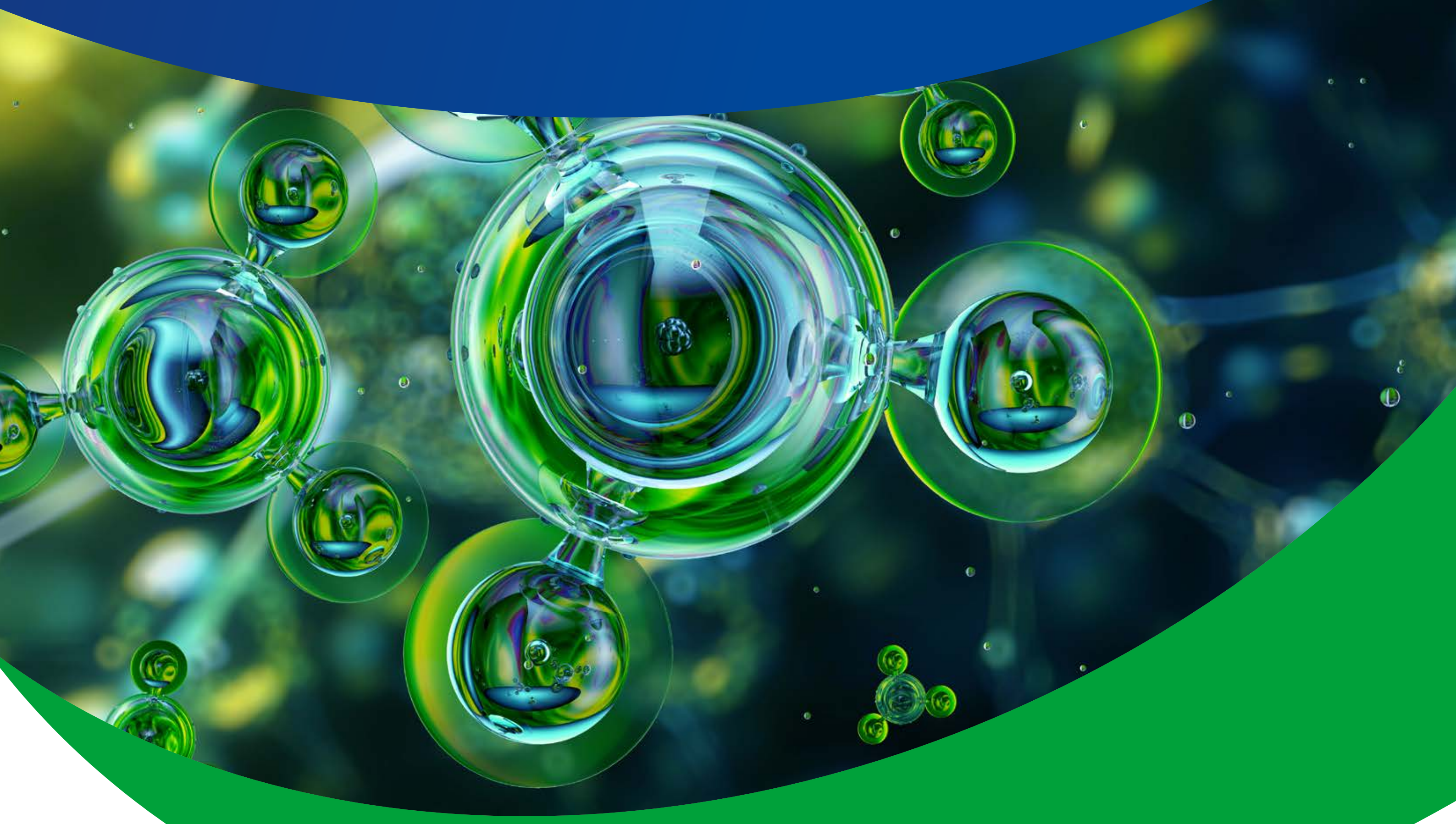
MariNH$_3$

UK National Clean Maritime Research Hub

Ammonia as a sustainable marine fuel: Policy challenges and recommendations

Policy briefing



Authored by:
Dr Laura Norris, MariNH$_3$, Cardiff University
Dr Claire Copeland, UK National Clean Maritime Research Hub, Durham University

This policy briefing results from a collaboration between MariNH$_3$ and the UK National Clean Maritime Research Hub, with contributions from Professor Agustin Valera-Medina (Cardiff University), Dr Steven Begg (University of Brighton), Dr Angad Panesar (University of Brighton), Professor Vladimir Molkov (Ulster University), Professor Dmitriy Makarov (Ulster University), Dr Sergii Kashkarov (Ulster University), Dr Srinivas Sivaraman (Ulster University), Professor Athanasios Tsolakis (University of Birmingham), Dr Alexis Cova-Bonillo (University of Birmingham), Dr Jose Herreros (University of Birmingham), Dr Ben Davies (University of Nottingham), Professor Jon McKechnie (University of Nottingham) and Professor Alasdair Cairns (University of Nottingham).

The authors would like to thank Department of Transport, Maritime and Coastguard Agency, the Department for Energy Security and Net Zero and the MariNH$_3$ Steering Committee who all provided comments and guidance on contents and drafts. The views expressed in this Policy briefing are those of the authors and should not be taken to represent the views of the UK Government.

Issued: March 2026

DOI: https://doi.org/10.17639/21E2-E926

MariNH$_3$ is funded by the Engineering and Physical Sciences Research Council [grant number EP/W016656/1]

The UK National Clean Maritime Research Hub is funded by the Department for Transport as part of the UK Shipping Office for Reducing Emissions (UKSHORE) Programme and the Engineering and Physical Sciences Research Council [grant number EP/Y024605/1]

MariNH$_3$ marinh3.ac.uk
UK National Clean Maritime Research Hub clean-maritime-research-hub.org

Suggested citation:

Norris, L., Copeland, C. (2026). Ammonia as a Shipping Fuel: Policy challenges and recommendations. Policy Briefing. MariNH$_3$ & UK National Clean Maritime Research Hub.

DOI: https://doi.org/10.17639/21E2-E926

The MariNH$_3$ partnership

Funded by

Executive summary

Shipping plays a vital role in our everyday lives, carrying the goods and products that keep our society running. However, ships still predominantly rely on fossil fuels, and the sector makes a significant contribution to global greenhouse gas emissions. As countries work to transition to a low carbon economy, the shipping industry is under increasing pressure to use alternative fuels.

One option gaining attention is green ammonia, a fuel that could help cut emissions while building on existing industrial systems. This briefing, drawing on research from MariNH$_3$ and the UK National Clean Maritime Research Hub, explains what green ammonia is, why it matters, and the policy actions needed to support its safe and effective use in the future.

Ammonia (NH_3) is a well-established industrial-scale chemical with a long history of use in refrigeration, cleaning products, chemical manufacturing, textiles and plastic for nylon production, pharmaceuticals, water treatment and in agriculture as a fertiliser. As a result, ammonia has a mature global supply chain. Its ease of storage – it becomes a liquid under slight pressure at ambient temperature – combined with well-established industrial handling practices make it a strong candidate for use as an alternative low carbon fuel.

The UK government's Maritime Decarbonisation Strategy has set an ambitious target of zero greenhouse gas emissions by 2050 with no out-of-sector offset. The UK government shows global climate leadership by being among the first nations to legislate national emissions targets, and has national missions for clean energy, economic growth and job creation. These ambitions align strongly with green shipping leadership. However, realising the potential of alternative low carbon fuels will require coordinated industry and government (national and local) action to address technical, safety and policy challenges. This includes investment in renewable-powered ("green") ammonia production, the development of bunkering infrastructure at strategically important ports, continuing to support international maritime framework negotiations, and through domestic regulation and incentives.

In this briefing we explore the policy implications of using green ammonia through three interconnected challenge areas: using ammonia as a shipping fuel, green ammonia supply, and safety considerations. A summary of our policy suggestions for the three challenges areas is given in Table 1.

Table 1: Policy recommendations for green ammonia as a shipping fuel

Ammonia as a fuel	Green ammonia supply	Safety management
Carbon pricing with ratchet thresholds to encourage shift to zero carbon fuels	Capitalise on ammonia and hydrogen's shared infrastructure requirement	Government support for skills and safety training in the new use of ammonia
Fuel standards based on whole life cycle (Well-to-Wake) and additional greenhouse gases (not just CO_2)	Green Shipping Corridors with ammonia fuel could encourage development of supply	World class safety standards should be maintained
R&D for nitrous oxide and ammonia leakage mitigation technologies	Strategic planning around which ports to provide incentives for development of ammonia bunkering facilities	Communications campaign for public acceptability of ammonia as a fuel

Contents

Glossary

Blue ammonia: Produced with fossil fuels coupled with carbon capture and storage

Bunkering: Supplying fuel for use by ships

CCS: Carbon Capture and Storage

CH_4: Methane

CII: Carbon Intensity Indicator

CO_2: Carbon dioxide

COSHH: Control of Substances Hazardous to Health

Cracked/cracking: A chemical process that decomposes ammonia into its constituent elements of hydrogen and nitrogen

E-fuel: Fuel produced using electricity

EEDI: Energy Efficiency Design Index

EEXI: Energy Efficiency Existing Index

EU: European Union

GHG: Greenhouse Gas

Green ammonia: Ammonia produced with renewable energy

Grey ammonia: Ammonia produced from steam-methane reforming typically from natural gas

H_2: Hydrogen

IGF Code: International Code of Safety for Ships using Gases or other Low-flashpoint Fuels

IMO: International Maritime Organisation

ISO: International Standards Organisation

LCA: Life Cycle Analysis

LNG: Liquid Natural Gas

MDO: Marine Diesel Oil

N_2O: Nitrous Oxide

NH_3: Ammonia

NO_2: Nitrogen Dioxide

NOx: Nitrogen Oxides

RFNBO: Renewable Fuels of Non-Biological Origin

TRL: Technology Readiness Level

TtW: Tank-to-Wake

WtT: Well-to-Tank

WtW: Well-to-Wake

Introduction

The purpose of this policy briefing is to set out the challenges and policy recommendations for the adoption of green ammonia as an alternative shipping fuel. In the next three sections we explore these principal challenge areas:

- **Challenge #1** Ammonia as a fuel
- **Challenge #2** Green ammonia supply
- **Challenge #3** Safety management

We first provide an overview of the current policy and regulation landscape within the UK and elsewhere to identify salient opportunities to encourage adoption. Then following the discussion of each of the challenge areas we make the case for policy opportunities in the Policy Recommendations section.

Policy and safety regulations

Legislation and policy instruments can fulfil multiple objectives in industry transformation. For example, safe limits can be set to limit harms to the workforce, the wider public and the environment, also financial or other penalties for non-compliance can be included. Policy and regulations can stimulate innovation and encourage the uptake of new technologies through market incentives or research and development funding. In this way, the role of policy, regulations and legislation in the development of sustainable innovation are well recognised. It is noted too that policy can have lasting impacts that may not lead to optimal outcomes; this is due to system complexity that makes for difficulties in being able to adequately control, assess, evaluate and predict outcomes[1].

Nevertheless, there are international efforts through the United Nations' International Maritime Organisation (IMO) to decarbonise the maritime sector with aims of net zero greenhouse gas emissions by 2050. Currently the IMO has implemented a raft of "short term" measures while negotiations conclude on a global framework for net zero emissions. These short-term measures focus on existing and new vessel energy efficiency and operational carbon intensity. These measures are referred to as the Energy Efficiency Design Index (EEDI)[2], Energy Efficiency Existing Index (EEXI)[3] and the Carbon Intensity Indicator (CII)[3]. EEDI and EEXI apply to ships weighing more than 400 gross tonnes and CII applies to ships weighing more than 5,000 gross tonnes. With the CII, ships are given a rating A-G and need to achieve rating C and above to comply.

Added to these measures there is the UK's Maritime Decarbonisation Strategy[4], and in the European Union (EU) – FuelEU Maritime and maritime extension to the EU emissions trading scheme (ETS)[5], [6]. Both governing entities have, or are introducing, market-based measures expanding their emissions trading schemes to include shipping emissions. FuelEU Maritime takes IMO operational measures further by calculating greenhouse gas emissions intensity from ships on a full life cycle basis ("well-to-wake") and includes methane and nitrous oxide emissions as well as carbon dioxide. Compliance means having an intensity lower than limits set by the EU that become stricter over time. Non-compliance incurs a penalty payment but there are flexible mechanisms that allow for carrying forward a compliance deficit, borrowing compliance from future years and pooling with other ships in a fleet.

Under the FuelEU Maritime regulations ships need to comply with a monitoring and verification process. The penalties and verification process contrasts with the IMO measures that use ratings and require submissions of plans to achieve compliance. FuelEU Maritime targets ports too with the need to provide an onshore power supply for ships from 2030.

Table 2 on page 8 contrasts the level of ambition and some of the policy measures encouraging emissions reduction; internationally through the UN's IMO, regionally with the EU and nationally in the UK. These measures will require shipowners and operators to prioritise energy efficiency measures and a transition to low-carbon fuels such as green ammonia.

Table 2: Comparison of IMO, EU and UK maritime policy measures [2], [3], [4],[5], [6]

Attribute	IMO	EU	UK
Ambition	Net zero by 2050 – interim targets to be agreed	2030: 55% reduction 2050: Net zero	2030: 30% reduction 2040: 80% reduction 2050: Zero emissions No out-of-sector offset WtW basis
Greenhouse gas (GHG) pricing & emissions trading schemes (ETS)	Market based measures under negotiation	EU ETS includes shipping from 1 January 2024 phase-in 100% from 1 January 2026 (intra-EU & 50% extra-EU voyages)	UK ETS includes shipping from 1 July 2026 (UK to UK voyages and at port emissions)
Energy efficiency & fuel standards	EEDI & EEXI for (new & existing) vessel design Carbon Intensity Indicator (CII), CO_2 only, TtW basis Global fuel standard under negotiation	IMO plus FuelEU Maritime GHG intensity with penalties for non-compliance, CO_2 + CH_4 + N_2O, WtW basis	IMO only. No additional UK specific measures Fuel Standard consultation expected in 2026

Table 2 notes:
EEDI = Energy Efficiency Design Index (for new ships)
EEXI = Energy Efficiency Existing Index (for existing ships)
WtW = Well-to-Wake – whole life cycle consideration from extraction through production processes and distribution to consumption
TtW = Tank-to-Wake – consumption of fuel only

Whilst the IMO sets the international baseline, the comparison shows the EU's ambition, and how the UK's approach lags – this reflects the intricacy of multi-level governance and the potential harms to competitiveness in the absence of international frameworks. Other countries are looking to implement similar decarbonisation strategies in the absence of a global framework being adopted. The result is that international shipping is facing overlapping obligations, which is contributing to market stasis as organisations seek to establish their requirements. At the same time there is potential for carbon leakage to regions where weaker policies and regulations are in place.

The EU's policy measures aim to encourage adoption of renewable e-fuels (classified as Renewable Fuels of Non-Biological Origin (RFNBO)) such as green ammonia. And it has signalled that regulations to increase RFNBO could be forthcoming from 2033 if these form under 1% of total fuel consumption by 2031. The UK's expansion of its emissions trading scheme could encourage adoption of renewables to an extent. In the absence of adoption and implementation of the IMO's Net Zero Framework however the outlook of adoption of green ammonia is likely to be patchy, with current measures generally supporting those fuels that might be quickest to market. There is an opportunity with the anticipated UK government's fuel standard as stated in the Maritime Decarbonisation Strategy[4] to support the adoption of renewable fuels.

Carbon pricing and trade compliance is viewed as a key lever in decarbonising shipping through encouraging adoption of alternative fuels[7], [8], [9], [10]. These methods work simply on the avoidance of additional costs associated with using fossil fuels[11]. At the moment, low carbon fuels of a biological origin appear more attractive to achieve compliance within initiatives such as FuelEU Maritime; this is due to costs and regional availability. These fuels are generally considered to be "drop in" fuel since biodiesel, for example, can be used without the need for a costly and complex engine retrofit. Biofuels however come with their own challenges such as land use competition, feedstock cost, diversion of crops for food and infrastructure constraints. These challenges, and the tightening of regulations over the coming years will make e-fuels such as green ammonia more attractive.

Carbon pricing and trade compliance is viewed as a key lever in decarbonising shipping through encouraging adoption of alternative fuels.

International safety legislation for ammonia as a maritime fuel has four key themes: controlling risk, occupational safety, impact on the environment and distribution infrastructure. Existing regulations address these four themes through the SOLAS (International Convention for the Safety of Life at Sea), MARPOL (International Convention for the Prevention of Pollution from Ships) and the IGF Code (International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels). There are also country-specific safety regulations for the use of substances in different contexts. A summary of some of the key safety regulations set by the UK, EU and USA is in Table 3.

Table 3: International Safety Regulations comparison UK, EU & USA[12], [13], [14], [15]

Country	Summary
UK	**Control of Substances Hazardous to Health (COSHH) Regulations:** Under COSHH 2002, employers must assess the risks from hazardous substances such as ammonia, ensure proper handling, provide personal protective equipment (PPE), and implement health surveillance. **COMAH Regulations:** The Control of Major Accident Hazards (COMAH) Regulations 2015 require high-risk industrial sites to prepare safety reports, conduct risk assessments, and establish both on-site and off-site emergency plans. [Aligns with the EU Seveso III Directive] **Marine Guidance Notes Certification:** For vessels using innovative technologies.
EU	**Seveso III Directive (2012/18/EU):** Prevents and limits the consequences of major industrial accidents involving dangerous substances. **Industrial Emissions Directive (IED) 2010/75/EU (EU):** IED ensures that NH_3 plants minimise air and water emissions using Best Available Techniques (BAT), thereby reducing the environmental and safety risks from accidental releases.
USA	**National Fire Protection Association (NFPA) 55 & American Petroleum Institute (API) 751:** These codes provide guidelines for the storage, handling, and piping of anhydrous ammonia, with emphasis on containment, leak detection, and fire protection measures. **Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) – 29 Code of Federal Regulations (CFR) 1910.119:** These standards mandates hazard identification, risk analysis, operating procedures, maintenance of critical equipment, employee training, emergency response plans, and management of change (MoC) for highly hazardous chemicals like ammonia.

Challenge #1 Ammonia as a fuel

The new use of ammonia as a fuel is at the heart of the adoption challenges. There are advantages in ammonia as a low carbon fuel choice, and the engineering side is well developed as discussed in this section. Remaining issues to be tackled are more sociotechnical in nature. This is further discussed in the challenges of supply and safety management. Many of these challenges are not unique to ammonia and arise in the adoption of other low carbon fuels. Here we explore the issues surrounding the use of ammonia as a fuel in terms of storage, ignition, flame stability and pollutants.

Storage

Ammonia can be liquefied at ambient temperatures with moderate pressure or by refrigeration at −33°C[16], [17]. This avoids the need for extreme cryogenic storage required for liquid hydrogen (−253°C) that suffers from boil-off losses and infrastructure limitations. Ammonia has higher energy density measured by volume when compared with hydrogen, though this is still significantly lower than fossil derived fuels, requiring approximately three times more storage space, or more frequent refuelling.

Note that all low carbon fuels have lower volumetric energy density when compared with conventional marine diesel oil to differing extents (see Table 4), and even biodiesel has a lower density to marine diesel oil by 10-12%[18]. This means that it is very important to combine switching to low carbon fuels with energy efficiency improvements. Energy efficiency improvements reduce the quantity of fuel needed for the same distance sailed, thereby saving required onboard storage space.

Table 4: Liquefied fuel comparison[19], [20]

Property	Ammonia (Liquid)	Liquefied Hydrogen	Liquefied Natural Gas	Diesel
Storage temperature (°C)	25	-253	-162	25
Storage pressure (kPa)	1,030	101.3	101.3	101.3
Autoignition temperature (°C)	924	844	538	503
Fuel density (kg/m³)	602.8	70.8	422.6	838.8
Energy density (volumetric) (MJ/m³)	11,333	8,539	20,825	36,403

Table 4 compares some properties of liquefied fuels. Note that these can take other physical forms such as gas (for example, hydrogen and natural gas), which would change the values in the table, particularly storage temperature and pressure (both higher), and volumetric energy density (lower). The last property is a critical consideration when constrained with storage space availability on a vessel and required distance for voyages.

Environmental impact

It is important to consider a wide range of environmental impact categories when assessing the merits of alternative marine fuels and in developing policies. Ammonia, like other fuels, contributes to other environmental impacts such as acidification, eutrophication, air quality and the formation of particulate matter[21]. Release of unburnt ammonia is highly toxic to aquatic animals and would be categorised under ecotoxicity.

The combustion of ammonia as a fuel does not produce carbon dioxide (CO_2), but can produce nitrogen oxides such as nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O) and releases of unburnt fuel referred to as “slip”[22]. These are all harmful to human and environmental ecosystem health, with N_2O having a global

> Releases can be controlled and managed in the combustion process with the development of innovative combustion technologies.

warming potential factor 273 times that of carbon dioxide. Some of these releases occur in the combustion of ammonia involving the recombination of the nitrogen, hydrogen and oxygen in the air. The quantity of all such releases can be controlled and managed in the combustion process with the development of innovative combustion technologies. Innovations include jet ignition, stratification, and spark-assisted compression, to name but a few.

Research conducted by the engine and propulsion systems manufacturers Wärtsilä[1] has shown that engine controls reduce N_2O to a very low level, and this can then be further reduced through exhaust after-treatment. But there are supply chain challenges for the materials used in these treatment systems, such as titanium, molybdenum and vanadium. It is expected that with the application of innovative combustion technologies and after treatment systems the release of nitrogen oxides from the use of ammonia as a shipping fuel will be very low.

Estimates of the life cycle greenhouse gas emissions from the use of ammonia as a shipping fuel have been made, but these vary depending predominantly on the production pathway. Ammonia can be produced by the steam reforming of natural gas, referred to as “grey”, releasing carbon dioxide in the process, or using renewable electricity and electrolysis of water referred to as “green”. (Ammonia production pathways are discussed in more detail in the next section.)

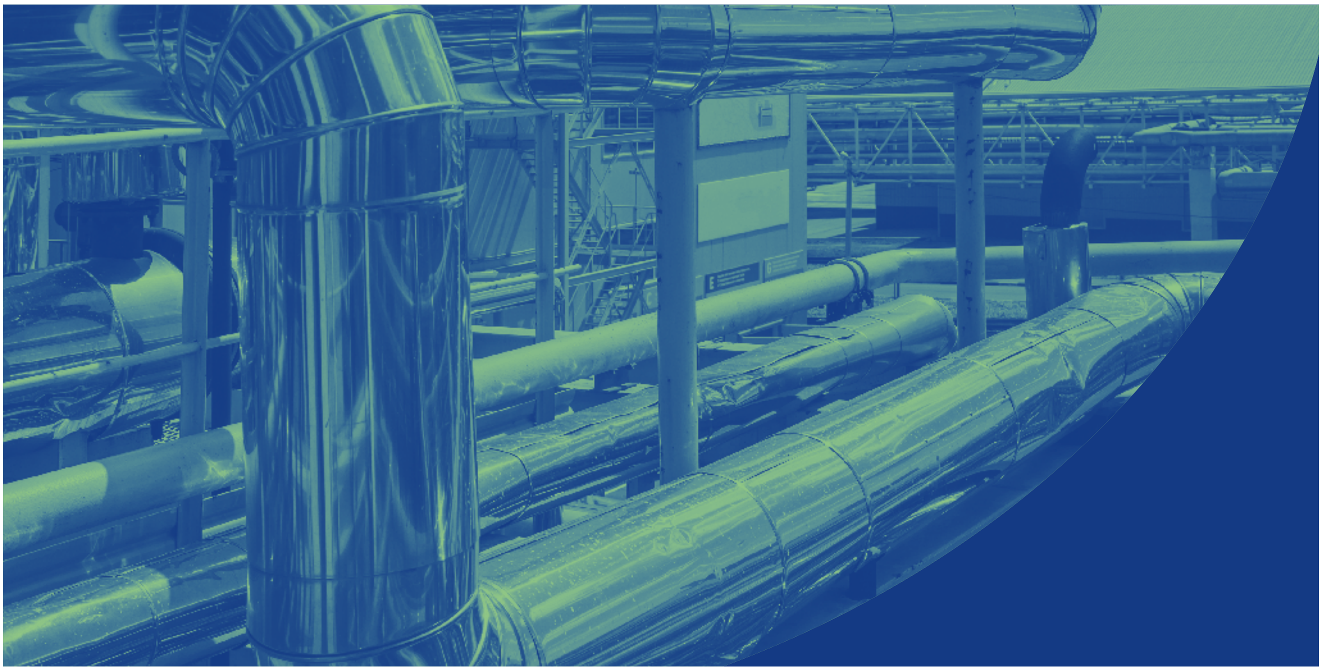
While “grey” ammonia represents no overall emissions savings compared with marine diesel oil, green ammonia can reduce emissions by 80%[23]. Though figures vary depending on scope, system boundaries, and the inclusion or exclusion of embodied emissions associated with infrastructure. When infrastructure is included, it is estimated that the life cycle emissions for green ammonia would increase from 1-8 g CO_2 eq. per MJ to 9-20 g CO_2 eq. per MJ[24]. Location factors, such as wind power availability and hydrogen electrolyser equipment are among the major sources of variation in results.

> Green ammonia reduces life cycle emissions since its production processes do not emit greenhouse gases.

Green ammonia reduces life cycle emissions since its production processes do not emit greenhouse gases. The anticipated introduction of well-to-wake (whole life cycle) emissions accounting by the IMO, as well as the tightening

---

[1] 'Ammonia-powered future: introducing Wärtsilä 25', CIMAC Congress 2025. Available: https://papers2025.cimaccongress.com/pdf/CIMAC_paper_528.pdf



over time of national and regional policies such as the UK and EU, is expected to improve green ammonia's cost competitiveness when compared with conventional fuels.

Ignition and flame stability

Ammonia has higher energy requirements for ignition and low combustion speed, when compared with other fuels for use in an internal combustion engine (see auto-ignition temperature row in Table 4 on page 11). This results in the need for some method of compensation. One solution is co-fuelling with fuels of low ignition energy and faster burning. This "pilot" fuel could be a conventional fuel like diesel, but note that this will have associated contribution to climate change and other environmental impacts[25].

Another solution is the use of hydrogen as a pilot fuel which has very good ignition characteristics. The hydrogen could be extracted, or "cracked", from the ammonia itself. However, engine combustion design solutions to poor ignition issues require complex retrofit changes on existing ships. It is expected that blends of ammonia (including with conventional fuels) are more likely to be used in the short to medium term.

One option in the short to medium term is for the ship to be capable of running on conventional fuel and ammonia – "dual-fuel". It is possible to switch between fuels and reduce greenhouse gas emissions from the overall voyage[11]. This provides flexibility to ship owners and operators in making fuel choice decisions dependent on price, availability and respective legislation or taxation measures. While dual-fuel engines capable of using ammonia are emerging, operational experience so far remains limited.

> The combustion of ammonia utilising existing infrastructure and retrofit offers a more immediate path to decarbonisation.

The future of alternative fuels is likely to include fuel cell technology; this will be more energy efficient and produce less emissions. However, combustion of ammonia utilising existing infrastructure and retrofit offers a more immediate path to decarbonisation, certainly in the short to medium term. This said, retrofitting existing vessels and developing efficient propulsion systems will demand significant R&D and policy support.

Challenge #2
Green ammonia supply

This section outlines the challenges of green ammonia supply through production processes and associated economic aspects. In brief, there are supply and demand co-ordinated issues within the green ammonia industry. These marketplace challenges are being faced by all the renewable electricity derived synthetic fuels, electro- or e-fuels, such as green ammonia, and many of the hurdles to be overcome are typical for emerging technologies. As a technology develops and is increasingly deployed, it would normally be expected for costs and challenges to reduce.

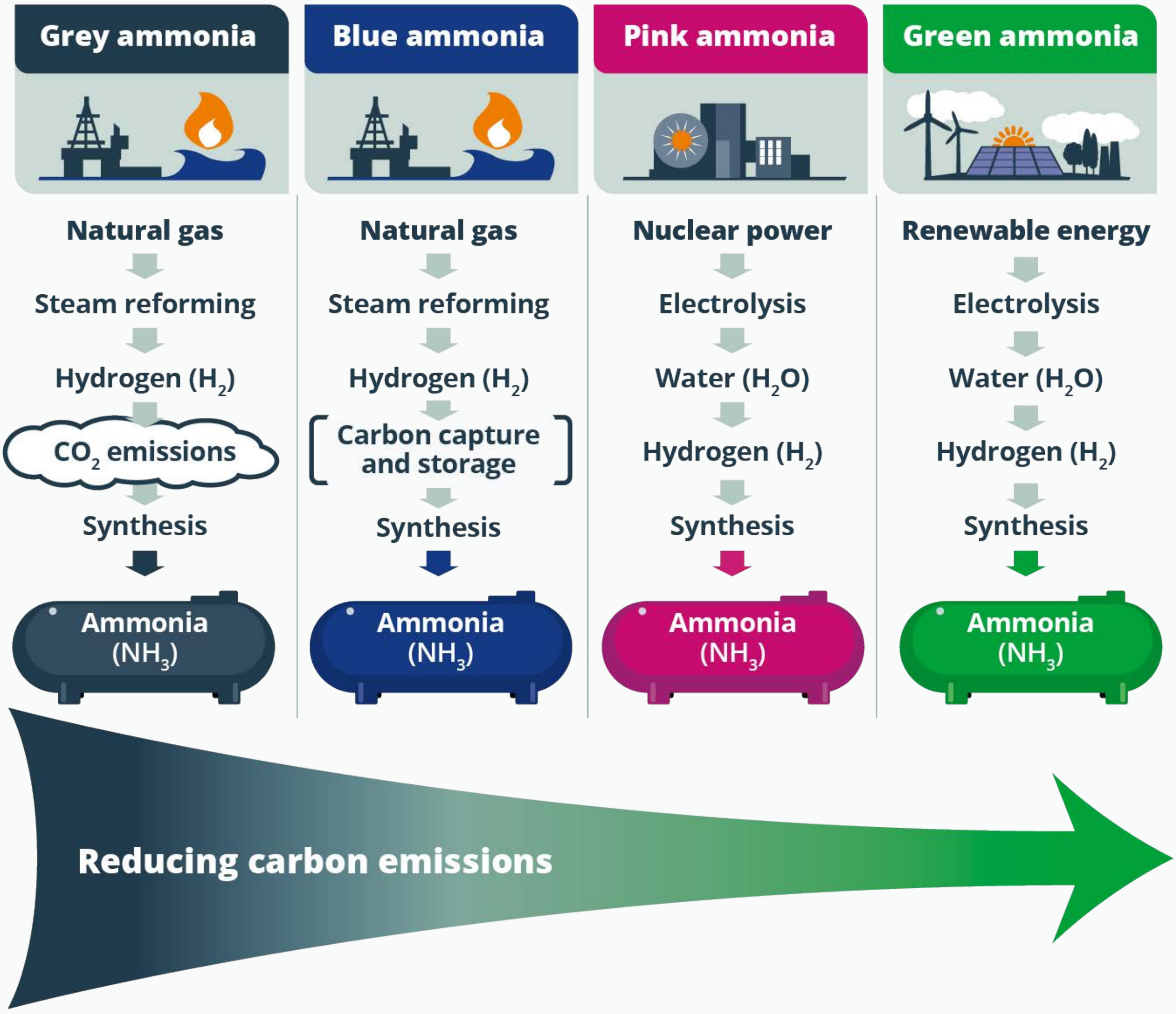
Production

The main source of carbon dioxide emissions in conventional ammonia comes from the production of its input – hydrogen – through steam methane reforming of fossil fuels such as natural gas. The hydrogen is then combined with nitrogen to make ammonia in what is called a Haber-Bosch process. The Haber-Bosch step requires high temperature and pressure and is an energy intensive process relying on fossil fuels.

This type of ammonia production is referred to as "grey" ammonia and contributes to almost 2% of GHG emissions[26]. "Green" ammonia is where the hydrogen input is produced through renewable electricity (such as from wind or solar sources) and water in a process called electrolysis. The Haber-Bosch process is then powered by renewable electricity rather than fossil fuels. This green production pathway for ammonia produces an alternative fuel that is carbon free in production and consumption but currently accounts for less than 1% of global supply. However, the market for green ammonia (currently $557 million) is growing rapidly and could be worth $74 billion by 2033, representing a year-on-year growth of c.74% over the period 2025-2033[27].

A further type of ammonia referred to as "blue" ammonia, is produced in the same way as "grey" ammonia but with carbon capture and storage technology, and "pink" ammonia using nuclear energy with electrolysis. Figure 1 illustrates the different routes to producing ammonia.

Figure 1: Ammonia production pathways



Ammonia's potential as a zero-carbon fuel has spurred projects globally with some countries declaring ambitions to become leading green ammonia suppliers. This includes Singapore, the world's largest fuel bunkering hub, which is leading initiatives to establish a comprehensive ammonia supply chain. The consortium; A.P. Moller – Maersk, Keppel Offshore & Marine, and the Sumitomo Corporation, is conducting feasibility studies to develop ship-to-ship bunkering operations in Singapore[2]. Similarly, the Port of Rotterdam is exploring ammonia bunkering solutions, collaborating with industry stakeholders to facilitate safe and efficient fuel supply[3].

In Australia, a global consortium comprising Mitsui O.S.K. Lines, Yara, and the Global Centre for Maritime Decarbonisation successfully executed the world's first ship-to-ship ammonia cargo transfer at the Port of Dampier[4]. These are but a few of the ammonia projects taking place internationally.

> Ammonia's potential as a zero-carbon fuel has spurred projects globally, with some countries declaring ambitions to become leading green ammonia suppliers.

Ammonia is considered as having another useful role – as energy storage. Recent research has focused on how to capture and make use of when renewable electricity supply is in surplus, i.e. when supply exceeds demand[28]. At these times the surplus renewable electricity is not captured, and the wind or solar farm's production is limited – referred to as curtailment[29]. Much of the thinking in this area has considered battery storage or utilising this surplus energy for producing hydrogen to use, for example, as a replacement for natural gas in heating systems. Another attractive proposition is going a step further and producing ammonia – using its favourable storage and energy density characteristics – to limit transportation and storage costs.

However, scaling up production requires substantial investment in electrolyser capacity and renewable energy infrastructure. It has been found that co-locating ammonia production and bunkering facilities offers several advantages. Such integration reduces transportation costs and risks associated with moving hazardous materials over long distances. These projects must then address the interconnectivity of production, storage, and supply chain infrastructure.

This means that ammonia can provide other benefits to the energy system through supporting demand and supply management, beyond its use as a fuel or input for fertiliser production. However, the Haber-Bosch process requires a constant source of energy, so for this part of the production process to be based on renewable energy supply requires some innovation around modular or intermittent production.

Indeed, small-scale ammonia production plants can be a sustainable and decentralised solution for fertiliser production and energy storage. These modular units, typically producing less than 200,000 metric tonnes per year, are particularly beneficial for regions with limited access to large-scale infrastructure or where renewable energy sources are abundant. Small-scale production reduces reliance on long-distance transport, lowering costs and improving safety management. As a result, there can be regional economic development benefits that address energy justice aspects such as displaced economic activity that come from industrial decarbonisation.

---

[2] https://www.sumitomocorp.com/en/europe/news/release/2022/group/15790

[3] 'Maritime industry leaders to explore ammonia as marine fuel in Singapore', Maersk. Available: https://www.maersk.com/news/articles/2021/03/10/maritime-industry-leaders-to-explore-ammonia-as-marine-fuel-in-singapore

[4] 'Global consortium pioneers ammonia cargo transfer between ships at Australian port', Reuters. Available: https://www.reuters.com/sustainability/climate-energy/global-consortium-pioneers-ammonia-cargo-transfer-between-ships-australian-port-2024-09-19/

Economics

Pursuing green ammonia as a shipping fuel can provide economic opportunities. The shipping industry operates on long-term supply agreements that can provide certainty of demand. This could be beneficial to commercial and domestic energy customers as it would encourage additional renewable energy capacity building, ultimately bringing down cost of electricity whilst further contributing to decarbonisation of the local economy.

New green ammonia plants can be built where there are abundant renewable energy sources such as wind and solar, and ammonia's potential as an energy store can help mitigate seasonality of demand challenges or in other circumstances where demand exceeds supply[28], [29]. This means that with sufficient capacity building there could be opportunities for regional renewal through replacing carbon intensive industries with greener economic activities.

With increased supply, the costs of these new technologies are anticipated to reduce with market maturity, due to economies of scale and learning, as with other nascent technologies. However, for e-fuel production a large proportion of their cost is from electricity which, in the UK, is high due to reliance on natural gas and associated charging structure[5]. The infrastructure and grid constraints within the renewable energy system present an opportunity for policy measures that seek to link production with the various consumers (electricity, hydrogen, ammonia), this in turn stimulates further renewable energy infrastructure development and investment.

Some illustrative supply costs of ammonia are currently higher than fossil fuels. Blue ammonia costs roughly $365–418 per tonne, while green ammonia is much higher at about $861–1351 per tonne due to its greater electricity demand and higher electrolyser capital costs[30].If, however, the cost of renewable electricity becomes cheaper than $50 per MWh, the cost of producing CO_2-free ammonia from renewable hydrogen could become lower than that from natural gas with carbon capture and storage (the "blue" production type)[31]. In one case study it has been found that where reducing curtailment of renewable electricity this can reduce the cost of green ammonia production by a third[28].

It is expected that blue ammonia is set to become more cost effective than traditional "grey" ammonia in some parts of the world within the next four years as various decarbonisation policies increase carbon costs for companies[32]. Green ammonia is expected to become cost competitive in the 2030s[27].

In the shipping sector, green ammonia enables compliance with tightening emissions standards such as the GHG Intensity Indicator under FuelEU Maritime. Green ammonia is also a candidate fuel for green shipping corridors and can act as hydrogen storage in the case of hydrogen fuelled green shipping corridors. Investing in green ammonia could position the UK as a leader in sustainable maritime innovation, creating opportunities in fuel production, export, port infrastructure, and high-value jobs across the clean energy supply chain.

> Investing in green ammonia could position the UK as a leader in sustainable maritime innovation, creating opportunities in fuel production, export, port infrastructure and high-value jobs across the clean energy supply chain.

---

[5] https://www.carbonbrief.org/factcheck-why-expensive-gas-not-net-zero-is-keeping-uk-electricity-prices-so-high/

Challenge #3
Safety management

It goes without saying that safety is a paramount factor in allowing the green ammonia market to form. There are associated hazards with ammonia such as toxicity, corrosiveness, and potential for high-pressure leaks or explosions which present significant safety challenges. It should be noted however, that there has been handling of ammonia for centuries, meaning that toxicological hazards, flammability, and thermal and pressure effects are well understood in a controlled industrial environment with trained personnel. Here we provide a brief overview of the main types of risk presented by ammonia – toxicity, flammability hazard, and corrosion.

Toxicity

Toxicity is a serious safety risk, and even small leaks can cause immediate harm to people. At higher concentrations this can quickly become life-threatening. In the event of an accidental release, depending on wind and weather, ammonia can spread over hundreds of metres creating risks for vessel crews, port workers, nearby communities and ecosystems. Ships may store and transfer large amounts of ammonia in enclosed or semi-enclosed spaces, meaning that even a minor leakage could lead to dangerous accumulations. To manage these risks, vessels will require strong safety measures, including robust containment, effective ventilation, continuous monitoring and clear emergency procedures supported by trained personnel.

For these reasons, the use of ammonia as a fuel requires a different regulatory approach to traditional fuels. Existing maritime fuel regulations have focused mainly on flammability, but ammonia's toxicity demands an equally strong regulatory framework. This includes updated rules for ship design, storage systems, bunkering operations, leak detection, crew training and personal protective equipment.

Modern modelling tools and safety assessments are essential to support effective regulation and to ensure that designs and procedures are proven to keep people and the environment safe. By developing these measures early – through research, standards, and clear regulatory pathways – the UK can support safe deployment of ammonia as a marine fuel while positioning itself as a leader in the global transition to low carbon shipping.

Flammability

Ammonia is technically a flammable gas, but its flammability risk is lower than many conventional fuels because it is relatively difficult to ignite. It only burns within a narrow concentration range in air and requires a very high temperature – over 650°C – to ignite without a spark. This means ammonia is less likely to catch fire accidentally when compared with fuels such as gasoline, methane or hydrogen. Its slow burning speed and high ignition threshold further reduce the likelihood of unplanned combustion. These characteristics make ammonia's fire risk manageable, particularly when strong safety systems are in place.

However, flammability risks cannot be disregarded, especially in enclosed spaces, in mixed fuel environments, or where ammonia may be present with hydrogen or hydrocarbons. These substances can significantly increase ammonia's flammable range and reactivity.

Ammonia can also react violently with certain chemicals, highlighting the need for careful material compatibility and system design. As the maritime sector begins to adopt ammonia as a fuel, more research is needed to understand fire and explosion behaviour - including how leaked ammonia disperses and behaves when ignited.

This evidence will support the development of appropriate detection systems, fire protection measures and engineering standards to ensure that ammonia fuelled ships can operate safely and reliably.

> Ammonia is less likely to catch fire accidentally when compared with fuels such as gasoline, methane or hydrogen. Its slow burning speed and high ignition threshold further reduce the likelihood of unplanned combustion.

Corrosion

Ammonia is highly corrosive to both people and equipment, and this hazard needs to be managed carefully as the maritime sector explores its use as fuel. When ammonia comes into contact with moisture – such as on skin, eyes or within the respiratory tract – it forms a caustic chemical (ammonium hydroxide) that can cause serious burns and long-lasting injuries. Splash exposure can lead to permanent eye damage, and symptoms may worsen over several days. This means that effective protection measures, emergency procedures and access to appropriate first aid equipment are essential in any environment where ammonia is handled.

Ammonia's corrosive effects also pose significant engineering and operational challenges. It can rapidly degrade metals such as copper, zinc, nickel and their alloys, and it can cause stress corrosion cracking – a sudden and often catastrophic type of material failure – especially where mechanical stress is present. Even commonly used carbon steels can become vulnerable if ammonia contains oxygen, although maintaining a minimum water content can reduce the risk.

In addition, hydrogen released during ammonia production or fuel use can cause hydrogen embrittlement, weakening metals further and increasing the likelihood of premature failure.

These issues mean that safe adoption of ammonia as a marine fuel will require stringent material selection, careful system design, strict maintenance procedures and appropriate regulatory standards to ensure long term integrity of ships and fuel systems.

Training and safety

The new use in maritime infrastructures means that ammonia could be being produced, stored and transported in closer proximity to the public. This requires new skills and safety awareness for operators in maritime environments including at ports and seafarers.

The scarcity of experimental data for predictive model validation and incomplete knowledge on consequences of ammonia accidental incidents creates significant safety uncertainties. The development of reliable safety provisions is fundamental for the safe use of ammonia in maritime systems, ports infrastructure and beyond. Safety measures and strategies outlined need to consider both ship-to-ship and shore-to-ship operations.

Table 5 provides a summary of the challenges outlined above for the safe management of ammonia as a shipping fuel.

Table 5: Summary of challenges for safety management of ammonia as a shipping fuel

	Toxicity	**Flammability & reactivity**	**Corrosion & material degradation**	**Training & operational safety**
Key risks	Small leaks can cause acute harms Releases can disperse hundreds of metres Accumulation risk in enclosed spaces	Lower ignition risk but hazards increase in confined spaces or when mixed with hydrogen or hydrocarbons	Caustic burns Corrosion of metals Stress corrosion cracking Hydrogen embrittlement	New skills required Uncertainties due to limited experimental data Increased public proximity
Typical maritime context	Shipboard tanks Machinery spaces Bunkering areas Enclosed compartments	Engine rooms Mixed-fuel systems Maintenance scenarios	Bunkering spills Long-term tank and piping integrity Stressed components	Ship-to-ship and shore-to-ship bunkering Emergency response Routine operations
Mitigations & controls	Containment Ventilation Gas detection Emergency procedures Personal protective equipment (PPE) Trained personnel	Ignition control Ventilation Leak prevention Compatible materials Fire detection and suppression	Material selection Corrosion monitoring Coatings Moisture/oxygen control Personal protective equipment (PPE) First-aid facilities	Training and certification Standard Operating Procedures Drills Coordinated safety management systems
Regulatory & standards	Rules for design Containment Detection Bunkering Crew training Personal protective equipment (PPE)	Guidance on ammonia fire/ explosion behaviour Detection & protection standards	Material standards Inspection intervals Decontamination requirements	Training standards Harmonised bunkering requirements Toxicity-focused risk frameworks
Evidence gaps, further work	Better dispersion & consequence data Model validation Community risk guidance	Research on ignition behaviour Mixed-fuel effects Explosion characteristics	Long-term integrity data Stress corrosion cracking thresholds Embrittlement guidance	Validated datasets for modelling Emergency planning Regulatory development

Taking a fuel agnostic approach to policy making can exacerbate lack of progress in the common knowledge and understanding needed around the safe use of alternative fuels like ammonia. We therefore recommend when designing policy that a holistic approach is taken to embrace the opportunities while minimising risks for the adoption of new fuels including those in a new use setting.

While ammonia has been used over a long period very successfully in other sectors, the maritime industry is establishing additional safety regulations through various organisations such as the IMO and classification[33], [34] such as Lloyd's Register. The IMO issued Interim Guidelines for the Safety of Ships Using Ammonia as Fuel (MSC.1/Circ.1687) in March 2025 for example[35]. These guidelines provide an international standard for ships using ammonia as fuel, aiming for the same level of safety and reliability as conventional oil-fuelled machinery installations.

The Policy and safety regulations section (page 7) gave a summary of these guidelines and regulations comparing UK, EU and USA in Table 3. Whilst classification societies such as Lloyd’s Register, The Royal Institution of Naval Architects (RINA) and the American Bureau of Shipping (ABS), are non-government bodies, the technical standards they set are essential. There is a challenge in that there are some variations among classification society regulations, and with around 50 of these organisations globally for marine classification this can introduce additional uncertainties.

For example, an area of deviation is acceptable ammonia leakage concentrations. ABS, the Korean Register of Shipping (KR) and Bureau Veritas (BV) mandate a maximum of 25 parts per million (ppm)[36], [37], [38], while RINA permits up to 50 ppm[39].

The safe use of ammonia as a maritime fuel will depend not only on its low-carbon potential but, more importantly, on the creation of strong, research-led safety systems. This requires detailed hazard and risk assessments, well designed emergency response procedures, and engineering solutions that specifically address ammonia’s toxicity, flammability and wider hazards.

Further research is essential to guide the design of containment systems, bunkering and handling protocols, sensing and ventilation technologies, and other measures needed to prevent, detect and manage incidents effectively. Without this robust technical foundation, gaining regulatory approval and public trust will remain major obstacles to the widespread uptake of ammonia as a next generation marine fuel.

Policy recommendations

Green ammonia is a credible zero carbon shipping fuel, but since it is at the early stages of deployment for fuel use in the sector there are high costs and risks. There are some demand signals stimulated by EU's FuelEU Maritime regulations, extension of emissions trading schemes to shipping emissions in the EU and the UK and anticipated further international emissions regulations from the IMO. National and international safety regulations are progressing too. However, without targeted action, adoption of green ammonia as a shipping fuel is likely to remain limited to a small number of first movers, at least in the short term.

The UK benefits from strong offshore wind capability, established industrial and port infrastructure, and political commitment with the government's UK Hydrogen Strategy, the Maritime Decarbonisation Strategy, and legislated national Net Zero emissions target by 2050[4], [40], [41]. As highlighted earlier in this briefing, ammonia as a fuel acts as a strong complement to a hydrogen-based economy.

The UK is already leading the way in developing small-scale production technology through the Ammonia Synthesis Plant with Intermittent Renewable Energy (ASPIRE) project[6]. Investing in green hydrogen and ammonia remains highly valuable for the UK in meeting net zero targets through the decarbonisation of sectors such as shipping, heavy industry and power generation. While the UK may not dominate exports, it could become a global leader in technology, innovation, and hydrogen expertise.

Policy measures and government support for ammonia as a marine fuel requires a comprehensive, multidisciplinary approach spanning from fundamental (low Technology Readiness Level) studies, engineering innovations, industry-driven, and pre-normative research to underpin safety regulations, codes and standards, to operational readiness of ammonia systems and storage infrastructure.

Key areas include, but are not limited to:

- **development of advanced transportation, storage and bunkering systems, including at sea ship-to-ship bunkering**
- **location of smart real-time leak detection technologies informed by contemporary simulations of ammonia dispersion in the meandering wind**
- **implementation of robust emergency response protocols for systems and infrastructure**
- **development and harmonisation of beyond the state-of-the-art regulations, codes and standards across international jurisdictions**

---

[6] https://www.ukri.org/news/uk-green-ammonia-prototype-plant-tackles-energy-storage-challenge/

Policy measures to encourage adoption could take the form of the following:

1. Market measures

Carbon pricing – sends strong market signals and aligns with our nearest neighbours, the EU, while pushing for high ambition on market-based measures at IMO negotiations. However, care is needed to ensure the UK maintains its international competitiveness.

Other types of market measure that could be considered are subsidies or preferential financial incentives such as lower interest rates for low carbon fuels and associated infrastructure and technologies.

2. Bunkering hub development funding

Green ammonia plants can positively impact regional infrastructure and lead to cluster development; the requirement for large and consistent electricity input (for electrolysis) safeguards the long-term demand for renewable energy, encouraging new wind, solar, wave and tidal investments.

Early adopters of green ammonia infrastructure (for example, bunkering terminals, storage, safety systems) will attract ammonia-fuelled vessels, which will grow under regional and IMO decarbonisation targets. These hubs can become global ammonia bunkering centres, offering competitive advantages similar to LNG ports today.

Refuelling of ships powered by ammonia poses notable supply chain and safety challenges in the UK. The Maritime and Coastguard Agency (MCA) and port authorities play key roles in regulation and oversight, but the provision and transport of ammonia is largely managed by third-party suppliers. Firms like Maersk believe that chemical-handling ports are better placed to transition, given their experience with hazardous materials. However, these ports often lack specific expertise in ammonia bunkering, which demands strict safety procedures, dedicated equipment, and trained staff.

3. Support development of green ammonia corridors

Initiatives such as the green shipping corridors will support market co-ordination, but it outlines the value of being an early provider of alternative fuels. Experts suggest that shipping companies will engage with port-only or vessel-only contracting to ensure security of supply. Whereas, for example, Norway's green shipping programme co-ordinates legislation, stakeholders, fuel producers and energy owners[7].

In the UK, two out of the six green shipping corridors committed to under the Clydebank Declaration in COP26 have been announced. These are between Port of Tyne and Ijmeuden (Netherlands), and Ports of Holyhead and Dublin[8]. So far these have conducted feasibility of methanol fuel between the two destinations.

4. Accelerate adoption of safety regulations and crew training programs

To enable this transition, ports need targeted investment in storage, bunkering facilities, safety frameworks, and collaboration with fuel providers. National policy support and workforce training are also crucial to address current infrastructure and skills gaps.

---

[7] https://greenshippingprogramme.com/about-green-shipping-programme/

[8] https://www.gov.uk/government/news/passengers-to-enjoy-cleaner-travel-between-uk-and-europe

5. Mandate the full life cycle GHG (not just CO_2) emissions plus R&D incentives for NOx and N_2O mitigation technologies

Currently there is one region – the EU – that has implemented measures to limit greenhouse gas emissions from shipping on a whole life cycle basis in its FuelEU Maritime GHG Intensity Indicator. Implementing a similar requirement in the UK could help reduce greenhouse gas emission leakage from the EU to the UK. This could encourage the adoption of fuels and associated technologies that are not only low in carbon dioxide but also in methane and nitrous oxide emissions.

In addition, there could be the provision of support for research and development (R&D) into technologies that reduce negligible emissions of nitrous oxides and ammonia from ships with ammonia fuelled engines.

6. Public information and communication

In promoting the use of ammonia, it would be beneficial to consider the need for public information and communication, particularly around safety aspects. Communication campaigns can enable policy effectiveness, build trust and mitigate misinformation.

A summary of these policy recommendations across the three challenge areas is in Table 6 (this also appears in the Executive summary).

Table 6: Summary of policy recommendations for green ammonia as a shipping fuel

Ammonia as a fuel	Green ammonia supply	Safety management
Carbon pricing with ratchet thresholds to encourage shift to zero carbon fuels	Capitalise on ammonia and hydrogen's shared infrastructure requirement	Government support for skills and safety training in the new use of ammonia
Fuel standards based on whole life cycle (Well-to-Wake) and additional greenhouse gases (not just CO_2)	Green Shipping Corridors with ammonia fuel could encourage development of supply	World class safety standards should be maintained
R&D for nitrous oxide and ammonia leakage mitigation technologies	Strategic planning around which ports to provide incentives for development of ammonia bunkering facilities	Communications campaign for public acceptability of ammonia as a fuel

Bibliography

[1] B. Mueller, ‘Why public policies fail: Policymaking under complexity’, *EconomiA*, vol. 21, no. 2, pp. 311–323, May 2020, doi: 10.1016/j.econ.2019.11.002.

[2] IMO (2018). Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships, MEPC.308(73). https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.308(73).pdf

[3] IMO (2021). Amendments to the Annex of the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto. 2021 Revised MARPOL Annex VI, MEPC.328(76). https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.328(76).pdf

[4] Department for Transport, ‘Maritime Decarbonisation Strategy’, HM Government, 2025. [Online]. Available: https://assets.publishing.service.gov.uk/media/67f4dcb3c2fea2548f4eff64/dft-maritime-decarb-strategy-25.pdf

[5] Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 Amending Directive 2003/87/EC Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union and Decision (EU) 2015/1814 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading System (Text with EEA Relevance), European Parliament, Council of the European Union, 130 OJ L (2023). http://data.europa.eu/eli/dir/2023/959/oj

[6] Regulation on the Use of Renewable and Low-Carbon Fuels in Maritime Transport, 2023/1805, European Parliament, Council of the European Union (2023). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1805

[7] A. Christodoulou and K. Cullinane, ‘Potential alternative fuel pathways for compliance with the “FuelEU Maritime Initiative”’, *Transp. Res. Part Transp. Environ.*, vol. 112, p. 103492, Nov. 2022, doi: 10.1016/j.trd.2022.103492.

[8] H. N. Psaraftis, T. Zis, and S. Lagouvardou, ‘A comparative evaluation of market based measures for shipping decarbonization’, *Marit. Transp. Res.*, vol. 2, p. 100019, Jan. 2021, doi: 10.1016/j.martra.2021.100019.

[9] I. Rojon, N.-J. Lazarou, N. Rehmatulla, and T. Smith, ‘The impacts of carbon pricing on maritime transport costs and their implications for developing economies’, *Mar. Policy*, vol. 132, p. 104653, Oct. 2021, doi: 10.1016/j.marpol.2021.104653.

[10] H. Schwartz, M. Gustafsson, and J. Spohr, ‘Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably?’, *J. Clean. Prod.*, vol. 254, p. 120069, May 2020, doi: 10.1016/j.jclepro.2020.120069.

[11] Grieg Star, ‘Ammonia powered bulk carrier Pilot report’, Green Shipping Program, 2023. [Online]. Available: https://greenshippingprogramme.com/wp-content/uploads/2023/06/Ammonia-powered-bulk-carrier.-Pilot-report..pdf

[12] European Environmental Bureau, ‘Revised Industrial Emissions Directive and Regulation Establishing the Industrial Emissions Portal: outcomes and opportunities’, European Environmental Bureau, Policy Briefing, 2024. [Online]. Available: https://eeb.org/wp-content/uploads/2024/08/IED-and-IEP-R-assessement.pdf

[13] Health and Safety Executive, ‘Workplace exposure limits - COSHH’. Accessed: Jul. 22, 2025. [Online]. Available: https://www.hse.gov.uk/coshh/basics/exposurelimits.htm

[14] Ministry of Housing, Communities & Local Government, ‘Hazardous substances’, HM Government, Guidance, Nov. 2019. Accessed: Jul. 22, 2025. [Online]. Available: https://www.gov.uk/guidance/hazardous-substances

[15] Occupational Safety and Health Administration, ‘Ammonia Refrigeration - Overview’, US Department of Labor, USA. Accessed: Jul. 22, 2025. [Online]. Available: https://www.osha.gov/ammonia-refrigeration

[16] P. E. Olli and K.-M. Voovere, ‘The Future of Ammonia is Green’, Stargate Hydrogen, White Paper, 2021. [Online]. Available: https://stargatehydrogen.com/wp-content/uploads/2021/11/StargateHydrogen_GreenAmmoniaWhitepaper_Oct2021-4.pdf

[17] O. Serpell, Z. Hsain, A. Chu, and W. Johnsen, ‘Ammonia’s Role in a Net-Zero Hydrogen Economy’, Kleinman Center for Energy Policy, University of Pennsylvania, Philadelphia, USA, 2023. Accessed: Jul. 22, 2025. [Online]. Available: https://kleinmanenergy.upenn.edu/research/publications/ammonias-role-in-a-net-zero-hydrogen-economy/

[18] DNV GL, ‘Comparison of Alternative Marine Fuels’, 2019–0567, Rev. 3, Jul. 2019. [Online]. Available: https://safety4sea.com/wp-content/uploads/2019/09/SEA-LNG-DNV-GL-Comparison-of-Alternative-Marine-Fuels-2019_09.pdf?utm_source=chatgpt.com

[19] P. Dimitriou and R. Javaid, ‘A review of ammonia as a compression ignition engine fuel’, *Int. J. Hydrog. Energy,* vol. 45, no. 11, pp. 7098–7118, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.209.

[20] A. K. Eswara, S. C. Misra, and U. S. Ramesh, ‘Introduction to natural gas: A comparative study of its storage, fuel costs and emissions for a harbor tug’, presented at the SNAME Maritime Convention, OnePetro, Nov. 2013. doi: 10.5957/SMC-2013-T22.

[21] A. Y. H. Wong, N. E. Selin, S. D. Eastham, C. Mounaïm-Rousselle, Y. Zhang, and F. Allroggen, ‘Climate and air quality impact of using ammonia as an alternative shipping fuel’, *Environ. Res. Lett.,* vol. 19, no. 8, p. 084002, Jul. 2024, doi: 10.1088/1748-9326/ad5d07.

[22] H. Wang et al., ‘Life cycle analysis of ammonia fuelled ship – case ship studies for marine vessels’, *J. Clean. Prod.,* vol. 520, p. 146105, Aug. 2025, doi: 10.1016/j.jclepro.2025.146105.

[23] B. Zincir, ‘Environmental and economic evaluation of ammonia as a fuel for short-sea shipping: A case study’, *Int. J. Hydrog. Energy,* vol. 47, no. 41, pp. 18148–18168, May 2022, doi: 10.1016/j.ijhydene.2022.03.281.

[24] S. Lilonfe et al., ‘Life cycle greenhouse gas implications of low-carbon gaseous fuel supply chains from technological, geospatial, and temporal perspectives’, *Energy Convers. Manag.,* vol. 333, p. 119803, Jun. 2025, doi: 10.1016/j.enconman.2025.119803.

[25] D. Nguyen, R. J. Fernandes, J. W. G. Turner, and D. R. Emberson, ‘Life cycle assessment of ammonia and hydrogen as alternative fuels for marine internal combustion engines’, *Int. J. Hydrog. Energy,* vol. 112, pp. 15–30, Mar. 2025, doi: 10.1016/j.ijhydene.2025.02.331.

[26] The Royal Society, ‘Ammonia: zero-carbon fertiliser, fuel and energy store’, The Royal Society, Policy Briefing, 2020. [Online]. Available: https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

[27] H. Ait Lahoussine Ouali, O. Abida, N. Ali, and M. Essalhi, ‘Green ammonia in the global research spotlight: Bibliometric insights and a review of renewable pathways and applications’, *Energy Strategy Rev.,* vol. 64, p. 102070, Mar. 2026, doi: 10.1016/j.esr.2026.102070.

[28] M. Laimon and S. Goh, ‘Unlocking potential in renewable energy curtailment for green ammonia production’, *Int. J. Hydrog. Energy,* vol. 71, pp. 964–971, Jun. 2024, doi: 10.1016/j.ijhydene.2024.05.022.

[29] Z. Cesaro, J. Thatcher, and R. Banares-Alcantara, ‘Techno-economic aspects of the use of ammonia as energy vector’, in *Techno-Economic Challenges of Green Ammonia as an Energy Vector,* Academic Press, 2020, pp. 209–219.

[30] S. Biswas, A. Menon, R. Field, G. Zang, and W. H. Green, ‘A Comprehensive Costing and Emissions Analysis of Blue, Green, and Combined Blue-Green Ammonia Production’, *Energy Fuels,* vol. 39, no. 38, pp. 18694–18710, Sep. 2025, doi: 10.1021/acs.energyfuels.5c03111.

[31] Marine Insight, ‘Introduction to Ammonia As A Potential Marine Fuel’, Green Shipping. Accessed: Jul. 22, 2025. [Online]. Available: https://www.marineinsight.com/green-shipping/introduction-to-ammonia-as-a-potential-marine-fuel/

[32] A. Derricott, ‘Blue ammonia nears cost viability, green stays pricey’, CRU Group Website. Accessed: Jul. 22, 2025. [Online]. Available: https://www.crugroup.com/en/communities/thought-leadership/2023/blue-ammonia-nears-cost-viability-but-green-to-stay-pricey/

[33] DNV, ‘FuelEU Maritime: How to prepare for compliance’, DNV. Accessed: Aug. 14, 2025. [Online]. Available: https://www.dnv.com/news/2024/fueleu-maritime-how-to-prepare-for-compliance/

[34] A. A. Levikhin and A. A. Boryaev, ‘Low-carbon ammonia-based fuel for maritime transport’, *Results Eng.,* vol. 25, p. 104175, Mar. 2025, doi: 10.1016/j.rineng.2025.104175.

[35] IMO, ‘Interim Guidelines for the Safety of Ships Using Ammonia as Fuel’, MSC.1/Circ.1687, 2025. [Online]. Available: https://www.bimco.org/media/bxvcygg1/msc1-circ1687-interim-guidelines-for-the-safety-of-ships-using-ammonia-as-fuel-secretariat.pdf

[36] Bureau Veritas, ‘Ammonia-Fuelled Ships’, Bureau Veritas, Rule Note NR671 R03, Feb. 2026. [Online]. Available: https://rulesexplorer-docs.bureauveritas.com/documents/nr671/feb2026/671-NR_2026-02.pdf

[37] Korean Register of Shipping, ‘Guidelines for Ships Using Ammonia as Fuels’, Korean Register of Shipping, Jun. 2021. [Online]. Available: http://bit.ly/4u6JIaK

[38] American Bureau of Shipping, ‘Requirements for Ammonia Fueled Vessels’, American Bureau of Shipping, Sep. 2021. [Online]. Available: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/325_guide_ammonia_fueled_vessels/ammonia-fueled-vessels-reqts-e-sept21.pdf

[39] RINA, *Rules for the Classification of Ships.* 2026. [Online]. Available: https://www.rina.org/en/rules

[40] Department for Energy Security & Net Zero, ‘Hydrogen Update to the Market’, HM Government, Jul. 2025. [Online]. Available: https://assets.publishing.service.gov.uk/media/6880b2139fab8e2e86160efe/hydrogen-update-to-the-market-2025.pdf

[41] *The Climate Change Act 2008* (2050 Target Amendment) Order. 2019. [Online]. Available: https://www.legislation.gov.uk/ukdsi/2019/9780111187654

MariNH$_3$

UK National
Clean Maritime
Research Hub

Contact us:

MariNH$_3$

✉ marinh3@nottingham.ac.uk
in /marinh3
↗ marinh3.ac.uk

UK National Clean Maritime Research Hub

✉ admin.clean-maritime-research-hub@durham.ac.uk
in /uk-national-clean-maritime-research-hub
↗ clean-maritime-research-hub.org

Published April 2026.