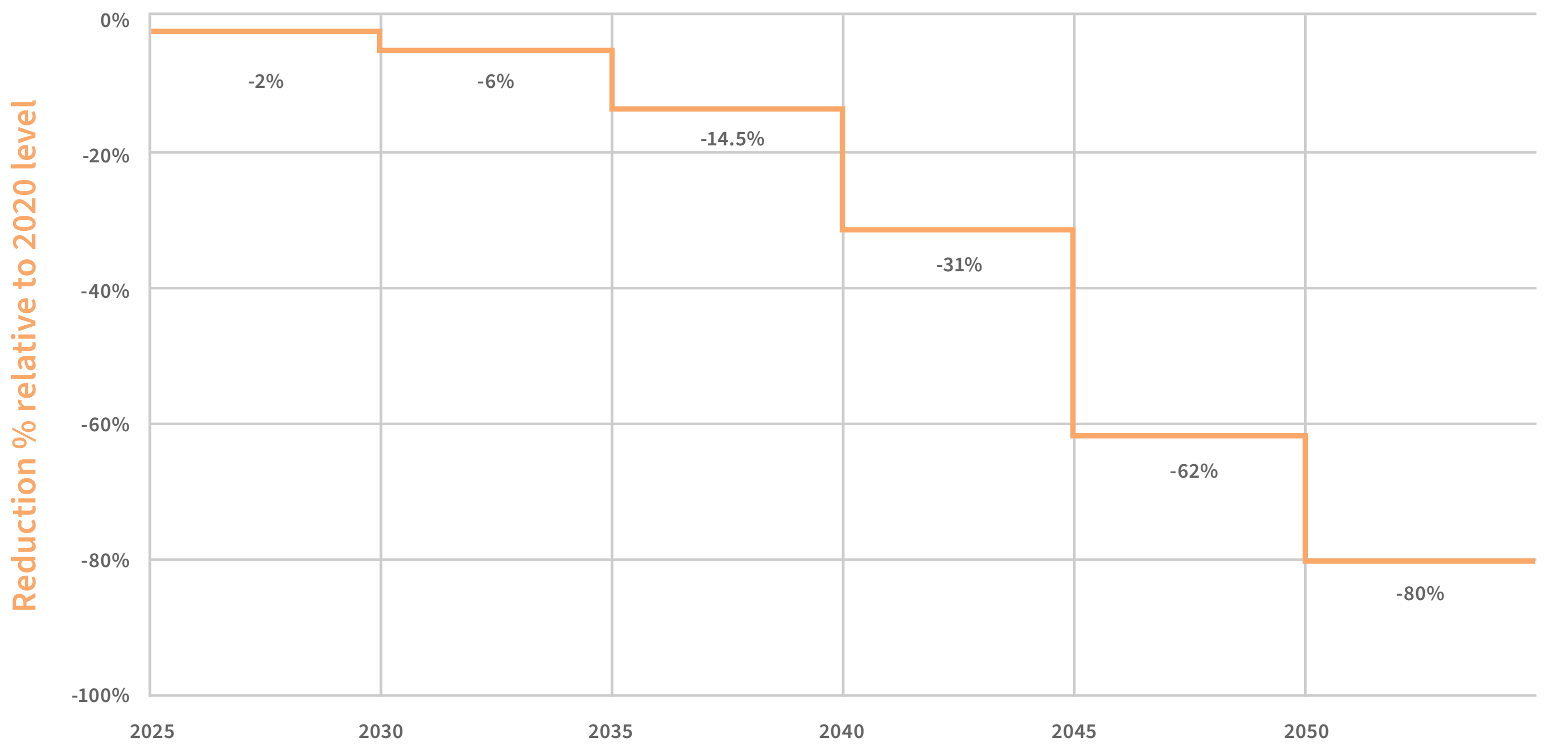
Surrender of allowances for each reported year will be required by 30 September of the following year.

FuelEU Maritime

This regulation will operate in alongside EU ETS and promotes the use of alternative low or zero carbon fuels. FuelEU creates demand for these fuels, noting that the carbon pricing policies in EU ETS (that in part, support improvements in energy efficiency) alone will not be sufficient to meet the EU's target to be a carbon neutral continent by 2050. From 1 January 2025, shipping companies, operating vessels of over 5000 GT calling at EEA ports, are required to meet stepped reductions in the GHG intensity of energy used onboard as shown in the table here, with an additional to have zero at-berth emissions (for container and passenger ships) coming into effect from 2030.

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 Reduction Factor



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

Pooling

Included in the provision of each vessel's FuelEU data is the optional notification of the decision to pool vessels. Pooling allows the responsible owners and managers to bring together vessels that have been operated within a fleet, within a company or among companies. The objective is to encourage the deployment of new vessels using low- or zero-GHG-emission solutions, instead of focusing only on improving the performance of existing vessels. Pooling allows the benefits of one vessel to be shared amongst a fleet to reduce the GHG intensity of the individual vessels. The purpose of pooling is to incentivise the use of and investment in other alternative fuels, including ammonia.

As noted in a 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 vessel 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

The regulation provides a methodology for establishing the GHG intensity of the energy used on board (Annex I of the regulation), with well-to-tank and tank-to-wake calculations. For ammonia, the FuelEU Maritime Regulation provides an emission factor of 0.0186 if the ammonia is e-ammonia.

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).

The IMO has now (at the 80th meeting of its Marine Environment Protection Committee (MEPC)) 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

These reductions are compared to 2008 levels. In addition, there is a target for a reduction in carbon intensity by 40% compared to 2008.

Questions remain as to how this zero-carbon fuel uptake will be reached and how indicative checkpoints can be achieved. This comes down to agreement within the IMO's MEPC on finalising mid- and long-term solutions. They are expected to include both a technical (fuel standard), and an economic element.

The IMO has now completed, agreed, and adopted fuel lifecycle analysis guidelines. These may support the technical and/or economic measures and is a point for further discussion. The Guidelines enable calculation of well-to-tank emissions (the emissions associated with the production and supply of a marine fuel) as well as well-to-wake emissions (also adding in emissions as a result of use on the vessel).

Lifecycle Assessment

Ammonia is not a hydrocarbon. Its combustion on a vessel produces no CO_2 emissions. However, other factors need to be considered when choosing to use ammonia as a fuel. The first is the fuel pathway, the production and supply of ammonia to a vessel. Currently, most ammonia is made through the production of hydrogen by reformation of natural gas, a process leading to the production of CO_2 emissions. The Haber-Bosch process, where hydrogen is combined with nitrogen, is also energy-intensive, with associated GHG emissions. Thus current (grey) ammonia is not considered a suitable source of ammonia fuel.

Green ammonia requires green hydrogen for production plus a source of green electricity for the Haber-Bosch process. Blue ammonia requires the CO_2 emitted in the stages of production (whether during hydrogen production or the Haber-Bosch process where hydrogen and nitrogen form ammonia) to be captured and utilised or sequestered. Ammonia slip and the production of N_2O during combustion then needs to be evaluated. N_2O, sometimes called laughing gas, is a potent greenhouse gas. Another factor in the determination of emissions is the percentage of pilot fuel used, and any emissions associated with that fuel. Experts suggest pilot fuel would be a minimum of 5%, increasing to 15% when a dual-fuel engine operates on lower loads.

Lifecycle Assessment (LCA) guidelines (and how they are applied by regulators) determine how each specific fuel is treated under any market-based measure. They have a crucial influence on shipowner investment decisions. The high-emission factor for blue ammonia in EU regulations and IMO LCA guidelines could make it a challenging fuel for owners to use. From a well-to-wake perspective, blue ammonia would not generate emissions reductions. Owners wishing to utilise ammonia need to secure a supply of verified green ammonia produced from renewable electricity. While nations are ramping up renewable electricity generation, and with it the production of green hydrogen, it will take time for sufficient supply to lead to widespread availability of green ammonia as a fuel.

LR foresees improvements in the process of producing ammonia that will improve its lifecycle GHG intensity. However, indications are that blue ammonia, produced from fossil fuels with direct carbon capture, will not offer a significant lifecycle benefit. Current default factors for blue and green ammonia, in IMO Lifecycle Assessment guidelines and FuelEU Maritime taxonomy, do not use the latest lifecycle data. Work is underway by industry groups to include more up-to-date information.

Well-to Tank GHG intensity factors for ammonia, IMO (proposed) and EU (published)

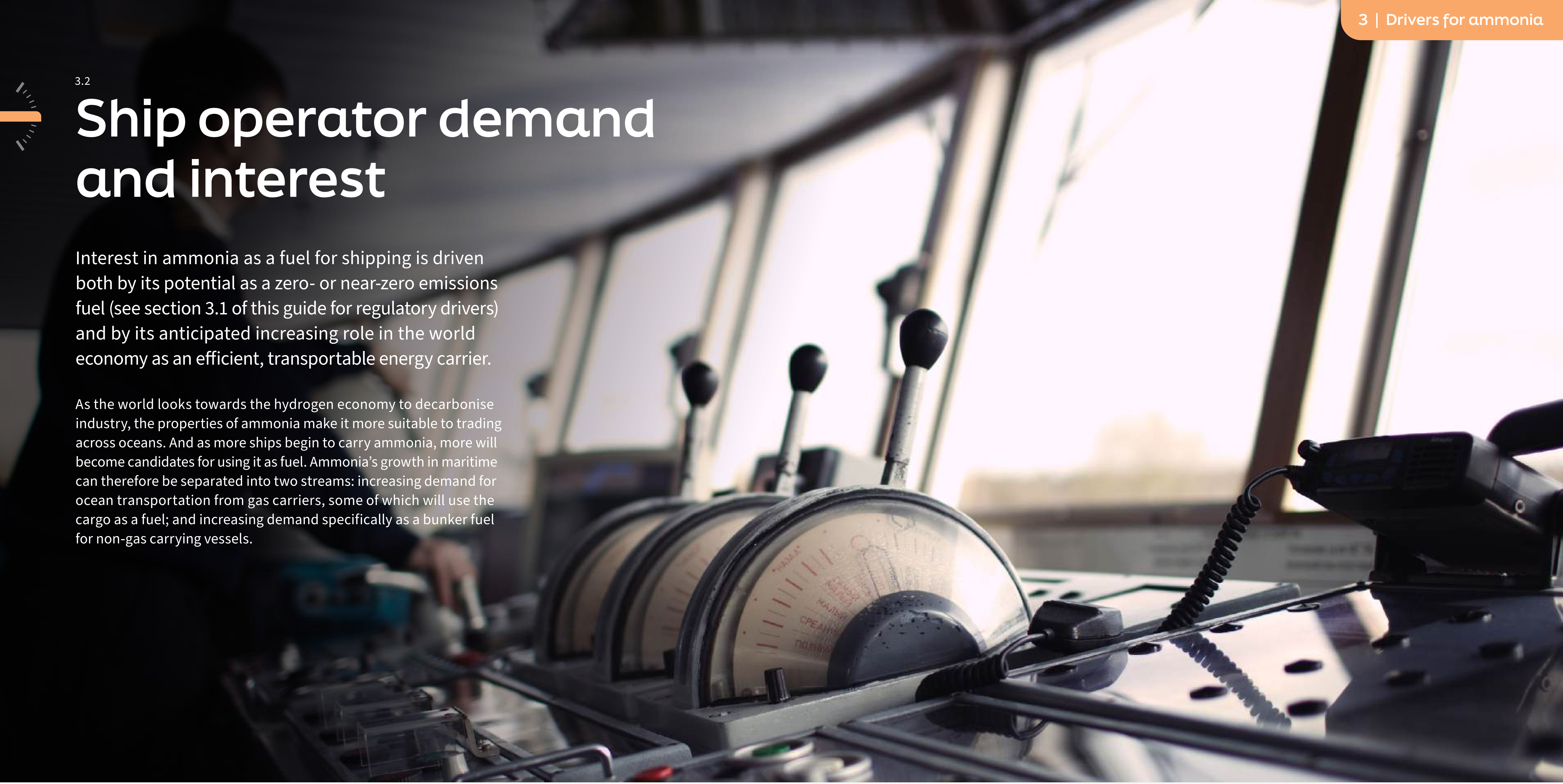
Source	Feedstock type	Nature/ Carbon Source	Process type	Energy used in the process	Proposed WtT default emission factor (gCO_2eq/ MJ(LCV))	Range	Note	GHGWtT (gCO_2eq/MJ) Inferred values
IMO LCA Guidelines	Natural Gas	Fossil	Steam Methane Re-formation of Natural Gas with Point Source Carbon Capture (PSCC), long-term storage and Haber-Bosch process	Grid mix electricity	TBD	TBD	More than three values but not for three sources – further investigation needed	49
	$N_2 + H_2$	Renewable	Haber-Bosch process	Grid mix electricity	TBD	141–239	Data proposed does not all consider renewable sources. Therefore not all appropriate to define the values	239
	$N_2 + H_2$	N_2: separated with renewable electricity H_2: Fossil Steam Methane Reformation	Haber-Bosch process	Grid mix electricity	TBD	TBD	Further investigation needed	61
FuelEU	Natural Gas	Fossil			121			121
	$N_2 + H_2$	Renewable			N/A			N/A

3.2

Ship operator demand and interest

Interest in ammonia as a fuel for shipping is driven both by its potential as a zero- or near-zero emissions fuel (see section 3.1 of this guide for regulatory drivers) and by its anticipated increasing role in the world economy as an efficient, transportable energy carrier.

As the world looks towards the hydrogen economy to decarbonise industry, the properties of ammonia make it more suitable to trading across oceans. And as more ships begin to carry ammonia, more will become candidates for using it as fuel. Ammonia's growth in maritime can therefore be separated into two streams: increasing demand for ocean transportation from gas carriers, some of which will use the cargo as a fuel; and increasing demand specifically as a bunker fuel for non-gas carrying vessels.



Oceanic transport demand

Evidencing emerging global demand for ammonia as an energy carrier, a Japanese government roadmap targets the use of 30 million tonnes of fuel ammonia in 2050, starting with co-combustion technologies and phasing out fossil fuels for 100% ammonia combustion. At ports in the Netherlands and Germany, large-scale ammonia crackers have been proposed to meet national hydrogen import demand, with capacities of up to 500,000 tonnes of hydrogen a year – requiring 3.7 million tonnes of imported ammonia.

There are challenges to building a value chain for ammonia as an energy carrier and there is a live debate about whether further developing the import/export chain for liquid hydrogen would be more viable. As an example, Japan's plan to co-fire coal powerplants using ammonia would rely on imported ammonia. But a similar effort in Europe failed due to last-mile complications, between the import terminal and the consumer. Specifically, nearby residents in the Netherlands revolted against the construction of ammonia infrastructure.

A report from the University of Manchester's Tyndall Centre, commissioned by the International Chamber of Shipping, has suggested that 20 large ammonia carriers need to be built per year between now and 2030 to meet transport requirements, adding to the existing fleet of less than 450.

What currently exists is a network of small- and mid-sized ammonia carriers, mostly combined LPG/ammonia carriers. But to meet anticipated increases in demand, very large gas carriers (VLGCs) or very large ammonia carriers (VLACs) would be needed. LR projects the need for around 130 VLACs by 2030, based on demand from Japan's co-firing ambitions. Just under 150 plants would need around 0.5 million tonnes of imported ammonia per year to meet the target of 20% co-firing by that date. The current orderbook indicates less than 80 VLGCs by 2026, not all of which will be ammonia capable, suggesting that this will not be achieved by 2030.

If demand for carriers is not met, or if there is further uptick in demand for ammonia, companies will need to borrow more capacity from the VLGC market. This presents several complexities. Firstly, it will alter the dynamics of the VLGC market in terms of the charter arrangements and rates. Secondly, many of the older large carriers (88,000m^3 or more) cannot carry a full loading of ammonia if not originally specified. This is because the requirements for yield stress of the steel material used in the construction of the tanks and the ships' structure on VLGCs were not intended for ammonia use. As a result, operational restrictions will need to be taken into consideration prior to their use. In addition, such carriers will only be able to transport partial loads. Otherwise investment in enhanced cargo handling and strengthening scantlings will be required.

Finally, there are port restrictions affecting cargo flexibility meaning that, if your last cargo was ammonia, it may be more difficult for the next to be LPG. The L3C information – last three cargoes – required by some terminals means that LPG cargoes will not be accepted if a vessel carried ammonia among its last three cargoes. This is due to the long-lasting retention of ammonia in steel structures.

Marine fuel demand

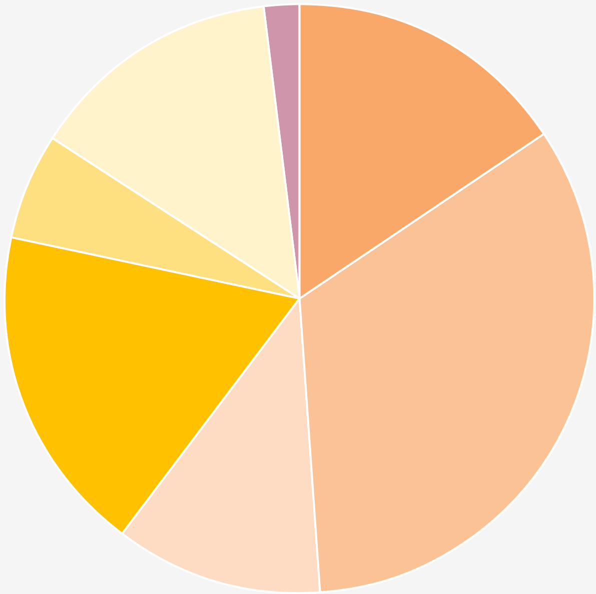
To date, there are no commercial ships in service using ammonia as a fuel, but as engine-makers near completion of the redesign of dual-fuel engines, interest is beginning to grow. This is reflected in the orderbook. Early orders for ammonia-fuelled vessels include two LPG/ammonia carriers for Exmar LPG, to be classed by LR, as well as at least one series of Newcastlemax carriers and a small container feeder vessel. These vessels are expected to enter service in 2025 and 2026. By 2050, IRENA estimates that the maritime sector is expected to consume 197 million tonnes of ammonia as fuel.

In September 2023 Eastern Pacific Shipping signed a Memorandum of Understanding (MoU) with MAN ES, Hyundai Heavy Industries and yards from China Shipbuilding Corporation (CSSC) to develop ammonia engines for fitting in EPS newbuildings (due for delivery from 2026). Lloyd's Register has also signed the MoU with MAN ES.

As well as ammonia-capable vessels, there is also growing interest in vessels ready for conversion to ammonia at a future date. Clarksons data shows 60 ammonia-ready vessels in service and an orderbook of 213. Nearly half (102) of the orderbook currently have tri-fuel options and are being built with options for ammonia and other fuels, with additional capability to use diesel and LNG. There are 24 ammonia-ready containerships capable of also running on diesel or methanol to be delivered.

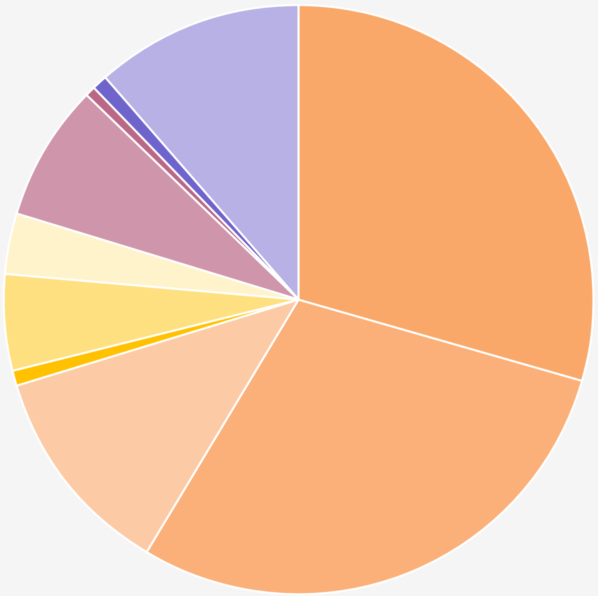
Grimaldi Group now has 15 car carriers with ammonia-ready notations, as has Höegh Autoliners. The latter, a Norwegian company, has eight vessels on order. It has formed a partnership with North Ammonia to help ensure supply of green ammonia.

Ammonia ready vessels by ship type



Source: IHS, Clarksons, Lloyd's Register, as of November 2023

Ammonia ready notations for newbuilding orders



3.3

Techno-economic drivers

Two key challenges for the delivery of green ammonia to the maritime sector must be overcome: allocation of green energy to shipping and creating a verified green supply chain. Traditionally grey ammonia has followed natural gas prices as this is its feedstock.

While there is established ammonia supply chain, there will be demands to verify that green ammonia is delivered to its designated destination for use. Estimates suggest that the cost of producing green hydrogen and the use of green electricity for the Haber-Bosch processes, as well as securing infrastructure links, will put a significant premium on green (e-)ammonia.

Techno economic modelling examples

Given the huge uncertainties for green ammonia costs, the modelling for various ship types remains variable.

Fuel comparisons (shown next) are assumed on the retrofit of vessels and compared to very low sulphur fuel oil (VLSFO) consumption and pricing. Additional costs for planning and undergoing a retrofit, along with lost revenue are not included, nor is the additional capital expenditure of ordering an ammonia dual-fuel (either capable or ready) vessel. However, in a 2022 paper from the European Maritime Safety Authority, the total cost for retrofitting an ammonia-fuelled ship, equipped with a 10–16 MW 2-stroke engine is in the range of $10m–$13m, depending on the type and size of the vessel, original engine and the number of retrofits being undertaken in particular.

Lloyd’s Register is looking at more detailed techno-economic modelling on a case-by-case basis.

3.4

Annual fuel cost predictions

Ammonia low-cost scenario $655/mt, ammonia high-cost scenario $1,200/mt VLSFO carbon tax low-cost scenario $100/mt, CO_2 tax high-cost scenario $350/mt

Modelling does not account for pilot fuel consumption in a dual-fuel engine (minimum 5% of total fuel consumption and rising, depending on operational profiles)

Fuel cost calculations (Difference per annum between VLSFO and green ammonia)

Vessel type	Low-cost scenario (How much more VLSFO will cost with 350/mt CO_2 tax and low green ammonia costing $650/mt)	High-cost scenario (How much more ammonia will cost as assuming $1,200/mt ammonia and CO_2 tax at $100/mt)
Large container ship	$13.7m	$98.1m
Large bulk carrier	$3.5m	$25.5m
Very large crude carrier (VLCC)	$2.5m	$37.0m
Cruise vessel	$18.1m	$129.5m

Reducing the cost gap

The Global Maritime Forum's NoGAPS project optimistically proposes two ways to successfully commercialise an ammonia-powered vessel. It suggests bunkering in the US is more competitive than elsewhere in the world. These geographical cost differences are due to the Inflation Reduction Act (IRA) which makes blue/green ammonia more competitive.

An alternative that the NoGAPS project presents is the option to deploy blue ammonia as a fuel in the beginning of an ammonia-powered vessel's operational life until the cost of green ammonia becomes more competitive. The potential of using contracts of difference, offsetting, and the FuelEU maritime pooling mechanism, are further potential ways to reduce the cost gap. Finally, there is the expectation that charterers would have to bear some of the cost burden of a more expensive fuel.

4.1

Chapter 4: Ammonia production and supply

Introduction

The availability of ammonia as a marine fuel depends on the production of near-zero or net-zero emissions, ammonia in sufficient quantities, with that fuel then being made available to the maritime sector at a cost-per-energy unit that is competitive with other fuels. An antecedent to green ammonia production is the availability of hydrogen produced from renewable sources. This also raises questions around the amount of renewable electricity generation that will be needed to deliver sufficient hydrogen to meet anticipated near-zero and net-zero ammonia demand.

Current ammonia production for fertilisers and chemical use is considered unsuitable because it is made from natural gas without any carbon capture. This renders it more polluting on a lifecycle analysis basis.

The Ammonia Energy Association (AEA) tracks announcements of low-carbon ammonia production projects. Currently, the approximately 230 million tonnes per year installed ammonia production capacity is centred on China and Russia. The vast majority of this global fleet delivers ammonia for immediate fertiliser production, with around 20 million tonnes traded over the oceans each year. But it is not yet known how much of this production will pivot to new markets such as ammonia energy.

Investment in production plants will be needed to ensure clean ammonia can be produced via electrolysis, carbon capture and sequestration, electrification and general efficiency improvements.

The AEA is tracking announced and operational projects totalling more than 245 million tonnes per year of low-carbon ammonia production. The bulk of this is in addition to the existing global fleet, with only 6.5 million tonnes per year of low-carbon production operational today. Most of the announced plants are in new and highly strategic locations: Australia, the Middle East, Africa and North America.

By 2025, more than 24 million tonnes of this low-carbon capacity is scheduled to be on line. By 2030, that figure rises dramatically to nearly 100 million tonnes. Renewable ammonia (or ammonia based on electrolytic hydrogen feedstock) dominates, representing more than 80% of the capacity being tracked by the AEA.

Due to the limited availability of green ammonia for use as a marine fuel, shipowners including Höegh Autoliners have taken steps to secure their supply. Höegh Autoliners has ordered a series of multi-fuel car carriers to run on green ammonia. To ensure steady supply, they have entered into offtake agreements with North Ammonia, a Norwegian ammonia startup.

Further information available in the report Future of Maritime Fuels by the Lloyd's Register Maritime Decarbonisation Hub.

4.2

Production pathways, projects and predictions

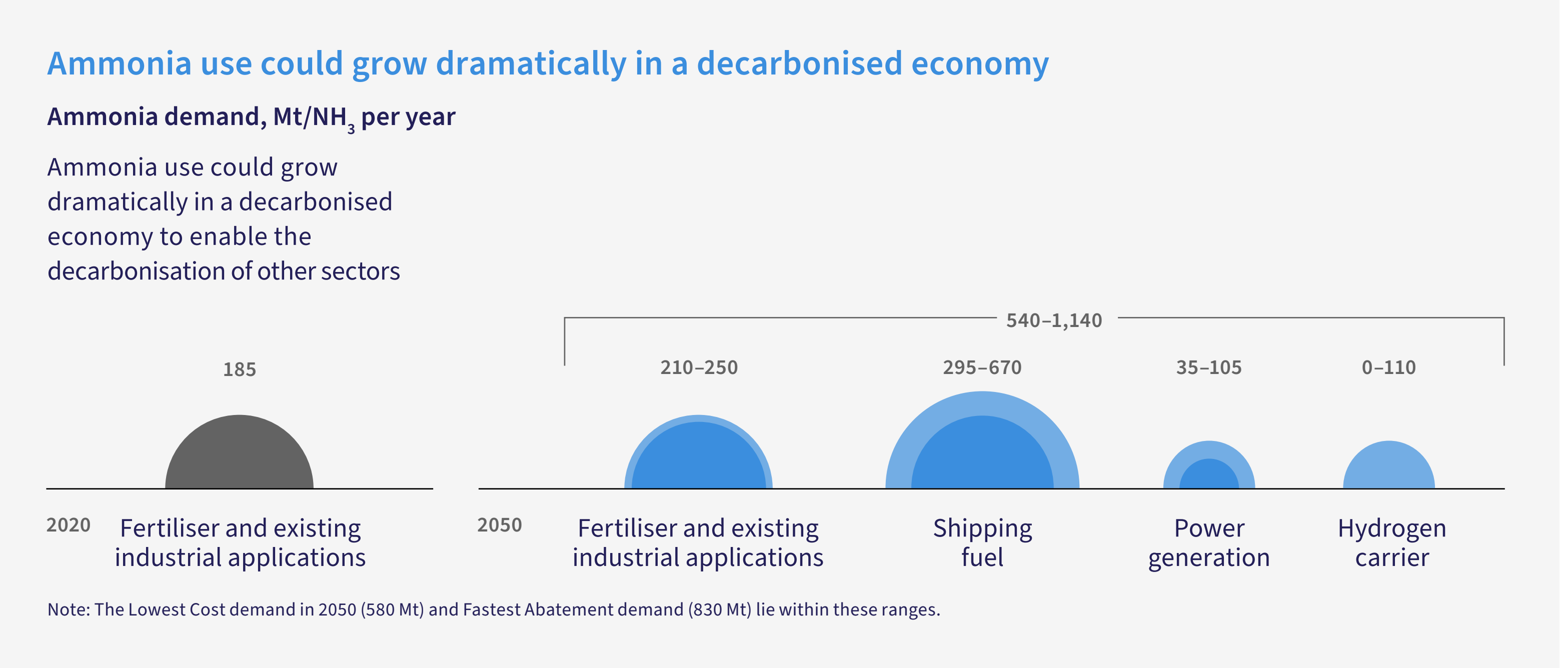
Ammonia producers are investing in green and blue ammonia production, with some announcing intentions to provide ammonia as an energy source for the maritime sector.

Challenges may come from countries which will begin importing green/blue ammonia for power generation. At a Mitsubishi presentation at the First International Conference on Fuel Ammonia (ICFA2021), Japan is estimated to source 30–100 million tons of ammonia (blue or green) by 2050.

Green ammonia production will need to compete for green electricity or green hydrogen, both of which are key components in green ammonia (70% of global renewable energy production according to Casale in 2021). More recently, market analysis firm, CRU, said in April 2023 that blue ammonia is nearing cost viability while green ammonia remains expensive.

In a collaboration with Mission Possible Partnership (MPP) in late 2022, the AEA forecast some fresh numbers on clean ammonia production. MPP forecasts there will be 40–140 renewable ammonia plants operating in 2030, producing up to 20m tonnes of ammonia a year. The numbers climb quickly with the possibility of 1,000 plants around the world by 2050, producing 830m tonnes renewable ammonia annually. The AEA is optimistic about the amount of this being allocated to marine fuel.

Ammonia demand per year (Source: MPP & AEA)



Selected green and blue ammonia production projects

- Yara: A new clean ammonia unit, including shipping business and projected blue/green ammonia production (2020 revenues at $1bn). The company has a deal with Azane Fuel Solutions to build and then supply fuel to ammonia bunkering vessels.
- Mitsui with CF Industries: CF industries has 10 Mt (grey ammonia production) capacity and anticipates producing up to 2 Mt per year of blue and green ammonia at its existing facilities, beginning in 2024. A dedicated blue ammonia production facility is to be developed in partnership with Mitsui on the US Gulf Coast and will be operational from 2027.
- Casale (Ammonia production plants) has developed a synthesis catalyst with Clariant to make blue ammonia).
- Saudi Aramco: Blue ammonia plans with CCS (SABIC) in the Jafurah gas field will enable a blue ammonia hub for export. Its blue ammonia supply chain has been transported to Japan in a pilot shipment and the organisation is also working with CoorsTek and Haldor Topsoe for e-reforming technology.
- Australia: Woodside (LNG producer in Australia) is looking to add ammonia and hydrogen to its business. Plans include renewable hydrogen production (hydropower) in Tasmania to make ammonia for export.
- USA: Grannus, a next-generation ammonia and hydrogen producer says it has been in talks with a US trading company to use blue ammonia. Grannus production involves creating a synthesis gas and uses CCS.
- New Zealand: Energy company Meridian to develop its Southern Green Hydrogen Project, partnering with Woodside Energy and Mitsui & Co. As well as generating green electricity for domestic use, plans include a target of 500,000 tonnes annual green ammonia production.
- Brazil: Unigel to build a green energy plant (10,000 t hydrogen and 60,000 tonnes green ammonia annually).

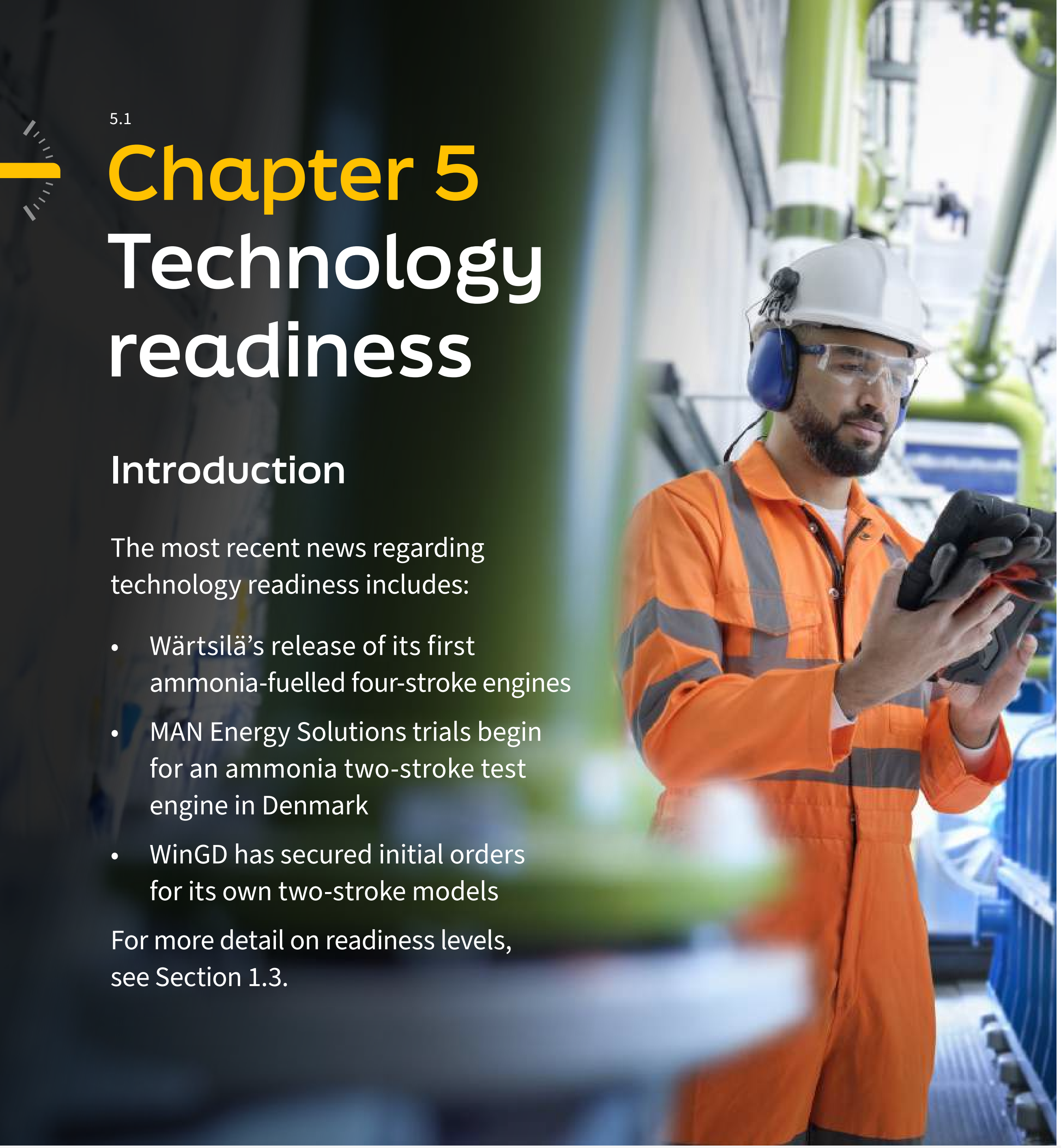
Key milestones in developing renewable ammonia fuel (source MPP and AEA)

	2025	2030	2040	2050
Supply share of near-zero-emissions ammonia	1%	20–42%	88–100%	97–100%
Near-zero-emissions ammonia produced	2 Mt	50–120 Mt	420–660 Mt	560–830 Mt
Number of green ammonia plants*	1	40–140	400–840	560–1,090
Electrolyser capacity for ammonia production	2–3	70–210	590–1,190	780–1,500
Number of blue ammonia plants*	1	15–25	25–180	25–210

*Assumed daily production capacity of 2,000 t NH_3 and 95% capacity utilisation

= 100 Mt; = 100 plants; = 100 GW; = 100 plants

See further production and demand forecasts from S&P here.



5.1

Chapter 5 Technology readiness

Introduction

The most recent news regarding technology readiness includes:

- Wärtsilä's release of its first ammonia-fuelled four-stroke engines
- MAN Energy Solutions trials begin for an ammonia two-stroke test engine in Denmark
- WinGD has secured initial orders for its own two-stroke models

For more detail on readiness levels, see Section 1.3.

Delivering a safe framework for ammonia technology acceptance

LR has assisted multiple marine stakeholders in assuring the safety of ammonia technology concepts, operating frameworks and vessel designs as the industry explores a promising, but challenging, decarbonisation pathway. In September 2023, LR awarded an approval in principle (AiP) to Exmar for its ammonia-fuelled 46,000 m_3 Midsize Gas Carrier (MGC). HD Hyundai Mipo Shipyard was responsible for the ship design, using WinGD's Ammonia Engine, while Wärtsilä Gas Solutions provided all input for the ammonia fuel gas supply system.

In February 2024, Lloyd's Register issued a feasibility statement for component testing towards the marinisation of Amogy's ammonia-to-electrical power system, which cracks liquid ammonia into hydrogen for use in fuel cells. The statement approves Amogy's intended testing plan and builds on approval in principle for the system awarded in 2022.

The Novel Technology Evaluation included an overall examination of the fundamental aspects of the design and compliance with LR's Rules and Regulations for the Classification of Ships and for the Carriage of Liquefied Gases in Bulk (for Gas Ships), incorporating the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).

A risk assessment was also conducted, using Exmar's extensive knowledge and experience of operating ammonia carriers, to ensure that risks arising from the use of ammonia fuel affecting persons onboard, the structural strength, or the integrity of the ship are addressed in accordance with LR's ShipRight Procedure for Risk-Based Certification (RBC). This included a Hazard Identification (HAZID) study which led to the approval in principle.

The ship design and fuel system AiP followed an earlier approval for WinGD's ammonia-fuelled, dual-fuel, two-stroke X-DF-A engine concept – the first such approval for an ammonia engine.

LR ammonia projects list, completed and ongoing, 2019–2023

Year	Project Description	Status
2019	C-Future Zero-carbon 23,000 TEU Concept Design (Ammonia Fueled)	Complete
2019	Zero-Carbon Emission 180,000 DWT BC Concept Design (Ammonia Fueled)	Complete
2020	91,000 m3 NH_3 Fueled Ammonia Carrier VLGC Design	Complete
2021	88,000 m3 NH_3 Fueled Ammonia Carrier VLGC Design	Complete
2021	13,000 TEU LNG Fueled Plus Ammonia Ready	Complete
2021	88,000 DWT NH_3 Fueled Bulk Carrier	In progress
2021	210,000 DWT Newcastlemax NH_3 Fueled Bulk Carrier	Complete
2021	16,000 TEU NH_3 Fueled ULCS	Complete
2021	5,900 TEU NH_3 Ready Container Vessel HAZID	Complete

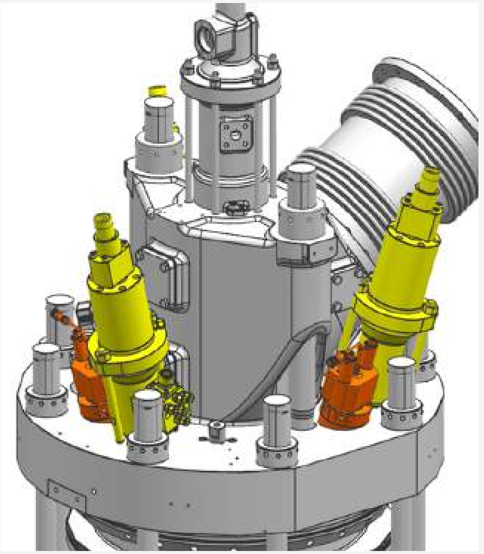
Year	Project Description	Status
2022	210,000 DWT Bulk Carrier NH_3 Ready	Complete
2022	16,000 TEU NH_3 Fueled Container Vessel	In progress
2022	NH_3 fuel Aframax Tanker (included Risk Assessment)	In progress
2022	NH_3-fitted VLCC and NH_3-fitted Suezmax	Completed
2023	NH_3 fuel Ready VLCC	Completed
2023	NH_3 fuel MR Tanker	In progress
2023	86K NH_3 Carrier (NH_3 Fueled)	Completed
2022	46K NH_3 Fueled LPG/NH_3 Carrier	In progress
2023	NH_3 FSRU Design	In progress

5.2

Marine engines and conversions

Wärtsilä has launched a small ammonia-fuelled four-stroke engine, while other leading engine makers (MAN Energy Solutions and WinGD) are developing dual-fuel two-stroke ammonia engines. A key characteristic of ammonia is the difficulty in creating consistent combustion in an engine, so the fuel will always require a pilot fuel to be mixed.

If the pilot fuel is an ordinary diesel or fuel oil, it would have a negative impact on the emissions factors for vessels operating on ammonia fuel. This leads to the conclusion that the pilot fuel would also need to be sustainable in the future for net-zero emission goals to be achieved.



Change to WinGD X52DF-A ammonia injection

MAN ES ammonia fuel injection

MAN ES ammonia dual fuel cylinder cross-section

Two stroke engines

WinGD announced in July 2023 that it is on track to deliver its X-DF-A two-stroke ammonia engines in 2025. The company has already publicised orders in two bore sizes, to power two ammonia carriers to be built for Exmar LPG and a series of 210,000 DWT bulk carriers being built for Bocimar. Lloyd's Register has issued an approval in principle for the engine design, covering engine sizes for most deep-sea fleet vessels.

WinGD has published technical specifications for its range of new dual-fuel engines, where ammonia is injected into the engine and a pilot fuel is used. The engine will be IMO NOx Tier II compliant and require Selective Catalytic Reduction (SCR) to achieve Tier III conformance. The company has an MoU with Mitsubishi shipbuilding that will see the X-DF-A ammonia-fuelled engines installed in a range of vessel designs. Mitsubishi will be the vessel designer and complete the fuel chain with its ammonia fuel supply system. WinGD is also co-developing ammonia-fuelled engines, specifically those linked to the Bocimar order, with Belgian group CMB.TECH. More recently, it signed an MoU with Samsung Heavy Industries to develop the X-DF-A with fuel systems.

MAN Energy Solutions has been trialling ammonia fuel in a dedicated test engine at its facilities in Copenhagen and, in summer 2023, announced the initial combustion of single-cylinder engine ammonia trials, a step towards making the engine designs available for licensees to begin construction for newbuilds. Mitsui, a MAN licensee, is now set to build a full-scale test engine which will be delivered to a shipyard for installation in a newbuild in 2024.

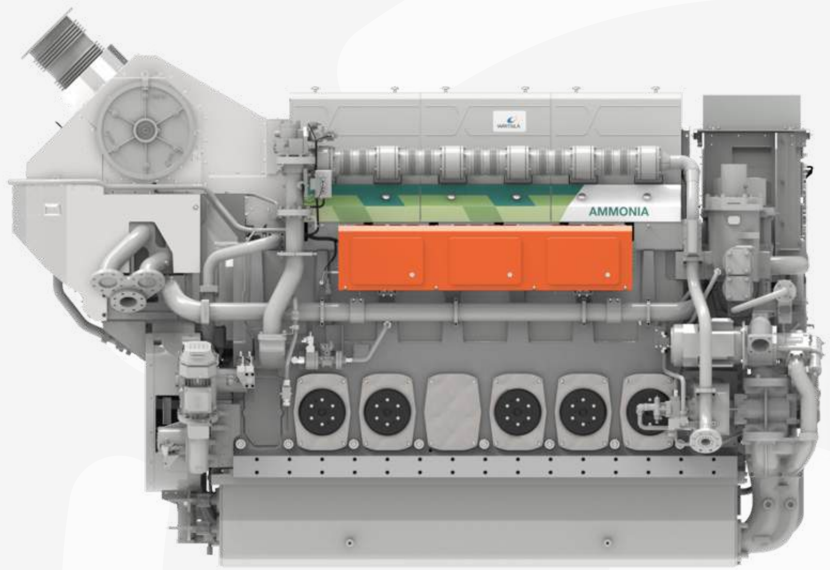
The test engine trials took longer than anticipated to evaluate ammonia bunkering hazards as the facility is situated in a Copenhagen suburb – the trials required a regular supply of ammonia to be bunkered on site via trucks. According to a company spokesperson, the first MAN ES model will be a 60-bore engine, with the delivery of designs for other size engines waiting until the engine maker has secured sea-going service data for the first delivery. There was no indication how long this would take.

MAN ES has also announced that, due to its engines being modular in design, it is also working on providing solutions for existing vessels to have engines retrofitted for dual-fuel ammonia and diesel.

Four stroke engines

Wärtsilä has announced that an ammonia option is now commercially available as part of the Wärtsilä 25 engine platform launched in September 2022. The ammonia engine is based on Wärtsilä's existing engine platform. More ammonia engines are expected to be added to the company portfolio over time. Norwegian shipowner Viridis Bulk Carriers has signed a letter of intent (LoI) for the use of the Wärtsilä 25 ammonia engine, targeting a commercial contract in early 2024.

Wärtsilä is part of a consortium that has $10m EU funds to develop ammonia-fuelled four-stroke engines, and has already demonstrated an engine concept running on a blend of 70% ammonia. In 2020, the company said it had commenced full-scale ammonia engine testing in Norway thanks to $2m funding from the Norwegian government.



5.3

Fuel tanks and other fuel systems

Fuel tanks

The ammonia storage and supply systems consist of the following:

- Ammonia bunkering station and storage (fuel) tanks
- Ammonia fuel supply system
- Fuel valve unit
- Ammonia piping system
- Venting system
- Ventilation system
- Nitrogen supply system
- Ammonia release mitigation system

Most important of these is the ammonia release mitigation system – it ensures any release of ammonia is mitigated to safe levels. To provide the same amount of energy, liquid ammonia requires about 2.8x more storage volume than marine gas oil, due to its lower heating value.

Fuel tank location and design considerations

Ammonia tanks will be able to store the ammonia as a liquid at a temperature of -33°C. There are requirements for protection against mechanical damage during a vessel's operation, as well as considerations for spills and leakage. Due to its toxicity, venting of ammonia to the atmosphere is not permitted, so fuel supply design also requires vapour return lines.

Ammonia can be stored in Type A, B and C tanks that are independent of the ship's structure. It can be also stored in membrane-type tanks suitably adapted to ammonia.

IMO Type A: Non-pressurised prismatic design with additional barrier, often used for LNG and other gas cargo carriage. Type A tanks will have additional anti-sloshing characteristics, notably longitudinal barriers.

IMO Type B: Non-pressurised spherical design with a partial secondary barrier.

IMO Type C: Pressurised tanks often deployed on smaller vessels and found on deck. Type C tanks do not need an additional barrier. Type C tanks can store gases at higher pressures than Types A and B.

Ammonia fuel tanks are required to have material properties that are not susceptible to stress corrosion cracking (SCC). The tank structure will also need to take into consideration impact loads at all filling levels.

Tanks, whether independent (except Type C) or membrane, will require secondary barriers to help contain possible ammonia leakages. All tank connections, fittings, flanges and valves must be enclosed in a Tank Connection Space (TCS). Ammonia fuel piping requires secondary barriers (double-wall piping) and must be placed away from a ship's side. All arrangements will need to be designed under a Risk Based Approach and different configurations may be available, depending on the ship's type and her own particular arrangements.

Fuel tank manufacturers have been working on developing tanks with multi-fuel capability. In 2021, GTT (Gaztransport & Technigaz), a cryogenic tank specialist, said it was supplying 12,000 m^3 fuel tanks for five container vessels that, while built to be LNG dual-fuelled, are suitable for conversion to ammonia. Other manufacturers of cryogenic tanks are also developing multi-fuel tanks.

Fuel supply system (onboard)

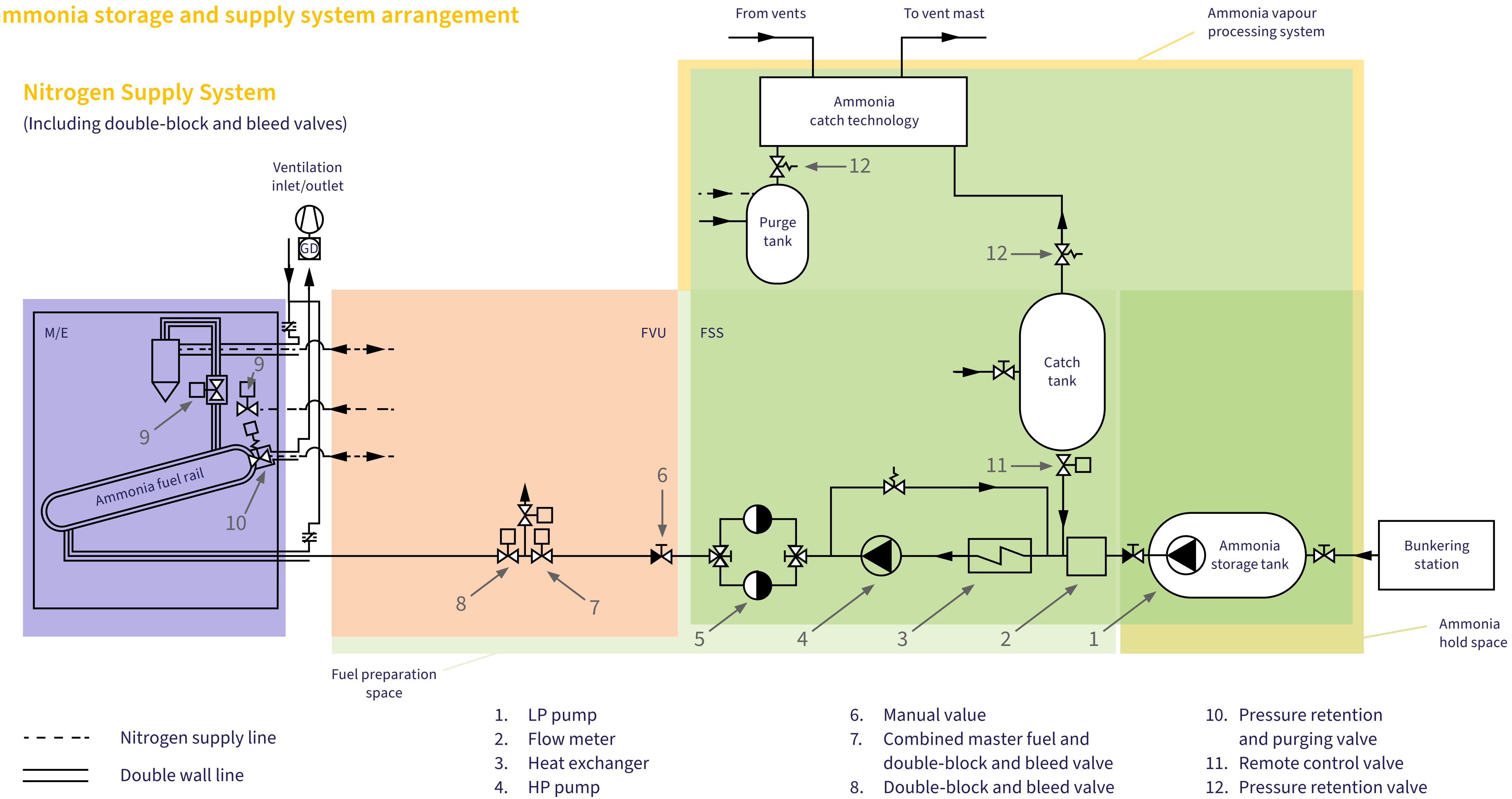
The fuel supply system will include low-pressure and high-pressure supply pumps. The low-pressure pump will be linked to the fuel tank with the high-pressure supply pump (at approximately 85 bar) supplying the engine fuel injection system. A catch tank return line is also needed. Fuel supply pressure depends on engine maker specifications. The fuel supply system will include a heat exchanger to ensure ammonia is supplied into the engine at the correct temperature.

A fuel valve unit, sometimes referred to as fuel valve train, is located outside the machinery space. It incorporates the safety block and bleed functions to isolate the ammonia supply to the engine room and also controls the return of ammonia to the ammonia-nitrogen separator. The shut-off valves need to be remotely and automatically operated and also accessible outside the space where the ammonia fuel supply systems are located.

Ammonia fuel supply systems are currently being developed by suppliers including Alfa Laval, Babcock LGE (ecoFGSS-FLEX), Mitsubishi (AFSS system), Wärtsilä, Hyundai, Samsung and MAN Energy Solutions. Japan Engine Corp is currently testing a fuel supply system for large two-stroke engines at Mitsubishi Heavy Industries test facilities in Japan.

Wärtsilä is developing a patented ammonia release mitigation system (ARMS) and currently working on gaining approval in principle for the system. The treatment system aims to collect and deal with any emissions to the atmosphere other than nitrogen and water vapour. Other options to develop the ammonia release mitigation system also exist.

Example ammonia storage and supply system arrangement



1. LP pump
2. Flow meter
3. Heat exchanger
4. HP pump
5. Duplex filter
6. Manual value
7. Combined master fuel and double-block and bleed valve
8. Double-block and bleed valve
9. Two-way valves
10. Pressure retention and purging valve
11. Remote control valve
12. Pressure retention valve

Nitrogen supply

Due to its toxicity and flammability, ammonia cannot be purged or released into the atmosphere. To facilitate the safe purging of ammonia to the ammonia collection or treatment system, a ship's fuel supply system needs to include a nitrogen supply. Before starting the engine on ammonia, the fuel system will need to be tested for tightness and after stopping the engine, such as in port or in the case of an emergency, the fuel system will be purged with nitrogen and the ammonia and nitrogen stored safely in a purging tank.

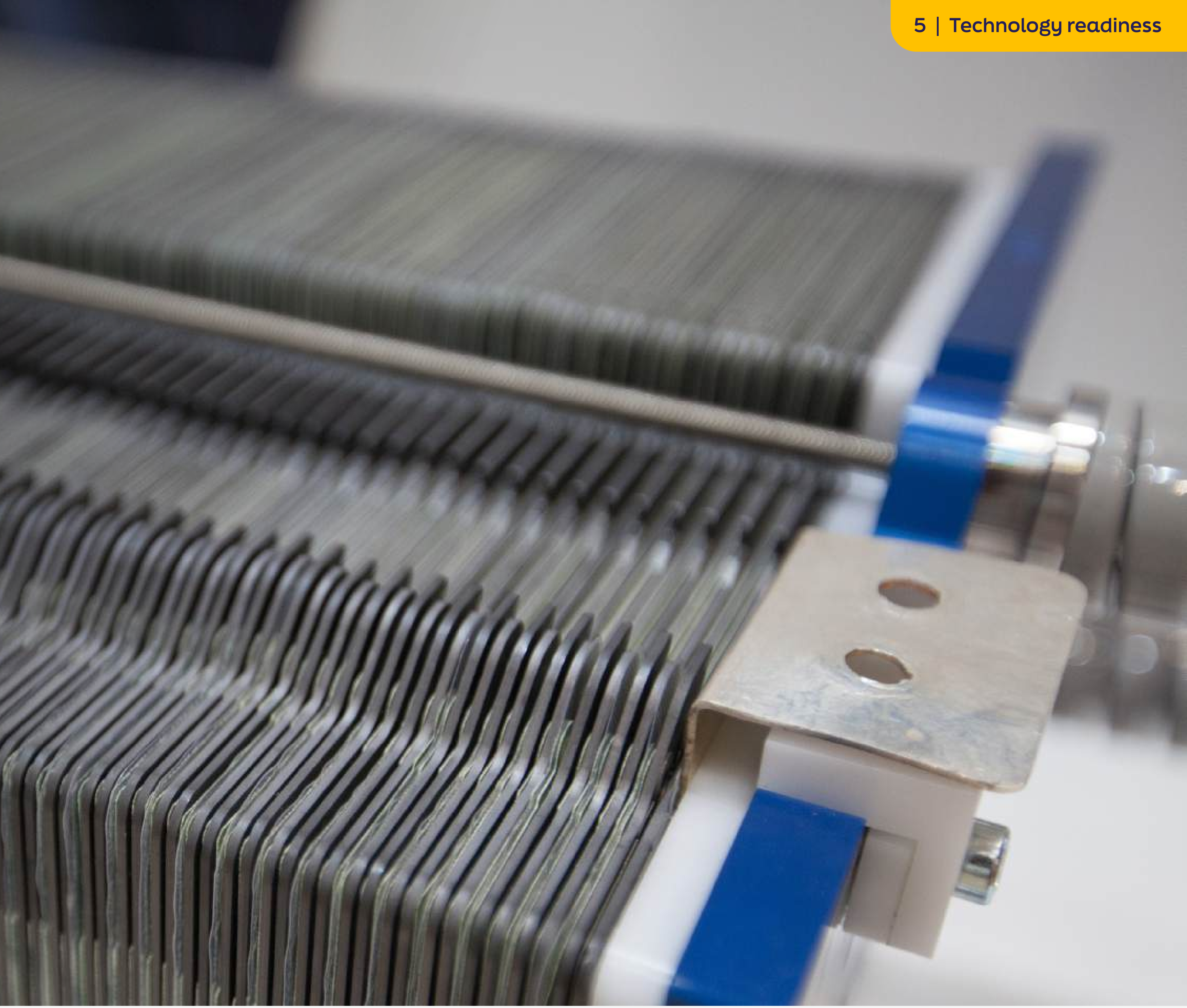
Exhaust emissions

Ammonia dual-fuel engines may require the use of SCR exhaust treatment systems (required for Tier III compliance) to also be used for Tier II NOx compliance. This is due to the higher fuel-bound nitrogen content and the production of NOx during combustion. Requirements will depend on the engine type and combustion technology used. Since existing SCR technologies already utilise an ammonia-based reductant (urea) to react across the SCR catalyst during the NOx reduction process, the use of ammonia as fuel can reduce the quantity of required urea. The SCR can also be used to limit the tailpipe emissions of any slipped NH_3 to acceptable levels. It is foreseen that ammonia slippage from the engine would also be limited as it reacts with the SCR.

Engine designs also need to account for the potential production of nitrous oxide N_2O. N_2O has an atmospheric lifespan of 114 years and a global warming potential of 265, measured across the 100-year timespan used in IMO's Lifecycle Analysis Guidelines. The levels of emitted N_2O will also depend on the engine type and combustion technology. It may be possible to limit these to acceptable levels with the engine control systems. Otherwise additional catalysis to reduce GHG emissions will be required. With levels of NOx, NH_3 and N_2O yet to be quantified, established SCR exhaust aftertreatment technologies can be applied to ensure that any ammonia slip is properly mitigated to a safe level.

5.4

Ammonia reformers and fuel cells



Because ammonia has higher energy density than hydrogen, some see it as a more suitable energy vector as society examines how a move away from fossil fuels can evolve. Using ammonia as a hydrogen carrier means being able to ship ammonia as a cargo and using reformers to convert the cargo at the receiving destination. Similarly, reformers are being developed that can produce hydrogen from ammonia fuel, with the hydrogen being used in fuel cells.

The ShipFC project, a consortium of European research institutions, shipping and technology companies, is assessing whether ammonia can be used in a high temperature ammonia-based fuel cell. The fuel cell maker is Alma Clean Power in Norway, with Fraunhofer IMM working on the catalyst that will remove any pollutants, including unburned ammonia from the fuel cell exhaust. The aim of the project is to demonstrate long-range ammonia use in a solid-oxide fuel cell. Ammonia reforming is a developing technology for hydrogen production, with companies like H2Site and Amogy actively involved in its advancement and commercialisation.

5.5

Ammonia readiness notations and rules

Lloyd's Register has created rules, class notation and general requirements for ammonia in its low-flashpoint fuel rules, under Appendix LR2.

These cover elements from ship design and arrangement through to bunkering, safety, control and monitoring systems.

For more information, visit: Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels July 2023 – R4S.

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Chapter 6
Summary and conclusion

In 2023, engine-makers began revealing their final designs. Shipbuilders will soon be able to complete and install these engines in frontrunner orders. Simultaneously, there is ongoing development in ammonia fuel supplies, with shipping companies securing offtake deals to ensure they have access to a steady supply of net-zero ammonia.

As with other low carbon intensity fuels, pricing of renewable electricity, green hydrogen and carbon capture will all play into ammonia fuel pricing calculations. Clean ammonia producers, whether those creating new plants or incumbent manufacturers seeking to upgrade production to create blue and green ammonia, see potential in increased demand from agriculture and other sectors, as well as from shipping. This will put pressure on supply.

Another key element in ammonia deployment will be the lifecycle assessment of the fuel source to ensure vessels are fully capable of remaining compliant in an uncertain regulatory landscape. Future carbon pricing remains a key determinant in the use of any low-carbon fuel, including ammonia. Production costs remain high and the fuels have lower energy density compared to conventional fuel oils.

LR has proven it has the credentials to support companies pioneering ammonia as a fuel in the field. These include detailed HAZID, HAZOP and quantitative risk assessments, as well as several approvals in principle for vessel designs and technologies and significant technical rule development. As a fuel-agnostic and safety-oriented organisation, LR's aim is to assist in the development of a safe framework for the adoption of the ammonia cargo market and for ammonia's use of other fuels.

There are significant safety challenges to the wider maritime use, and carriage of, ammonia. By taking steps to develop this framework today, LR aims to rigorously address these challenges and avoid delay to the use of a potentially valuable fuel option for decarbonising industry and shipping.

Challenges notwithstanding, demand for oceanic transport of green ammonia as an energy carrier continues to grow. Projections indicate that a significant proportion of the world's merchant fleet will, in the long term, benefit from the use of ammonia as fuel – delivering the first carbon-free power source for global shipping since the (first) age of sail ships.

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Chapter 7 Other resources and annexes

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.

	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

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

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.

	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

Annex 2: Ammonia types

Ammonia colour	Other names	Definition focusing upon production
Black	–	The use of coal as a feedstock, significantly less common than grey ammonia.
Blue	–	Produced from natural gas (see grey ammonia), but by utilising carbon capture and storage (CCS), the overall CO_2 emissions are greatly reduced.
Brown	–	The same as “black” above – terms used interchangeably.
Green	E-ammonia	Sustainable electricity (usually wind or solar) is utilised in its production, emitting the lowest possible CO_2. The most common method for producing green ammonia is using hydrogen (produced from water electrolysis). Ammonia (NH_3) also requires nitrogen for production, this is typically produced through air separation. The hydrogen and nitrogen are then made into ammonia using the Haber-Bosch process.
Grey	–	Has uncontrolled release of CO_2. This production is often based on fossil fuels as raw materials. Usually refers to the use of natural gas which is used to produce hydrogen through steam methane reforming. Ammonia (NH_3) also requires nitrogen for production, this is typically produced through air separation. The hydrogen and nitrogen are then made into ammonia using the Haber-Bosch process.
Pink	Red	Produced using nuclear power (sometimes also referred to as Red).
Yellow	–	The same as green ammonia but using electricity from the national grid.

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