GROUP TECHNOLOGY & RESEARCH, WHITE PAPER 2020

AMMONIA AS A MARINE FUEL

SAFER, SMARTER, GREENER

TABLE OF CONTENTS

INTRODUCTION

Ammonia has attracted wide interest as a source of zero emission fuel for shipping. This paper examines the current use of ammonia in shipping and other industries and considers what it would take for ammonia to be adopted at scale as a maritime fuel. We think that there are significant but not insurmountable technical and safety challenges associated with ammonia as a marine fuel. Barriers to adoption relate to the source of ammonia and the future cost of green ammonia. Almost all ammonia in use today is made from hydrocarbons, and as such confers almost no carbon abatement advantage, while simply adding costs. By contrast, green ammonia – produced by electrolysis powered by renewables or nuclear – is an excellent source of zero-emission fuel, provided that associated NO_x emissions are managed appropriately. However, green ammonia is currently only produced in negligible amounts, and a massive investment programme would be required not only to produce a meaningful supply of green ammonia, but to drive down the costs of doing so, such that the fuel becomes financially viable for the shipping industry.

AUTHORS

Hendrik Brinks
Principal researcher zero-carbon fuels
DNV GL – Group Technology & Research
hendrik.brinks@dnvgl.com

Erik Andreas Hektor
DNV GL – Group Technology & Research
erik.andreas.hektor@dnvgl.com

BACKGROUND

There are a number of drivers for developments in maritime fuels. Compliance with sulfur emission control areas (SECAs), in combination with the 0.5% global limit on sulfur, has been one of them. However, the upcoming IMO regulations on reduction of greenhouse gas (GHG) emissions from shipping will be even more important. The total GHG emissions will have to be reduced by at least 50% in 2050 compared with 2008 emissions, while the fleet grows. At the same time, the CO_2 intensity, i.e. emissions per transport work, must also be reduced by at least 70% within the same time frame, while a 40% reduction in CO_2 intensity by 2030 also has been agreed. In order to reach these ambitions, technical and operational energy efficiency measures will be essential, but not sufficient by themselves. Therefore, low-carbon or carbon-neutral fuels have to be introduced into the fuel mix, to reach the ambitious reductions agreed by the IMO.

There is a large variety of other alternative fuels that can be used in shipping, such as Liquefied Natural Gas (LNG), methanol, dimethyl ether, ethanol, Liquefied Petroleum Gas (LPG), biodiesel (renewable diesel, FAME-based biodiesel or diesel from Fischer-Tropsch-related processes), electricity, liquified biogas (LBG), hydrogen and nuclear power. So far, LNG is the most commonly used alternative fuel. As of September 2020, there are 173 LNG-powered vessels (excluding LNG carriers) and 227 confirmed orders for new vessels[1] while the consumption of LNG as fuel is expected to grow five times from 2018 to 2022, due to larger vessels using it for propulsion. The first methanol-powered ships have been delivered and the first LPG-powered ships are being retrofitted during 2020. The first hydrogen-powered fuel-cell passenger ferries are planned to be put in operation in the next 1-2 years in the San Francisco Bay in USA and in Norway in 2021.

These alternative fuels all reduce local emissions to a varying extent, and most of them contribute to reduced GHG emissions. However, few are able to reach the 70% target in emission intensity on a well-to-wake perspective by themselves. Methanol produced from natural gas increases the GHG emissions by a few percent,[2,3] LNG reduces emissions from 10 to 25%, depending on the technology used, and LPG will typically lead to 17% GHG reduction.[4,5] In a life-cycle-assessment, biofuels will result in GHG emissions, which is very dependent on how they are produced and transported. GHG reductions for biofuels may be in excess of 50%, depending on the production pathway. Synthetic fuels, produced by combining clean hydrogen and CO_2 captured from the atmosphere or other biogenic processes, also have the potential to be carbon-neutral, at the expense of very high fuel cost.

Options that will lead to near 100% GHG reduction include nuclear fission reactors and carbon capture and storage on-board. The former is controversial and capital-intensive, whereas the latter is currently complicated, costly and voluminous, and depends on reception facilities in ports.

GHG emissions from electricity production, and to an even larger degree hydrogen, will depend strongly on the source, but these options have the appealing possibility to be virtually emission-free when produced from renewable power. These energy carriers however are difficult to store, thus limiting the range of ships significantly for battery-propulsion and pressurized hydrogen storage. Liquified hydrogen storage at 20 K requires less space and mass, but does not come without challenges. In addition, the cost and size of the storage and fuel cells are other limiting factors.

Another possible energy carrier is ammonia. Ammonia has the key benefit of being easier to store than hydrogen, i.e. nearly identical to propane (LPG) at low pressure under ambient conditions. Hence, the cost of storage per energy unit is significantly cheaper than either hydrogen, electricity in batteries or LNG. Furthermore, ammonia does not contain carbon and processes for producing it from renewable energy are known, even though it typically is produced in industrial processes from natural gas. Therefore, it is possible to regard ammonia as an energy carrier that is more convenient than hydrogen, but still CO_2 emission free under the right circumstances. For the purposes of this paper, CO_2 emission-free ammonia from renewable electricity is labelled green ammonia, whereas ammonia from fossil sources like natural gas and coal is labelled brown ammonia. Ammonia from fossil sources with carbon capture and storage (CCS) is labelled blue ammonia.

Green ammonia
CO_2 emission-free (from renewable electricity)

Blue ammonia
Fossil sources with carbon capture and storage (CCS)

Brown ammonia
Fossil sources like natural gas and coal

There are, however, drawbacks with ammonia such as toxicity, limited experience as a fuel in combustion engines and low energy utilization rate that calls for a further analysis. This white paper provides an overview of issues relating to ammonia as a marine fuel, including production and utilization, engine and tank technology, safety considerations including toxicity, environmental performance, pricing, and financial feasibility.

PRODUCTION AND UTILIZATION OF AMMONIA

WHAT IS AMMONIA?

Ammonia (NH_3) is a colourless gas under ambient conditions with a lower density than air. The boiling point is -33.3°C and hence by applying a moderate pressure it can be handled as a liquid at room temperature. At pressures above 8.6 bar at 20°C, ammonia is a liquid with a density of 0.61 t/m^3.[6] At the boiling point, the density is 0.68 t/m^3. The heating value for ammonia on a lower heating value basis is 18.6 MJ/kg. Thus, compared to MGO the energy content is less than half on a mass basis and about 30% on a volume basis in liquid state.

When ammonia is stored under pressure in Type C tanks, the volumetric energy density can be compared to MGO, LPG and hydrogen as shown in Table 1 and Fig. 1. In addition to the density of the fuel, there will also be a penalty in volume related to the cylindrical shape of the tank and the penalty will be larger if an insulation system is required.

In spite of the lower energy content for ammonia per tonne compared with hydrogen, the density of the fuel results in less volume required to store the same

	MGO	LPG	H_2 350 bar	H_2 liquid	Ammonia
Density (t/m^3)	0.835	0.49	0.023	0.071	0.61
LHV (GJ/t)	42.7	46	120	120	18.6
GJ/m^3	35.7	22.6	2.80	8.52	11.4
Volume (m^3/GJ) normalized	1	1.58	12.75	4.18	3.14

Table 1: Comparison of volumes required per energy unit on lower heating value basis for ammonia compared to MGO, LPG and hydrogen

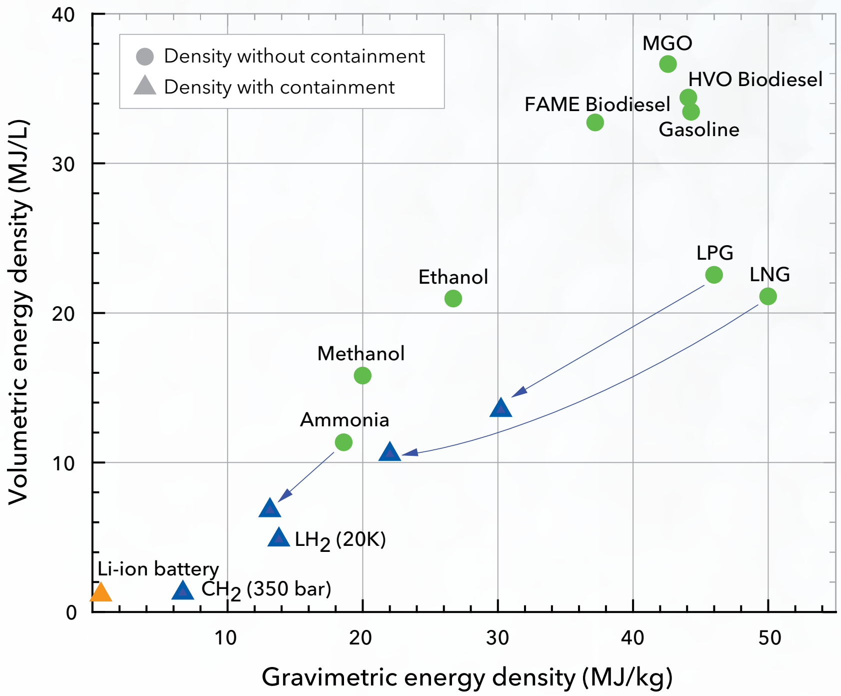


Figure 1: Densities for selected alternative fuel with and without containment on lower heating value basis

energy for ammonia compared with hydrogen (cf. Figure 1). This is especially the case for compressed hydrogen, but also for liquid hydrogen. Compared with MGO and LPG, the space requirement is significantly higher.

Ammonia is a basic compound with a distinctly pungent, suffocating odour. The typical detection limit by humans varies considerably from 0.04 to 53 ppm with a mean of 17 ppm.[7] Hence the detection limit may be above concentration that is considered dangerous for long term exposure, and detectors should be used where there are risks for exposure to ammonia.

The recommended exposure limit varies by jurisdiction and over time. The US Occupation Safety and Health Administration (OSHA) has set an 8-hour exposure limit of ammonia to 25 ppm and a 15 minutes exposure limit to 35 ppm.[8] For EU the corresponding exposure limits are 20 and 50 ppm. OSHA has defined the level at which persons can be exposed without suffering irreversible health effects as 300 ppm. Exposure to very high concentrations of gaseous ammonia can result in lung damage and death. One reported fatal limit is 5,000 ppm or only 0.5%.[9] Ammonia solutions with water have strong alkali reaction. Being extremely soluble, ammonia is absorbed by body fluids (sweat, tears, saliva) and may cause severe chemical burns. Safety of personnel onboard in case of ammonia spill and emergency equipment for work in gas filled space shall be particularly addressed in the maritime industry. Water spray is used as an effective means to absorb ammonia from air. Emergency showers and eye wash stations are currently being used in gas carrier cargo areas to prevent injury to personnel in contact with ammonia. For gas carriers, ventilation arrangements in accommodation and work areas are designed to shut ventilation fans and seal the compartment from the inside.

Ammonia is corrosive to some materials like copper, copper alloys and zinc, and care must be taken in the selection of materials. Ammonia is known to cause stress corrosion in carbon manganese and nickel steels. Furthermore, dissolved oxygen in liquid ammonia increases stress corrosion risk. Care must be taken to purge air from the ammonia systems prior to filling them with ammonia; new tanks must be thoroughly purged to eliminate air contamination.[10] Ammonia is also reactive with CO_2 that may be contained in inert gas.

The probability of stress corrosion cracking is also significantly reduced by adding a small amount of water, not less than 0.1 wt%. Low-level water additions to ammonia are often done, but not if ammonia is transported at lower temperatures and require refrigeration or if it is premium grade. In addition, the probability is decreased by using post-weld stress relieved tanks if ammonia is stored and transported under pressure (at ambient temperatures or semi-refrigerated). Use of steels with nickel content exceeding 5% is generally prohibited. For carbon manganese steels, material grades lower tensile strength, not exceeding 410 N/mm² shall be selected. Lower transportation temperatures preferably closer to boiling point and not warmer than -20°C significantly reduce stress corrosion risk.

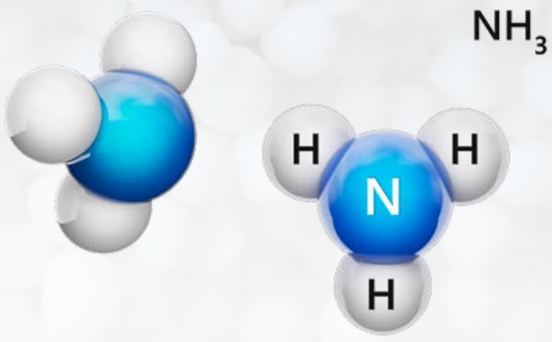


Figure 2: Chemical structure of ammonia; NH_3

UTILIZATION

Most ammonia is used for fertilizers. According to Centre for European Policy Studies, about 80% of the global ammonia production is used for fertilizer,[11] and for the US the fertilizer usage is about 88%.[12] The remainder is used variously for explosives, plastics, synthetic fibres and resins, refrigerants, and chemicals like nitric acid.

Ammonia may be used directly as a fertilizer, which it is to some extent in the US, but mostly it is applied as another chemical. The most common fertilizer is urea, produced by a reaction between ammonia and carbon dioxide. The high nitrogen content of urea results in a low transportation cost per unit of nitrogen nutrient. In the soil, carbon dioxide is released within days and the nitrogen is made available to the plants. Wheat, corn and rice crops are responsible for about half of the global nitrogen use in fertilizers.[13] Global food production has become increasingly dependent on nitrogen produced by the Haber-Bosch process. In 2008, for example, nearly half the world's population consumed food was produced with Haber-Bosch nitrogen – a nutrient that has in effect made the population growth possible.[14] Hence, the use of ammonia in large quantities as a fuel must be considered in relation to the fertilizer supply, cf. Section Production volumes and availability.

PRODUCTION PATHWAYS

Key production pathways for ammonia
Most ammonia is produced by the Haber-Bosch process, which combines nitrogen gas and hydrogen gas at high pressures and elevated temperatures to form ammonia. The Haber-Bosch process was commercialized in 1913 by BASF, using gasification of coke as feedstock. Natural gas has later become common, and the share in 2017 of natural gas, coal and oil feedstock for the global production of ammonia was about 68%, 28% and 4%.[15]

Typically, when produced from desulfurized natural gas, the hydrocarbons are converted by a primary steam reformer followed by a secondary reformer, where air is introduced. The product is mainly a mixture of CO, hydrogen and nitrogen. Subsequently, a water gas shift reaction is carried out to convert CO and water to CO_2 and hydrogen, and CO_2 and CO are then removed in several steps. The resulting mixture consists of hydrogen and nitrogen in 3:1 ratio and in addition some methane and argon. In order to form ammonia in the Haber-Bosch process, this mixture is typically reacted at up to about 300 bar at 400-500°C in the presence of an iron-based catalyst. In each pass through the reactor, about 15% is converted and several passes are required to achieve a complete conversion. Ammonia is normally removed by condensation in each pass.

The efficiency at a lower heating value basis for converting natural gas into ammonia has improved over time and is currently about 66% on lower heating value basis with the best available technology.[16] However, it has been reported that in 2012 the weighted average European energy consumption of natural gas is 10.8 MWh per tonne ammonia, which corresponds to only 48% efficiency,[11] and one of the largest ammonia producers describes 53% as an efficient plant.[17] Hence, few plants reach the highest efficiencies.

Biogas, e.g. from a landfill or a wastewater management system, may, after purification, be used instead of natural gas as a methane source. Similarly, various gases from steel manufacturing containing mixtures of among others hydrogen, CO and nitrogen have been demonstrated to be able to be used as feedstock for ammonia synthesis, e.g. coke oven gas, blast furnace gas and converter gas.[18] In such a process, hydrogen is separated from coke oven gas and the other gases are after water gas shift and CO_2 removal mixed with the hydrogen prior to Haber-Bosch synthesis.

Biomass or coal may also be turned into ammonia by the Haber-Bosch process. In this case, a gasification process is typically used in combination with oxygen from an air separation unit, with sulfur removal integrated in the process, to produce the hydrogen/nitrogen mixture for the Haber-Bosch process. Another source of hydrogen for the Haber-Bosch process is by electrolysis of water based on renewable energy. The efficiency for such a process at large scale would typically be 68%.[19] Nitrogen is obtained from an air separation unit. For the entire process from electricity to ammonia, the efficiency is reported to be approximately 52%.[20] Examples of the production of renewable (green) ammonia include Norway in the town Rjukan from 1927 to 1988 as well as in the town Glomfjord from 1949 to 1993 by use of hydropower, but this process was not competitive with ammonia produced from natural gas and was therefore discontinued. In Pilbara in Australia, plans have been proposed to build electrolysers, fed by solar PV, to produce a small fraction of the production capacity of the large plant of 840,000 tonnes per year. Mixtures of fossil and renewable electricity-based plants have been labelled hybrid green ammonia.[21] Similarly, standalone plants may be constructed to supply the ammonia demand from regions with abundant renewable resources without sufficient power demand, where ammonia will serve as an energy carrier.

In addition, hydrogen for the Haber-Bosch process may also be thermochemically produced through the sulfur-iodine cycle from nuclear power. The sulfur-iodine cycle is a three-step reaction utilizing high-temperature heat with the net reaction of splitting water into hydrogen and oxygen, instead of using electricity as for electrolysis. A simplified overview of the various production pathways is presented in Fig. 3 based on the work of Bartels.[22]

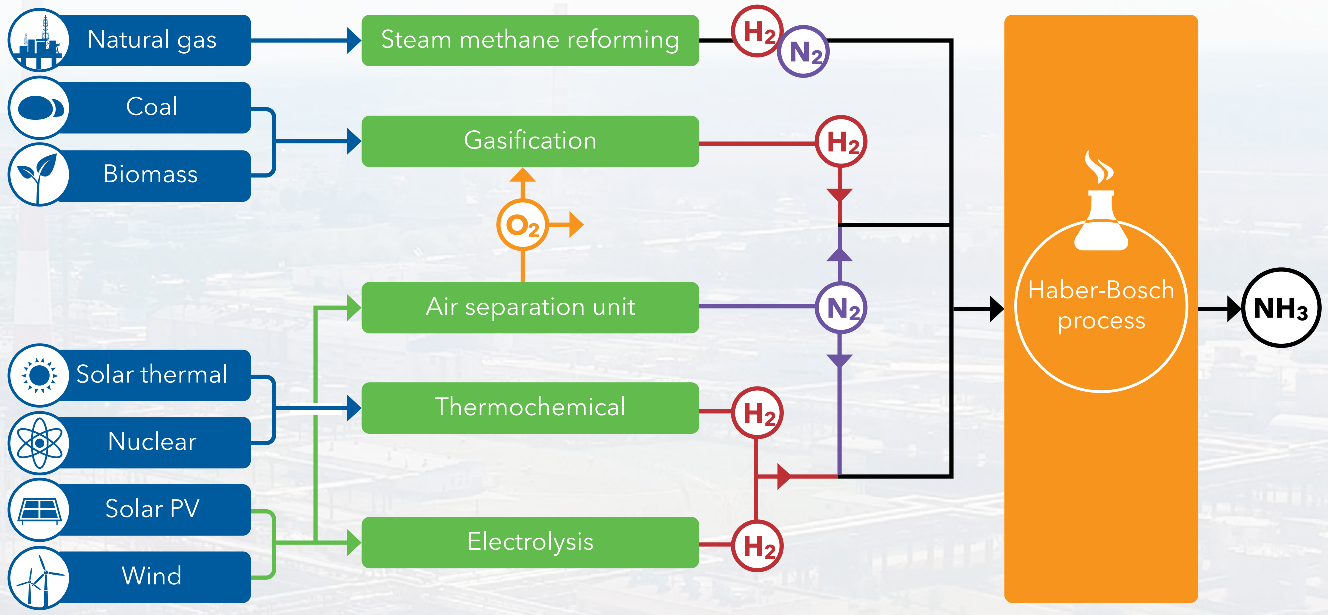


Figure 3: Ammonia production pathways

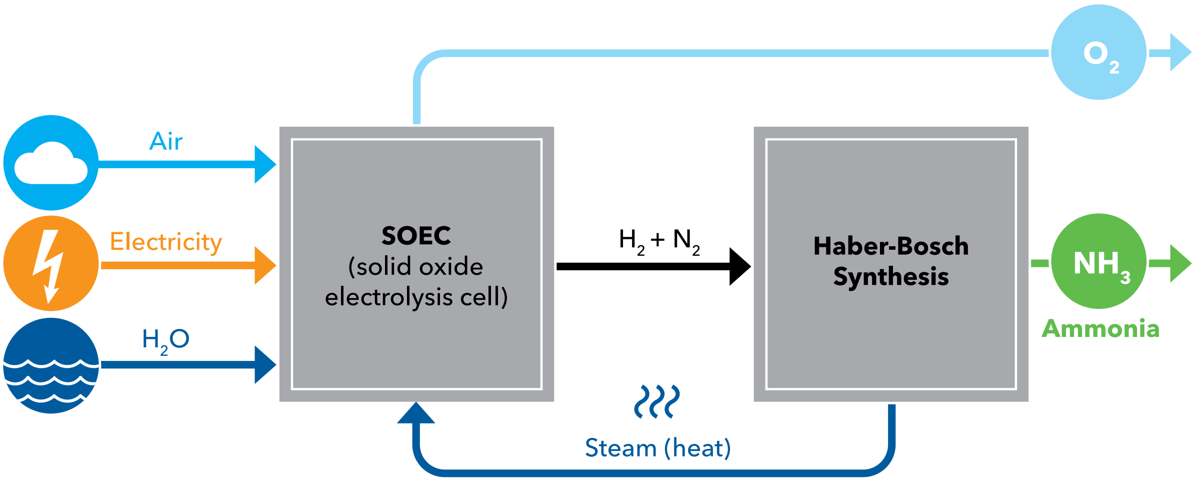


Figure 4: The SOEC concept for ammonia production by Haldor Topsøe[24]

The efficiencies for best available technologies for brown ammonia are lower for other feedstocks than natural gas and has been reported to be 53% for naphta, 49% for HFO and 44% for coal.[23] Natural gas as a feedstock has both higher efficiency and lower capex and opex than use of coal as feedstock. The capital requirements for natural gas, oil and coal have been reported to be USD 860, 1 203 and 2 063 per tonne of annual production capacity, whereas annual opex is estimated to be 2.5%, 2.5% and 5% of the capex, respectively.[24]

Other methods exist to produce ammonia, but are not commercially available at a large scale. One of them is by a chemical looping process where certain metal hydrides are used for fixation of nitrogen to form an imide, and hydrogen are used in a second stage to both release ammonia and to regenerate the metal hydride.[25] With catalysts, this process may be performed at low pressure and moderate temperature at lab scale.

For production of ammonia from natural gas, there are four key companies that are providing ammonia plants: Haldor Topsøe, ThyssenKrupp/Uhde, Casale and KBR. Another approach, that is under development by Haldor Topsøe, is a combination of solid oxide electrolysis cell (SOEC) and Haber Bosch process.[26] In this concept, the SOEC separates the oxygen from the air/steam mixture, such that an air separation unit would not be required. The efficiency from electricity to ammonia has been estimated to about 71%. The energy demand for the Haber-Bosch synthesis is estimated at only 6% of the energy consumption of the complete process.

COMPARISON OF DIFFERENT MARITIME FUELS FROM NATURAL GAS

Natural gas can be used as a feedstock for conversion into a range of marine fuels. The conversion efficiency varies both with the production pathways and the convenience of transporting and storing the fuel.

Purified natural gas can be used directly in liquid state. The conversion efficiency for LNG is about 90% and transport and storage of LNG with a boiling point of -163°C will result in losses. During ship transport, the boil-off is typically 0.08-0.15% per day, although most of this can be used as a propulsion fuel for the ship.

Natural gas can be converted into methanol with a conversion efficiency from natural gas of up to 70%, and the handling of the liquid fuel at ambient temperature is simpler. Methanol is a drop-in fuel, but it does require modified engines.

Brown ammonia has a lower conversion efficiency of up to 66% and is required to be stored at a low pressure or moderately refrigerated. The efficiency is less than methanol and handling is more challenging. However, ammonia has the benefit of not containing carbon. Therefore, conversion of natural gas into ammonia may be combined with carbon capture and storage technologies, which, as is the case with hydrogen, should reduce the GHG emissions by up to 90%.[27] This will of course reduce the conversion efficiency (see below).

Furthermore, brown hydrogen may be produced from natural gas with an efficiency of up to 75%.[27] It is possible to produce hydrogen with CCS at an efficiency of 69%.[27] Hydrogen needs to be stored either at high pressure at 250-700 bar or at very low temperature of 20 K, which is expensive and volume intensive. Typically, hydrogen is considered in relation to conversion in fuel cells, which are both expensive and have a limited lifetime.

EMISSION-FREE MARINE FUELS

There are limited options for marine fuels that are GHG emission free. Most fuels will lead to significant emissions at varying parts of the supply chain, e.g. biofuels will generally have emissions related to the collection of biomass, methane emissions and energy for the conversion processes. Renewable biodiesel (HVO) has been reported to offer about 60% reductions in emissions compared with fossil diesel.[28] Options that may be regarded as close to GHG emission-free are:

- nuclear power;
- ships with a carbon capture and storage system;
- synthetic energy carriers not containing carbon, produced from nuclear power or renewable energy;
- synthetic energy carriers containing carbon from a carbon-neutral source and produced from nuclear power or renewable energy.

For nuclear propulsion, there are significant political and societal barriers to its adoption. Carbon capture will be both costly and space demanding on ships, and furthermore requires a new infrastructure to store CO_2.

For the last of the four options above, fuel is typically produced with hydrogen from a renewable source in combination with a CO_2 source. Methanol is currently been produced in such a way in Iceland under the brand name Vulcanol, where CO_2, obtained by processing of gas emissions from underground in a geothermal power plant, is combined with hydrogen from electrolysis with renewable energy from the grid (geothermal, hydro and wind sources). When the CO_2 source can be considered carbon-neutral, the emissions for the fuel are minimal. For the Vulcanol product, the reduced GHG emissions compared with fossil fuels are considered to be more than 90%.[29] However the conversion process of electricity to renewable methanol has been reported to have lower efficiency than producing ammonia from the electricity.[30]

Another example of this could be to extract the CO_2 fraction of biogas and combine it with hydrogen from electrolysis with renewable energy to produce synthetic methane.[31] Methane can be turned into LNG and used as a marine fuel. Biogas sources typically have relatively low capacity and the total process would be comparatively energy intensive.

Another source of carbon-neutral carbon would be to separate CO_2 from a biomass power plant in combination with renewable hydrogen to make a fuel that is easier to transport than hydrogen. CO_2 may also be in theory be captured from air with renewable energy.

The remaining category comprises synthetic energy carriers where carbon is avoided altogether. Hydrogen and ammonia are in this category and both have their challenges as described throughout this paper. The storage of ammonia is easier and cheaper than hydrogen and it is possible to develop an internal combustion engine for ammonia that is cheaper than a fuel cell. This makes ammonia, despite its challenges, one of the better options for emission-free marine fuel.

PRODUCTION VOLUMES AND AVAILABILITY

The global production of ammonia was 170 million tonnes in 2018, up from 126 million tonnes in 2,000, cf. Figure 5.12 Global production capacity is expected to increase by 6% by 2021. 97% of the planned capacity increase is based on natural gas as the feedstock, and mainly in countries with cheap natural gas. It has been estimated that the global unexploited available production capacity is 40 million tonnes.[21]

31% of global ammonia was produced in China, 10% in Russia, 8.9% in the US and 7.9% in India.

For comparison, the fuel consumption of all ships was estimated to be 300 million tonnes in 2012, which corresponds to 650 million tonnes of ammonia on an energy basis. Since shipping fuel demand is also expected to increase further,[34] the current production of ammonia can only cover a moderate fraction of the demand for marine fuels. Furthermore, since the largest use of ammonia is for fertilizers, other uses of ammonia may compete with food production, with serious socio-economic ramifications.

However, for ammonia to become attractive as a carbon free marine fuel, emissions from production will need to be lower than is the case for the current best available technology, which uses natural gas as feedstock. This would require expanded production capacity either of renewable ammonia, i.e. electrolysis based on renewable electricity, or from ammonia production from natural gas in combination with CCS. Currently only about 1% of hydrogen produced is based on electrolysis, and ammonia production in combination with CCS is not known.

The International Energy Agency (IEA) estimates the global hydrogen demand in 2018 to about 73 million tonnes of pure hydrogen and 42 million tonnes of hydrogen as part of gas mixtures.[30] In the first category, about 32 million tonnes are used to produce ammonia and is thus second only to the main consumer of hydrogen – refining (at 38 million tonnes). Methanol production consumes about 12 million tonnes of hydrogen annually.

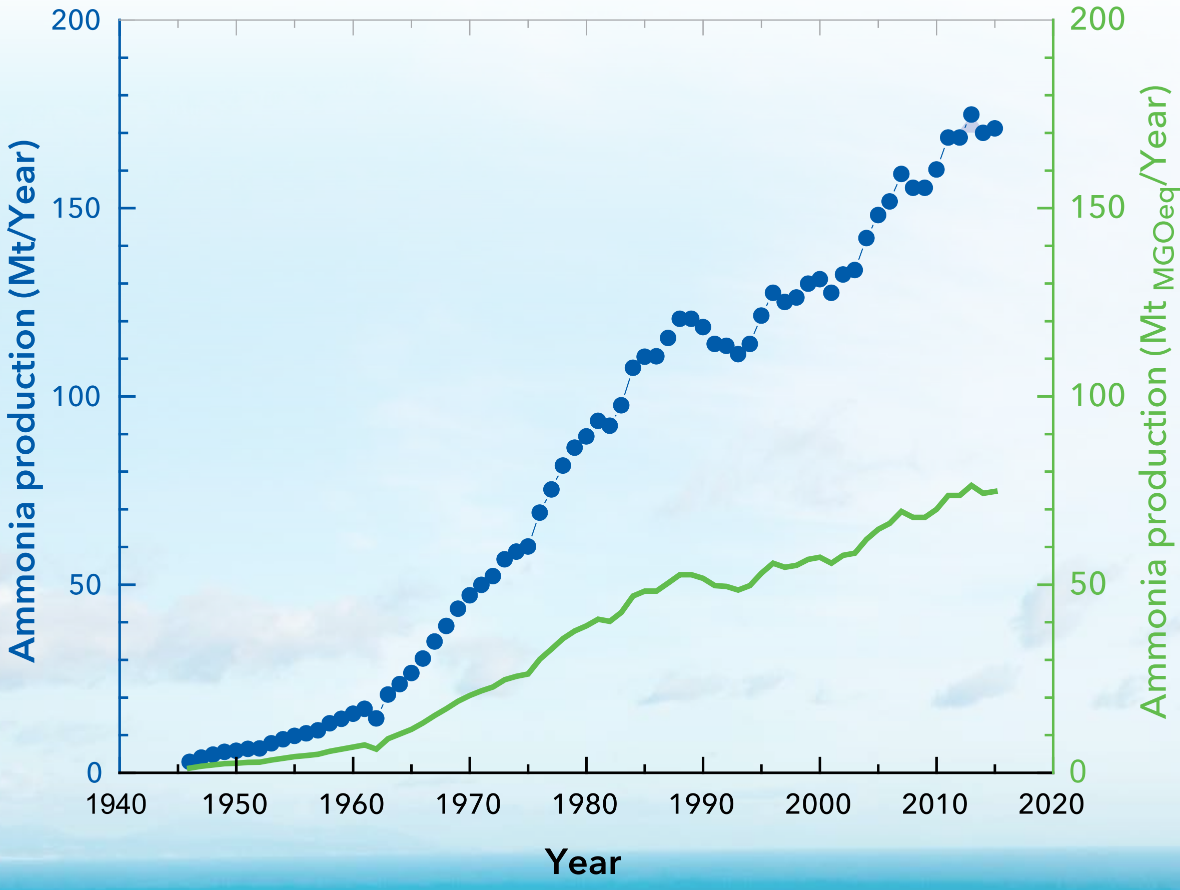


Figure 5: Global production of ammonia and corresponding amount of oil, compared to the oil-based fuel consumption in maritime sector of 300 million tonnes. Source: USGS

TRANSPORTATION

Some 11% of global ammonia production, or 18.5 million tonnes, is traded as ammonia.[35] This trade is mainly for industrial users, fertilizer producers or for direct utilization as fertilizers, which is partly done in the US,[17] where there is also an extensive network of ammonia pipelines transporting around 2 million tonnes of ammonia each year.[35,36] Key exporters are large natural gas producing countries, in particular Trinidad and Russia with 4.6 and 3.7 million tonnes respectively in 2016, but also Saudi Arabia, Algeria, Canada and Indonesia exported more than 1 million tonnes in that year. The two largest importers in 2016 were the US and India. The main centre for ammonia trade is Yushnyy in the Black Sea, where most spot trades take place. The relative pricing in other geographies is typically consistent with prevailing freight rates.[17] The main global trade flows of ammonia are shown in the figure below.

Main ammonia flows 2016 (million tonnes)

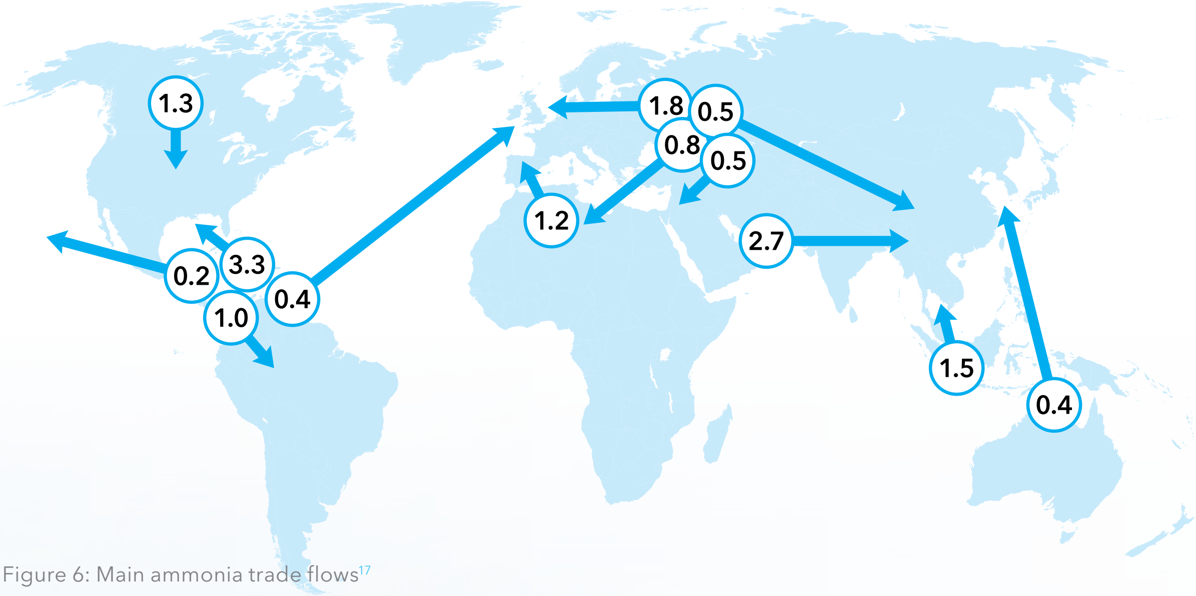


Figure 6: Main ammonia trade flows[17]

Anhydrous ammonia is transported in gas carriers designed for ammonia transportation. Since ammonia is similar to propane with regards to saturated vapour pressure, ships for ammonia transportation are similar to LPG carriers. However, owing to corrosivity, toxicity and reactivity, not all LPG carriers may be used for ammonia transports. Besides, ammonia shipments are typically smaller than LPG parcels and therefore normally transports are done by a selection of gas carriers up to LGC size at 60,000 m^3.

Ammonia can be transported by three different ship types, depending on how the cargo is stored:

- refrigerated, typically at -50°C at close to ambient pressure;
- semi-refrigerated, typically at -10°C and 4-8 bar pressure;
- under pressure, typically at 17 bar, corresponding to the vapour pressure of ammonia at about 45°C.

The latter two categories transport smaller amounts of ammonia. In large quantities, ammonia is typically stored in tanks onshore as refrigerated ammonia.[37]

The ship transportation of ammonia is covered by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), which is aimed at the safe carriage of liquids with a vapour pressure above 2.8 bar at 37.8°C, and applies to all ship sizes. Were an ammonia carrier to be powered by ammonia, in principle that particular ship type would be covered by the IGC Code without having to comply with the IGF Code (International Code of Safety for Ship using Gases or Other Low-flashpoint Fuels). The IGC Code (chapter 16) can be used for further clarification. A challenge with this, however, is that the IGC Code chapter 16.9.2 does not allow for the use of toxic cargo as a fuel, which thus excludes ammonia cargo as fuel. This is a regulatory barrier that can be overcome if and when a flag state takes action in conjunction with the IMO. For other ships, the use of ammonia as fuel has to be covered through alternative compliance with the IGF Code.

In addition to handling of ammonia as a cargo, some ships have refrigeration systems with ammonia as refrigerant. DNV GL has also developed rules for this.

AMMONIA PRICING

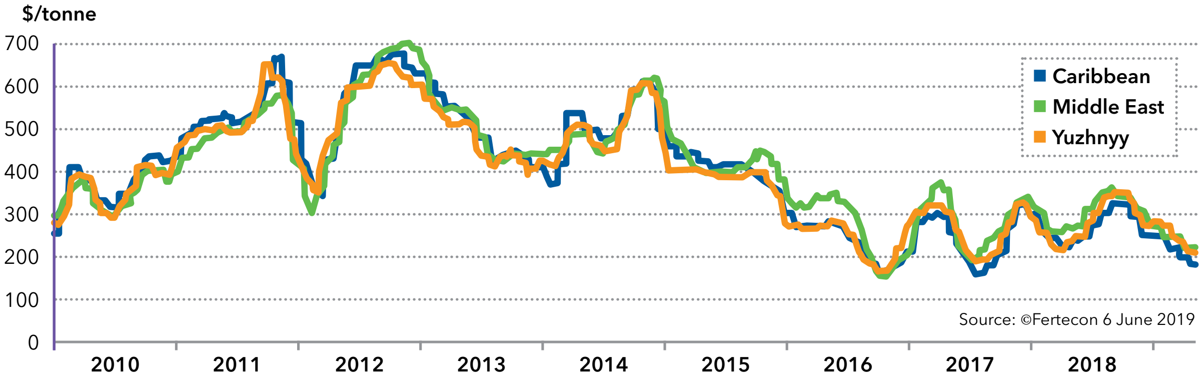


Figure 7: Ammonia pricing in various regions since year 2010. Source: Fertecon

Ammonia prices vary significantly over time and are not the same in all geographies. Prices lower than 200 and up to 700 $/t have been reported in the last decade. Since 2016, the price has been below 400 $/t and typically 200-300 $/t owing to market conditions for natural gas and ammonia availability.[38] The average for 2008 to 2017 is about 400 $/t.

The natural gas cost contributes 70 to 85% of the production cost in US for ammonia, depending on the natural gas price.[35] Similar results are also found for other geographies.[11] The local cost of natural gas will therefore largely determine the cost, which has been reported to be 100 $/t in Middle East to more than 400 $/t in Western Europe as of 2013.

Typical efficiencies and capital expenditures along with typical US energy prices are shown in the table below. The reduced efficiency and increased capex will make ammonia from coal more expensive than from natural gas. Renewable ammonia, produced from renewable energy like wind power, will also be more expensive than natural gas feedstock. This will depend heavily on the cost of electricity, but also on advances in capex. The cost has been estimated at 2 200 to 3 500 $ per tonne annual production capacity, depending on the scaling of the equipment related to the electrolyser stacks.[37] Before scaling, the electrolysers contribute, in this estimation, around 77% of the capex, based on a price of 1,000 $/kW. With scaling, the electrolyser price is nearly 50% lower and the electrolysers contribute 65% of the capex (see Fig. 8). Larger electrolysers have also been reported to be available at this lower price level. Ammonia from renewables are close to being competitive with coal-based ammonia.[39]

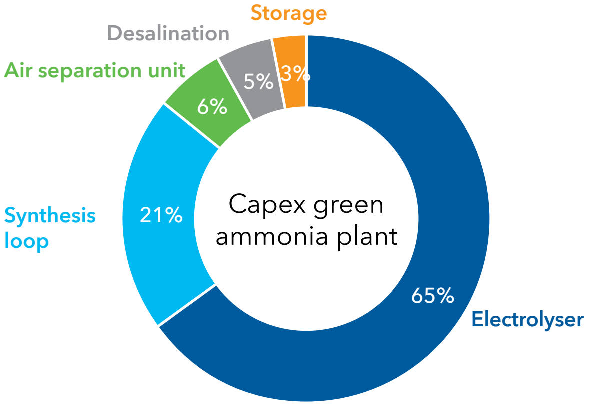


Figure 8: Capex breakdown of a 300 t/day green ammonia plant with electrolyser scaling. Based on Morgan[37]

	Natural gas	Coal	Wind
Energy cost ($/GJ)	3.3	2.1	16
Efficiency	66%	44%	52%
Capex ($/$t_{NH3}$)	860	2,063	2,200 to 3,500

Table 2: Energy costs, efficiency and capital expenditure per tonne annual production capacity for various feedstocks for the production of ammonia.

The production cost of renewable ammonia will largely depend on two parameters: The price of electricity and capital expenditure. We have calculated a hypothetical ammonia production price for a plant producing ammonia from electricity (see Fig. 9). This is calculated as a function of electricity prices for various capex values, and is based on an internal rate of return for the project over 20 years at 10%, with an efficiency of 52%, a 5% discount rate, and annual operational expenditures at 2.5% of the capex.

The cost of onshore wind power is largely determined by the capex and capacity factor, and it has been estimated at 0.04 to 0.05 $/kWh.[40,41,42] in favourable locations. The International Renewable Agency (IRENA) estimates the 2020 global weighted average cost to be reduced for on-shore wind power to 0.045 $/kWh and for solar PV to 0.048 $/kWh.[43] The cost of PV solar is similar to on-shore wind, whereas offshore wind is higher. Based on these estimates, the current renewable ammonia price would be in the 650 to 850 $/t range, but electricity prices for renewable energy from wind and solar will be highly site specific. It is reasonable to expect that the renewable electricity prices will decrease over time and also that the capex for electrolysis will also decrease to some extent. Hence renewable ammonia will become more competitive.

For comparison, IEA has indicated, in its study on ammonia production from renewable resources in China, a price range of 450 to 700 $/t based on their model.[30,39]

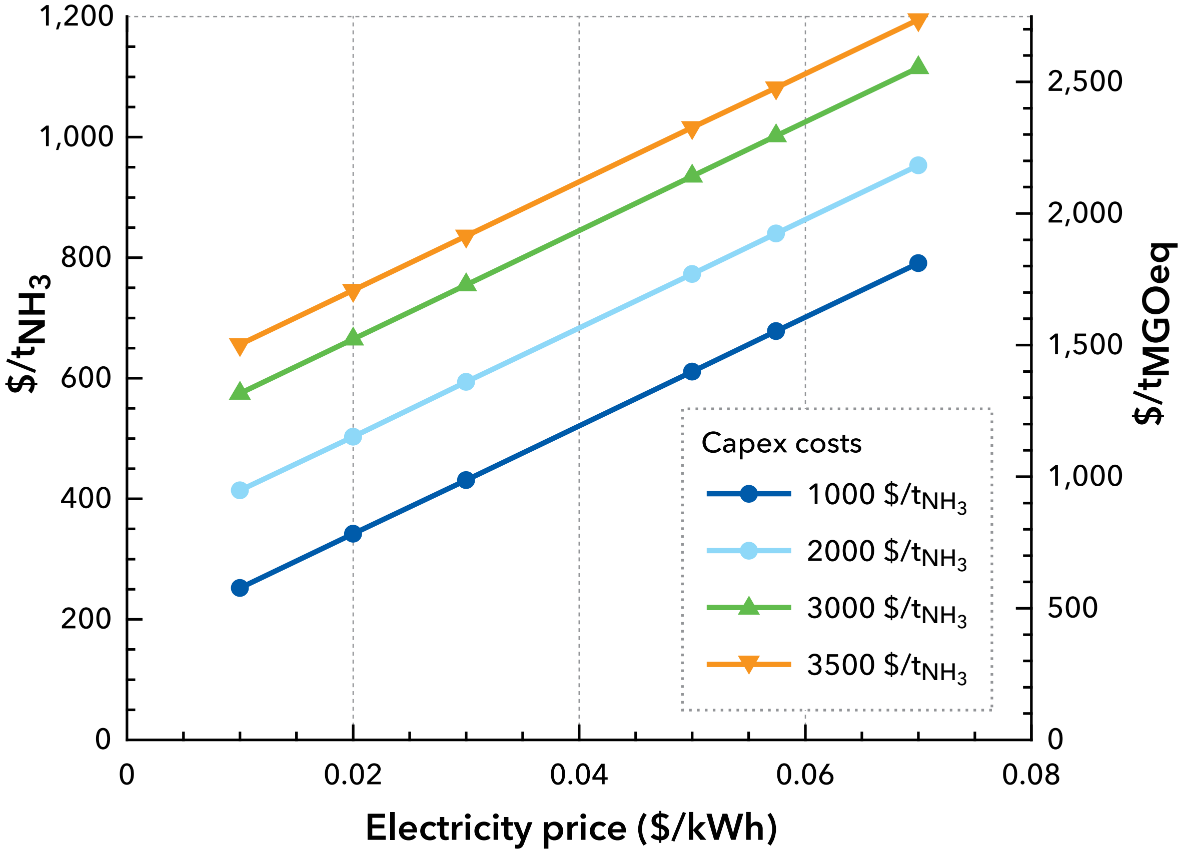


Figure 9: Estimated production cost of renewable ammonia as a function of the electricity cost at various capital expenditures (per tonne annual production capacity)

ENGINE TECHNOLOGIES

HISTORIC DEVELOPMENT

Ammonia for propulsion probably started in New Orleans around 1872, where US patent 105,581 was filed and tested for street cars. The system exploited the energy of low pressure of ammonia in a fireless engine and the ammonia exhaust was absorbed in an aqueous solution, thereby avoiding any loss of the gas. The ammonia was regenerated in a central facility. This system was succeeded by electricity for street cars. Rudolf Diesel continued working on similar ammonia engines in the 1890s, but after an explosion and serious injury, he moved on and invented what was later known as the diesel engine.

In 1935, the first practical applications on a limited scale of ammonia in an internal combustion engine was described in patents by Ammonia Casale.[44] Their system was characterized by partial thermal decomposition of ammonia in a catalytic reaction chamber heated with exhaust gases from the motor. Hence ammonia was co-fired with hydrogen.

During the Second World War, fuel starved Belgium, successfully used a mixture of ammonia and compressed coal gas (mainly consisting of H_2 and CO) in 100 vehicles in the winter 1941-42 and in eight buses from 1943.[45] The Belgians found that compressed coal gas alone reduced power output too severely to be feasible. Even though the energy content of ammonia is low, the engine consumed less air since no CO_2 is formed and ammonia expands during combustion, unlike gasoline and hydrogen. Furthermore, the octane number is 130 and high compression and thus good efficiency could be achieved. The efficiency was considered fairly equivalent to the diesel engines before modification.

In the 1960s, the US army investigated on-site manufacturing of fuels by mobile nuclear reactors from water and air in their concept Mobile Energy Depot.[46] They considered the fuels hydrogen, ammonia, hydrazine and hydrogen peroxide, and concluded that ammonia had the greatest potential. However, the US Army considered conversion of the present fleet to ammonia operation as extremely costly and impractical. The challenges were mainly very high autoignition temperature (630°C),[47] low flame speed, narrow flammability limits (15-28%)[48] and high heat of vaporization. This required at that time the use of spark-ignited engines. The use of hydrogen or hydrocarbon in addition to ammonia improved the performance of the engine.

More recently, some demonstration vehicles have been built successfully, e.g. a car fuelled by ammonia and gasoline that was used to cross USA in 2007.[49] As stated above, ammonia has a high octane rating and high compression ratios are possible without undesirable knocking. Furthermore, ammonia has a lower stoichiometric air-fuel ratio compared with diesel and for the same amount of air, more ammonia can be introduced and thereby compensate for the lower energy content and maintain the power density of the engine. The lower flame speed and narrow flammability range may lead to unburnt ammonia in part of the engine and hence ammonia slip.

Research has been successfully carried out both on spark-ignited engines and compression ignited engines. For the diesel-type engine tests, pilot fuel was typically used to improve combustion. The research thus far has been carried out on smaller, automobile-size engines.

Finally, in 2017 it was demonstrated in Japan that ammonia may be co-fired with a 1% share on energy basis in a commercial coal power plant without elevated NO_x emissions and without ammonia slip.[30] Successful demonstrations have also been carried out for co-firing in gas-turbines with up to 20% ammonia in the natural gas on energy basis.[50]

CURRENTLY AVAILABLE TECHNOLOGIES

There are a number of conversion processes for ammonia as a fuel. Ammonia has been considered as a fuel in fuel cells, primarily solid oxide fuel cells (SOFC) since a PEM fuel cell would require cracking of ammonia and is very sensitive to ammonia impurities. Research on SOFC has been carried out, but there are no such commercially-available fuel cells.[51]

However, the ShipFC project funded by EU was recently initiated.[52] This project will convert one of the gensets on the Norwegian offshore vessel Viking Energy to a 2 MW solid oxide fuel cell, thereby planning to run 3,000 hours per year solely on ammonia. A 100 kW SOFC will first be tested on land and then upscaled with planned installation in the ship in late 2023. The budget is 230 million NOK (25 million USD).[53]

Internal combustion engines are considered a better option than fuel cells in the near future because of cost, power density, load response and robustness.[54] Two-stroke diesel engines are the preferred main propulsion systems for large ships. The large combustion chamber and the long time scales with low rpm of a two-stroke engine may represent a benefit compared to the smaller engines used in previous demonstrations. For two-stroke engines, MAN ES has developed the dual fuel engines series ME-GI and ME-LGI that have been developed to address a number of new fuels including LNG, methanol, LPG and ethane. Ammonia is considered to be a more challenging fuel, and it is expected that pilot fuel like diesel would be required and possibly a larger amount than for LPG. MAN ES has started to develop two-stroke engines for ammonia, which likely will be based on the ME-LGI engine used for LPG, and are expected to be able to be delivered within five years. It is expected that retrofit packages will be available for existing MAN engines.

The fuel valve train connects the fuel supply system with the engine through a master fuel valve. For purging purposes, the valve train is also connected to a nitrogen source. Typically, the valve train will be placed outside the engine room in a dedicated space above the weather deck to improve safety. From the valve train, the fuel is fed to the engine in a double-walled pipe through the engine room. The system is monitored by sensors (sniffers). If ammonia is detected inside the double-walled pipe, the safety system will switch to fuel oil operation smoothly and without any loss of power.

For the ME-LGI engines liquid fuel, injection takes place via a so-called fuel booster injection valve, which uses hydraulic power to raise the fuel pressure and thus eliminates the need for high-pressure fuel lines. The low-pressure fuel supply system reduces the cost and weight and adds to the simplicity of the system.

Regarding four-stroke engines, Wärtsilä is investing in research and development to enhance fuel flexibility to also cover carbon free fuels like ammonia. Technologies for its use in marine vessels are currently under development. The latest product platforms like the W31 provide modularity for the potential future conversion for ammonia use, either from diesel, dual-fuel or spark-ignited platforms. The final decision to develop a commercial product will depend on the market interest and potential. In planning a marine vessel today, it is beneficial to choose a modern modular engine platform which gives a good basis for future fuel conversions. As Wärtsilä also supplies fuel systems, it is important to take into account the system needs at an early stage in order to cope with the properties of ammonia.

A challenge for internal combustion engines is the possibility of unburned ammonia in the exhaust, that is toxic and highly pungent even in small amounts. If this occurs during normal running operation, it may be mitigated by an ammonia catch system, like a water curtain. However, if the level of ammonia slip is the same as or lower than the NO_X emissions, this can be mitigated in an SCR. Also, it has been suggested that ammonia slip may cause reduction of NO_X in the expansion stroke.[54]

EMISSIONS TO AIR

Ammonia does not contain carbon and the combustion of ammonia is as follows without any CO_2 emissions:

$$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O$$

Based on the efficiencies in the processes and the emission factors of the feedstock, the emissions for best available technologies are 1.6, 4.0 and 2.4 tonne CO_2 per tonne of ammonia for the feedstocks natural gas, coal and oil, respectively. This corresponds to 85 $kgCO_2$/GJ for natural gas up to 215 $kgCO_2$/GJ for coal. Ammonia produced from natural gas is hence similar to low-sulfur MGO (88 $kgCO_2$/GJ). The benefit of ammonia is only apparent when renewable energy, like wind, solar or hydroelectric energy is used to produce the ammonia. This will bring the GHG emissions close to zero. Ammonia from natural gas without CO_2 capture will have higher emissions than LPG at 72.7 $kgCO_2$/GJ and LNG at 71.5 $kgCO_2$/GJ (based on the assumptions of 1% slip and 7% energy consumption for liquefaction).[4] A small amount of an additional fuel is expected to be required with internal combustion engines. This would typically be MGO as pilot fuel, but it could also be renewable diesel (HVO) with about 60% lower GHG emissions. In principle, a small fraction of the renewable ammonia may also be cracked into hydrogen to improve the combustion.

The emissions of ammonia produced from natural gas are much lower than the emissions from electrolysis from electricity in electricity grids with a significant contribution of fossil fuels, like Germany and the US. E.g. if the emissions in the grid are 0.45 tCO_2/MWh and the energy consumption is 10 MWh/tNH_3 (corresponding to 52% efficiency), the emissions will be 4.5 tCO_2/tNH_3. This is higher than ammonia produced from coal.

Another option is to use produce ammonia from natural gas with carbon capture and storage, i.e. blue ammonia. Ammonia production largely consists of producing hydrogen and then reacting the hydrogen with nitrogen from air (that albeit is introduced in the hydrogen production process), and most of the energy consumption and CO_2 emissions are in the production of hydrogen as evidenced by the efficiencies of 75% for hydrogen production and 66% for ammonia production via hydrogen. Hence, carbon capture for ammonia will be similar for ammonia and hydrogen production. IEA has published a technical report on the latter in 2017.[27] There are several options for carbon capture and higher capture rates will typically be more expensive in terms of capital cost, energy demand and operating costs. For instance, the CO_2 from the shifted syngas has a higher partial pressure of CO_2 than the flue gases from the reformer reactor, which reduces costs and energy demand. IEA estimates for the case of carbon capture for shifted syngas only that the CO_2 avoidance (CO_2 capture in the process) will be 54% with increased natural consumption rate of 3.3%. The capital cost will increase by 18% and with a CO_2 avoidance cost of 47 Euro/tCO_2. Furthermore, the case for carbon capture of all

the flue gases will give a CO_2 avoidance of up to 89% (at a capture rate of 90%) with a natural gas consumption rate increase of 10%, increased capital costs of 79% and CO_2 avoidance cost of 70 Euro/tCO_2. For the case of the largest capture rate at a CO_2 cost of about 80 \$/tCO_2, this is still less expensive than the CO_2 avoidance cost of around 140 \$/tCO_2 for renewable ammonia (based on the moderate price of 600 \$/t) as discussed in the section below. However, there will also be costs and emissions related to transport and storage of the CO_2, and access to CO_2 storage sites in the vicinity of the ammonia plant is required. The Global CCS Institute estimates that the combined cost of transport and storage ranges from 7 to 12 \$/t of CO_2 for onshore storage and from 16 to 37 \$/t CO_2 for offshore storage.[55] Hence, there may be cases with similar costs for blue ammonia based on natural gas with CCS as for renewable ammonia based on cheap wind and/or solar energy. However, if a substantial capacity of natural-gas-based ammonia plants with CCS is built, natural gas prices may rise and thereby increased ammonia prices. For green ammonia this relationship is not so obvious, and increased efforts for this approach may also decrease the capex for the electrolysers and solar electricity, if this is used. Currently there are only two commercial CCS projects related to hydrogen production. One project is in a hydrogen plant in a refinery in Port Arthur in the US and the CO_2 used via a pipeline for extended oil recovery. The other project is the Quest CCS project in an oil sand refinery near Edmonton in Canada, where CO_2 is stored underground via a 65 km pipeline. The use of ammonia also has benefits related to pollutant emissions. It virtually eliminates sulfur emissions, and can be used as a means of compliance with low sulfur local and global regulations. The use of ammonia as a fuel will, like LNG, almost eliminate particulate matter and black carbon emissions.

There will however be NO_X emissions, which will depend on the engine technology used. More experiments need to be carried out in order to determine the amount of NO_X emissions, but it has been assumed that the NO_X will be at approximately the same level as for MGO.[54] Even though the fuel contains nitrogen which will increase the likelihood of NO_X formation, the flame temperature during ammonia combustion is lower.

Furthermore, the N_2O release, which has a high global warming potential of 265, is not known and needs to be further investigated. One benefit of using ammonia as a fuel is that SCR normally is based on urea that is decomposed to ammonia in the process, which is then used to reduce NO_X to N_2. When ammonia already is available in large amounts as fuel, this can potentially be used directly for the SCR. It might be possible to find catalysts that will also reduce the N_2O level at the same time as reducing NO_X.[21]

SAFETY CONSIDERATIONS

The choice of the fuel is important for the safety barriers required for a ship. Which safety aspects that are most important varies from fuel to fuel. For ammonia, toxicity is the main issue, but also flammability and lowered temperatures need to be taken into account. Safety rules will have to be defined against this background.

STORAGE AND HANDLING

In transportation, acceptable tanks are independent tanks type A, B and C and membrane tanks. These tanks are defined in the IGC code and can be used for transportation of ammonia. In practice only type A and C are used for this purpose.

The anticipated choice for storing ammonia for use as propulsion fuel likely to be a pressurized tank type C, at ambient temperature. Storage in a semi-refrigerated or refrigerated tank is also possible, but in order for such an arrangement to be sufficiently reliable, back-up systems must be in place to ensure continuous low temperature (and hence pressure) in the tank. This makes pressurized tank storage a more reliable and simple solution. The limitations of placement of the tanks and fuel pipes are expected to be similar to the DNV GL requirements for LPG fuel. This includes a minimum distance from ship sides and bottom to limit the risk of tank damage in a collision and grounding scenario. The tank location must be away from engine rooms and other high fire risk spaces, and it should be protected from crane operations or other mechanical damage risk areas.

Due to its toxicity and flammability, double-walled pipelines must be used as secondary containment whenever pipes are inside enclosed spaces, like below the deck line. Double-walled pipelines can also be relevant when pipes are located in open air to ensure efficient detection of leakages and to keep hazardous zones to a minimum. Sniffers will detect any leakage and contain the fuel within the secondary containment before it reaches areas where humans and ignition sources are present.

Anhydrous ammonia has a lower density than air (60% of the density of air), but when compressed liquified ammonia evaporates and comes in contact with moisture in the air, it will form a cold fog that is heavier than air and remains at the ground.[56,57] This will prevent ammonia gas from rising in the air. Therefore, the leak detection system and the ventilation system should be designed accordingly.

Ammonia is a low-flash-point fuel. The minimum ignition energy of ammonia has been determined to 8 mJ,[58] whereas for methane (LNG) it is 0.3 mJ, for hydrogen it is 0.017 mJ and for propane (LPG) it is 0.26 mJ. The auto ignition temperature for ammonia (630°C) is higher than for e.g. LNG (580°C) and LPG (490°C), and therefore the requirement for lower temperature near electrical equipment, as explosion protection, might be less severe. The lower explosion limit is higher for ammonia with 15% in mixtures with air, but for mixtures with oil lower explosion limits down to 8% have been reported, depending on the type and concentration.[59] Ammonia has fewer challenges related to temperature because it is not kept at cryogenic temperatures and has a higher explosion limit, but on the other hand it is toxic. The challenges are different, but overall the safety management for ammonia will probably be comparable to LNG for cargo-carrying ships.

TOXICITY

The issue of toxicity of ammonia needs close consideration and new ways of handling gas releases will likely be needed, compared with other gaseous fuels. In order to assess safety and in particular toxicity, HAZIDs (HAZard IDentification) have been carried out by DNV GL in cooperation with a number of parties like engine manufacturers, ship owners and fuel supply system manufacturers. The HAZIDs have covered the operations of transfer of ammonia from cargo to storage tanks, transfer of ammonia to engines, running of engines and safe handling of ammonia in the engine room and on deck. The risks have been considered as a combination of likelihood and consequence.

A high risk identified was venting of ammonia during normal operations. This can be mitigated by designing fuel systems that prevents such discharges. Alternatively, an ammonia recovery system in the vent line could be considered.

Pipe rupture, exposure to ammonia during maintenance, venting of ammonia during emergency shutdown and uncontrolled venting of ammonia, e.g. because of malfunction of a safety valve, were other risks considered. The level of mitigation required for these types of hazards will depend on ship type and arrangement.

The risk level will depend on the type of ship, ship arrangement and operations. A risk assessment as required by the IGF Code must be carried out and sufficient risk reducing measures implemented. E.g. for a gas carrier, releases from ammonia safety relief valves of the tanks are not considered a major safety challenges due to the separated and dedicated cargo areas, the specially trained crew and the limited number of locations where cargo operations find place. On other ship types, this will be a major safety hazard and additional safety barriers will likely have to be arranged.

For ships using ammonia as a fuel, additional crew training will be required. However, the additional training required for an ammonia carrier crew would be less than the training required for other crews, like for other cargo-carrying ships that are not trained to handle ammonia.

For passenger or cruise vessels additional considerations like location of life saving equipment, arrangement of mustering stations, evacuation time and safe return to port arrangements must be evaluated in relation to ammonia leakages. In addition to stricter requirements, for these ship types the public perception should also not be underestimated.

AMMONIA BUNKERING

Ammonia has a very similar vapour pressure to propane and is stored in the same fashion as a liquid, i.e. cooled to -33°C at around ambient pressure or pressurized to above 10 bar at room temperature. Onshore storage is typically pressurized below 5,000 tonne ammonia and liquified by cooling for larger storage units in combination with a reliquefication plant.[60] The capital cost for a refrigerated storage facility has been reported to be around 700 $ per tonne ammonia.[37]

Ammonia bunkering can, in principle, take place in many different ways, e.g. from terminals or trucks onshore or from bunkering ships. Loading and unloading from terminals to ammonia-carrying ships is currently handled safely with proper specialized training, and safety is believed to be improved by using a bunkering ship as an intermediate between the terminal and the ship using ammonia as fuel. At least for deep sea shipping with significant amounts of fuel to be bunkered, a bunkering ship would be the preferred solution. Particular care should be taken when bunkering in densely populated areas.

Worldwide ammonia ports

Figure 10: Worldwide ammonia ports. Source: Navigator Gas

The ammonia may be stored under pressure or refrigerated, and ammonia will not always be available in the temperature and pressure range that a ship can handle. The bunkering vessel and the ship to be bunkered must therefore have the necessary equipment and installations to bunker safely.
There are different possible combinations of bunkering vessels with pressurized tanks, semi-refrigerated tanks or fully refrigerated tanks and similar arrangements in the ship to be bunkered. Four cases illustrate some key bunkering challenges:

- In the case of **pressurized tanks** both in the bunkering vessel and the ship to be bunkered, the ammonia is transferred using a general transfer pump located in the bunkering vessel. When filling the ammonia tank, pressure will build up because of less gas volume available, and since it takes time to condense ammonia, this can cause the safety valve in the tank to open. For practical purposes and to comply with safety regulations, the ammonia tank must be equipped with a vapour return system back to the bunkering vessel, i.e. a gas outlet connection in addition to the liquid inlet connection.

- In the case of **semi-refrigerated tanks in the bunkering vessel and a pressurized tank in the ship** to be bunkered, it is necessary to have a heater and a booster pump in the bunkering ship and a vapour return system in the ship to be bunkered. The heater is needed because the fuel has a lower temperature than the tank design temperature, and this will typically be handled by a heat exchange system using heat from seawater. The bunkered ammonia will have a lower than ambient temperature, but needs to be above the tank design temperature. The booster pump is needed to raise the pressure of the ammonia before bunkering. Both the heater and booster pump are typically installed on semi-refrigerated ammonia carriers, that may be used as bunkering ships. The pressure of the vapour return from the ship to be bunkered may be too high for the semi-refrigerated tank, and must be handled by the re-liquefaction plant in the bunkering vessel, which may require some modifications. An alternative to vapour return in this case is to fill the cold ammonia with a spray-line to condense the ammonia vapour.

- In the case of **pressurized tanks in the bunkering vessel and a semi-refrigerated tank in the ship** to be bunkered, the pressure needs to be reduced by lowering the temperature in a liquefaction plant. An ammonia carrier with pressurized tanks is typically not equipped with this, thus requiring comprehensive modifications of the equipment and cargo handling system. This case also requires a vapour return system with a compressor in the bunkering ship that needs to be set up to increase the pressure of the vapour return. Ammonia carriers with pressurized tanks are typically equipped with a compressor, but only for the purpose of emptying the cargo tanks.

- In the case of **semi-refrigerated tanks** both in the bunkering vessel and the ship to be bunkered, cooling (and probably not heating) may be necessary. A vapour return system and some modifications of the re-liquefaction plant in the bunkering vessel to ensure a higher capacity may also be necessary.

Based on the cases discussed above, a pressurized ammonia fuel tank is the preferred solution when bunkering the ship, because the ship can be bunkered by a bunkering vessel based on an ammonia carrier (either with pressurized tanks or semi-refrigerated tanks) without major modifications. Both types of bunkering vessels are possible, depending on the size of the fuel tanks to be bunkered and the number of ships to be served. Semi-refrigerated ammonia carriers typically have larger capacity than pressurized ammonia carriers and enough capacity for all ship types. They are also more flexible, e.g. in terms of filling ships with semi-refrigerated fuel tanks and have a limited cost premium.

FINANCIAL FEASIBILITY

It is expected that capital expenditure for an ammonia two-stroke internal combustion engine and fuel supply system will be at the same level as the corresponding LPG engine. The tanks for ammonia are twice the size as LPG and correspondingly more expensive. Previously, DNV GL and MAN Diesel & Turbo examined a set of scenarios for various versions of an LR1 tanker to determine the most economically feasible fuel type to plan for.[4,61] One of the results was that LPG was financially feasible both in the high price and low price scenario; despite its higher investment costs, this was more than compensated for by the lower fuel costs of LPG compared with very low-sulfur fuel oil (VLSFO).

For brown ammonia, the cost has been about 275 \$/t the last three years. Based on the energy content, this corresponds to about 600 \$/t fuel oil. This is close to the price reported globally for VLSFO in December 2019 and for MGO reported in Rotterdam at the same time. Therefore, by using ammonia as a fuel today, there will be capital expenditures without operational cost benefits. In addition, ammonia produced today, even from state-of-the-art plants, would result in GHG emissions at the same level as VLSFO (see above).

The benefits from ammonia will be when the GHG emissions are significantly reduced, either from renewable energy or nuclear power or through CCS. Based on the calculations above, the ammonia price would then be expected to be at least 600 $\$/tNH_3$. A sensitivity analysis has been carried out based on the LR1 study mentioned above by using the same input parameters, including trading pattern and capex, for the other alternative fuels. The previous sensitivity analysis has been extended by including the use of ammonia as a fuel in addition to methanol, LPG and LNG. The results are shown in Figure 11, from which it appears that the prices would have to be about 15% lower for ammonia (independent of its colour brown, green or blue) than VLSFO to be financially viable, i.e. to be able to compete with VLSFO on the financial merits

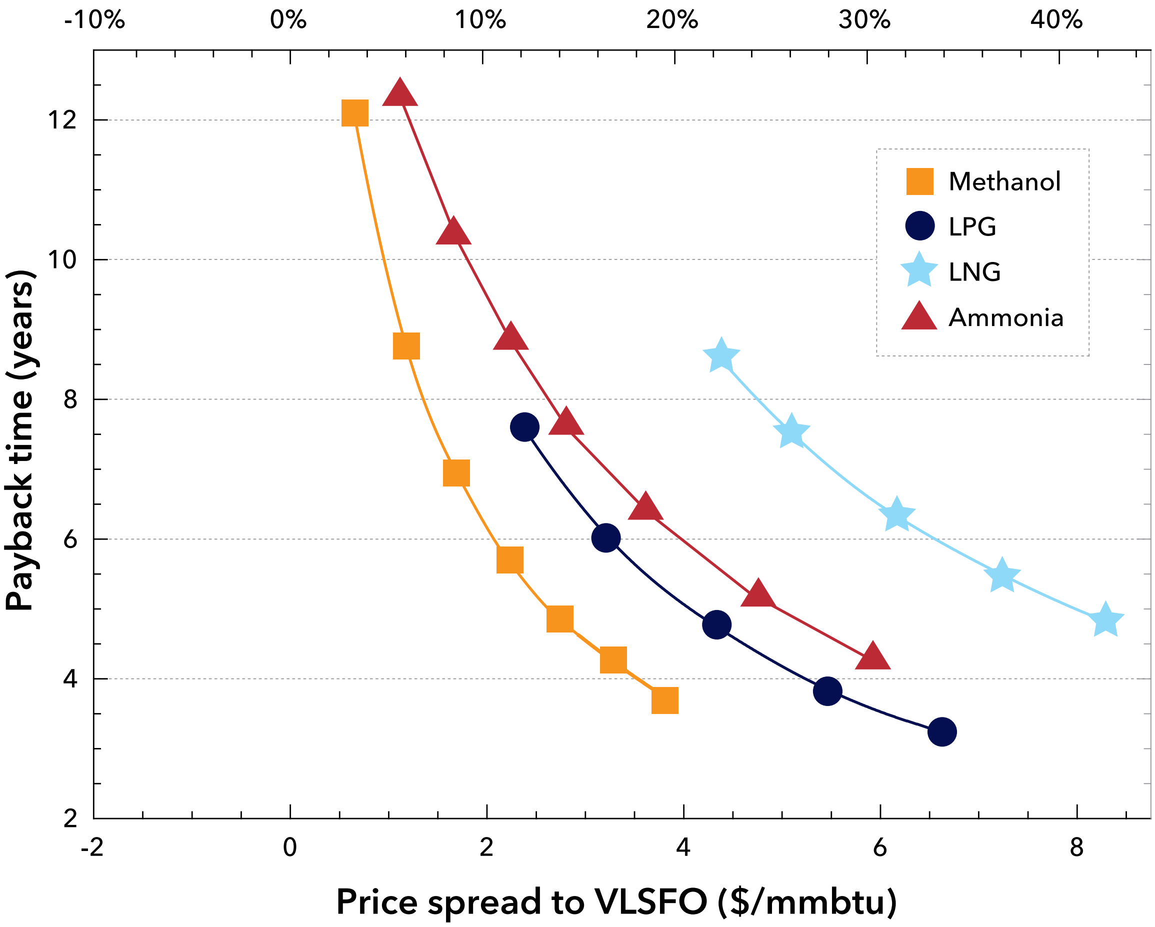


Figure 11: Sensitivity analysis of payback time compared to the price spread of each fuel to VLSFO

alone. This is slightly higher than LPG because of the increased capital expenditure related to the increased tank size.

Since the cost of green and blue ammonia is higher, rather than lower, compared to VLSFO, the emission reductions will come at a cost. This makes it impossible to calculate any payback times. Instead, a different metric is used to compare alternative fuel options, i.e. GHG abatement cost in $\$/tCO_2$ over a lifetime of 25 years. The GHG abatement cost is the cost for reducing one tonne of CO_2 emission (on a well-to-wake basis), and this is calculated over the lifetime of the mitigation project.

This has been done for several segments, based on technical information of the ship from the IHS Fairplay database and the speed and trading pattern from AIS data. The fuel consumption for each ship has been calculated and averaged for the segment. The fuel storage requirement has been estimated based on the fuel consumption and the number of port calls. Average engine size has been calculated from the technical data.

Capital expenditure per installed capacity for newbuild has been used in accordance with the LR1 study.[4,61] The discount rate was defined as 5% and 15% of the fuel consumption was considered to be in a SECA. The fuel prices are based on prices in end of 2019, and the calculations assume no loss of cargo capacity. Further details are given in Table 3.

	Tanker <10' DWT	Tanker 80'–120' DWT	Container <1,000 TEU	Container >15,000 TEU
Engine size (MW)	1.91	15.31	6.55	70.73
Fuel storage (GJ)	2,088	23,769	2,243	69,272
Annual fuel consumption (tHFO)	1,833	7,263	2,945	45,000

Table 3: Engine size, annual fuel consumption and storage capacity assumed in the calculations of the GHG Abatement Cost Curve in Figure 12.

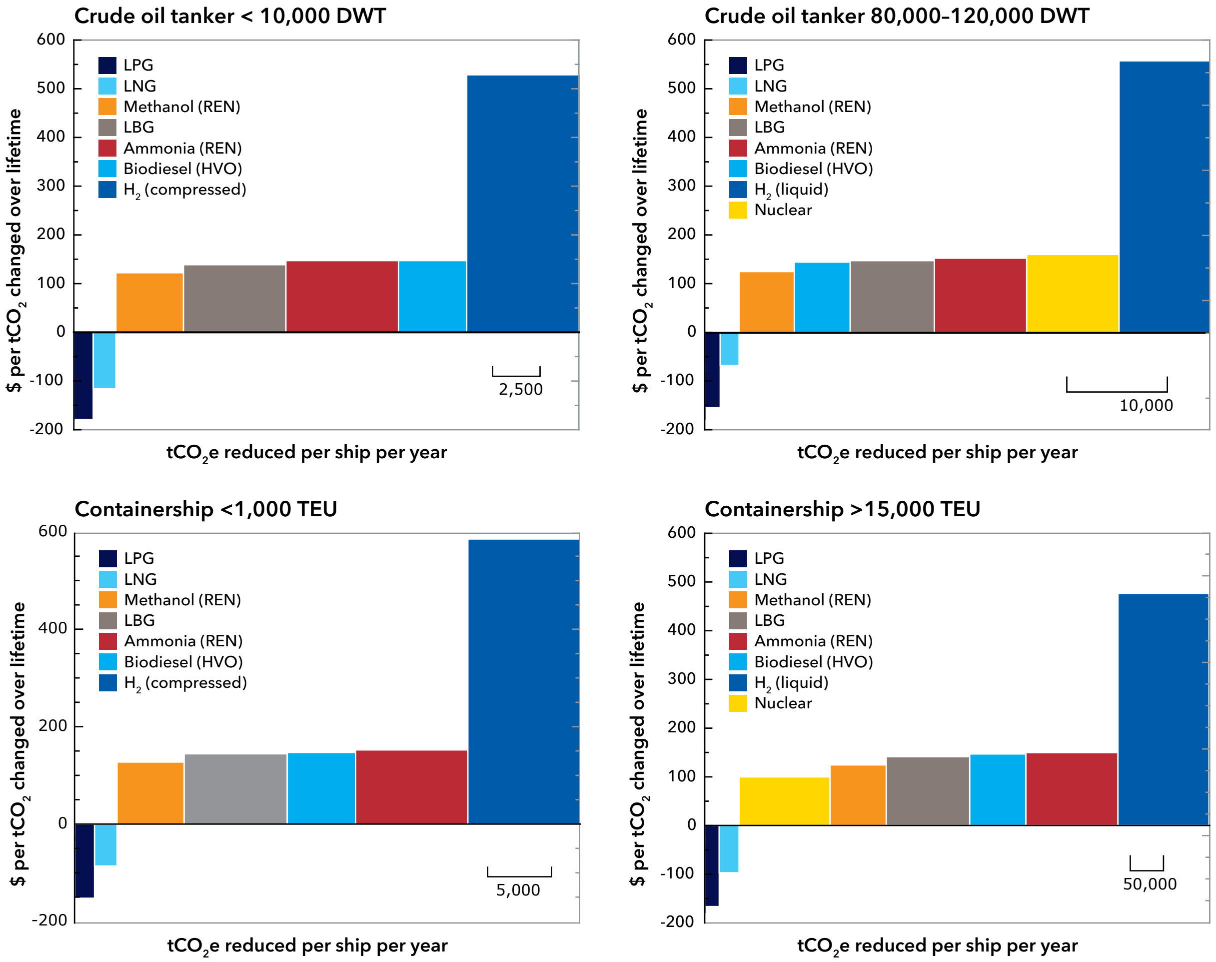


Figure 12: GHG abatement cost curves for alternative fuel for an average ship in terms of technical data and operations.

The GHG abatement costs are negative for LPG and LNG based on the fuel prices used, which means that they are financially attractive over the lifetime of the vessel for a newbuild compared to use of an oil-based fuel. Compressed and liquefied hydrogen has a larger emission reduction potential, but is costly and this is related to expensive storage and fuel cells. It should also be noted, with reference to Figure 1, that hydrogen, and in particular compressed hydrogen, is space demanding, which might result in reduced payload or shorter range (and more frequent bunkering). In the intermediate region there are, in addition to nuclear propulsion for large ships, four fuels with a marginal abatement cost of approximately 150 $/tCO_2$. Renewable methanol and renewable biodiesel (HVO) are considered to have a lower emission reduction potential. Liquified biogas has a high reduction potential, but limited availability. Ammonia has approximately the same abatement cost price, a large emission reduction potential and possibility of upscaling. Fuel prices will vary and the abatement costs will correlate to the fuel prices. E.g. for the low oil prices as of March 2020, it is difficult for new green technologies to compete successfully unless regulatory or market-based measures are introduced that significantly alters this.

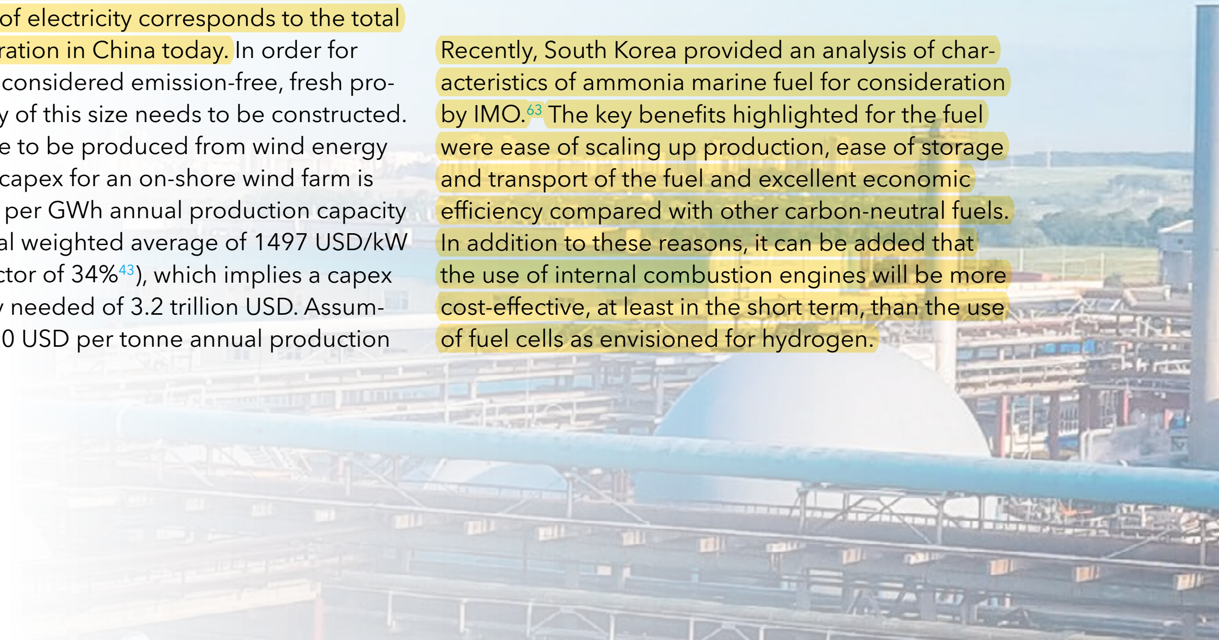
SCALABILITY

In principle, since only renewable energy, water and air are required to produce ammonia, ammonia production can be scaled up to supply the entire marine sector with fuel. However, the investment costs related to the supply of all ships with ammonia from renewable energy would be massive, since new capacity with renewable ammonia or ammonia from natural gas with CCS needs to be built. The fuel consumption today of 300 million tonnes oil corresponds to 650 million tonnes ammonia, which would require about 6 500 TWh renewable electricity. This amount of electricity corresponds to the total electricity generation in China today. In order for ammonia to be considered emission-free, fresh production capacity of this size needs to be constructed. If ammonia were to be produced from wind energy today, a typical capex for an on-shore wind farm is 0.5 million USD per GWh annual production capacity (based on global weighted average of 1497 USD/kW and capacity factor of 34%[43]), which implies a capex of the electricity needed of 3.2 trillion USD. Assuming at least 2,000 USD per tonne annual production capacity for the ammonia plant (via electrolysis of water), 650 million tonnes of ammonia would lead to 1.3 trillion USD investments in ammonia plants. The total investments for the fuel alone would need to be 4.5 trillion USD before taking into account economies of scale which would reduce the investment costs. However, the investments in infrastructure for transportation and bunkering of the fuel as well as the investments in the ships itself are not included in this estimate. The investments in renewable electricity capacity are therefore significantly higher than the investments in ammonia plants at today's prices, and the prices for electrolysers will likely also decrease further if many plants are constructed.

A study has been published,[62] which is based on building ammonia plants and local solar and wind power plants to fuel all container ships and dry bulk ships passing through Morocco's ports. The electricity demand was estimated to about 100 TWh per year with investment costs of about 100 billion USD, with a resulting ammonia price of 830 USD/t. The investment costs are large, but the electricity required to generate the 10 million tonnes of ammonia is claimed to be less than 1% of the theoretical potential from wind and solar sources in the country.

Additional renewable electricity needed to produce ammonia would compete with decarbonization efforts in other sectors, in particular the power sector. If the renewable power for example can replace coal power plants, that would reduce more emissions than using the renewable electric energy to make ammonia to replace oil-based marine fuel (which has lower emissions per energy unit than coal). However, in some countries, ammonia production may be used to stabilize the grid and allow for a higher fraction of intermittent renewable electricity than otherwise possible. In addition, the technology allows for transportation of renewable resources from regions without sufficient electricity demand.

Recently, South Korea provided an analysis of characteristics of ammonia marine fuel for consideration by IMO.[63] The key benefits highlighted for the fuel were ease of scaling up production, ease of storage and transport of the fuel and excellent economic efficiency compared with other carbon-neutral fuels. In addition to these reasons, it can be added that the use of internal combustion engines will be more cost-effective, at least in the short term, than the use of fuel cells as envisioned for hydrogen.



CONCLUSIONS

Ammonia is a carbon-free fuel that can potentially play an important role in the decarbonization of deep-sea vessels. Even though ammonia is toxic, and the energy density is lower than currently used oil-based fuels, ammonia is more favourable than hydrogen and can be a suitable option for future use in cargo-carrying ships with modified internal combustion engines and low-pressure fuel tanks.

Due to the high toxicity and corrosiveness of ammonia appropriate safety barriers need to be in place and material selection is of paramount importance. DNV GL, in collaboration with several industry stakeholders, is currently developing requirements for the safe use of ammonia as fuel, based on experience from ammonia as cargo and ammonia as a refrigerant. Finally, the existing production capacity of ammonia needs to be developed considerably and production with renewables or with CCS technology is required, to make sure that the environmental potential of ammonia can be realized. The cost of green ammonia is currently at least twice the 2019 cost of VLSFO, and this is a barrier for the uptake of this fuel. The cost depends mainly on renewable electricity price and capex, which will likely decrease in the future.

Currently there are about 200 gas tankers that can take ammonia as cargo and typically 40 of them are deployed with ammonia cargo at any point of time. Such tankers will naturally be candidates for the first ammonia-fuelled engines since they already have the fuel as cargo and have experience with handling ammonia. Other cargo-carrying ships could also use ammonia as fuel, and the experience from such ships should be used before introducing ammonia on passenger ships and cruise vessels.

REFERENCES

[1] DNV GL Alternative Fuel Insight platform: https://afi.dnvgl.com/

[2] K. Andersson, C.M. Salazar, Methanol as a marine fuel report, October 2015.

[3] C. Chryssakis, O. Balland, H.A. Tvete, A. Brandsæter: «Alternative fuels for shipping», DNV GL strategic research and innovation position paper 1-2014.

[4] H.W. Brinks, C. Chryssakis: “LPG as a marine fuel”, DNV GL strategic research and position paper, 2017.

[5] SEA\LNG 2019: “Life-cycle GHG emission study on the use of LNG as a marine fuel”

[6] NIST Webbook.

[7] US National Library of Medicine: Hazmap.

[8] https://www.osha.gov/chemicaldata/chemResult.html?recNo=623

[9] National Institute for Occupational Safety and Health: https://www.cdc.gov/niosh/idlh/7664417.html

[10] A.W. Loginow, Materials Performance 25(12) 1986, p. 18-22.

[11] Centre for European Policy Studies 2014: For a study on composition and drivers of energy prices and costs in energy intensive industries: The case of chemical industries – Ammonia

[12] United States Geological Survey publication: https://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/mcs-2019-nitro.pdf

[13] H. Vroomen, Fertilizer Institute, 2013: The History of Ammonia to 2012.

[14] J.W. Erisman, M.A. Sutton, J. Galloway, Z. Klimont, W. Winiwarter, Nature Geoscience 1 (2008) 636-639: How a century of ammonia synthesis changed the world.

[15] https://www.iea.org/publications/freepublications/publication/TrackingCleanEnergyProgress2017.pdf

[16] K. Noelker, J. Ruether, “Low Energy Consumption Ammonia Production: Baseline Energy Consumption , Options for Energy Optimization”, Paper submitted for the Nitrogen + Syngas conference 2011, Duesseldorf.

[17] Yara Fertilizer Industry Handbook, October 2018.

[18] K. Büker, ThyssenKrupp: “Carbon2Chem® – Production of ammonia from Steel Mill Gases” presented at the NH$_3$ power to ammonia conference, June2019 in Rotterdam, Netherlands.

[19] DOE H$_2$A analysis (2005) http://www.hydrogen.energy.gov/h2a_analysis.html

[20] M. Will (ThyssenKrupp): “Realization of large-scale ammonia plants”, 2018 AIChE Annual meeting – NH$_3$ Energy + Topical conference. Data for 20 MW electrolysis plant and 50 tpd ammonia plant.

[21] Alfa Laval, Hafnia, Haldor Topsøe, Vestas, Siemens Gamesa: “Ammonfuel – an industrial view of ammonia as a marine fuel”, August 2020.

[22] J.R. Bartels, Iowa University, Graduate Thesis and Dissertations, 2008: A feasibility study of implementing an Ammonia Economy.

[23] https://ammoniaindustry.com/ammonia-technology-portfolio-optimize-for-energy-efficiency-and-carbon-efficiency/

[24] IEA: The Future of Petrochemicals, Towards more sustainable plastics and fertilizers, Methodology annex, 2018.

[25] W. Gao, J. Guo, P. Wang, Q. Wang, F. Chang, Q. Pei, W. Zhang, L. Liu, P. Chen, Production of ammonia via a chemical looping process based on metal imides as nitrogen carriers, Nature Energy 3 (2018) 1067-1075.

[26] John Bøgild Hansen, Haldor Topsøe: “The SOC-4NH$_3$ project in Denmark” presented at the NH$_3$ power to ammonia conference, June2019 in Rotterdam, Netherlands.

[27] IEA technical report 2017: Techno-Economic Evaluation of SMR based standalone (Merchant) Hydrogen Plant with CCS.

[28] Neste Renewable Diesel Handbook, May 2016.

[29] https://www.carbonrecycling.is/vulcanol, last assessed 9. August 2019.

[30] IEA: “The Future of Hydrogen”, June 2019.

[31] M. Auer, M. Bauer, G. Ganzer, S. Schnurrer, A. Knafl, G. Stiesch, Cimac Congress 2019 paper #449: Power-to-X: The key for the maritime energy transition

[32] IHS Market, July 2017: https://ihsmarkit.com/products/ammonia-chemical-economics-handbook.html

[33] IMO: Third IMO Greenhouse Gas Study, 2014.

[34] DNV GL 2019, “Maritime Forecast to 2050, Energy Transition Outlook 2019”

[35] USGS 2016 Minerals Yearbook – Nitrogen.

[36] The Royal Society, 2020: “Ammonia: Zero-carbon fertiliser, fuel and energy store.”

[37] E.R. Morgan, PhD thesis, University of Massachusetts Amherst: “Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind”, 2013.

[38] DNV GL, Alternative Fuel Insight platform.

[39] C. Philibert, IEA: “Hydrogen and Ammon’IEA” presented at the NH_3 power to ammonia conference, June2019 in Rotterdam, Netherlands.

[40] https://www.wind-energy-the-facts.org/the-cost-of-energy-generated-by-wind-power.html

[41] DNV GL: Energy Transition Outlook 2019: Data used for power production costs for 2019.

[42] http://publikasjoner.nve.no/faktaark/2019/faktaark2019_03.pdf

[43] IRENA, “Renewable power generation costs in 2018”, May 2019.

[44] French Patents of Ammonia Casale: 799,610 and 802,905

[45] E. Kroch, “Ammonia – a fuel for motor buses”. Journal of the Institute of Petroleum. 31 (1945) 213-223.

[46] C.G. Garabedian, J.H. Johnson, 1966: The theory of operation of an ammonia burning internal combustion engine

[47] https://encyclopedia.airliquide.com/ammonia, last assessed 10 January 2020.

[48] https://www.mathesongas.com/pdfs/products/Lower-(LEL)-&-Upper-(UEL)-Explosive-Limits-.pdf

[49] http://www.nh3car.com/index.htm, last assessed 10 January 2020.

[50] S. Ito, M. Uchida, S. Onishi, T. Fujimori: “Performance of Ammonia – Natural Gas co-fired Gas-Turbine for Power Generation”, October 2018, 2018 AlChE Annual meeting presentation.

[51] S. Giddey, S.P.S. Badwal, C. Munnings, M. Dolan, ACS Sustainable Chem. Eng. 2017, 5, 10231-10239.

[52] https://maritimecleantech.no/2020/01/23/major-project-to-convert-offshore-vessel-to-run-on-ammonia-powered-fuel-cell/ last assessed 5 February 2020.

[53] https://www.ammoniaenergy.org/articles/viking-energy-to-be-retrofit-for-ammonia-fuel-in-2024/ last assessed 5 February 2020.

[54] N. de Vries, June 2019, MSc thesis, Delft University: “Safe and effective application of ammonia as a fuel”

[55] Global CCS institute: «Global costs of carbon capture and storage”, 2017 update, Lawrence Irlam.

[56] http://www.brannmannen.no/fagstoff/ammoniakk/ last assessed 3 February 2020

[57] https://www.cdc.gov/niosh/ershdb/emergencyresponsecard_29750013.html last assessed 3 February 2020.

[58] S. Biyani, G. Jagdale, “Effect of Ammonia Injection on Performance Characteristics of a Spark-Ignited Engine”, International Journal of Trend in Research and Development, Vol 3 (2016).

[59] D.L. Fenton, K.S. Chapman, R.D. Kelley, A.S. Khan, “Operation characteristics of a flare/oxidizer for the disposal of ammonia from an industrial refrigeration facility”, Annual meeting of the American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. (ASHRAE), USA, 1995.

[60] Institute for Sustainable Process Technology: “Power to ammonia”, February 2017.

[61] H.W. Brinks, P.C. Sames, C. Chryssakis, C. Mørch, N.B. Clausen: Costs and benefits of alternative fuels – Key results from a DNV GL and MAN Diesel & Turbo joint study for an LR1 product tanker, 2016.

[62] N. Ash, T. Scarbrough, «Sailing on solar: Could green ammonia decarbonize international shipping”, Environmental Defense Fund, London, 2019.

[63] South Korea for IMO, Sub-committee on Carriage of Cargo and Containers, 10 July 2020: “Forecasting the alternative marine fuel: Ammonia”

SAFER, SMARTER, GREENER

Regional Maritime offices

Americas
1400 Ravello Dr.
Katy, TX 77449
USA
Phone: +1 2813961000
houston.maritime@dnvgl.com

Greater China
1591 Hong Qiao Road
House No.9
200336 Shanghai, China
Phone: +86 21 3279 9000
marketing.rgc@dnvgl.com

North Europe
Johan Berentsens vei 109-111
Postbox 7400
5020 Bergen, Norway
Phone: +47 55943600
bergen.maritime@dnvgl.com

South East Europe & Middle East
5, Aitolikou Street
18545 Piraeus, Greece
Phone: +30 210 4100200
piraeus@dnvgl.com

West Europe incl. Germany
Brooktorkai 18
20457 Hamburg
Germany
Phone: +49 40 361495609
region.west-europe@dnvgl.com

Korea & Japan
7th/8th Floor, Haeundae I-Park C1 Unit,
38, Marine city 2-ro, Haeundae-Gu
48120 Busan, Republic of Korea
Phone : + 82 51 6107700
busan.maritime.region@dnvgl.com

South East Asia & India
16 Science Park Drive
118227 Singapore
Singapore
Phone: +65 65 083750
singapore.maritime.fis@dnvgl.com

DNV GL AS
NO-1322 Høvik, Norway
Phone: +47 67 579900
www.dnvgl.com

DNV GL – Maritime
Brooktorkai 18
20457 Hamburg, Germany
Phone: +49 40 361490
www.dnvgl.com/maritime

About DNV GL
We are the independent expert in risk management and quality assurance. Driven by our purpose, to safeguard life, property and the environment, we empower our customers and their stakeholders with facts and reliable insights so that critical decisions can be made with confidence. As a trusted voice for many of the world's most successful organizations, we use our knowledge to advance safety and performance, set industry benchmarks, and inspire and invent solutions to tackle global transformations.

DNV GL is the world's leading classification society and a recognized advisor for the maritime industry. We enhance safety, quality, energy efficiency and environmental performance of the global shipping industry – across all vessel types and offshore structures. We invest heavily in research and development to find solutions, together with the industry, that address strategic, operational or regulatory challenges.