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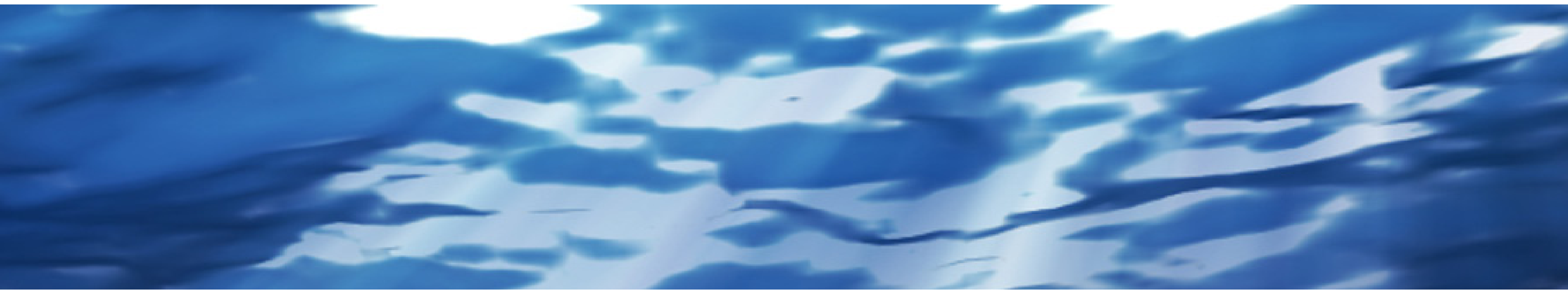

LIGHTHOUSE REPORTS

On the potential of ammonia as fuel for shipping

A synthesis of knowledge

En förstudie utförd inom branschprogrammet Hållbar sjöfart

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On the potential of ammonia as fuel for shipping

A synthesis of knowledge

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Denna förstudie har genomförts inom Trafikverkets branschprogram Hållbar sjöfart, som drivs av Lighthouse.

Summary

Introduction of alternative fuels is required for a large reduction in greenhouse gas emissions associated with shipping. The overall aim of this study is to assess the potential of ammonia as marine fuel. More specifically we contribute with a synthesis of knowledge on ammonia as an alternative marine fuel including possible production pathways, cost estimates, technical feasibility, safety and environmental aspects. Ammonia is a carbon free compound that can be produced by renewable energy sources and as a fuel be used in fuel cells or internal combustion engines.

In comparison with other potential renewable marine fuels the future price for ammonia is expected to be in the same range. However, this requires a substantial expansion of reliable production of renewable ammonia. The larger space requirement onboard a ship for ammonia compared to several other fuels except hydrogen may limit the use of ammonia in long distance shipping. It is central that a working fuel infrastructure and bunkering systems are implemented for ammonia to be used as marine fuel, however there does not seem to be any main issues like in the case of hydrogen.

In the limited number of tests of engines using ammonia there is a high fraction of pilot fuel used, there are also issues with emissions and the demonstrated efficiency is low. However, there is no reason to believe that the emissions cannot be dealt with and that the engines will not be improved. Still, before ammonia can be used on ships demonstrations of emissions and efficiencies are called for.

Safety is a major concern when considering ammonia as a fuel. Besides impact on water and air quality upon major release of ammonia, a leak inside the ship could also be disastrous for the crew. It is thus necessary to develop firm rules for design of ammonia systems and for the handling of such systems and further assessments of the effects in case of an accident is needed.

The following projects are suggested to bridge the excising knowledge gap: (i) An in-depth assessment of ammonia as marine fuel from a system perspective considering, technical and economic feasibility, safety and environmental performance including comparison with other fuels, (ii) A feasibility study, on the potential to apply ammonia as a marine fuel including analysis of fuel systems, bunkering, safety routines etc., (iii) A demonstration where an engine is converted for ammonia as a fuel, and (iv) A demonstration using fuels cells in combination with ammonia, initially tested as an auxiliary system.

Sammanfattning

För att minska sina växthusgasutsläpp behöver sjöfarten introducera alternativa marina drivmedel. Det övergripande målet med denna förstudie är att bedöma potentialen för ammoniak som marint bränsle. Mer specifikt presenteras en kunskapssyntes av ammoniak som marint bränsle inkluderandes möjliga produktionsvägar, kostnadsuppskattningar, teknisk genomförbarhet, säkerts-relaterade och miljömässiga aspekter. Ammoniak är ett flytande kolfritt bränsle som kan tillverkas från förnyelsebara källor och som drivmedel användas i bränsleceller eller förbränningsmotorer.

I jämförelse med andra möjliga förnybara marina bränslen förväntas den framtida kostnaden för ammoniak kunna vara i samma storleksordning. Detta kräver emellertid en betydande ökning av tillförlitlig förnybar produktion av ammoniak. Det större platsbehovet ombord för att förvara ammoniak jämfört med flera andra bränslen, med undantag för vätgas, kan begränsa användandet av ammoniak för långväga sjöfart. Fungerande bränsleinfrastruktur och bunkringssystem är centrala för att ammoniak ska kunna användas som sjöfartsbränsle men det verkar inte finnas några stora hinder för detta.

I de begränsade antalet motortester med ammoniak används en relativt stor andel pilotbränsle, det finns också en utsläppsproblematik och den uppnådda effektiviteten är låg. Det finns emellertid ingen anledning att tro att motorerna inte kommer att förbättras och utsläppen att kunna hanteras, men innan ammoniak kan används på fartyg behövs fler studier av utsläpp och effektivitet.

Säkerhetsaspekter är centrala för ammoniak som bränsle. Utöver påverkan på vatten och luft vid ett större utsläpp skulle ett läckage inne på fartyget vara ytterst allvarligt för besättning och eventuella passagerare. Strikta riktlinjer för design av ammoniaksystem och för hanteringen av sådana system behövs och effekterna av en olycka behöver utredas vidare.

Följande projekt föreslås för att täcka kvarvarande kunskapsluckor: (i) en fördjupad analys av ammoniak som marint bränsle från ett systemperspektiv och i jämförelse med andra bränslen, beaktandes teknisk och ekonomisk genomförbarhet, säkerhet och miljömässig prestanda, (ii) en genomförbarhetsstudie av möjligheten av att använda ammoniak som marint bränsle inkluderandes analyser av bränslesystem, bunkring, säkerhetsrutiner etc., (iii) ett demonstrationsprojekt där en motor konverteras för ammoniakdrift, (iv) demonstration av bränsleceller i kombination med ammoniak, inledningsvis testad för ett hjälpsystem.

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1. Introduction

The UN agency for international shipping IMO has agreed to reduce greenhouse gas (GHG) emissions from shipping by at least 50% by 2050 and to reduce the carbon dioxide (CO_2) emissions per transport work by 40% to 2030 and 70% by 2050, compared to 2008 (IMO, 2018). To reach these objectives the phasing out of fossil fuels will be necessary together with the introduction of operational and technical measures to reduce fuel consumption and energy carriers associated with low or near zero emissions of greenhouse gases (ICCT, 2011; Taljegård et al., 2014).

There is a range of different fuel options with different characteristics. Important criteria for marine fuels include:

- fuel price where new fuels inevitably will be compared with today's marine fuel oils;
- reliable supply of fuel including potential limits in production capacity, geographical distribution of production facilities and competition with other end products;
- energy density and other fuel properties in order to optimize the space requirements on the ships and decide the suitability for use in combustion engines and potentially fuel cells;
- operational costs, maturity/availability and required changes of propulsion technology where costly upgrade of engines and fuel systems may be required;
- fuel infrastructure costs and availability, including bunkering facilities;
- impact on climate when assessing the whole fuel life-cycle;
- impact on air and water quality including risks of accidents and potential health impact;
- safety issues for bunkering, storage and operation onboard (Hansson et al., 2019).

In recent years ammonia has been put forward as a potential marine fuel (CSR Netherlands 2017; Lloyds Register, 2017; Maritime Knowledge Centre, TNO and TU Delft, 2017; Kirstein 2018; DNV GL, 2019). Ammonia (NH_3) is a carbon free compound and if produced from renewable energy sources it may contribute to low climate impact. However, there is a need for further studies about ammonia as a fuel in order to assess its potential future in the maritime sector.

The aim of this study is to assess the potential of ammonia as a future fuel for the shipping sector in relation to other marine fuel options. More specifically we contribute with a synthesis of knowledge on ammonia as an alternative marine fuel including possible production pathways, cost estimates, technical feasibility, safety and environmental aspects. We conclude by outlining the additional knowledge and initiatives needed before a potential introduction of ammonia as marine fuel can be realized.

2. Current Market

The global ammonia production in 2016 amounts to approximately 180 million tons with China representing roughly 30% and Russia, India and the US almost 10% each (Giddey et al., 2017; Yara, 2018). Ammonia is also traded globally and currently mainly produced in large-scale production plants (up to about 3000 tons a day) from fossil fuel-based hydrogen and nitrogen from the air (see further below) (Ahlgren et al., 2015). There is currently no production of ammonia in Sweden but from a Northern-European perspective there is ammonia production in for example Norway, the Netherlands and Germany.

Ammonia is currently sold as anhydrous ammonia which is undiluted extra dry ammonia of high purity grades, supplied as a compressed or cryogenic liquid or as ammonia solution or aqueous ammonia representing ammonia in a solution dissolved with water in different concentrations (Yara, 2019a). Ammonia is transported by multi-cargo gas carriers (DNV GL, 2019).

Ammonia is one of the most used intermediate products in the chemical industry and is mainly used in production of fertilizers, such as urea, ammonium nitrate, ammonium phosphate, direct use of ammonia or other fertilizer, representing roughly 80% of the total global consumption (Figure 1) but ammonia is also used in various industrial applications including explosives, textile, healthcare, cosmetic (e.g., hair dye), household goods, animal nutrition, nutrition, plastics, resins, electronics and in NOx control systems e.g., in the automotive industry (Giddey et al., 2017; Yara, 2018).

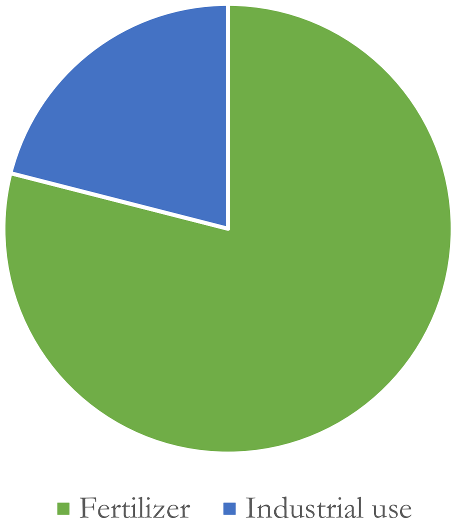


Figure 1. Main fields of use of ammonia globally (Yara, 2018).

The production processes for renewable ammonia are today only in small-scale and still under development. It is uncertain if there today is any production of ammonia using hydrogen from electrolysis of water but there have been examples historically, e.g., Yara Glomfjord, Norway until 1991 (Stevens, 2019; ISPT, 2017). Yara, the second largest ammonia producer in the world, plans to build a demonstration plant for producing ammonia from solar energy in Australia (Valera-Medina et al., 2018). Another example is Haldor Topsoe that hopes to demonstrate its next-generation green ammonia synthesis plant (using a solid oxide electrolysis cell) by 2025 (Brown, 2019). In Sweden, Yara and Lantmännen have recently initiated a collaboration for exploring the possibilities for production of renewable ammonia (Yara, 2019b) and globally there are more initiatives (Yara, 2019c; WCROC, 2019).

Fertilizers including ammonia are crucial for the agricultural sector and food production. In case of an increased demand for ammonia as fuel in shipping, the production and particularly the production of renewable ammonia would need to increase substantially. However, as is the case for biofuels, the production of ammonia is not limited by raw material supply.

For comparison, the current total global ammonia production could replace about 30% of the global shipping fuel consumption if assuming equal efficiencies when used in ship propulsion systems (Figure 2).

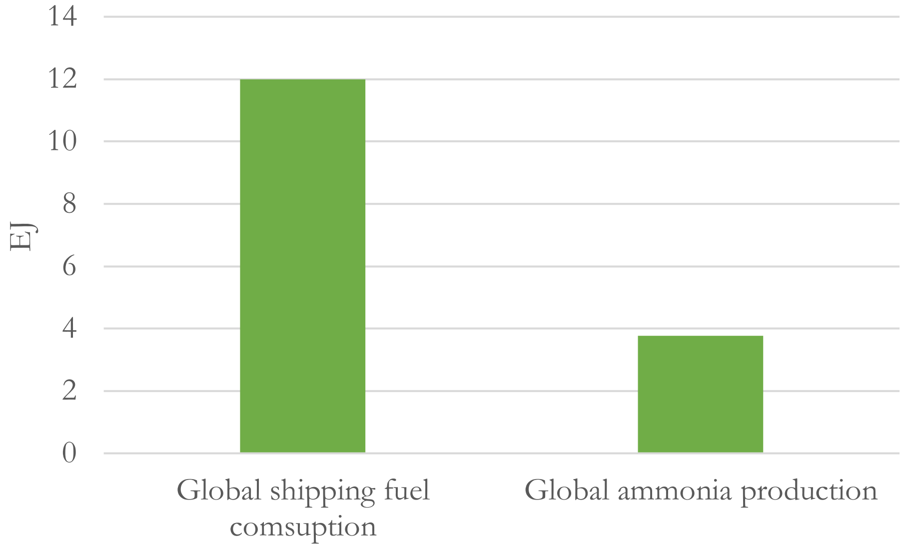


Figure 2. Approximate total global shipping fuel consumption in 2015 and total current global ammonia production in EJ on an energy basis. Sources: Olmer, et al., 2017; Giddey et al., 2017; Yara, 2018.

3. Possible production pathways

Ammonia is produced from hydrogen and nitrogen, currently mainly by the Haber-Bosch process (HB, $N_2+3H_2 > 2NH_3$). This process is exothermic and requires temperatures of 450−600 °C and pressures of 100-250 bar (Giddey et al., 2017). . At present the hydrogen used in ammonia production is produced mainly through steam reforming of natural gas (about 70%), gasification of coal (about 20%) or oil (about 5%) (Giddey et al., 2017). Hydrogen can also be produced from reforming biogas/renewable methane or from electrolysis of water using renewable energy sources like wind, solar and water power. Nitrogen for the HB process is produced from air via the reforming step or from air by a separate air separation process using cryogenic distillation, polymer membrane separation or pressure swing absorption (Ash and Scarbrough, 2019). Production of ammonia is energy-intensive due to the production of hydrogen through steam methane reforming (requiring in total about 8-12 MWh electricity per ton of ammonia, Giddey et al., 2017).

Other possible ammonia production pathways include electrochemical synthesis where ammonia is synthesized in a single electrochemical reactor using water or steam, nitrogen and electricity. This process occurs at temperatures between room temperature and 800 °C depending on the electrolyte used but it is not yet available on a commercial scale (Giddey et al., 2013; Shipman & Symes, 2017). The ammonia production rates from these processes are still relatively low and further development is needed to obtain rates high enough for commercialization (Soloveichik, 2019). For an overview of the production routes see Figure 3.

Further improvement of the Haber-Bosch process is expected in the coming years while the electrochemical ammonia production routes are relatively far from commercialization (Soloveichik, 2019). Potential benefits with electrochemical ammonia production include somewhat reduced energy use, scalability, the ability to follow the intermittent electrical power production and reduced purity requirement of nitrogen input (Soloveichik, 2019). However, as indicated the production processes for renewable based ammonia are yet small-scale and under development.

A promising option for renewable ammonia according to Brown (2019) is the technology being developed by Haldor Topsoe that uses a solid oxide electrolysis cell to make hydrogen and nitrogen (synthesis gas) from water and air then fed into the Haber-Bosch process. This technology represents an integration of the electrolyzer and the Haber-Bosch (HB) units, without the need for an air separation unit potentially resulting in reduced cost and energy use. The energy demand is expected to be in the same range or better than state of the art ammonia plants using natural gas. Commercialisation is expected by 2030 (Brown, 2019).

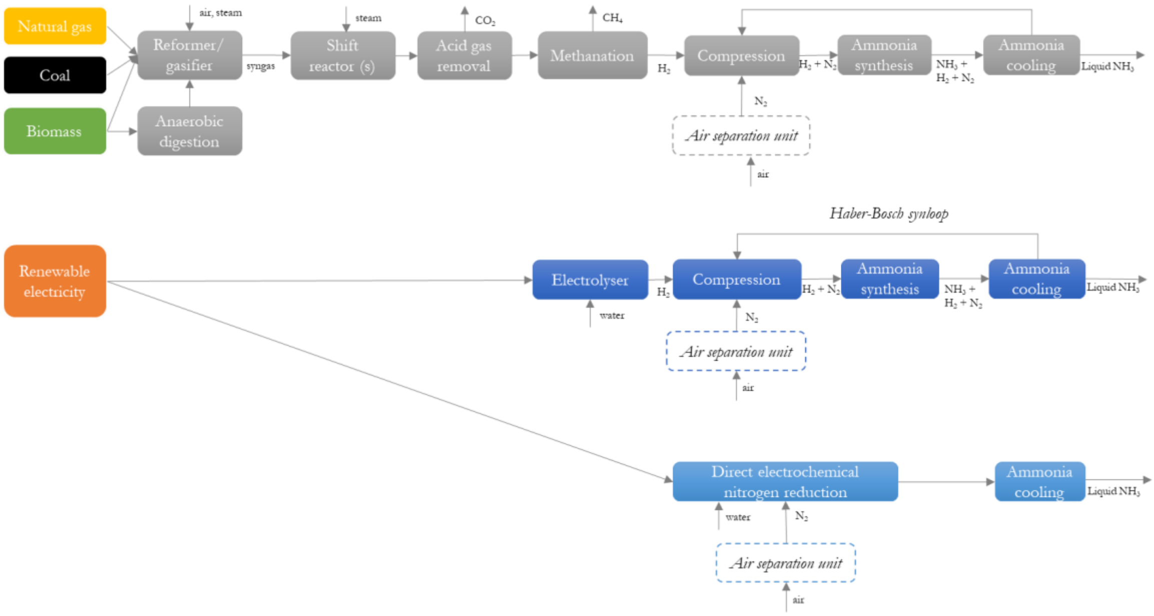


Figure 3. Overview of different production pathways for ammonia (based on Giddey et al., (2017), Ahlgren et al., (2015) and Hochman et al., (forthcoming)), more production pathways are possible, and this is a simplified picture of ammonia production through the HB process which may include several other steps and more details. Nitrogen generation may be integrated in the hydrogen production process or separate in an air separation unit.

4. Technical feasibility and other implementation issues

Ammonia, for energy purposes, can be used either in fuel cells or in combustion engines with some changes to existing technologies. Ammonia has been demonstrated as a fuel in compression ignition (CI) engines, spark ignition (SI) engines and fuel cells. Fuel properties include low flame temperature, low burning velocity, high ignition temperature, and narrow flammability limits. At room temperature and atmospheric pressure ammonia is a gas. For storage it is either frozen below -33°C or under pressure. Table 1 summarizes some physical and chemical properties of ammonia and other potential fuels.

Table 1. Summary of properties of ammonia and some other potential marine fuels. L=liquid, G=gaseous (Reiter, Kong, 2008; Zamfirescu and Dincer, 2008, Kennedy et al. 2019)

Fuel	**Ammonia**	**Hydrogen-L**	**Hydrogen-G**	**LNG**	**MGO/ diesel oil**	**Petrol**	**Methanol**
Storage phase	L	L	G	L	L	L	L
Storage Temperature (C)	25	-253	25	-162	25	25	25
Storage Pressure (kPa)	1000-1700	101-3600	25000	101-125	101	101	101
Density (kgm-3)	603*	71	17.5	430-470	840	698	786
LHV (MJ/kg)	18.6 -18.8	120	120	49	43	42.5	19.7
Octane	>130	>130	>130	120		92-95	109
Flame velocity (m/s)	0.015	3.5	3.5	0.34		0.28	0.43

*Liquid ammonia at 25°C

One advantage with ammonia is that it is more energy dense compared to compressed hydrogen and liquid hydrogen and thus can store more energy per unit volume (Figure 4). Ammonia is normally stored in insulated pressurised tanks which requires larger space requirement onboard ships than LNG and methanol (DNV GL, 2019). In contrast to liquefied hydrogen, there is no need for cryogenic storage when using ammonia (Kirstein et al., 2018).

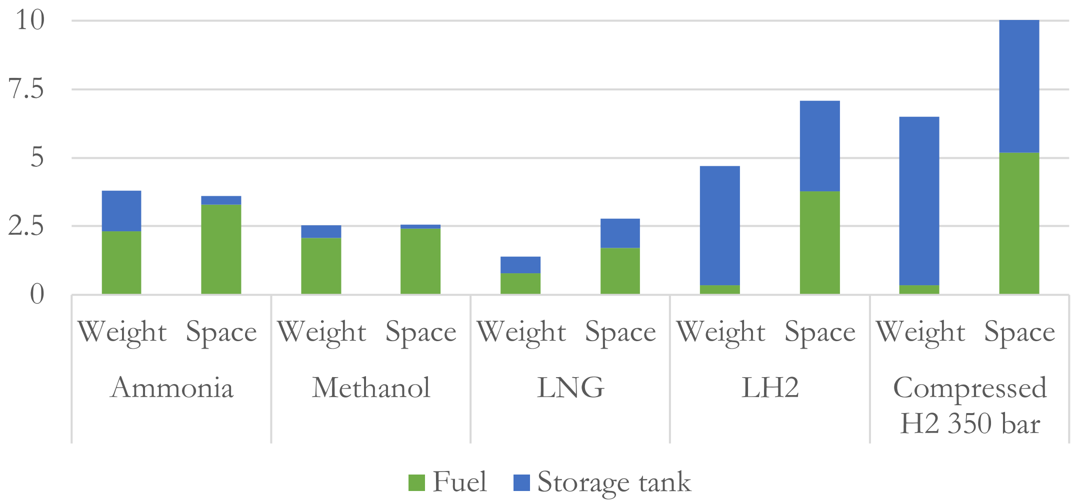
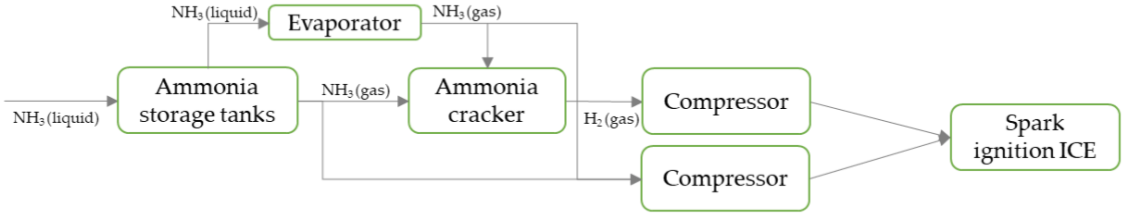


Figure 4. Indicative increase in space and weight requirement for different fuels compared to diesel (the weight and space requirement of diesel is set to 1 and would thus amount to 1 in the figure). Source: DNV GL (2019).

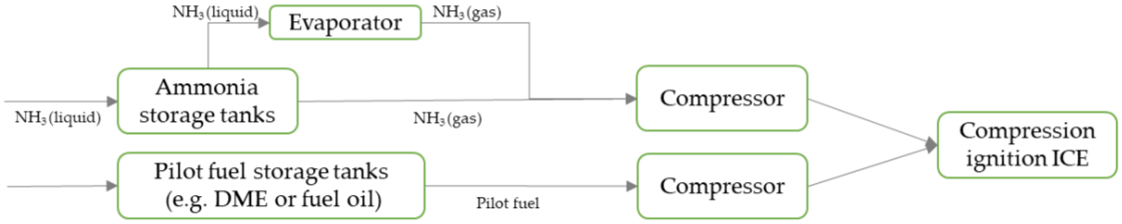
4.1 Possible marine propulsion systems

Figure 5 illustrates four simplified potential marine propulsion systems setups using ammonia. No propulsion technologies for ammonia have yet been commercialised for marine operation. However, MAN Energy solutions have developed a dual-fuel engine for LPG that they claim also can be used with liquid ammonia (in a dual fuel setup) (Laursen 2018, MAN Energy solutions, 2019). MAN Energy solutions, Shanghai Merchant Ship Design & Research Institute (SDARI) and American Bureau of Shipping (ABS) has initiated a joint development project for an ammonia-fueled feeder container vessel which will utilize the dual fuel technology by MAN (ABS, 2019). MAN Energy solutions (2019) also indicate that LNG engines can be converted to ammonia operation where tanks used for storage of LNG with the same requirements can be used for storage of ammonia. When designing the propulsion system, the chemical properties of ammonia need to be addressed. Since ammonia is corrosive, for example to copper, copper alloys, alloys with a nickel concentration larger than 6% and plastic, marine fuel systems using ammonia need to consider this e.g., for alloys with nickel the material strength might need to be increased (MAN Energy solutions, 2019).

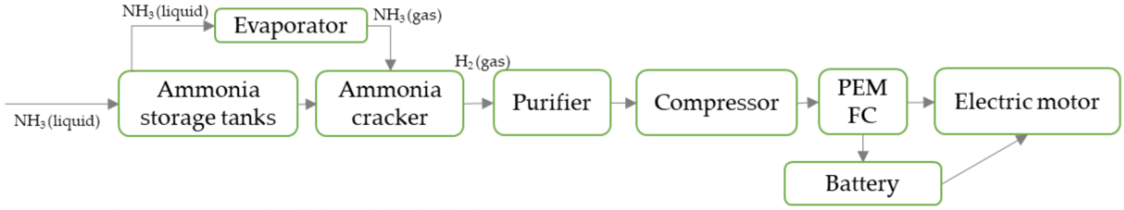
(a) ammonia propulsion system with spark-ignited ICE



(b) ammonia propulsion system with compression ignition ICE



(c) ammonia propulsion system with proton-exchange membrane fuel cells (PEM FC)



(d) ammonia propulsion system with solid oxide fuel cells (SOFC)

Figure 5. Four simplified possible propulsion system configurations using ammonia as marine fuel based on de Vries (2019), Giddey et al (2017) and MAN Energy solutions (2019).

4.2 Literature on engine tests with ammonia

Ammonia has been used in combustion engines since the second world war. However, there are a limited number of tests published and remaining issues with materials, ignition, specific fuel consumption and emissions. Ammonia have rather poor ignition and combustion properties and an ignition fuel is needed for both CE and SI engines; e.g. diesel oil or DME for CI and hydrogen or alcohols for SI. Here follows a short review of the published tests.

Gray et al. (1966) tested ammonia as a fuel for both spark ignition and compression ignition engines. For SI it was found that 4-5% of hydrogen mixed in with ammonia was necessary for ignition and successful operation. The specific fuel consumption (SFC) was found poor and the emissions of NOx may be an issue. For CI the best results were obtained with diesel oil as an ignition fuel and ammonia as a vapour. When it comes to materials, they see no big issues with ammonia as a fuel.

We then jump to 1977 and the paper by Bro and Pedersen. They tested methanol, ethanol, methane and ammonia in a dual fuel diesel engine, with diesel oil as pilot fuel. The other fuel was mixed with the intake air. They found ammonia to be the least suitable of the fuels. For high SFC they needed a high fraction of diesel oil (around half). The NO emissions were significant as well as the fraction of unburnt ammonia.

Reiter and Kong (2008, 2011) used a turbocharged diesel engine in a dual-fuel setup only modifying the fuel intake system. Ammonia was introduced into the air intake system and diesel oil was injected directly into the cylinder. The engine could be run with up to 95% (energy%) replacement of diesel with ammonia but with reasonable fuel economy only in the interval 40-80% in a test with constant engine power (varying the diesel and ammonia injection simultaneously). NO_x emissions increased significantly with a higher part being ammonia. Also, ammonia emissions were an issue. A test with constant pilot fuel injection and varying ammonia injection, to get variable engine power, resulted in poor fuel efficiency and high ammonia emissions.

Gross and Kong (2013) used the same engine but replaced the injector to inject mixtures of ammonia and DME (dimethyl ether). They tested both injection of a premixed fuel and double injection with DME as pilot fuel. All tests are done at relatively low engine loads. They observed higher emissions of NO_x and NH_3 with the introduction of ammonia, but low soot emissions.

There seems to have been a program to develop a homogeneous charge compression ignition (HCCI) engine for ammonia combustion at Sandia (Blarigan 2000). However, the results of this have not been found.

Ruy et al. (2013) tested ammonia-DME mixtures in a diesel engine. For high ammonia fraction (above 60%) the combustion became unstable and the emissions of NO_x, HC and CO increased while soot emissions remained low.

Frigo and Gentile (2013) presented experiments for a 4-stroke SI engine with a mixture of ammonia and hydrogen. The fuels were injected as gases. The fraction of hydrogen needed varies with load and speed but is around 6% (energy) at high load and optimal speed, i.e., for other cases it is higher. NO_x emissions are high (up to 1700 ppm) but can be dealt with a three-way catalyst (TWC) since the engine is run at lambda 1.

Mörch et al. (2011) also used an SI engine where ammonia was mixed with hydrogen before injection. The mixture with 10%vol of hydrogen worked best with an efficiency of about 35%. NO_x emissions were high, around 1500 ppm.

Pochet et al. (2017) tested ammonia-hydrogen mixtures in a HCCI engine with stable combustion up to 70% ammonia. The NO_x emissions were significant but could be reduced with exhaust gas recirculation (EGR), in turn producing some N_2O.

MAN have developed a dual-fuel engine for LPG that they claim also can be used with ammonia (in a dual fuel setup) using liquid ammonia (Laursen, 2018). However, no engine tests and no data on combustion properties or emissions have been found.

The review of literature on engine tests with ammonia is summarized in Table 2. In summary there are only few published tests with ammonia in combustion engines. Ammonia is hardly flammable and for SI engines a mix with hydrogen or hydrocarbons (Rehnbein et al. 2019) may be required. Hydrogen could be obtained from (partial) decomposition of ammonia. CI engines have been demonstrated with different pilot fuels (diesel, DME, methanol). With a high fraction of ammonia there are issues with NOx and ammonia emissions. Also elevated emissions of HC and CO are reported but soot (PM) emissions seem to be under control.

Table 2. Summary of review of literature on engine tests with ammonia. The efficiencies are typically not explicit in the papers but calculated from other information.

Refernce	**CE-type**	**Injection type**	**Ignition Fuel**	**Max efficiency**	**NH_3 fraction in mixture**	**NO_x emission**	**NH_3 emission**	**Other emissions**
Bro & Pedersen, 1977	CI	Pilot direct, ammonia with air	Diesel oil	18%	50 energy-%	1500 ppm	2500 ppmV	Smoke 4 (% harttridge); HC 300 ppm
Frigo & Gentile, 2013	SI	Gas	H_2	26%	94 energy-%	1700 ppm (can be dealt with using TWC)	No	No
Reiter and Kong, 2008, 2011	CI	Pilot direct, ammonia with air	Diesel	Ca 20%	50 energy-%	8 g NO /kWh		HC 1 g/kWh; CO 90
Gross & Kong, 2013	CI	Direct. Mixed or double	DME	18%	40 energy-%	5 g/kWh	Up to 1600 ppm	Soot 0.01 g/kWh; THC 20 g/kWh, CO, 50 g/kWh
Mörch et al. 2011	SI	Mixed	H_2	35%	90 vol%	1500 ppm		

4.3 Development of ammonia fuel cells

An option to combusting ammonia in internal combustion engines is to use fuel cells. This can result in higher thermal efficiencies, less noise and lower emissions of air pollutants. There are different options for fuel cell systems utilizing ammonia. Proton-exchange membrane fuel cells (PEM) using purified hydrogen and solid oxide fuel cells (SOFC) using ammonia are two alternatives that may be used in marine applications (de Vries, 2019).

Basically, ammonia can either be used directly in fuel cells or ammonia is used as a hydrogen source where a converter is used to split ammonia into hydrogen and N_2 where after the hydrogen is used in the fuel cell.

PEM fuel cells cannot use ammonia directly, instead they need high purity hydrogen, but they are commercial and tested in marine applications (Tronstad et al., 2017). There is development of fuel cells that can use ammonia directly including alkaline, alkaline membrane and SOFC (Lan and Tao, 2014). No tests onboard vessels have been found of fuel cells using ammonia directly, but there have been tests with SOFC using methanol and methane (Tronstad et al., 2017).

SOFC is perhaps the most promising direct ammonia fuel cell, but it is still far from commercialisation (Lan and Tao, 2014, Afif et al., 2016). It is difficult to estimate what emissions that may be associated with ammonia fuels cells as they are still under development. There is for example a risk for NOx emission. Lan and Tao (2014) suggests that ammonia SOFC can be associated with NOx emissions but that this can be reduced by using proton-conducting electrolytes.

In summary the use of fuel cells in combination with ammonia has a potential to be an alternative to internal combustion engines but there are many questions to resolve, not least the costs.

5. Environmental aspects

The available tests on combustion engines show issues with ammonia slip, NOx emissions and potentially emissions of CO and hydrocarbons (depending on pilot fuel) and N_2O. These emissions can likely be handled with after treatment, either TWC (three-way catalyst) if the combustion is stoichiometric or SCR/EGR (Selective Catalytic Reduction/Exhaust Gas Recirculation) for lean combustion. However, the ammonia slip and low efficiency in combination with a high fraction of the pilot fuel are factors that would have to be addressed before tests on ships.

Ammonia that is released into the atmosphere can have health risks if at high concentrations. It will also contribute to formation of secondary particles and to eutrophication. Ammonia evaporating from the use in farming is one major issue regarding air pollution in Europe.

An LCA, considering selected environmental impacts, of ammonia production pathways using the Haber Bosch process and non-fossil energy sources for the hydrogen production report the lowest GHG emissions from the use of hydropower when compared to nuclear, biomass and municipal waste (Bicer et al., 2016). Bicer and Dincer (2018) assess the GHG emission reduction potential from marine transportation by replacing conventional heavy fuel oil with renewable hydrogen and ammonia and find that ammonia and hydrogen used as dual fuel with heavy fuel oils (50%) can decrease the GHG emissions per tonne-kilometre by around 30% and 40%, respectively.

When producing renewable ammonia (from electricity) an electricity input of 3-4 times the actual work propelling the ship is needed (Figure 6).

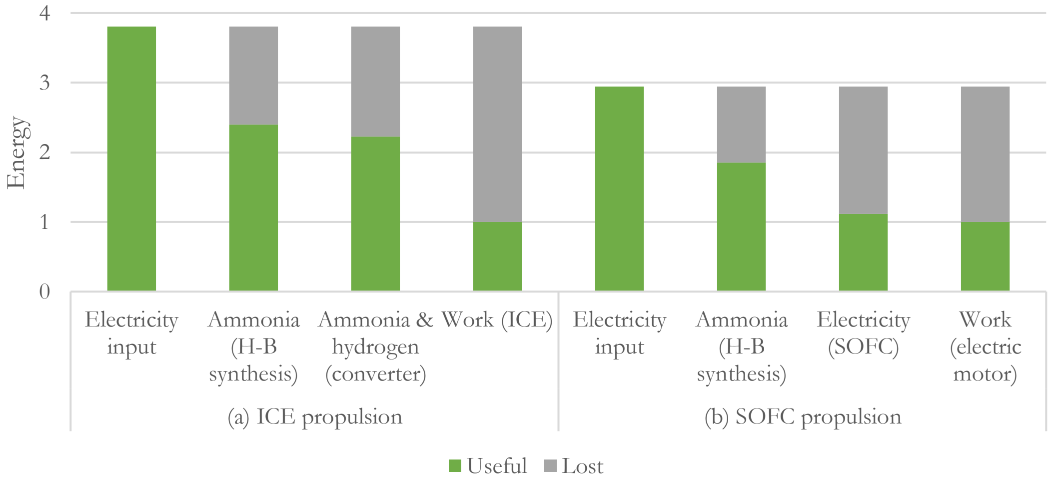


Figure 6. Simplified schematic view of losses (approximate values) in a chain starting with electricity and ending with work propelling the ship for (a) an ICE propulsion system and (b) and SOFC propulsion system.

6. Safety aspects

In terms of safety issues linked to ammonia, leakage and the potential exposure to humans and the environment seem to be key concerns.

Ammonia is a toxic and corrosive substance and potential leakage and spills will be hazardous to the human and the environment including aquatic life (the latter if leakage in water). Ammonia is for example hazardous to inhale over certain levels and time periods and is toxic for organisms living in water with potential long-term effects (de Vries, 2019; ammonia safety data sheets). The limits for ammonia exposure at workplaces in Sweden are 20 ppm for 8 hours and 50 ppm for 5 minutes (ammonia safety data sheets). According to de Vries (2019) ammonia can be lethal to humans at 2700 ppm when exposed for a duration of 10 minutes, Valera-Medina et al. (2018) report that less than half an hour of exposure at 2000-3000 ppm may be fatal, while Klüssmann et al. (2009) report that the immediately dangerous to life or health limit is estimated to 300 ppm. Safety issues around ammonia has for example been discussed linked to the use of anhydrous ammonia as a refrigerant in mechanical compression systems at industrial facilities where it has been replaced to a large extent (US EPA, 2001).

Ammonia is biodegradable and ammonia released in water will be converted into ammonium ions (NH_{4+}) which are harmless for human and plants (De Vries, 2019). However, as indicated above ammonia released in water may cause damages to organisms in the water if exposed directly and potential long-term effects need to be clarified. Ammonia released in the dry air will due to its lower density dilute and evaporate upwards, however several factors influence how fast and to what extent ammonia diffuses in the air (Valera-Medina et al., 2018).

Even though there are handling experience and regulations linked to the current transport and use of ammonia (bulk ammonia transport vessels follows the requirements of the 2014 International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk - IGC Code, Ash & Scarbrough, 2019), specific safety regulations linked to the use of ammonia as marine fuel will be needed in case of implementation. These regulations need to be considered when designing the fuel handling system for bunkering as well as during operation. This might add extra cost for the ammonia pathways. For example, according to De Vries (2019) separate spaces for fuel storage and fuel treatment rooms seem needed and the fuel lines should be located with a distance to the shell or considered in other ways which influences the use of the space on-board.

Linked to ammonia fuel system on ships gas detection systems, ventilation and appropriate chemically resistant protective clothing and other safety measures for those handling the fuel will be needed (Ash & Scarbrough, 2019; de Vries 2019). Ammonia can also be detected by its odour.

Minor ammonia slip can, according to studies referred to by Klüssmann et al., (2019), be removed together with NOx with modified SCR catalyst after treatment while larger slips may require the implementation of a dedicated ammonia trap or oxidation catalyst. Klüssmann et al., (2019) suggest that storing of ammonia in mineral salts or metal ammine complexes can reduce safety issues related to on board storage of liquid ammonia. However, this technology is under development.

In addition, Ash and Scarbrough (2019) mentions the risk of formation of hydrogen cyanide (HCN, which is highly toxic) in combustion of a hydrocarbon fuel and ammonia (Gail et al., 2012). However, they claim that studies indicate acceptable levels in SI and CI-engines (Moussa et al., 2016; Baum et al., 2007) and that there have been no reports regarding emission of hydrogen cyanic when ammonia and hydrocarbon fuels are used in ICE but that there is still a risk (Ash & Scarbrough, 2019).

Ammonia has a relatively low flammability compared to other fuels which imply a relatively low risk of fire, but can form explosive mixtures with air (though, larger amounts are needed compared to many other fuels according to Klüssmann et al. (2019)). However, as highlighted by de Vries (2019), since hydrogen, which can be obtained from cracked ammonia, represents an extremely flammable gas this risk needs to be considered.

In terms of rules and regulations for ammonia as a fuel, it is indicated that "*MAN Energy Solutions is already working with DNV-GL and Navigator Gas on an early-stage risk assessment to use ammonia as a maritime fuel*" (Ash and Scarbrough, 2019) and that ABS linked to the joint development project for an ammonia-fueled feeder container vessel (between MAN, SDARI and ABS) will "*assess safety-related issues and contribute to the development of rules and standards in relation to ammonia as a fuel*" (ABS, 2019). The IGF Code (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels) will likely need to be further developed in case of use of ammonia as marine fuel (de Vries 2019).

Public acceptance for the use of ammonia as fuel is important as this will influence all actors (producers, users, policy makers). This will be influenced by public perception and the development and observants of safety regulations as well as media.

7. Economic feasibility

From 2016 to mid-2019 the global prices on ammonia have been in the range $180-$380 per ton (Fertecon, 2019). This corresponds to about $10-20 per GJ and $34-73 per MWh (using a lower heating value of 18.8 MJ/tonne for ammonia). Between 2010 and 2016 the ammonia prices varied from $260-$700 per ton (corresponding to $14-37 per GJ and $50-134 per MWh and (Fertecon, 2019). Figure 7 shows the historical ammonia prices in the US, approximate ammonia prices from three markets (Caribbean, Middle East, Yuzhnyy) compared to the historical price of natural gas, LNG and crude oil per energy content. This indicates a large price difference historically between ammonia for agriculture in the US and natural gas. This is one indication of how the future ammonia prices may develop even if it is for another sector.

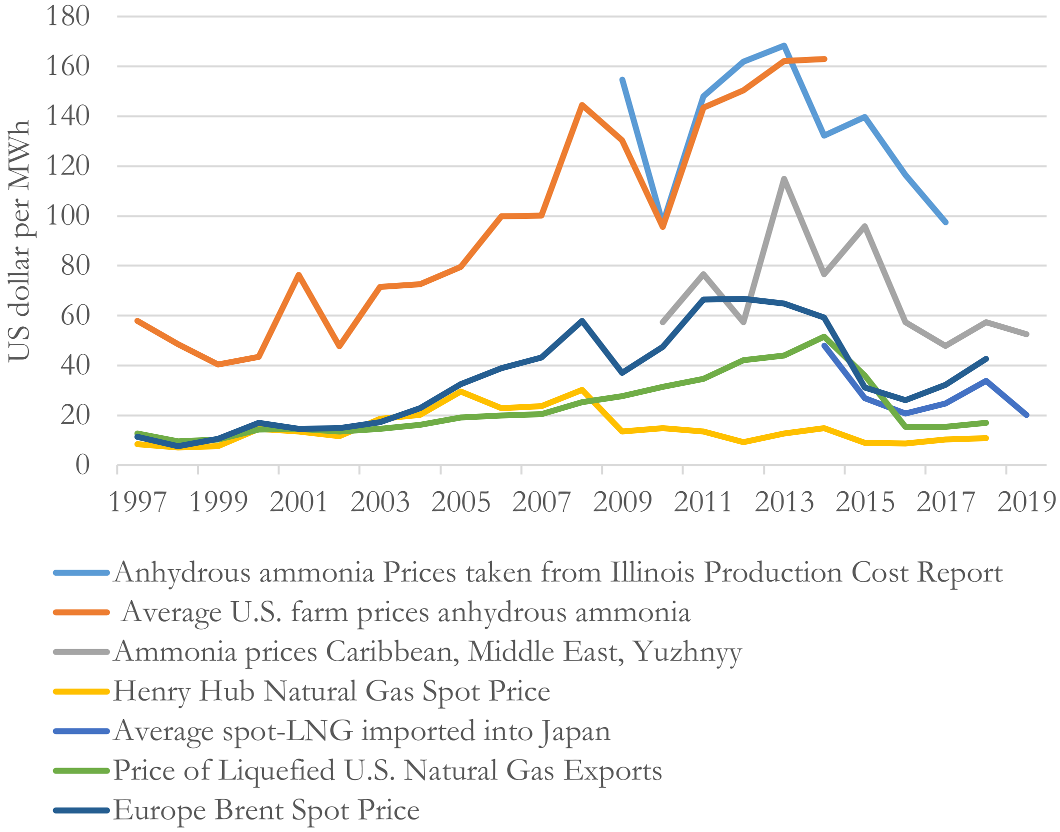


Figure 7. Historical prices for ammonia, natural gas and crude oil. Sources: Schnitkey (2017), ERS (2019), Fertecon (2019), EIA (2019ab), METI (2019).

The cost of ammonia production will vary depending on the production route. The natural gas price is a major factor in the cost of producing ammonia from natural gas while the electricity price is a major factor in the cost of producing renewable ammonia based on electricity, where the latter is the main production way for ammonia as marine fuel. Bicer et al., (2016) indicates that roughly 70-90% of the current production cost of ammonia generally originates from the cost for natural gas. In another study it is indicated that ammonia prices can be 100-200 USD per ton higher than production cost, due to transportation and storage cost (ISPT, 2017).

The ammonia production cost for renewable ammonia (the ammonia to be used as marine fuel) was estimated to range from $130 to 440 per ton ammonia for the various cases studied by Tun et al., (2014). In a forthcoming study (Hochman et al., 2019) the cost of ammonia production in 2040 for five routes are compared: conventional route via steam reforming of natural gas, with and without carbon capture and storage, followed by the Haber-Bosch synthesis; electrolysis of water followed by the Haber-Bosch synthesis; electrochemical ammonia production (direct electrochemical nitrogen reduction) (Figure 8). These costs are per energy unit based on lower heating value and does not consider that different fuels and ship propulsion systems have different efficiencies.

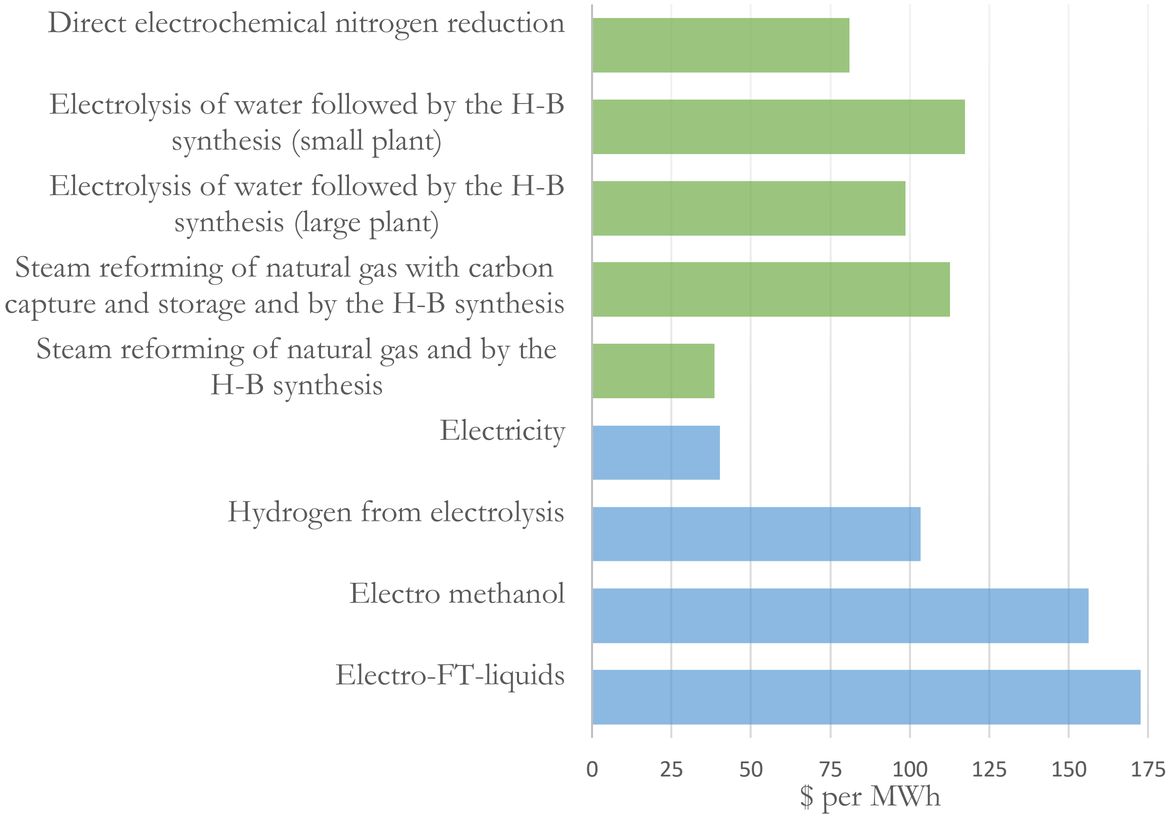


Figure 8. Indicative future production cost for different ammonia production routes in 2040 based on Hochman, et al. (2019) and compared with the cost for electricity, hydrogen and selected electrofuels production routes in 2030 based on Brynolf, et al. (2018). An electricity price of $40.2/MWh and a natural gas price of $14/MWh is assumed in the assessments.

Lloyd's Register (2017) have estimated the additional propulsion system cost for an ammonia-fuelled vessel to be approximately 2-60% when using internal combustion engine and 8-300% when using fuel cells, relative to a conventional HFO-fuelled vessel. De Vries (2019) have estimated the capital and operational costs for the different ship propulsion systems using ammonia as fuel, but the figures are so far very uncertain as these technologies are under development. There is also a cost for distributing ammonia. DNV GL (2019) suggest that this cost could be similar to transporting LNG measured on a volume bases and assumes the cost to between 20-70 $ per MWh.

8. Discussion and conclusions

In the search for fuels for shipping that will lead to significantly lower emissions of CO_2 from the sector, ammonia has attracted a lot of attention recently (e.g., CSR Netherlands 2017; Lloyds Register, 2017; Maritime Knowledge Centre, TNO and TU Delft, 2017; Kirstein 2018; DNV GL, 2019). The potential of and issues with ammonia as a marine fuel will be discussed here together with suggestions for further studies.

The price of ammonia is today significantly higher than for MGO and LNG. However, looking into the future where fossil fuels must be replaced, ammonia should rather be compared with other renewable alternatives such as biofuels and hydrogen. In such a comparison the price for ammonia is expected to be in the same range (DNV GL, 2019, Kirstein et al., 2018). Thus, the price is not expected to be a decisive hinder. However, for this scenario the production of ammonia produced from renewable sources needs to be expanded substantially.

In order to reduce emissions of CO_2 the production of ammonia must be produced from renewable electricity or biofuels (or from natural gas in combination with carbon capture and storage). One obvious route is to produce electricity in solar panels at favourable geographic locations, and then produce hydrogen and finally ammonia through the HB process (Ash and Scarbrough, 2019; Giddey et al., 2017). This type of facilities can be located at many places in the world, close to the equator, and the ammonia then transported in tankers. The geopolitical issues will thus be much less than for fossil fuels. Further, local production facilities in other parts of the world could utilise surplus wind or hydro power (Ash and Scarbrough, 2019).

In case of demand for renewable ammonia as fuel, there is a competition with production of fertilizers that are crucial for food production assuming that these also need to be produced by renewable sources in the future. At least in the short-term this might influence the ammonia price and potentially lead to higher food prices. However, there are no practical limits to expand the production facilities provided enough solar or other renewable based electricity can be produced. There is thus not the same issue with competition with food production as for biofuels.

The space requirement onboard a ship are higher for ammonia than for marine fuel oils or bio-oils and higher than for LNG and methanol but lower than for hydrogen (DNV GL, 2019). This may limit the use of ammonia in long distance shipping and will marginally reduce the cargo space in relation to other fuels. However, if for other reasons, hydrogen and ammonia are the fuels to compare, ammonia has an advantage.

There have been limited number of tests of engines using ammonia. The tests done show that a high fraction of pilot fuel is often used, there are issues with emissions and the demonstrated efficiency is low (Table 2). However, there is no reason to believe that the emissions cannot be dealt with and that the engines will not be improved. The most promising initiative now is the development of an ammonia engine by MAN (MAN Energy solutions, 2019.). Still, before ammonia can be used on ships demonstrations of emissions and efficiencies are called for. There are some issues with materials that seems to be under control (Klüssmann et al., 2019; MAN Energy solutions, 2019). Fuel cells for hydrogen together with converters or direct ammonia fuel cells need to be demonstrated and to show a business case regarding costs and durability.

Ammonia is already today a commodity that is transported around the world in tankers (DNV GL, 2019). If ammonia is becoming popular as a marine fuel, there does not seem to be main issues with fuel infrastructure or bunkering. This is another advantage compared with hydrogen. However, it is central that a working fuel infrastructure and bunkering systems are implemented for ammonia to be used as marine fuel.

The fact that no CO_2 is emitted when ammonia is combusted is of course the main advantage. This limits the need for biomass-based fuels and for technologies like carbon capture. If ammonia is produced from carbon-containing sources the capture of CO_2 will also be less complicated to apply at a production facility than onboard ships. However, there is a cost for carbon capture and renewable ammonia is preferable in order to reach low climate impact.

There is an issue with impact on water and air quality upon major release of ammonia and smaller continuous ones will have effects on particle formation and eutrophication (de Vries 2019). This problem already exists today but may be more problematic if ammonia is used as fuel in large-scale. Thus, it is essential that systems are developed to minimise the risks for ammonia release (de Vries, 2019; Ash & Scarbrough, 2019). The potential emissions from engines of NO_x and other air pollutants can likely be dealt with using after treatment.

Safety is a major concern when considering ammonia as a fuel. A leak inside the ship could be disastrous for the crew and it is thus necessary to develop firm rules for design of ammonia systems and for the handling of such systems.

It is interesting to compare ammonia with other propulsion alternatives that are under discussion to replace fossil fuels. Table 3 gives a simplified overview. Preliminary findings from a comparison of different marine fuels applying a multi-criteria decision analysis (MCDA) approach also indicates that ammonia (in particularly when used in fuel cells) might be as interesting as hydrogen and biomass-based marine fuels (Lövdahl & Magnusson, 2019). These findings need to be confirmed.

Table 3. Summary data for different propulsion alternatives.

Power system	**Use in ICE**	**Use in FC**	**Fuel cost**	**Capital cost**	**Maturity**	**Production potential**	**Safety**	**Sailing distance**	**Sailing speed**
Ammonia	Likely	Likely	High	Medium	Low	High	Risks	Medium	High
Methanol	Yes	Yes	Medium	Medium	Medium	Medium	Low risks	Medium	High
Hydrogen	Yes	Yes	High	Medium	Low	High	Explosion risks	Short	High
Biodiesel	Yes	No	Medium	Low	High	Medium	Low risks	Long	High
LBG	Yes	Yes	Medium	Medium	Medium	Medium	Low risks	Medium	High
Wind	n.a.	n.a.	Low	Medium	Low	High	Low risks	Long	Low
Batteries	n.a.	n.a.	Low	High	Medium	Medium	Low risks	Short	Medium

Before ammonia is promoted and introduced as marine fuel there are some key issues that need to be addressed and more research needed. These include:

- The production of renewable ammonia needs to be expanded substantially and with a reasonable production cost. Renewable ammonia will not be available in large scale in the short term.
- Results from maritime ammonia engine tests are lacking
- Fuel cell systems need to be demonstrated for marine applications
- What happens in case of an accident? This should be investigated further.
- Is it possible to convert e.g. LNG fueled ships to ammonia propulsion?

To address these issues the following projects are suggested:

- An in-depth assessment of ammonia as marine fuel from a system perspective considering, technical and economic feasibility, safety and environmental performance comparing ammonia with other potential marine fuels.
- A feasibility study, on the potential to apply ammonia as a marine fuel including analysis of fuel systems, bunkering, safety routines etc.
- A demonstration where an engine is converted for ammonia as a fuel. For demonstration the MAN engine seems closest to application (MAN Energy solutions, 2019).
- A demonstration using fuels cells in combination with ammonia. Fuel cells should initially be tested as an auxiliary system.

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