



Enabling the safe, clean and cost-efficient implementation of ammonia as a maritime fuel:

Key findings
from the Norwegian
MaritimeNH3
project



<https://www.sintef.no/maritimenh3>

About MaritimeNH3

MaritimeNH3 is a Knowledge-building Project for Industry (KSP), financed by the Research Council of Norway, which ran from 2021 to 2024. It aimed to develop and disseminate new knowledge to facilitate the realisation of a cost-efficient value chain and safe use of ammonia as a zero-carbon maritime fuel. Partners in this project were SINTEF Energy Research, SINTEF Industry, Yara Clean Ammonia, Azane Fuel Solutions, Amon Maritime, ECONNECT Energy, Ocean Hyway Cluster, HYEX Safety and Viridis Bulk Carriers.

The project was the competence development part of the “Ammonia Fuel Bunkering Network for the Marine Sector” project, funded under Norway’s Green Platform scheme. This industry-led project aimed to realise an ammonia bunkering network by developing, constructing and testing a scalable ammonia bunkering hub, while simultaneously establishing a supply chain and regulatory framework for ammonia.

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Executive summary

The MaritimeNH3 project explores the possibility of ammonia as a safe, clean and cost-efficient alternative to fossil fuels in the maritime industry. Shipping relies heavily on fossil fuels, and is currently responsible for 2% of global CO₂ emissions. To align with international climate goals, the International Maritime Organisation (IMO) has mandated a 70% reduction in greenhouse gas emissions from the industry by 2040.

Ammonia, a carbon-free compound, has a high energy density, and can either be a source of energy in itself or an energy carrier for hydrogen. Its history of production and use for other industrial applications means there is a well-established knowledge base on its handling and transportation, which provides a strong foundation for its use as a maritime fuel.

However, there are several challenges that must be addressed before ammonia can be applied as a maritime fuel. MaritimeNH3 has aimed to address some of these challenges, and thereby advance ammonia as a viable alternative fuel for the maritime industry. The project has been organised into five core areas: value chains, safety, production, combustion engines, and fuel cells. This document outlines the work done in each area, presents their key results and findings, and gives recommendations for future work.

Value chains

A working value chain is crucial to realising ammonia's potential as a maritime fuel. However, establishing this value chain faces regulatory, technical and logistical challenges across the key areas: production, transport and bunkering.

MaritimeNH3 has produced two models that can support the establishment of new value chains by providing a general overview of the associated costs and emissions, in relation to ammonia demand and ammonia transport. A techno-economic assessment was also produced on the feasibility of creating an ammonia-based energy system in Norway, which showed that ammonia production is initially centralised in areas with lower costs, such as Northern Norway, before expanding to meet growing demand in the southern regions.

Key findings from this work include:

- While currently expensive, ammonia costs could reduce significantly as demand grows, potentially reaching 121.5 GWh/day by 2055.
- Ammonia produced from fossil fuels with CCS is a viable short-term solution, but ammonia produced from solely renewable sources will ultimately be necessary to ensure a zero-carbon supply chain.
- In Norway, retrofitted tanker ships are a more cost-effective means of transporting ammonia from production facilities to ports than by road.

Safety

Ammonia is highly toxic even in small concentrations, and the possibility of leaks, and the subsequent formation of toxic clouds, presents a significant safety concern. Cold storage (non-pressurised) is generally considered safer than warm storage (pressurised) because the cloud following a warm release is denser, and thus spreads closer to the ground. However, both storage forms require careful management to prevent hazardous leaks.

MaritimeNH3 has developed a computational fluid dynamics (CFD) model to predict how ammonia behaves upon an accidental release into humid air from both cold and warm storage. This model can provide valuable data that can inform safety regulations and emergency response planning, particularly in regard to fog formation.

Key findings from this work include:

- Ammonia leaks from cold storage into humid air can reduce the hazardous zone by 30%.
- Visibility should not be considered as an indicator of safety. In humid air, ammonia clouds can appear larger than the actual hazardous area, while in dry air, the danger can spread beyond what is visible.
- While the hazardous zone from a cold release is reduced by fog formation, it is increased for warm releases.

Production

Ammonia is primarily produced through the Haber-Bosch process, which traditionally relies on a synthesis gas of nitrogen and fossil-based hydrogen, resulting in significant CO₂ emissions. Transitioning to low-carbon ammonia production methods is essential to achieve zero-carbon shipping.

MaritimeNH3 has designed a chemical ammonia production process that is independent of synthesis gas production. The project also highlighted the need for smaller, decentralised ammonia plants to reduce transport emissions, though these plants face higher costs compared to larger facilities.

Key findings from this work include

- Producing ammonia via electrolysis is more energy intensive than from natural gas with CO₂ capture.
- More efficient electrolysis processes will be key to reducing the associated costs and energy demand of producing ammonia from renewable resources.
- Increased flexibility in ammonia production, in terms of both plant operation and energy sources, would also reduce costs and increase efficiency.

Engines

Ammonia is promising in its ability to be used in internal combustion engines, but several technical challenges remain. In particular, ammonia has low chemical reactivity, which can lead to difficulties with ignition, inefficient fuel use, and the formation of undesirable nitrogen compounds.

MaritimeNH3 has conducted an in-depth analysis of the chemical reactivity and emissions of ammonia fuel blends. Partially decomposing the ammonia to produce a fuel consisting of ammonia, nitrogen and hydrogen could address these technical challenges, enabling an easier and more efficient use of ammonia as a fuel without harmful byproducts.

Key findings from this work include

- Even small rates of ammonia decomposition can produce a fuel blend that burns as fast as methane.
- Larger rates of ammonia decomposition can produce a fuel that is almost as combustive as hydrogen.
- Using a hydrogen-fired prechamber is well suited to igniting ammonia mixtures.

Fuel cells

Solid oxide fuel cells (SOFCs) are currently the most efficient technology for converting ammonia to electricity. However, in order for SOFCs to be deployed at scale, more research is needed to mature the technology and reduce the associated costs.

MaritimeNH3 has identified several potential developments for ammonia use in fuel cells. In particular, these relate to mitigating the risk of nitridation, which can reduce the cell's power efficiency over time as well as the lifetime of the SOFC stacks.

Key findings include:

- Operating the fuel cells at a higher temperature may reduce the risk of nitridation.
- Alternative electrode materials to conventional nickel-based materials used in SOFCs may improve the cell's ammonia cracking ability and nitridation resistance.
- Pre-decomposing the ammonia into hydrogen and nitrogen may also resist nitridation.

MaritimeNH3 demonstrates that ammonia has significant potential in contributing to the decarbonisation of the maritime sector. However, its realisation depends on a coordinated effort to address the associated technical, economic and safety challenges.

The project's findings highlight a need for investment in infrastructure, further R&D efforts, and regulatory frameworks. Policymakers, industry leaders and researchers must work together in order to build a robust ammonia fuel value chain that will support a global transition to zero-emission shipping.

The role of ammonia in decarbonising shipping



Shipping urgently needs to be decarbonised

There is an urgent need for shipping to decrease its greenhouse gas emissions as part of the energy transition. According to the International Energy Agency, 99% of international shipping's total energy demand was met by oil-based fuels in 2022, and the sector was responsible for approximately 2% of energy-related CO₂ emissions¹.

In order to align with the goal set by the Paris Agreement in 2015, to limit the increase in global temperatures to below 2°C compared to pre-industrial levels, the International Maritime Organisation (IMO) has mandated that shipping must reduce its greenhouse gas emissions by at least 70% by 2040². This requires a shift from fossil fuels to fuels with low, and ultimately zero, greenhouse gas emissions during production, distribution and use.

Ammonia is a leading clean alternative to fossil fuels

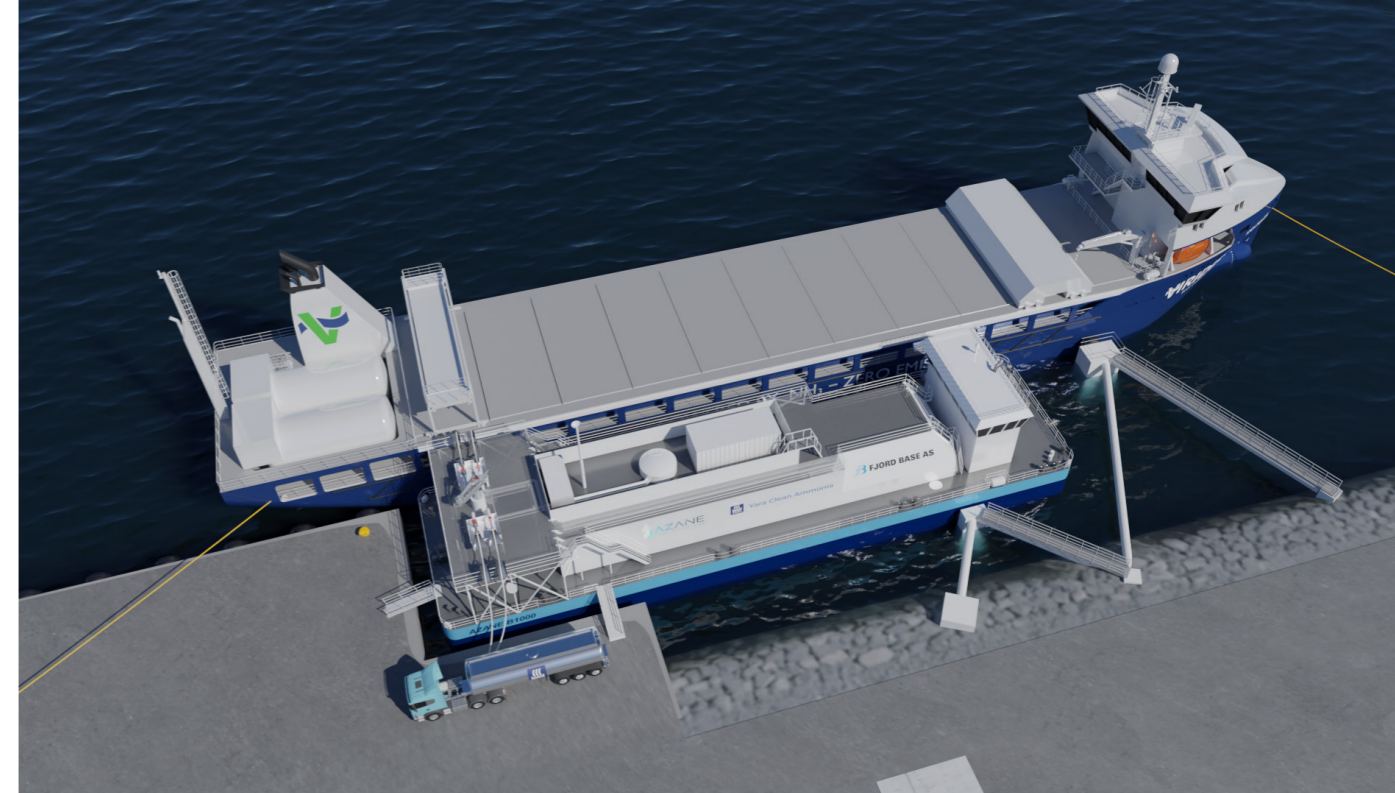
Ammonia is the second most traded chemical product globally³, with a wide range of applications from fertilizer to cleaning products. It is a naturally occurring inorganic chemical compound, but can also be produced industrially by combining hydrogen with nitrogen. Crucially, as ammonia does not contain carbon, it does not produce any CO₂ emissions. This makes it one of the leading, carbon-free alternatives to fossil fuels.

Ammonia is particularly promising as a means of decarbonising the shipping industry, either as a fuel in itself or as an energy carrier for hydrogen. Ammonia yields a high volumetric energy density, containing fifty percent more energy than the same amount of liquid hydrogen, and ten times more energy than lithium batteries. Furthermore, ammonia is relatively easy to transport and store, as it does not require high-pressure or cryogenic storage. As of the time of this report's publishing, there are 120 terminals for importing and exporting ammonia in gas carriers worldwide. This provides an excellent starting point for an infrastructure for ammonia as a maritime fuel⁴.

Currently, ammonia is most commonly produced from hydrogen generated from fossil fuels, such as natural gas, ("grey ammonia"), which has associated CO₂ emissions. In order for ammonia to be a low- or zero-carbon fuel, the hydrogen needs to be produced from fossil fuels with carbon capture and storage ("blue ammonia") or entirely from renewable electricity ("green ammonia").

Since the transition from grey ammonia has just begun, the costs of green and blue ammonia are currently relatively high. Nevertheless, green ammonia is still considered to be one of the cheapest fuels for decarbonising EU-related shipping by 2050, with costs likely to decrease even further in the future⁵.

In their Energy Transition Outlook, the DNV predicts the global share of ammonia in the maritime fuel mix to increase from only 1% in 2030 to 13% in 2040, and 36% in 2050⁶. According to the Net Zero Roadmap⁷ issued by the International Energy Agency (IEA), ammonia will be the primary low-emission fuel used to decarbonise shipping, constituting a share of over 40% in 2050. To achieve the IMO's goals of a total phase-out of greenhouse gas (GHG) emissions in this century, the IEA estimates that an ammonia share of over 50% will need to be achieved by 2070⁸.



Concept picture of an ammonia bunkering barge, developed as part of the "Ammonia fuel bunkering network for marine sector" green platform project. Image: Azane Fuel Solutions.

Significant barriers still need to be addressed

As ammonia is already produced industrially in large quantities, extensive expertise already exists on its safe use, storage and transportation. However, there are still significant barriers to ammonia's use as a maritime fuel across the value chain. Manufacturers must overcome key technical hurdles and safety issues when designing ammonia engines and fuel cells. Port operators and fuel suppliers must build safe and flexible bunkering infrastructure. Energy companies and governments must invest heavily in order to produce sufficient amounts of zero-carbon ammonia. Awareness also needs to be increased around ammonia as a safe, cost-efficient and clean fuel.

Key findings from the MaritimeNH3 project

The Norwegian MaritimeNH3⁹ project has aimed to accelerate the maritime industry's transition to zero-carbon fuels by contributing to technological advancement and an improved understanding of the use of ammonia as a fuel. The project has focused on five main areas: **value chains, safety, production, combustion engines, and fuel cells**.

Key findings from this work are organised in this document, with the intention that it may be used to inform policy, regulations or fields of further study, which would aid the realisation of an ammonia fuel value chain for the maritime industry.



Value Chains

Ammonia has emerged as a potential solution for decarbonising maritime transport due to its ability to produce zero-carbon energy, particularly when produced from renewable sources¹⁰. Its high energy density, suitability for long-distance shipping, and established global infrastructure make it an attractive alternative fuel¹¹. However, the ammonia value chain (comprising production, transport, and bunkering) requires significant development to ensure it can meet the maritime sector's demands, particularly in countries like Norway, which rely heavily on maritime transport^{12, 13}. These challenges and opportunities have been studied as part of the MaritimeNH3 project. The activities focused on performing a techno-economic assessment of a future ammonia-based energy system in Norway that could meet the future ammonia demand of the maritime fleet segments to be decarbonised. This assessment provided a means of investigating the most effective solution for ammonia production, transport and delivery, considering uncertainty in the Norwegian maritime sector, and evaluating alternative solutions that can reduce emissions even more than the most cost-effective solution.

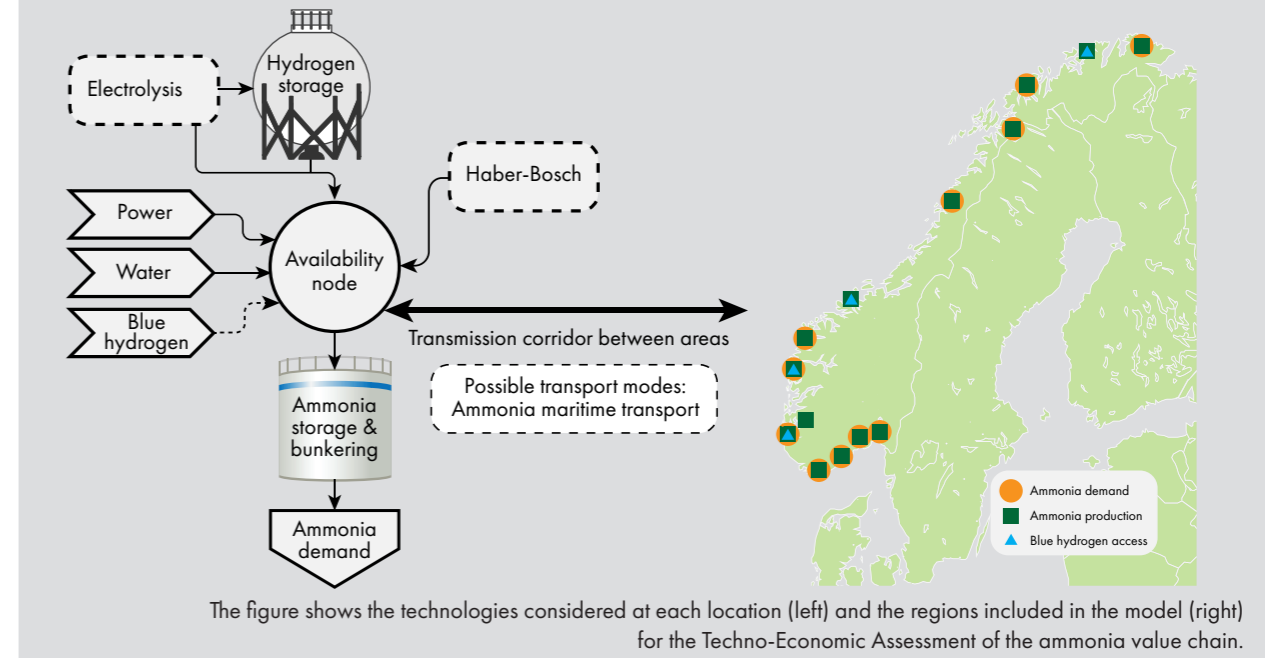
Associated challenges

The adoption of ammonia as a maritime fuel faces regulatory, technical, and logistical challenges across its value chain, including production, transport, and bunkering. The main challenges are at the start and end of the value chain. On the one hand, there is a lack of ammonia demand in the maritime sector, which makes it difficult to justify a fast deployment of this new ammonia value chain. On the other hand, the production of low-carbon ammonia (from electrolysis or natural gas reforming with carbon capture) is not yet cost effective, despite ammonia synthesis being an established technology^{14, 15}.

Transporting ammonia requires robust infrastructure and safety regulations. While ammonia's non-cryogenic storage requirements make it easier to transport than liquid hydrogen, there is still a lack of road and sea transport networks capable of efficiently and safely delivering ammonia. Bunkering ammonia for ships necessitates building new facilities or retrofitting existing ones. While Norway has some experience with

ammonia import/export terminals, these facilities are not yet configured for widespread maritime fuel use¹⁶. Safety is also a key aspect for establishing an ammonia value chain for maritime transport¹⁷.

Decision-support tools, like the optimisation model developed in MaritimeNH3 (an extension of EnergyModelsX¹⁸), can help address these challenges by providing an overview of the costs and emissions of such a new value chain. Nevertheless, these tools require us to make several assumptions, such as the expected ammonia demand, cost evolution or simplified technology descriptions and operation to be solved. Thus, the focus when using these models should be on the general trends rather than specific numbers (like ammonia production costs), and several sensitivities are needed to study the effect of critical parameters on the value chain deployment. With the MaritimeNH3 optimisation model, we can evaluate ammonia demand, Haber-Bosch plant size, CO₂ emissions penalty, and the availability of



MaritimeNH3 has developed model for optimising the entire value chain

blue hydrogen (produced by natural gas reforming including carbon capture and storage) at varying prices as an alternative to green hydrogen (produced from electrolysis).

We analysed the ammonia value chain for a time horizon from 2030 to 2055, considering the associated emissions, and distributing the total demand across 11 coastal locations (two of which have access to blue hydrogen), one inland green ammonia plant, and two extra blue hydrogen production regions. These regions are based on current and future ammonia-related projects, and the demand distribution is based on offshore-sector estimations. The model is also a deliverable of the project, which anyone will be able to use for their own analyses.

The techno-economic assessment revealed that production starts as centralised, with the first plant consistently installed in Northern Norway due to lower costs. As ammonia demand increases, peaking 121.5 GWh/day by 2050-2055, newer plants are installed at a later stage, mostly in southern regions closer to the larger demand. Blue hydrogen was observed to be a very cost-effective alternative, but its emissions can be up to several times greater than for green hydrogen, although still better than the fossil-based alternative fuels. Another important finding is that ammonia

demand has a significant impact on the costs per delivered MWh of ammonia, with these relative costs being reduced exponentially as demand grows.

MaritimeNH3 has also developed an ammonia transport model that includes both road transport and maritime transport, including associated costs and emissions. The findings indicated that maritime transport, using specialised LPG tankers retrofitted to carry ammonia, is more cost effective than road transport for long-distance transport between Norway's coastal production facilities and ports. Liquid ammonia storage at -33°C was chosen, with storage capacity increasing in each location in line with ammonia demand.

Trade-offs for emission reduction have also been considered. As transport is the main emissions contributor in the analysis, one can reduce ammonia costs by increasing or varying the Haber-Bosch plant location and/or installing more distributed and smaller plants (more expensive per installed capacity) to reduce ammonia transport and thus overall emissions.

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Safety

Like all other fuels, ammonia comes with its own unique safety challenges, and several incidents have occurred in connection with its use. While ammonia is not as flammable as traditional fossil-based fuels or hydrogen, it can explode under certain conditions. However, ammonia's main challenge is its high toxicity, even in small concentrations. This makes the possibility of toxic clouds following an accidental release a main safety concern. The worst incident involving ammonia was the 1992 Dakar incident, which claimed 129 lives and injured another 1150 people¹⁹. As such, safety will be a crucial aspect of scaling up global ammonia production from today's ~150 million tonnes per year²⁰.

Associated challenges

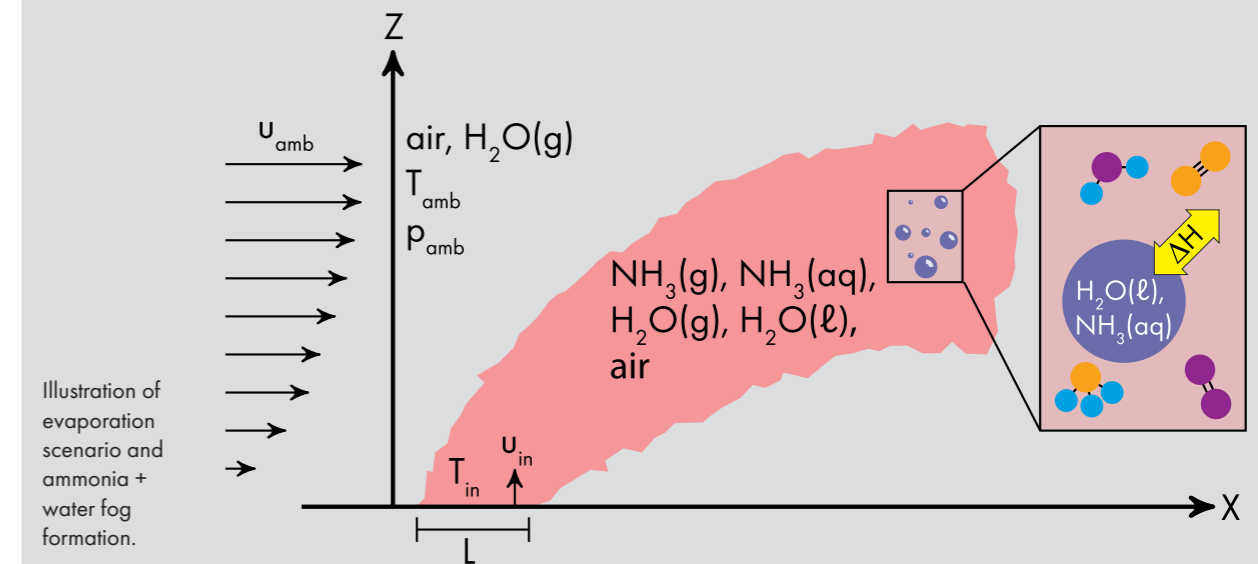
Ammonia's leakage and dispersion characteristics are strongly influenced by the way it is stored. To achieve sufficiently dense energy storage, ammonia should be liquified. This can be achieved by either pressurising the ammonia to above approximately 10 bar, where the boiling temperature becomes 25°C (and increasing with higher pressures), or by cooling to -33°C, which is the boiling temperature at ambient pressure. These two options are referred to as warm and cold storage, respectively. A combination of cooling and pressurising is also possible.

A release from a warm storage condition is characterised by choked flow and significant flash evaporation as the fluid depressurises. This results in a dense aerosol cloud, consisting of small ammonia droplets dispersed in ammonia gas. As air mixes into the aerosol cloud, the droplets start to evaporate. This evaporation requires energy, which is taken from the air. The ammonia-air mixture will then cool to below the atmospheric boiling point of ammonia. Since cold air is denser than warm air, this mixture is denser than the surrounding air. As such, ammonia leaks from warm storage spread as a heavy cloud.

Cold storage is very different; a leakage will be driven by gravity (otherwise known as "hydrostatic pressure"), and spill onto the ground. Once it comes into contact with the relatively warm ground, the liquid will boil. If the ground is sufficiently warm, this boiling will continue, producing -33°C ammonia vapor. The absence of any aerosol makes this cloud buoyant, thus giving it a tendency to rise. Generally, this will result in a smaller hazardous zone than the warm storage scenario²¹, and the leakage rate is much lower.

Due to this difference in the leakage and dispersion characteristics, cold storage is generally considered safer. However, it should be noted that given the right conditions, a cold storage release can also produce a dense cloud. This can occur if the spill is confined and left stagnant for an extended period²².

For both cold and warm storage releases, the air that is mixed into the cloud can be cooled to the point that fog forms. Just as evaporation of ammonia droplets requires energy, cooling the air as a result, the formation of water droplets releases energy, making the cloud warmer. Interestingly, ammonia is very hygroscopic, which means it has strong a tendency to



interact with water. In an ammonia-rich atmosphere, a water droplet can absorb ammonia, thereby increasing the heating effect of the droplet formation. As such, describing mixtures of humid air and cold ammonia requires a model for the humid air and cold ammonia thermodynamics, coupled with the dispersion dynamics.

The lack of such a model when conducting a safety analysis can result in either over-conservatism, or worse, under-conservatism. Furthermore, an improved understanding of the fog can give insights into the role of visual observation in evacuation and hazard response.

MaritimeNH3 has developed a CFD model for predicting how ammonia clouds will react with humid air

In MaritimeNH3, we have developed a computational fluid dynamics (CFD) model based on OpenFOAM with an accurate submodel for the thermodynamic equilibrium. This model can be used to predict how a toxic ammonia cloud from cold or warm storage will react with humid air. This interaction can have a particularly significant impact on ammonia leaks from cold storage, where dispersion in humid air can result in as much as 30% smaller hazardous zones²³. We also find that the extent of the visible cloud is affected by the interaction, and that the extent can be correlated with its ammonia concentration for a given ambient temperature and relative humidity.

Interestingly, while for warm high-humidity air, the visible cloud can extend beyond the lethal region, less fog is produced for dryer air, meaning that the hazardous cloud extends much further than the visible part of the cloud. At no point should therefore the boundary of the visible cloud be seen as a marker for

the limit of the hazardous zone. Although it can give some indication of spreading direction and more likely safe evacuation paths.

We have also done validation work against pressurised releases in a modelling campaign orchestrated by Health and Safety Executive (UK) and RAND Corporation (US) (to be published). Here the model was compared to the Desert Tortoise tests²⁴ and the FLADIS tests²⁵, both on pressurised releases. In this work we also show that the reduced density from fog-formation leads to reduced gravitational spreading, thus increasing the hazardous zone. This is in contrast to cold releases. For the Desert Tortoise test 2 (120kg/s release) we found that if the humidity had been much higher than when the tests were done the average concentration could have increased by as much as 35% 800m downwind from the release point.



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Production

Ammonia is one of the most important industrial chemicals. Today, ammonia is mostly used in the production of nitrogen-based fertilisers. The Haber-Bosch process has been the main production method for ammonia since its development in the early 20th century. This process is operated at high pressures, wherein synthesis gas (a stoichiometric mixture of hydrogen and nitrogen) reacts to ammonia. The high pressure is necessary to shift the chemical equilibrium to ammonia. Nevertheless, the synthesis gas still needs to be recycled back to the reactor, as the conversion is limited, and a large fraction of the synthesis gas will otherwise be lost.

The source of the synthesis gas is not important for the Haber-Bosch process. Due to the lower cost, synthesis gas production is dominated by natural gas reforming or coal gasification. For both chemical processes, the required nitrogen is introduced directly to the process. Synthesis gas derived from renewable sources via electrolysis is less utilised today, and requires an air separation unit to produce the nitrogen. Due to the amount of electricity required for this combined process, it is frequently utilised when abundant hydropower is available in a remote location. As an example, Norsk Hydro produced ammonia from the Haber-Bosch process in Glomfjord until the 1990s and Rjukan until the 1970s.

In order to reduce energy consumption, ammonia production is a highly integrated process. While this results in noteworthy cost savings, it also leads to significant economies of scale where large plants are desirable, and modern plants can reach a capacity of 3,000 tons per day. As a consequence, smaller plants experience both reduced efficiency (as heat integration is less economical) and increased relative capital expenditure (as smaller equipment is more expensive). The latter point is partly compensated by reduced heat integration, as fewer heat exchangers have to be installed.

Associated challenges

As outlined, current synthesis gas production for ammonia production is fossil based, resulting in significant CO₂ emissions. Achieving global greenhouse gas reduction targets will require greatly reducing these emissions, either by installing CO₂ capture units in existing plants or switching from fossil fuels to renewable resources for synthesis gas production.

In addition, different forms of energy (such as thermal energy from coal and natural gas, and electrical energy) are used in the production of ammonia. The process conditions are optimised to minimise the overall costs. As the different forms of energy have different associated costs, process conditions and designs have

to be chosen depending on the energy requirement for producing the synthesis gas.

A third important point is the flexibility (or lack of flexibility) of current ammonia processes. As ammonia is produced in large plants, start-up and shutdown times are slow. Furthermore, the processes are designed to operate at the nominal production capacity, with few intraday variations. As a consequence, producing hydrogen from intermittent renewable energy sources, like wind or solar PV requires either a change in the process design to increase production flexibility or significant investments in hydrogen storage. Similarly, operating at lower production capacities reduces efficiency.

Key findings
from the Norwegian "MaritimeNH3" project



Chemical plant for production of ammonia and nitrogen fertilization at night time. Image: Shutterstock

MaritimeNH3 has designed a chemical process for producing ammonia, independent of synthesis gas

The work in MaritimeNH3 has focused on designing a chemical process for ammonia synthesis without directly coupling it to the production of synthesis gas. The process includes only synthesis gas purification and compression, the reactor, ammonia separation, and recycling unreacted ammonia. The design utilises conventional technologies for both the reactor and the separation section. It can be applied to:

1. facilitate easy variations of the synthesis gas production process,
2. evaluate different designs for the reactor and separation section, including the optimal process conditions, and
3. estimate the capital costs of the ammonia process.

From the individual analyses, we can conclude that electrolysis-based ammonia requires more energy compared to ammonia from natural gas reforming with CO₂ capture. This increased energy demand is exclusively based on the hydrogen production. As such,

developing more efficient electrolysis processes is important for reducing the energy demand. However, process conditions in the separation section will change when switching from natural gas reforming with CO₂ capture to electrolysis for synthesis gas production. Specifically, the different form of energy in hydrogen production, electric vs. electric and thermal, results in an adjustment of the cost-optimal parameters towards a process that minimises the loss of ammonia.

While the flexibility of ammonia production was not the focus of the work in MaritimeNH3, there is ongoing work, by both academia and by engineering, procurement and construction companies, on increasing flexibility through different process designs or component designs. As an example of the latter, there is significant research focusing on the application of sorption-based processes, either as sorption-enhanced reactors or using temperature-swing adsorption for the separation.



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Key findings
from the Norwegian "MaritimeNH3" project



Engines

Recently within the maritime sector, the use of ammonia as carbon-free fuel has started to be assessed for operating internal combustion engines. Maritime transport of goods and passengers is presently enabled in its entirety by such (piston) engines, which are solely responsible for 3–4% of GHG emissions in the EU, with similar figures applying worldwide. Due to its toxicity at relatively low concentrations and its unpleasant odour at even lower concentrations, ammonia is today primarily considered for use as fuel in cargo ships, which can be more easily designed to minimise exposure risks and have crews with experience in handling dangerous goods.

Associated challenges

Extensive expertise on handling ammonia onboard ships is already available, due to the fleet of reefers and fishing vessels that already use ammonia for refrigerating purposes and tankers transporting ammonia as cargo. However, two technical challenges must be addressed to enable the use of ammonia as a maritime fuel:

1. ammonia's low chemical reactivity and combustion velocity, which could potentially lead to ignition difficulties and incomplete fuel combustion, and
2. the presence of fuel-bound nitrogen, which can potentially facilitate the formation of large quantities of harmful and undesirable nitrogen compounds (NO_x and N_2O).

Ongoing attempts by leading industrial actors within piston engine manufacturing to address the issue of ammonia's low chemical reactivity have mainly consisted of developing port- or direct-injection engines. Here a diesel pilot charge is used to reliably ignite the ammonia main charge, ideally minimising cycle-to-cycle variations too. Using a well-known pilot fuel like diesel for the robust ignition of the ammonia main charge has several advantages, but this approach also has two crucial disadvantages:

Firstly, the use of a diesel pilot results in non-zero carbon emissions, which can be significant if large pilot-to-main charge ratios are required at specific operating conditions (e.g. low load). Secondly, relying on a diesel pilot implies onboard bunkering and storage of an additional fuel besides the ammonia main fuel, which already requires significant storage volumes due to its relatively low energy density.

However, through MaritimeNH3, a radically different approach has been adopted. The issue of ammonia's low chemical reactivity has been addressed by using waste heat from the combustion process (high-temperature exhaust gases) to partially decompose the ammonia into its constituting elements, resulting in a fuel mixture of ammonia, nitrogen and hydrogen. Partial decomposition is a relatively straightforward process at moderate temperatures (~400 Celsius). The hydrogen content of this mixture helps to initiate and accelerate the combustion process, ensuring efficient and complete fuel combustion. Internal combustion engines exploit large volumes of surrounding air to boost power output, enabling up to 80 MW output per engine.

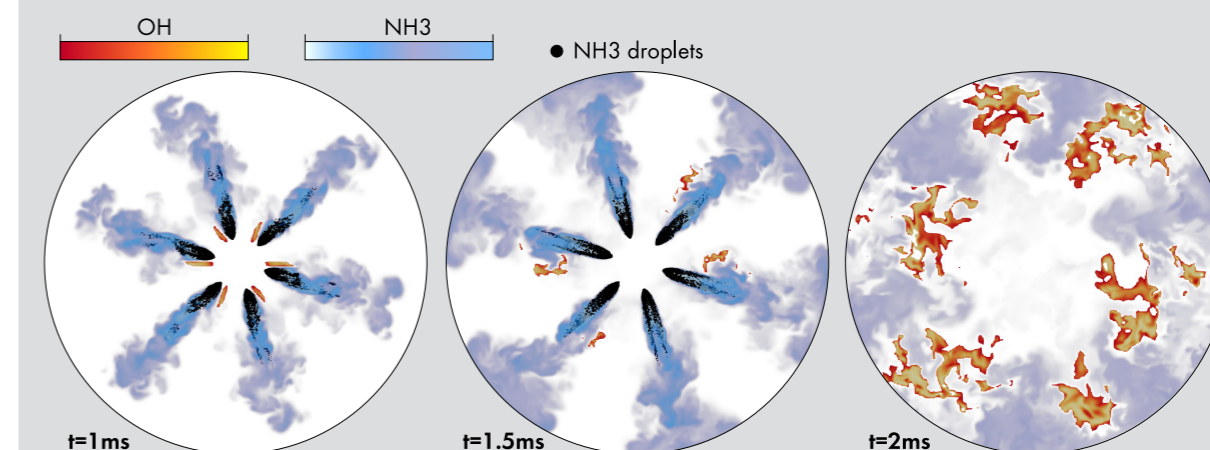


Illustration of the injection, ignition, and combustion processes when liquid ammonia is sprayed directly into the combustion chamber.

MaritimeNH3 has performed a detailed assessment of ammonia's suitability in internal combustion engines

The work in MaritimeNH3 has focused on conducting a detailed assessment of the chemical reactivity and emissions characteristics of partially decomposed ammonia fuel blends. This was done by leveraging high-resolution, direct numerical and large eddy simulations (DNS & LES) as well as high-performance computing (HPC) facilities.

First, a first-of-its-kind fundamental study was performed by running a state-of-the-art DNS code in parallel on approximately 30,000 processor cores on Norway's "Betzy" supercomputer. The aim of this study was to compare the turbulent burning rate of an ammonia-hydrogen-nitrogen fuel blend, resulting from partial ammonia decomposition and mixed with air, with the burning rate of other gaseous fuels, such as methane and hydrogen. The DNS results, though based on a very simplified geometrical configuration (a cubical chamber), suggest that relatively small ammonia decomposition rates (approximately 10-20%) can provide a fuel blend that burns as fast as methane, which is already widely used in gas-fired engines. For larger decomposition rates (approximately 20-60%), the ammonia-hydrogen-nitrogen fuel mixture can significantly exceed the burning rate of conventional hydrocarbons, approaching burning rate values only

achieved by hydrogen. This confirmed that partial ammonia decomposition represents a very robust method of increasing the reactivity of ammonia as maritime fuel for internal combustion engines.

In a second numerical study, high-resolution LES calculations were performed on a more realistic piston-engines configuration, featuring a hydrogen-fired prechamber for igniting the main ammonia charge. The focus of the LES study shifted away from the theoretical burning rate estimates of the earlier DNS study, and aimed to assess:

1. the robustness of the ignition source provided by the hydrogen-fired prechamber and,
2. the emissions characteristics of two injection methods for the ammonia main charge: port injection, where gaseous ammonia is mixed with air early, vs direct injection, where liquid ammonia is sprayed directly into the combustion chamber.

The LES results revealed that the hydrogen-fired prechamber seems to be well suited to igniting ammonia-air burnable mixtures across a wide range of equivalence ratios (fuel-oxidiser ratios), and that the direct-injection strategy is preferable, with respect to minimising both NO_x and N_2O emissions.



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Fuel cells

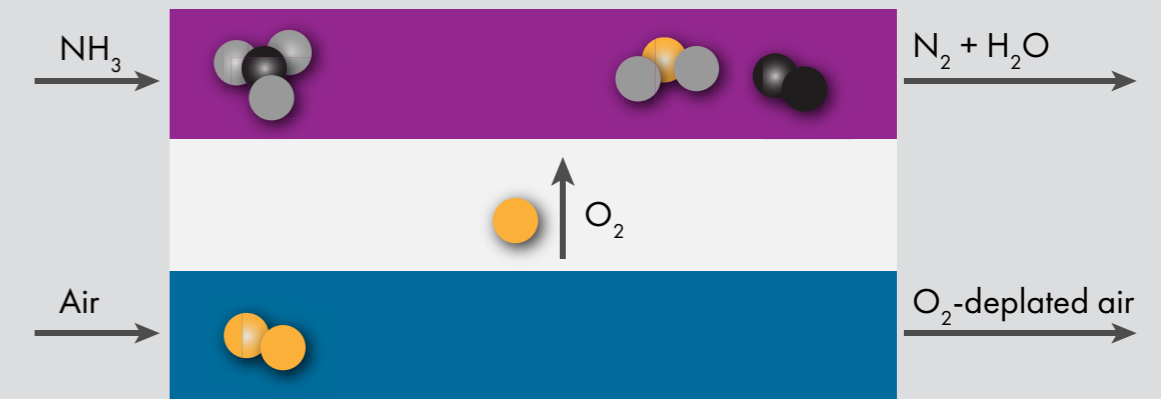
Currently, the most efficient technology for converting ammonia to electrical energy is the solid oxide fuel cell (SOFC), which has a demonstrated electrical efficiency of up to 60 %²⁶. Ammonia can be supplied directly to the cell, as the high operating temperature of the SOFC (600-900 °C) and nickel-based fuel electrode facilitate the separation of ammonia into hydrogen and nitrogen. The hydrogen is utilised by the cell to produce electricity, while the nitrogen is released into the exhaust together with steam.

As this process involves electrochemical conversion of the fuel rather than combustion, no oxygen is present. Therefore, the potential of undesirable nitric oxide (NO_x) or nitrous oxide (N_2O) formation is minimal, and no $\text{NO}_x/\text{N}_2\text{O}$ have been detected in analyses of the exhaust gas of an SOFC operated with ammonia²⁷. SOFC testing in Maritime NH₃, and as reported by others in literature, suggest that a similar performance can be achieved when fuelling with ammonia as when fuelling with hydrogen^{28, 29}.

Associated challenges

So far, commercial SOFCs have been primarily employed in stationary applications (e.g. providing reliable power for datacentres) and operated with natural gas and hydrogen fuels³⁰. The high efficiency and fuel flexibility have also led to increased interest in utilising this technology for maritime transport. Several research and maritime demonstration projects up to 250 kW have been completed in the recent years, and SOFC manufacturers such as Bloom Energy and Alma Clean Power have developed systems specifically for the maritime sector, which have received approval-in-principle from DNV^{31,32}. Alma Clean Power recently reported successfully testing a 100 kW direct ammonia fuel cell system that was fully integrated in a simulated maritime environment and the EU-funded project ShipFC has ambitions of installing a 2 MW ammonia-fuelled SOFC system onboard the supply ship Viking Energy^{33, 34}.

Nevertheless, in order for SOFC to become a realistic contender for ship owners considering investment into an ammonia propulsion system, the technology needs to be further developed and demonstrated at a higher technology readiness level (TRL). The cost is also currently prohibitive, but this is expected to decrease with improved automation and increasing production volumes in the future.



Operating principle of a solid oxide fuel cell powered by ammonia.

MaritimeNH3 has identified several potential developments for ammonia use in fuel cells

One concern when operating SOFCs with ammonia is the risk of nitridation of the fuel electrode and steel interconnects, which could increase power loss over time and reduce the lifetime of the SOFC stacks. The available literature suggests that operating the cell at higher temperatures (>750 °C) may mitigate this risk³⁵. Nevertheless, more research is needed to verify the long-term durability of ammonia-fuelled SOFCs, and map out safe operating conditions.

Conventional nickel-based materials employed in state-of-the-art SOFCs have been optimised for use with hydrogen and reformed hydrocarbon fuels, and may not be the optimal solution for a fuel cell operated with ammonia. As such, it may be attractive to investigate alternative electrode materials with improved ammonia cracking abilities and resistance to nitridation. More research should also be directed towards the potential corrosion of the components required to operate the system, such as heat exchangers and pumps, which

have to endure the exposure to ammonia at high temperatures.

Another solution to prevent nitridation could be to pre-decompose the ammonia to hydrogen and nitrogen in a thermal cracking process. The heat needed to power such a cracker can be supplied by the SOFC, which generates heat at high temperatures during operation. Thus, including an external cracker is expected to have a minimal impact on the system's overall electrical efficiency²⁶.



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