August 2020

Ammonfuel
An industrial view of ammonia as a marine fuel

This paper discusses the use of ammonia as a marine fuel. It covers all aspects of the process including conventional and future green ammonia production, experience regarding safety of ammonia from other areas, the logistics of providing ammonia where it is needed, and the application on board vessels. The focus is on cost, availability, safety, technical readiness, emissions and the elimination of risks related to future environmental and climate related regulations and requirements. The conclusion is that ammonia is an attractive and low risk choice of marine fuel, both in the transition phase towards a more sustainable shipping industry and as a long-term solution.

Contents

1 Executive summary

The aim of the Ammonfuel report is to provide the shipowners with a general overview about ammonia as a product and its applicability as a marine fuel. The members of the working group contributed to the white paper by their direct expertise in various fields of the entire process: from renewable energy generation, allowing the production of a zero-carbon footprint ammonia, to distribution and use onboard as a fuel. In this way, the white paper can provide the owners with a solid and up to date overview of the applicability, scalability and sustainability of the ammonia fueled ship.

First of all, the physical properties, storage conditions and safety aspects of ammonia are described and compared with those of other substances that are considered as possible alternative fuels. Further comparison with the same properties of the HFO currently in use is provided as a benchmark.

The white paper provides a picture of the current production of ammonia supplied by the energy from fossil fuels (so-called conventional ammonia) and analyzes the possibility to implement a supply chain powered by renewable energy only (producing so-called green ammonia). Based on a scenario where 30% of the shipping industry is converted to this fuel, the study assesses the required amount of the product and the consequent demand of renewable energy and of territory to secure it. With this target in mind, the scalability of the process is analyzed and confirmed. That ammonia is produced in bulk worldwide and history demonstrates that the industry has always been able to quickly resize according to product demand. Moreover, today a significant production overcapacity is available to sustain the initial request of the product for marine propulsion, making smooth introduction of this fuel in the shipping industry possible with stable costs and availability.

The later and progressive shift to production based on green energy will make possible the achievement of a zero-carbon footprint as aimed at by the IMO strategy. Once this process is complete, the study foresees that the cost to fuel a ship with green ammonia will be similar to that of compliant fuel, while the cost of today’s conventional ammonia is already comparable, confirming the sustainability of ammonia powered shipping. The introduction of market-based tools like renewable energy certificates that are already in use for other products can further sustain and promote a profitable implementation of green ammonia onboard ships.

The white paper also analyzes the experience in handling and use of the product. Ammonia is mainly used as a fertilizer in agriculture, but also as a refrigerant, and is distributed worldwide by means like trucks, trains, ships and pipelines. Today, thanks to safety procedures, training of personnel and considerable handling experience, the level of safety has proven to be high, in spite of the extreme widespread use of the product and the variety of users.

The extensive use of the product also needs a substantial logistics chain in place. Today ammonia can count on a large number of facilities in the world: 120 ports are already dealing with the import and the export of the product, sometimes with their own storage facilities. This infrastructure represents an excellent starting point for securing the availability of ammonia fuel for ships adopting it as forerunners. As for LNG, the product availability can be further enhanced by gas carriers used as bunker barges, allowing quick implementation of the bunkering facilities where the product demand is, with bunkering procedures similar to those of LNG.

Finally, this white paper analyzes how ammonia can be practically handled onboard and burnt in a reciprocating engine. The industry is now developing ammonia powered engines, with a clear roadmap for implementation within 2024. The dual-fuel technology is a well-proven solution to burn this product and, thanks to the possibility of using a variable mix of alternative and traditional fuel, it allows for the progressive introduction of ammonia for ship propulsion.

Furthermore, the solutions adopted for LNG and LPG as fuels provide a solid starting point for the specific implementation of engine room safety measures and the fuel supply process, respectively.

1.1 Highlights from the report

AMMONIA AVAILABILITY AND PRODUCTION SCALABILITY

- 120 ports already equipped with ammonia trading facilities worldwide.
- Annual ammonia production: 180 million tons.
- Conventional production overcapacity of 60 million tons/year ensures availability.
- Additional ammonia production to meet 30% marine fuel demand in 2050: 150 million tons/year.

DEMAND FOR RENEWABLE ENERGY TO PRODUCE GREEN AMMONIA

- 400 GW power needed to meet 30 % of future marine fuel demand.
- In 2019 alone, 184 GW additional power production was installed.

COST OF ENERGY FROM VLSFO OR AMMONIA

- 12.5–15 $/GJ for VLSFO (primo 2020, price is volatile).
- 13.5 $/GJ for today's conventional ammonia (stable since end 2018).
- 13.5–15 $/GJ forecasted cost for green ammonia from solar and wind energy in 2040–2050.
- 16–21.5 $/GJ for carbon-neutral ammonia as dual fuel in 2025–2030.

SAFETY AND APPLICABILITY

- 17.5 million tons of ammonia safely traded and transported yearly by ship, truck, and train.
- Existing practices and know-how for safe ammonia handling already established in marine and other industries and adaptable for ammonia as a fuel for shipping.
- Availability of dual-fuel ammonia engine forecasted availability from 2024.

ENVIRONMENTAL BENEFITS

- Ammonia is a carbon and sulfur-free fuel.
- Green ammonia is produced entirely from renewable electricity, water, and air. Unlike sustainable carbon-based fuels, green ammonia feedstocks are unlimited.
- Ammonia can burn in an internal combustion engine with no SO_X, CO_2, or particulate emissions. The installation of catalytic (SCR) technology eliminates N_2O/NO_X emissions to very low levels leaving an exhaust of nitrogen and water.
- Ammonia is metabolized in the environment and does not build-up.

2 Introduction

The shipping sector plays a fundamental role in the global economy, transporting more than 80% of the world's total trade volume. Compared with other modes of cargo transportation, shipping enables the regional and intercontinental movement of large quantities of cargo in the most fuel- and cost-efficient way.

Heavy fuel oil (HFO) has become the predominant fuel for the shipping industry since the 1950s as a result of its broad availability and low cost. However, there is a concern over the sustainability of the current practice of using traditional fossil fuels for shipping.

In line with the Paris Agreement from the UN Climate Change Conference 2015, the International Maritime Organization (IMO) has adopted a strategy for the progressive reduction of greenhouse gas (GHG) emissions by the shipping sector, aiming to halve it by 2050 compared to 2008 figures. The strategy proposed by the IMO includes different paths for the progressive reduction of GHG emissions, including short-, mid- and long-term measures, but the target set by the IMO for 2050 cannot be achieved without the adoption of alternative carbon-neutral fuels. The term carbon-neutral refers to a source of energy that has no net GHG emissions.

It is in this picture that ammonia is encountering a growing interest as one of the potential fuels candidates for the decarbonization of the shipping industry[1,2,3,4]

Ammonia (NH3) is a carbon-free molecule and therefore burning it in an internal combustion engine leads to zero CO2 emissions from the stack. Additionally, ammonia becomes a carbon-neutral fuel when it is produced from renewable energy sources like electricity from wind and solar generation (green ammonia) or from fossil sources associated with carbon capture and storage technologies (blue ammonia).

Ammonia is also a sulfur-free fuel. Therefore it does not require any SOx removal system on the exhaust to comply with environmental limitations on sulfur emission. Furthermore, any NOx generated from ammonia combustion can be removed from exhaust gases with selective catalytic reduction (SCR) technology.

This report shows that ammonia is not only an attractive long-term solution for carbon neutrality but also can play a strategic role in the transition phase. By shifting gradually from fossil-fuel based ammonia to green ammonia, the CO2 footprint can be progressively lowered at low risk for the shipowner, also achieving the sulfur emission requirements.

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[1] Alternative fuels for international shipping – Maritime Energy & Sustainable Development (MESD) Centre of Excellence

[2] DNV-GL Maritime forecast to 2050 – Energy Transition Outlook 2019

[3] Forecasting the Alternative Marine Fuel, Korean Register.

[4] "Green shift to create 1 billion tonne green ammonia market?", June 2020, argusmedia.com

There are various potential alternative fuels for the shipping sector, the evaluation of which shall consider not only use onboard, but also overall availability, the sustainability of the production process, distribution logistics, and the level of development of the technology involved. For the specific case of ammonia, these aspects will be detailed in the following chapters of the present report.

Ammonia production is described in the next chapter, Chapter 3. A detailed analysis of electricity availability and cost is provided, including the expected growth of renewable electricity demand to sustain the production of green ammonia in the next decades. Chapter 3 also includes a description of the technologies required to produce green hydrogen via electrolysis and an estimate for the cost of production of conventional, blue, green, and hybrid ammonia from 2030-2050. The scalability of ammonia production, which is a critical point to sustain shipping, is also analyzed in detail.

Chapter 4 is an overview of the current uses of ammonia across industries, with a focus on agricultural applications (mainly as refrigerant and fertilizer), demonstrating the already ubiquitous use of ammonia across the world and in cross-sectional types of business.

Chapter 5 deals with logistics. Infrastructure for ammonia bunkering is a key prerequisite for enabling ammonia as a marine fuel and is expected to develop from the existing ammonia terminals initially. Chapter 5 shows the actual status of ammonia import/export terminals worldwide and a description of how ammonia is traded, transported and stored today.

The application of ammonia as a marine fuel is described in Chapter 6. After a comparison with other traditional and alternative marine fuels, the status of the technology for bunkering ammonia, handling it onboard and burning it in an internal combustion engine is described, including some considerations on safety, toxicity and emissions.

To conclude, Chapter 7 outlines a pathway for how to approach the transition phase from 2030-2050.

Different propulsion technologies are currently under evaluation for the implementation of the energy transition of the shipping sector. Among these, the marine two-stroke internal combustion diesel engine is the propulsion technology selected for the present study. Thanks to the well-established technology, it can be reasonably assumed that this type of engine which can be adapted for green fuels will continue to have a central role in ship propulsion for decades[5].

The IMO's commitment toward the protection of the environment reflects a new growing consciousness in favor of sustainability and of divergence from fossil energy sources. With increasing research and development on alternative fuels we are entering the energy transition phase, with ammonia playing an important role in this process (already exemplified in the Japanese SIP strategy[6]).

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[5] DNV-GL – "The role of combustion engines in decarbonization – seeking fuel solution"

[6] http://injapan.no/wp-content/uploads/2019/02/3-SIP-Energy-Carriers.pdf

3 Ammonia production

3.1 General properties

Ammonia, or anhydrous ammonia, is a globally traded commodity. Annual global ammonia production is approximately 180 million tons, of which approximately 80% is used for fertilizers. A typical product specification is summarized in Table 1, below. There is always a minimum water content in the range 0.2-0.5 wt % which is required to prevent stress corrosion cracking in the containers.

Ammonia	>99.5 wt%
Water	0.2 - 0.5 wt%
Oil	Max 5ppm
Specific gravity at 16°C	0.62
Density at 16°C	0.62 kg/l

Table 1. Typical commercial grade anhydrous ammonia specification.

The chemical formula for ammonia is NH_3. It is inherently free of carbon. When fully combusted as a fuel, the end products are harmless nitrogen and water. As discussed in chapter 6, standard exhaust treatment technology (SCR) is necessary to achieve this. Ammonia is conventionally produced from natural gas, and by this route CO_2 is a byproduct of the ammonia production. In this chapter we shall also discuss the alternative production route from renewable electricity, air and water which eliminate the CO_2 footprint.

Feedstock availability defines where the ammonia plants are constructed. Natural gas is abundantly available in Russia, the Middle East and North Africa, and that is also where many natural gas-based ammonia plants are located. With shale gas production in US, there is plenty of gas available for new ammonia plants. Even with scarce natural gas resources, India is a country with many ammonia plants, based on the import of LNG to become self-sufficient in fertilizer supply.

Ammonia will probably always be produced where energy is abundantly available and at relatively low costs. With the new energy landscape for renewables, new ammonia plants can be constructed in areas where it was not feasible with fossil feedstock. This means ammonia can be produced in new regions where there are good resources for renewables such as in Australia with solar and wind, and Iceland with geothermal and wind. The capacity factor will play a major role in the overall economics for these green ammonia plants. Some regions will have advantages if the combination of renewables can bring the capacity close to 100%.

Renewable energy as wind and solar power can be harvested by wind turbines and solar panels and in principle in abundant quantities to substitute a significant part of the fossil energy consumed globally. However, the availability of these renewable energies is not there on demand. This is one of the biggest challenges for the substitution of fossil-based energy by renewables, calling for energy storage media.

Ammonia is an excellent hydrogen carrier and energy storage medium. It is easily compressed and stored as a liquid in either atmospheric tanks or pressurized tanks depending on the tank capacity. When stored in large quantity above 10,000 tons, the tank pressure is near atmospheric and refrigerated at -33°C. In quantities between 100-1,000 tons, the tank pressure is few bar and still refrigerated around 0°C. Tank capacities below 100 tons will typically store ammonia at ambient temperature and up to approximately 20bar. Ammonia has been identified as one of the carbon-free fuels that can also be an excellent energy storage medium. Its energy density is 12.7MJ/l.

3.2 Ammonia production from fluctuating renewable resources

The use of electrical energy in water electrolysis to produce hydrogen for the synthesis of ammonia is not a new technology. From the late 1920s until the 1990s ammonia was produced by Norsk Hydro in Norway using alkaline electrolysis and air separation powered by renewable hydropower and the Haber-Bosch process for the ammonia synthesis. While this production method was replaced last century by inexpensive natural gas as the source of hydrogen, the Haber-Bosch process is still the industrially applied process for ammonia synthesis.

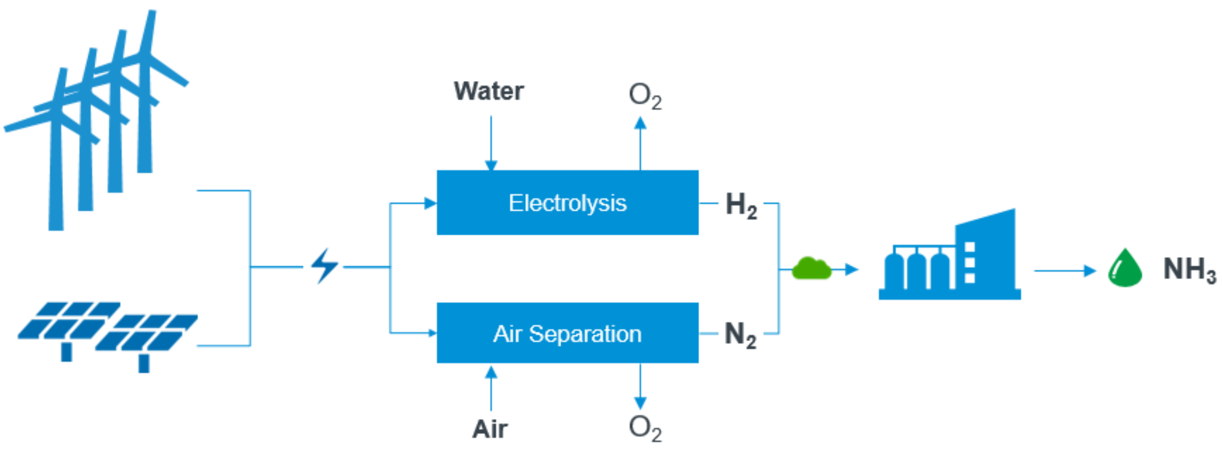

Figure 1. Illustration of a green ammonia (NH_3) plant using only sustainable resources.

Now the focus is to produce ammonia from renewable wind and solar energy, water and air, as shown in Figure 1 above. Does it make sense to reintroduce one of the old production methods? The answer is yes, since the feedstock, atmospheric air, water and renewable energy are all sustainable and abundantly available in many places, and some of the key cost drivers, electrolysis and power generation, have experienced substantial cost reductions recently.

From a risk mitigation standpoint, all the units for the production of sustainable green ammonia production are well-proven. The only and most important difference between earlier green ammonia production and the next wave of green ammonia plants lies in the electricity supply. Earlier it was supplied from a stable power grid, whereas today and in the future, it could be behind the power meter directly coupled to wind and solar power plants.

The main concerns are whether the ammonia plant can handle the fluctuations in renewable electricity supply. The answer from Haldor Topsøe A/S (a leading technology licensor and catalyst supplier within the ammonia industry) is yes. They are ready with design solutions for ammonia synthesis that handle any fluctuation which may arrive from the supply of hydrogen and nitrogen. A rule of thumb is the design will have a turn-down ratio from 10-100% with a constant synthesis pressure without power or hydrogen storage. With such storage a turn-down ratio of 0-100% is feasible.

Multiple electrolyzer technologies can handle fluctuations in electricity supply and, if necessary, could be combined to obtain the highest reliability with a fast response time.

Moreover, Haldor Topsøe A/S has patented solutions based on more efficient solid oxide electrolysis technology (SOEC) that can increase the efficiency of green ammonia production by approximately 30%. The efficiency increase is in part achieved by utilizing waste heat from the ammonia synthesis to produce steam for the high-temperature electrolysis.

3.3 Electricity availability and cost

Over the course of recent decades, wind and solar power generation has rapidly evolved from a costly curiosity into well-established players in the mainstream power market. Traditionally, virtually all electric power generation was generated in large central combustion-based facilities consuming vast amounts of low-cost fossil fuels. Even though fossil fuels are still inexpensive, factors like industrialization, fierce competition and optimization throughout the renewable energy value chain have now driven the cost of renewable power below fossil fuels in most of the power markets[7]. The continuous cost reductions justify considerations of expanding the use of renewable power beyond the traditional power sector through direct and indirect electrification of neighboring energy sectors. Marine fuel is one of the obvious sectors to electrify indirectly via electrolysis and electro-fuels, with ammonia as the primary energy carrier.

With the vast amounts of marine fuel consumed by the world's shipping fleet, a considerable but realistic expansion of the renewable energy generation capacity is required. The current marine fuel consumption is approximately 250 million tons[8]. By 2050 it can be expected that 25-50% of the fuel consumption is replaced by ammonia[2]. As an example, supplying 30% of the current

[7] https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf

[8] https://www.iea.org/reports/tracking-transport-2019/international-shipping

marine fuel consumption as renewable ammonia would require the production of 150 million tons of ammonia, when taking its lower energy density into account. With current, established electrolysis and synthesis technology, the electrical power required would be approximately 10 MWh/tNH_3, so producing the 30% of fuel demand would require 1500 TWh of renewable energy. The energy efficiency of the power-to-ammonia process is expected to increase by up to 20% over the next decade especially due to more efficient electrolysis technologies.

The power production capacity required will be dependent on the choice of technology and the quality of the resource at the site of construction. As the power production will have to be matched by a similar amount of electrolysis and ammonia synthesis, the capacity factor will be important from a financial perspective, as it also defines the utilization factor of the electrolyzers and synthesis plants. Practically, it is expected that many plants will be located either at sites with extraordinarily good wind or solar resources, where the capacity factor of one of the technologies is in the high end of the range, or at sites where the two resources complement each other and enable even higher utilization of the electrolysis and synthesis than each of the technologies could provide alone. The final power production could be achieved by installing, for example, 200 GW of wind power and 200 GW of solar photovoltaics (PV) in sites with good wind and solar resources. They would produce power for a corresponding amount of electrolyzers and ammonia synthesis plants.

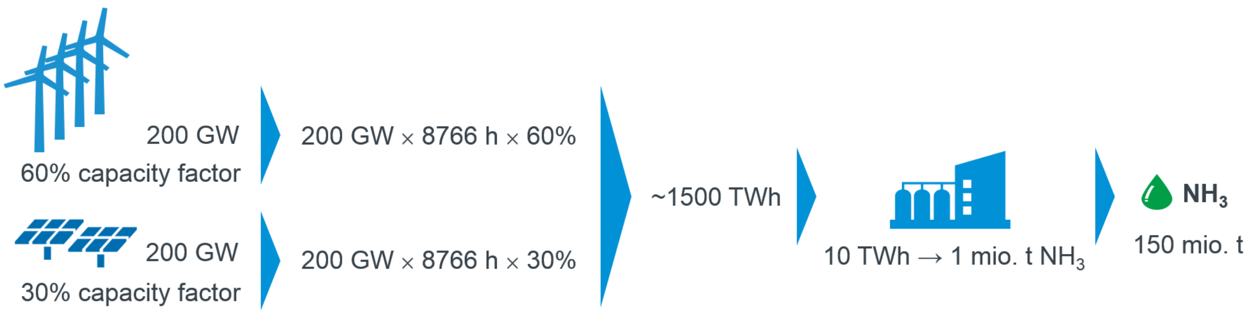

Figure 2. 200 GW of wind and 200 GW of photovoltaics in good sites would be enough to supply 30% of marine fuel consumption.

To put this amount of wind and solar power production into perspective, the current cumulative global installed capacity of wind power is available in Table 2.

	Wind power	Solar PV
Cumulative installed capacity end 2019	650 GW	636 GW
Capacity installed during 2019	60 GW	124 GW

Table 2. Globally installed wind and solar power[9,10].

As is evident from the cumulative and new installations, the installations of renewable power generation are growing strongly, with typical annual growth rates in the 20-30% range over the recent decade to supply power for the traditional electricity sector. From the perspective of the wind and solar OEMs, to add 200 GW of installed capacity for fuel production in the years between 2020 and 2040 would be a very manageable task.

Beyond the technical feasibility of producing renewable energy production assets, another key requirement is the availability of land and sea areas with good wind and solar resources. On a good wind site, 1 GW of wind turbines would take up approximately 100 km^2 and a corresponding 1 GW PV plant would cover approximately 20 km^2, which could be located between the wind turbines in hybrid power plants. Figure 3 and Figure 4 have sketches of what area would be required for 1500 TWh and hence 30% of global marine fuel consumption.

Figure 3. Wind power in one of the boxed areas would alone be able to supply 30% of global marine fuel consumption.

9 https://wwindea.org/blog/2020/04/16/world-wind-capacity-at-650-gw/

10 https://www.businesswire.com/news/home/20200107005144/en/

The actual roll-out of renewable ammonia production can take many forms. The initial projects will most likely be grid-connected in established power grids with available hydropower and new PV and/or wind power. The hydropower will ensure a steady baseload and continuous operation of the ammonia plant, which ensure high utilization of the electrolysis and ammonia plants. As the technology matures and plant costs decrease, the utilization[11] of new plants can decrease while still maintaining competitiveness. As utilization is allowed to decrease, the optimal sites and mix of power generation technology will evolve. The nature of ammonia, requiring only air, water and power to produce ensures fewest possible constraints on the sites for the plants. Thereby the power production cost, and ultimately the fuel cost, becomes a pure resource game. Project developers can screen the globe for superior resources independent of the constraints they have been subject to when developing projects for supplying power to the traditional power market, like grid availability and proximity to consumption centers.

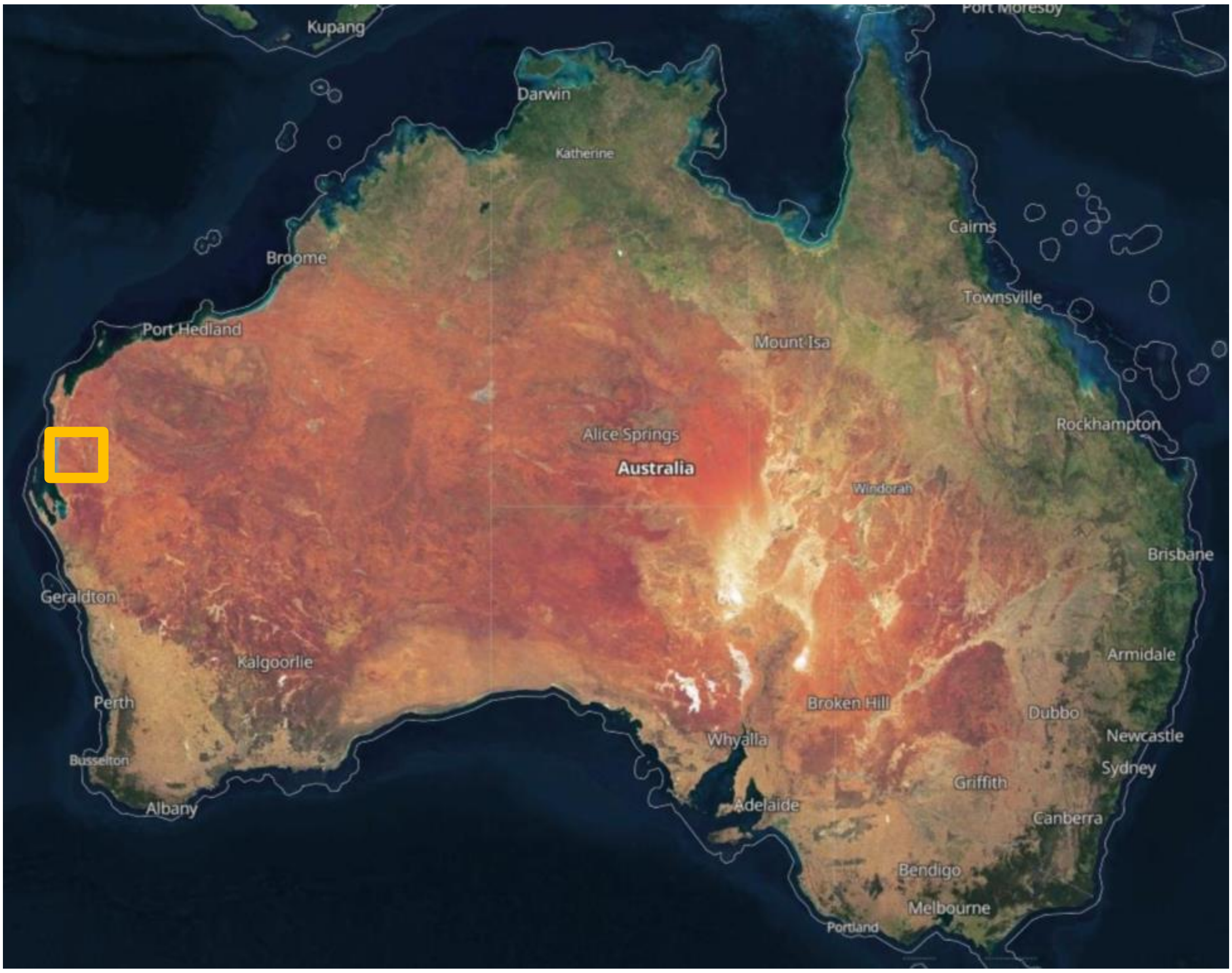

Figure 4. Vast areas of Australia have excellent, complementary wind and solar resources. The boxed area alone would be enough to supply 30% of the world marine fuel.

[11] The so-called capacity factor or the average load factor.

Power input constitutes the majority of the running costs of a renewable ammonia plant. The cost of power from a renewable power plant associated with the ammonia plant is defined by several factors, with resource quality, cost of finance and choice of technology being the most important. As stated above, world-class resources can be selected when ammonia production does not have to be restricted by grid availability. Technology can also, to some extent, enable decreasing costs of finance as the plant concepts and manufacturers are further proven. But the most significant lever for financing is certainty on the off-take and income side of the plant business case. If that is established, the economies of scale and larger site availability will enable the mix of power generation technologies required for acceptable capacity factors to provide power in the cost range of 25-35 €/MWh (6.9-9.7 €/GJ) by 2030 and 10-30 €/MWh (2.8-8.3 €/GJ) by 2040.[12]

3.4 Water electrolysis

The increasing trend to replace fossil fuels as a source of energy, fuels and chemicals and the continuous lowering of the cost of renewable electricity is again driving a general interest in conversion of electricity via water electrolysis to produce hydrogen. The open literature offers numerous studies comparing technologies for water electrolysis[13,14,15]. In general, three technologies are highlighted as the most promising currently or in the future: Alkaline Electrolysis (AE), Proton Exchange Membrane Electrolysis (PEM) and Solid Oxide Electrolysis Cells (SOEC). Being the mature technology with several >100MW plants in operation last century, Alkaline Electrolysis (AE) is again being scaled up. To our knowledge, the largest AE plant currently in operation is a 25 MW, 5500Nm3/h hydrogen plant in Malaysia delivered by NEL hydrogen[16], but new large projects are emerging rapidly.

PEM electrolyzers were introduced in the 1960s by General Electric and are based on a polymer membrane electrolyte and precious metal electrodes, avoiding the recovery and recycling of the potassium hydroxide solution necessary in AE. Compared to AE, PEM achieves better current densities allowing for significantly more compact water electrolysis units. PEM advantages also include a very fast response time of milliseconds and a dynamic load range of zero to above 100% of capacity. Disadvantages are mainly production costs due to the precious metals and lower energy efficiencies. PEM is currently undergoing rapid commercialization for various applications among other local hydrogen production at fuel cell vehicle refueling stations.

SOEC is the least developed of the three electrolysis technologies and has not yet been scaled up or commercialized. SOECs operate at high temperatures of typically 700-800°C and because of

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12 The International Energy Agency: Offshore Wind Outlook 2019, 2019, p. 26 & 42; The Global Wind Energy Council: Global Wind Report 2019, p. 32; Hydrogen Council: Path to Hydrogen Competitiveness, 2020; and internal projections.

13 "The Future of Hydrogen", Report prepared by the IEA for the G20, Japan, June 2019.

14 "Hydrogen from renewable power, technology outlook for the energy transition", IRENA, September 2018.

15 "Future cost and performance of water electrolysis: An expert elicitation study", International Journal of Hydrogen Energy 42 (2017) 30470-30492, O. Schmidt et.al.

16 https://nelhydrogen.com/; http://www.h2forum.kr/upload/speaker/pdf/kor/2-3.pdf

that have an inherent energy efficiency advantage compared with the low temperature AE and PEM technologies. Part of the energy needed for the hydrogen production can be supplied as high temperature heat, and hence when integrated with a heat generating chemical reaction such as ammonia synthesis, the overall energy efficiency becomes particularly attractive. Furthermore, no precious metals are needed for the SOEC, and the future cost potential is attractive and in general comparable with AE.

It is of key importance how the electrolyzer cost and energy efficiencies will develop in the future. NEL has announced to be able to reach 420USD/kW with ongoing production expansion and ~320USD/kW in future large-scale plants[17]. These numbers are used when estimating future prices for green ammonia in 2025-2030 and 2040, respectively. More ambitious cost estimates predict levels as low as 100-150USD/kW[18], making future green ammonia cost levels realistic if not conservative. The alkaline electrolysis system energy efficiency[19] at full load is currently ~63% based on LHV and expected to increase to >65% in the future. More ambitious AE efficiency estimates predict efficiencies >70% in the long term. PEM electrolysis is expected to stay somewhat more expensive due to the precious metal content. Yet it will reach similar energy efficiencies and continue to be the technology with the best potential for following fast electrical load changes. SOECs are expected to achieve similar cost levels as the alkaline electrolysis and maintain the energy efficiency advantage being able to reach 90% overall energy efficiency when integrated with the ammonia synthesis, indicating that SOEC will be the long-term technology winner.

3.5 Production of ammonia, green versus conventional ammonia

While green and conventional ammonia carry very different carbon dioxide footprints, the physical product is in the end the same. Using ammonia as a marine fuel can from an operational point of view equally well be conventional or green ammonia, or any mix of the two. This fact significantly lowers any risk related to investing in a ship operating on ammonia as fuel, since conventional ammonia is a commercial commodity traded in very large quantities. A shipowner can start using conventional ammonia and going forward the percentage of blending in green ammonia can gradually increase as governed by economics, legislation, requirements as well as the need or desire to contribute with increasingly sustainable and carbon neutral shipping.

Ammonia does not contain carbon, and no CO2 will be emitted from a ship when fueled by ammonia – whether conventional or green. The CO2 footprint related to ammonia fuel all originates from the production of ammonia and its transportation to the bunkering site. In fact, the shipowner or operator can use any of the below types of ammonia, physically equal but of different manufacturing origin and hence CO2 footprint. We use the following nomenclature:

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[17] https://nelhydrogen.com/wp-content/uploads/2020/02/Company-presentation-2020.pdf; https://www.ammoniaenergy.org/articles/yara-and-nel-collaborate-to-reduce-electrolyzer-costs-announce-green-ammonia-pilot-in-norway-by-2022/

[18] https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

[19] Based on Hydrogen LHV

Conventional ammonia is conventionally produced from fossil feedstock, most often from natural gas but can also be from coal. The CO2 footprint depends on plant efficiency and feedstock. While modern highly efficient ammonia plants may have a footprint as low as 1.6 tons of CO2 per ton of ammonia, existing plants are typically close to 2 tons of CO2 per ton of ammonia, and for coal-based plants it can be up to 3 tons of CO2 per ton of ammonia.

Blue ammonia is basically produced in the same way as conventional ammonia except that the CO2 from the production is captured, liquified and transported to permanent storage, called CCS, carbon capture and storage.

Green ammonia – or renewable/sustainable ammonia - is produced without fossil feedstocks but entirely from renewable electricity, air and water. The CO2 footprint of green ammonia is assumed to be zero, ignoring full lifecycle analysis which should include plant construction and transport to the bunkering site. Initial estimates of the life-cycle emission reduction for green ammonia is >90% for wind power-based ammonia and >75% for photovoltaic based ammonia. The reduction will increase over time, as the life cycle emissions from renewables decreases with the further application of renewable energy in the production of wind turbines and photovoltaics.

Hybrid green ammonia is ammonia produced in hybrid plants which are partially fueled by fossil fuel and partially by renewable electricity. Such a plant can potentially be a new-build hybrid plant or a revamp of an existing conventional plant. The latter is interesting since it represents an economically feasible transition to green ammonia production. We assume that hybrid plants can be certified to produce partly conventional ammonia with conventional CO2 footprint, and partly a fraction of certified green ammonia with zero CO2 footprint.

In the following sections we will estimate future market prices of these different classes of ammonia. Our conclusions for the cost of ammonia going forward is summarized in Table 3. Ammonia has about 46% of the energy per weight of low sulfur fuel oil, and the ammonia prices are provided per ton of ammonia as well as per energy content (GJ lower heating value, LHV).

	2025-2030		**2040-2050**	
Assumed renewable electricity price	30EUR/MWh		20EUR/MWh	
	Price Per ton USD/MT	Price per GJ LHV USD/GJ	Price Per ton USD/MT	Price per GJ LHV USD/GJ
VLSFO (<0.5%S)	500-600**	12.5-15	500-600**	12.5-15

Conventional ammonia	250**	13.5	250**	13.5
Blue ammonia	350-400	18.8-21.5	350-400	18.8-21.5
Green ammonia	400-850*	21.5-45.7	275-450	14.8-24.1
Hybrid Green ammonia	300-400***	16.1-21.5	250	13.5

Table 3. Summary of the market prices estimated in this report for the different classes of ammonia. *650-850 in ~2025, 400-600 in ~2030. **We have not attempted to predict the evolution of fossil fuels or natural gas and simply assume the cost levels from primo 2020. Particularly VLSFO cost is volatile. * Existing plants revamped with additional green capacity fed by renewable energy.**

3.5.1 Cost of conventional ammonia

The annual global ammonia production is approximately 180 million tons, of which approximately 80% is used for fertilizers. China is by far the biggest ammonia producer, with India and Russia as number two and three. Ammonia is produced in more than 50 countries[20]. The ammonia plant size ranges from very small electrolysis-based plants of approximately 20 MTPD [21] to 3500 MTPD large scale fossil-based plants. Typical sizes of conventional plants are in the range from 1000 MTPD to 2400 MTPD.

Here, the conventional ammonia cost is estimated as:

- Fixed operating costs including storage costs,
- Cost of energy,
- Potential CO2 emission penalty cost.

The CAPEX cost for conventional ammonia will to a start be considered a sunk cost. The reason for this is that there is a global surplus capacity for ammonia production. Plants located in areas of high natural gas cost can as the market is today not expect to create a return on the investment.

The fixed operating cost is typically in the range of 40-70 USD/MT including storage costs but may vary greatly depending on plant size and geographical location and will be higher for small plants or plants in high cost areas.

The cost of energy is the biggest contributor to the production cost, typically 75-85%. The specific energy consumption for a modern stand-alone ammonia plant including utilities and off-site is approximately 8.4 MWh/MT (28.6 MM BTU/MT) giving an energy cost in the range 70 – 200

[20] IndexMundi.com

[21] MTPD: Metric tons per day.

USD/MT for natural gas prices of 2.5 - 7.0 USD/MM BTU. Existing ammonia plants may have more than 20% higher energy consumption.

A future CO2 emission penalty cost in some form in the range of 25-75USD/T CO2 seems very realistic[22] and is considered here. Considering a typical plant producing 2 tons CO2 / tons NH3, the anticipated CO2 penalty cost is in the range of 50–150USD / MT NH3.

The estimated conventional ammonia production cost is then shown as a function of the natural gas cost in Figure 5 below, together with a market price of 250 USD/MT which corresponds to the average over the past few years.

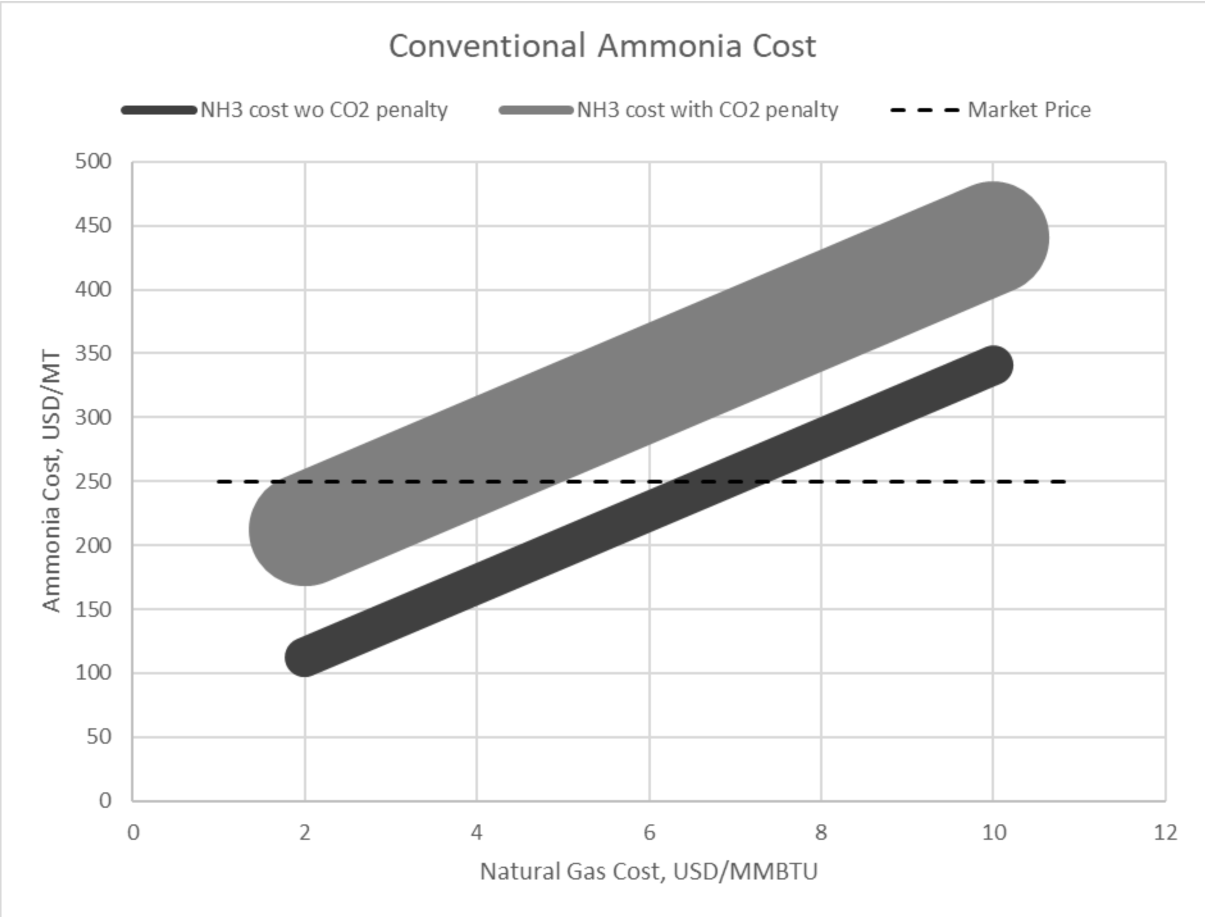

Figure 5. Estimated production cost and market price of conventional ammonia (definition see text).

[22] "Carbon pricing watch 2017" (http://documents.worldbank.org/curated/en/699641497346643090/pdf/116068-WP-wb-cpw-170609-screen-PUBLIC.pdf); "European producers must adapt to high ETS prices as a new normal" https://www.crugroup.com/knowledge-and-insights/spotlights/2019/european-producers-must-adapt-to-high-ets-prices-as-a-new-normal/

Figure 6 below shows the price development of conventional ammonia since 2001. The average market price of ammonia over the past few years is approximately 250 USD/MT. With this market price, it can be very challenging for ammonia producers having a high natural gas price and thus a high production cost.

However, the conclusion here is that even with anticipated increasing CO2 penalty cost, we can still expect a market price of 250 USD/MT going forward, as production will slowly shift to locations with low natural gas cost where new installations can be profitable and create an appropriate return on investment.

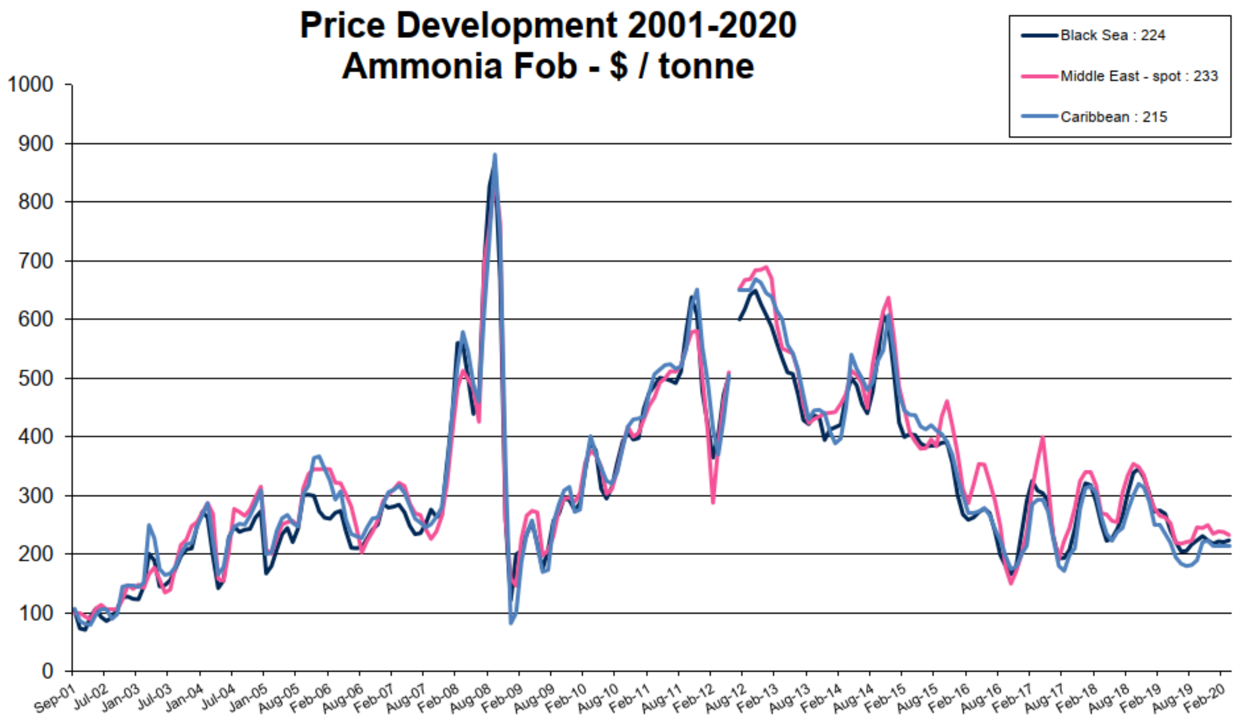

Figure 6. Ammonia price development. (Source: CRU - Fertilizer week)

3.5.2 Cost of blue ammonia

Here, blue ammonia cost is estimated as:

- Cost of conventional ammonia without CO2 penalty,
- Cost of CO2 capture from flue gasses (0.8 T_{CO2}/T_{NH3}),
- Cost of CO2 liquefaction, short-term storage, transport and long-term storage (2 T_{CO2}/T_{NH3}).

For a natural gas-based ammonia plant, the CO2 production and emissions from the ammonia production is the sum of two contributions: 1) Approximately 1.2 ton of CO2 per ton of NH3 (T_{CO2}/T_{NH3}) is typically obtained as a pure CO2 stream originating from the separation process of the ammonia synthesis feed and 2) between ~0.4 to >1 T_{CO2}/T_{NH3} is emitted in low concentrations in the flue gas from heat-generating combustion processes. Here we assume 1.2 T_{CO2}/T_{NH3} of pure CO2and 0.8 T_{CO2}/T_{NH3} in the flue gas.

The total cost (CAPEX and OPEX) of Carbon Capture of the 0.8 T_{CO2}/T_{NH3} from the flue gas is estimated to be ~60 USD/T_{CO2}, which then amounts to ~50USD/T_{NH3}.

The remaining cost of CO2 liquefaction, transport and storage can be in the 25-50 USD/T_{CO2} range for all 2 T_{CO2}/T_{NH3}, in other words, 50-100 USD/T_{NH3}. As a consequence, the total cost of eliminating CO2 emissions from an NH3 plant is estimated to be in the range 100-150 USD/T_{NH3}, for plants which in the future will offer blue ammonia to the market.

Today's conventional ammonia market price is determined by the production cost in locations with a natural gas cost of 6-7 USD/MMBTU. It can be expected that the same market mechanism will hold true for blue ammonia. The expected market price for blue ammonia is then 350-400 USD/MT, which is the market price of conventional ammonia plus the additional cost of carbon capture, liquefaction and storage. This is illustrated in Figure 7 below.

When looking into the future, a learning curve effect could be expected for the CO2 capture part, whereas this is limited for the other parts, and the cost of long-term CO2 storage could actually increase. Hence, we assume the same blue ammonia market price in the near and long term.

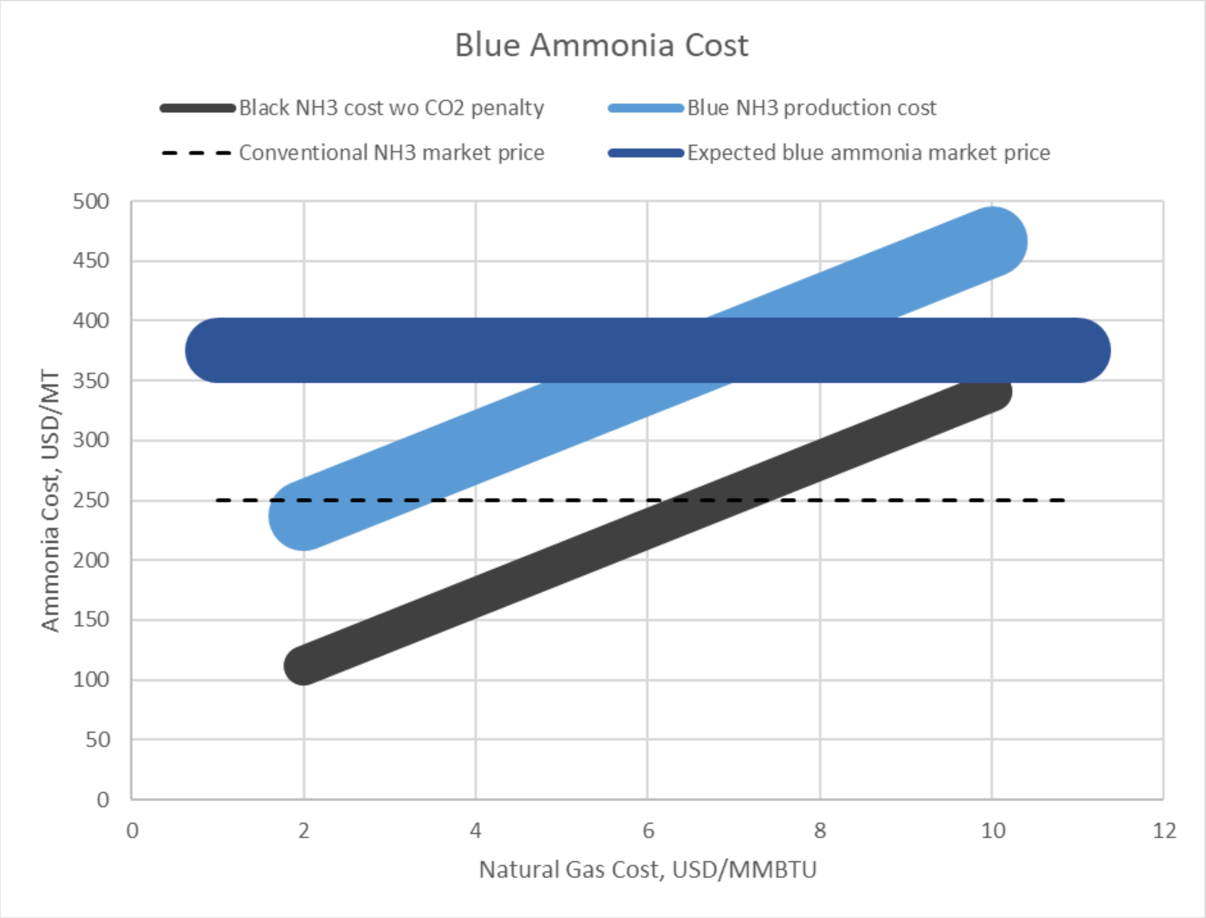

Figure 7. Estimated production cost and market price of conventional and blue ammonia (definition see text).

3.5.3 Cost of green ammonia

Here, the green ammonia cost is estimated as:

- Cost of capital investment,
- Fixed operating costs including staff, overhead, maintenance, insurance and storage,
- Cost of energy.

We have studied the expected production cost of green ammonia and assumed a process consisting of water electrolysis, electrically driven air separation and traditional Haber-Bosch synthesis. The plant uptime is assumed to be 96% and with a capacity factor of 85% corresponding to 7150 full load hours per year. While the core of the electrolysis unit – the stack – will scale almost linearly with plant size, other installations costs in numbers relative to the production will drop with increasing plant size. Considering both Alkaline, PEM and SOEC electrolysis, we estimate the total sum of capital investment cost and fixed operating costs to be in the range of 375-475USD/MT for a 100 MW size plant and ~190 USD/MT for a 1 GW sized plant, both numbers valid for a 2025-

2030 time scale. If we look into the future, we expect the learning curve to take this cost towards the 150-190 USD/MT range from 2040.

Depending on the choice of electrolyzer technology, the total energy consumption will be either 10-10.5 MWh/MT for alkaline or PEM technologies or as low as 7.6-7.8 MWh/MT for SOEC independent of scale.

The expected break-even sales price for green ammonia is then shown in Figure 8 below. A realistic estimate for renewable electricity will be 30 EUR/MWh in a 2025-2030 time-scale. If we look into the future, we expect the learning curve to take this cost towards 20 MWh/MT in 2040 or earlier.

Summing up, we expect smaller plants appearing from 2025 to result in a green ammonia cost in the 650-850 USD/MT range. In 2030 we expect larger plants to appear and the green ammonia cost will drop towards 400-600 USD/MT, and by 2040 we expect the learning curve brings the cost to a 275-450 USD/MT level.

These price projections of green ammonia may not have fully considered the advances in both renewable electricity and electrolyzer costs. Recent BloombergNEF reports have indicated electrolyzer costs of 100-150USD/kW and solar and wind price projections have continually underestimated actual development in price reductions, green ammonia’s cost trajectory could see significant decreases, making the green ammonia price estimates presented here conservatively high.[18]

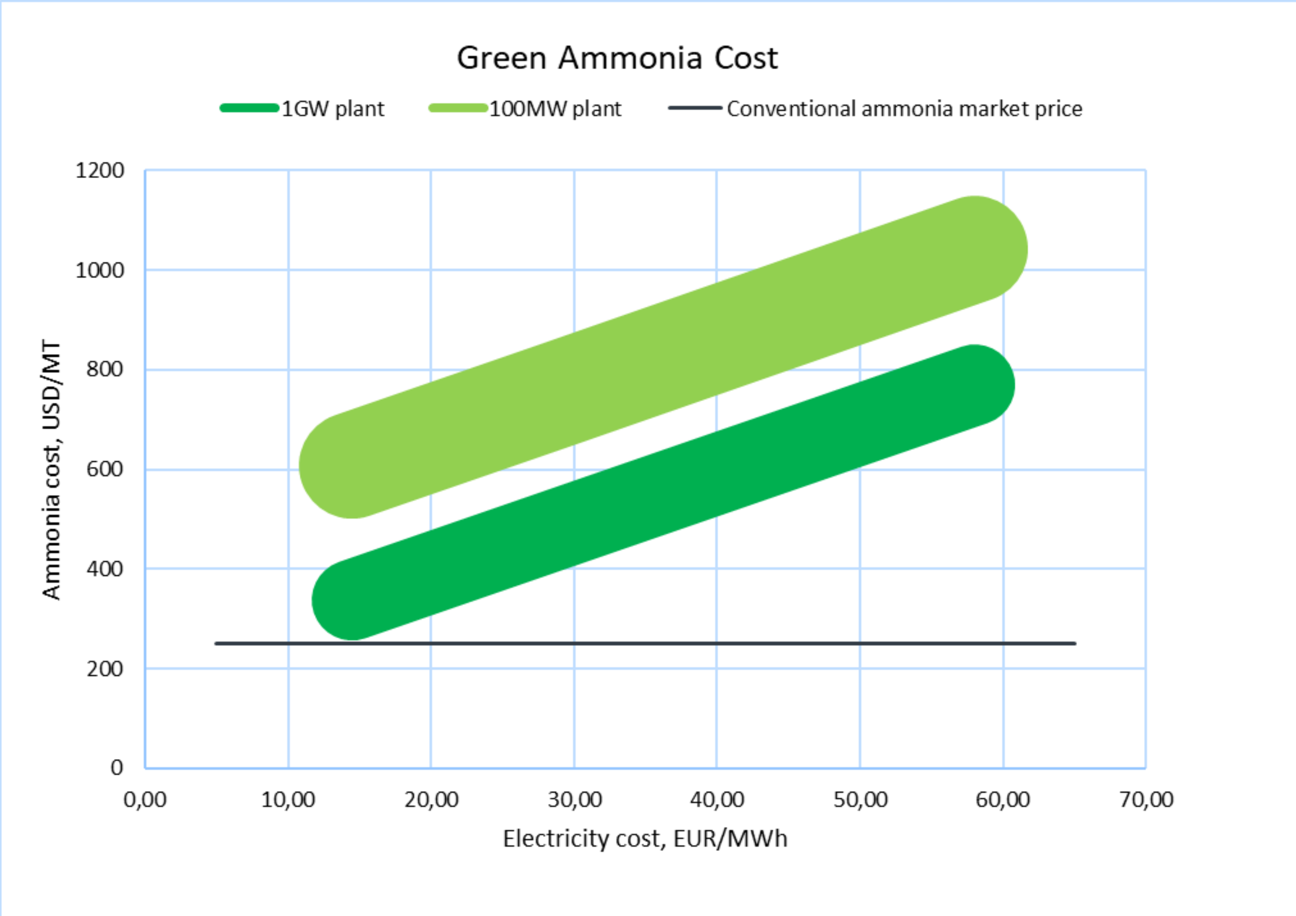

Figure 8 Estimated production cost of green ammonia (definition see text).

3.5.4 Cost of hybrid green ammonia

It is very interesting to consider revamping existing natural gas-based ammonia plants since, as we shall see here, it constitutes a very promising and economically feasible early supply to a green ammonia market. In a hybrid revamp, the existing ammonia synthesis plant is used, and an electrolysis front end is added in parallel with the natural gas front end.

The green ammonia cost based on revamping existing plants is estimated as the cost of conventional ammonia plus the change in cost due to the revamp:

The change in cost due to the revamp has these contributions:

- The additional revamp CAPEX and fixed operating costs,
- The additional cost of electricity,
- Minus the cost of saved natural gas,
- Minus the saved CO2 penalty.

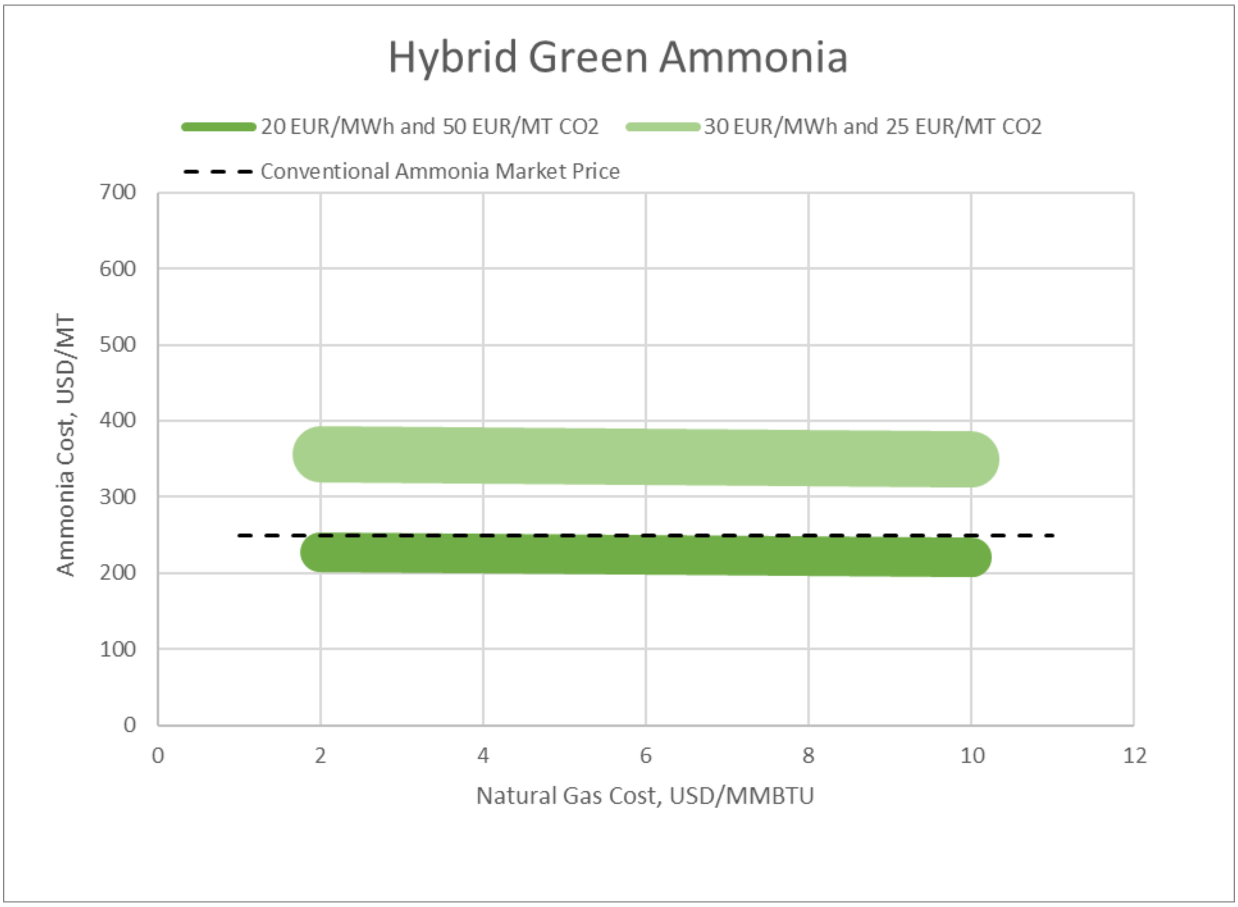

Figure 9. Examples of hybrid green ammonia break-even prices.

In the revamp scenario considered here, the only cost significant plant modification is the electrolyzer installation. The plant ammonia production is kept unchanged, but 10% of the hydrogen feed to the synthesis is produced by the electrolyzer. The existing synthesis gas front-end operation is optimized to this new operating point.

For a 10% hydrogen revamp of a natural gas-based ammonia plant, the front-end can be optimized to save 13-16% of the total consumed natural gas. The relative amount of green ammonia is identified as the relative total (feed and fuel) natural gas savings which is the same as the relative total CO2 savings. Hence, if a 1000 MTPD ammonia plant is revamped with 10% green hydrogen, 130-160 MTPD of green ammonia is produced and the remaining 840-870 MTPD of ammonia will have identical production cost and identical CO2 footprint per ton. The entire CO2 savings and the additional production cost are associated with the proportion of green ammonia.

The revamp option is lucrative because it benefits from existing ammonia plant scale and assets with all process equipment and off sites and utilities. The additional total sum of capital expenditure and fixed operating costs for the revamp is estimated to be in the range of 80-130 USD/MT. Due to the integration in the existing plant operation, the specific additional electricity consumption can be as low as 6-9 MWh/MT of green ammonia produced. The natural gas savings equals the reduction in conventional ammonia produced, and the breakeven green ammonia sales price becomes almost independent of the natural gas price the plant experiences. Examples of the breakeven price are shown in Figure 9 below. Between 2025-2030 we expect green ammonia to be offered to the market from revamped existing ammonia plants at a price of 300-400 USD/MT. From 2040 we expect this level to drop to the present market price of conventional ammonia, i.e. 250 USD/MT. Going forward we may also see greenfield hybrid green ammonia plants built.

3.6 Mapping existing ammonia production

As seen in Figure 10, the world production of ammonia tracks the increase in world population since most of the ammonia production is used for fertilizer production. Global ammonia production today is approximately 180 million tons, with 120 million tons of that production coming online in the past 50 years. Technologically speaking, production could have grown faster, but the growth followed the market demand.

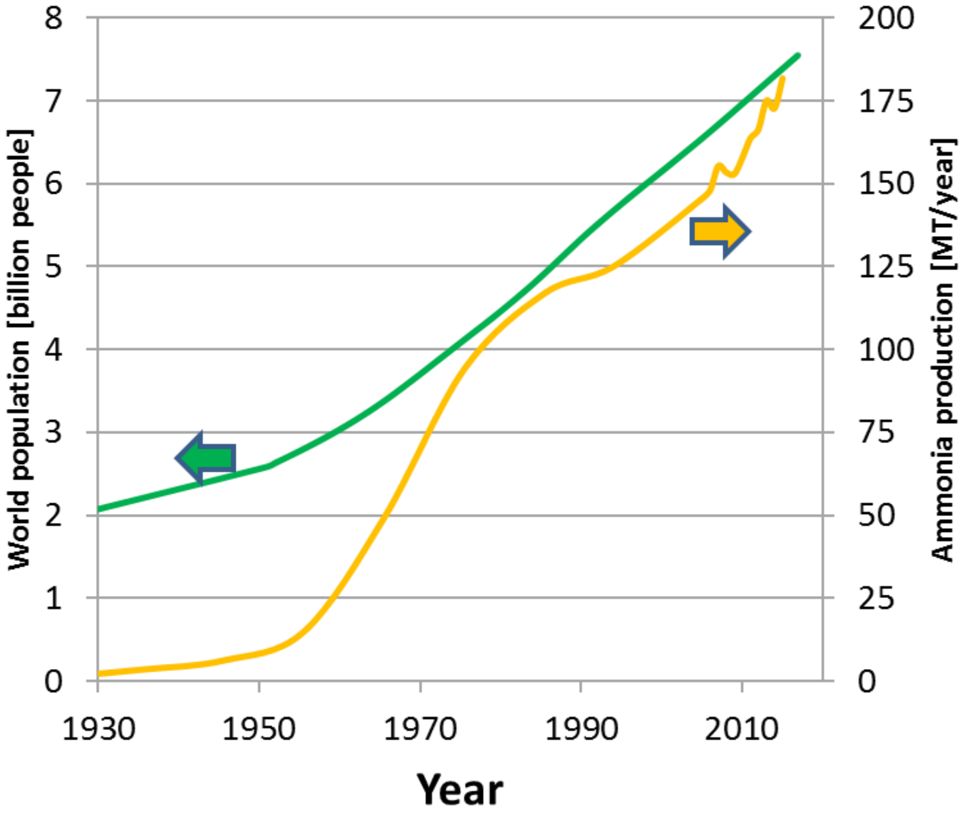

Figure 10. Development in world population (green, left axis) and ammonia production (yellow, right axis).

How much production capacity is installed worldwide? Table 4 below lists the available production capacitiy by region. With today's ammonia production of 180 million tons out of 243 million tons available capacity, only approximately 75% capacity is used. Since many of the ammonia plants are vintage plants one would expect a capacity factor of 90% should be viable, corresponding to 220 million tons produced and an additional available production capacity of 40 million tons.

Region	**2018/19**
	(1000 metric tons Ammonia)
North America	19.477
Latin America	13.644
Western Europe	12.214
Central Europe	8.341
Eurasia	31.033
Africa	12.828
West Asia	22.247
South Asia	22.426
East Asia	98.819
Oceania	2.259
World Total	**243.288**

Table 4. World ammonia production capacity by region. (IFDC – FSR-10, June 2016)

3.7 Scaling up the production for shipping

In order to supply 30% of the current marine fuel consumption, an additional 150 million tons of ammonia production is required on top of today's production of 180 million tons, which results in a future total production requirement of 330 million tons per year. As mentioned, scaling up the last 120 million tons took 50 years. In principle, the additional 150 million tons should be realized in 30 years. This extra capacity could be achieved by revamping existing plants together with new plants.

An additional 25% ammonia synthesis capacity can easily be obtained through revamping existing ammonia plants with available compressor and reactor technologies. This would provide an extra 25% on top of the available 220 million tons capacity, resulting in a total global capacity of 275 million tons. New ammonia plants would then need to provide an additional 55 million tons to meet the figure of 330 million tons required for existing global demand plus the marine fuel industry.

It is expected that the majority of the additional capacity by revamp and new plants will be based on sustainable hydrogen production from renewable energy and electrolyzers. Revamp into hybrid plants can come in steps starting from a few percent and gradually increase to approximately 10% with only minor modifications. Going above 10% green will then require modifications in the ammonia plant heat integration, which will require more investment.

New plants can be constructed as hybrid ammonia plants (up to 25% green ammonia) with capacities more than double a conventional plant today. New plants can also be 100% green ammonia. Some of the ammonia plants selected for hybrid revamp could be plants located in areas with high penetration of renewable power production. In power grids with high renewable penetration, the plant could be producing green ammonia in periods of high wind and solar production with low traditional power demand, as the power prices will be lower during those hours.

Are there bottlenecks for scaling up green ammonia production in hybrid plants or 100% green ammonia plants? The bottleneck identified is the production capacity for electrolyzers, which is currently at a relatively low level since the demand is correspondingly low. Therefore it makes sense to begin the journey for green ammonia production by revamping existing ammonia plants into hybrid plants by introducing an electrolyzer and gradually adding more. This should stimulate the demand for electrolyzers. There is no reason to believe that the production capacities for electrolyzers cannot be scaled up since the most cited technology is well-proven over decades and requires no scarce materials. In fact, this scale-up is already happening as electrolyzer suppliers are investing heavily to increase capacity.

The first 100% green ammonia plants will also depend on the electrolyzer supply and will probably start at a so-called commercial scale of approximately 100 MW. By the time these green ammonia plants will reach a conventional standard size or bigger.

In conclusion, the additional 150 million tons of annual ammonia production over 30 years is a very achievable growth rate, even if shipping uptake is higher than the 30% of global marine fuel consumption projected by 2050.

3.8 Vision and roadmap for making green ammonia

The road map for moving from conventional ammonia plants to 100% green ammonia plants is technically feasible. Technically, and especially commercially, the path towards green ammonia production should occur via revamping existing ammonia plants into hybrid plants. Figure 11 shows one projection for how the additional ammonia capacity of 150 million tons for the maritime sector can be achieved by using existing non-utilized capacity, by revamping with hybrid solutions, and new hybrid plants and by new green ammonia plants. The contribution from hybrid covers both revamp and new plants. No additional consumption is factored in from the existing ammonia market.

Green ammonia is currently commercially challenged when compared to conventional ammonia. By first scaling up green ammonia production via a hybrid ammonia plant, the lowest possible cost of green ammonia will be achieved. Once the green ammonia production has started in hybrid plants and the market grows, the new green ammonia plant will follow. These new green ammonia plants will be built at places where renewable energy can be produced at low cost and with a high capacity factor. Table 5 below shows how this may happen.

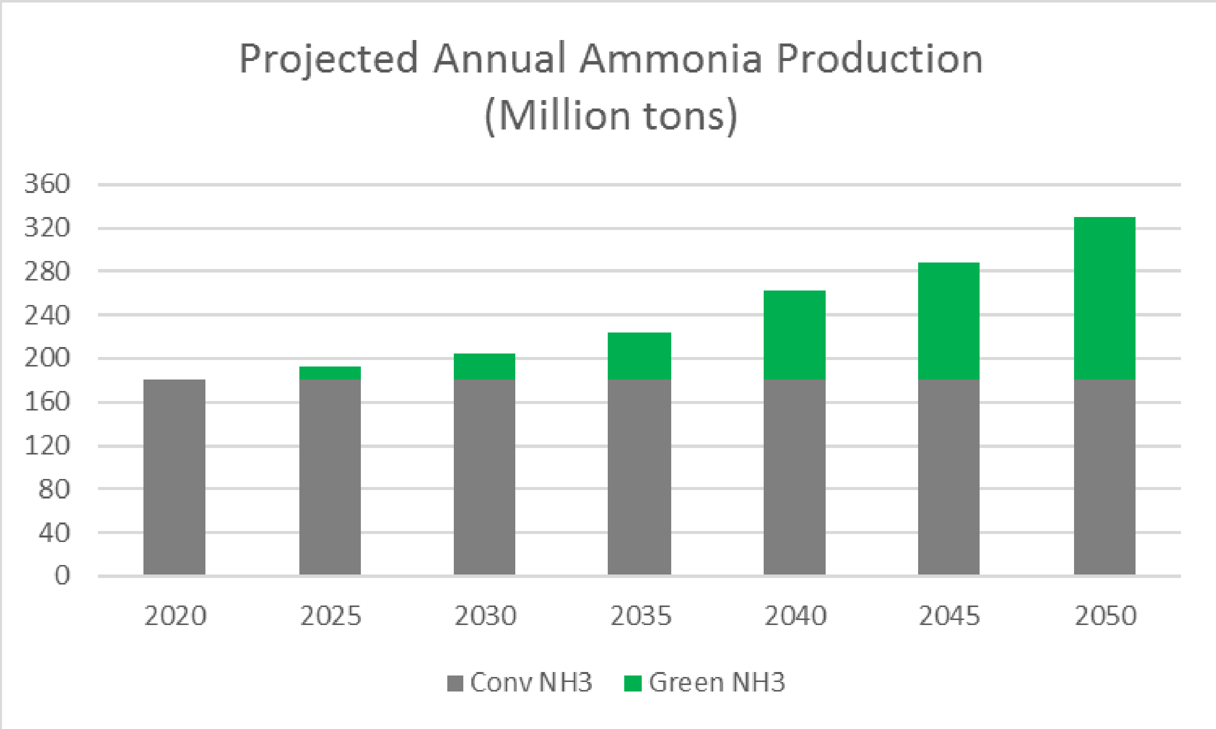

Figure 11. One projection for reaching additional ammonia capacity of 150 million tons per year. Conventional ammonia production is here assumed constant, while it is actually expected to increase.

Initial phase 2020-2030	Scale-up phase 2025-2035	Green commercial phase 2035-2050
• Conventional ammonia amply available worldwide for ammonia fueled ships • Allows competitive solution to meet sulfur requirements in shipping • No CO2 emission from the ship due to ammonia driven propulsion • Certified blue ammonia (central carbon capture) and hybrid revamp green ammonia (renewable energy) increasingly available at moderately higher cost	• Continued growth of certified blue ammonia and hybrid revamp green ammonia • First dedicated green ammonia plants followed by initial scale up in size and number of plants • Learning curve for electrolysis, green ammonia and power-to-X technologies in general drives down cost of green ammonia • Lowering life-cycle CO2 emissions from shipping with increasing percentage of green ammonia	• Emerging and later multiplication of large scale green ammonia plants in regions of low cost and high capacity factor renewable energy • >150 million tons / year of green ammonia available for the shipping industry • Green ammonia contributes 30% or more to total shipping fuel need towards the end of the period enabling fulfillment of IMO GHG emission goals

Table 5. Vision for the scaling up of zero-carbon footprint ammonia and impact on the GHG emissions from the shipping industry.

3.9 Certified green ammonia

As mentioned, green and conventional ammonia is the same physical product and will obey the same commercial specification worldwide. This greatly simplifies fuel logistics compared to conventional marine fuels. The only operational difference between operating on green versus conventional ammonia is the additional purchase of a green ammonia certificate.

Certified sustainability is today primarily prevalent in the electricity market but is emerging in many other areas as well. In general, electricity from wind turbines or solar PVs is fed into the electricity pool formed by the grid, where it is mixed with any other availably source of electrical energy. The additional value that the sustainable electricity may have for the electricity consumer is paid for by trading a renewable energy certificate.

Renewable Energy Certificates (RECs) are a market-based instrument certifying that the bearer owns one megawatt-hour (MWh) of electricity generated from a renewable energy resource. Once the power provider has fed the energy into the grid, the REC received can then be sold on the open market as an energy commodity. The physical electrical energy and the REC are separated and can be traded independently. However, RECs can go by many names, including Green Tag, Tradable Renewable Certificates (TRCs), Renewable Electricity Certificates, or Renewable Energy Credits.

As an example, bio-methanol can receive the International Sustainability and Carbon Certification (ISCC), which is a widely used and recognized establishment of an internationally oriented, practical and transparent system for the certification of sustainable biomass and bioenergy. Bio-methanol can be produced from industrial bio-based residues and biogas and is physically identical to conventional methanol but because of the bio-based origin has well-to-wheel CO2 emissions which are reduced by up to 90%. The bio-methanol producer can sell the physical methanol at the conventional market price to any trader of conventional methanol and deliver it to the closest methanol trading facility. In addition to this they can sell the ISCC certificate to the methanol consumer who can then claim to be a sustainable methanol consumer while receiving his physical methanol from any local supplier of conventional methanol.

This widely accepted trading mechanism not only favours the development and scaling up of renewable energy, fuels and chemicals, it also circumvents meaningless global transport of such fuels, which carries the sustainable low CO2 footprint but is otherwise identical to the conventionally produced product.

In the future, similar trading of green ammonia certificates is expected. Green ammonia will be produced worldwide in locations suitable for the purpose and supplied locally to the existing ammonia infrastructure in the form of ammonia terminals with significant ammonia storage and transport facilities. Sustainable and conventional ammonia are physically identical and will be mixed. At the same time the green ammonia producer will sell a green ammonia certificate to the consumer such as a shipping company operating ammonia driven ships which will bunker at any of the globally widespread ports hosting ammonia terminals. The additional cost of the zero CO2 footprint ammonia will be subject to a market economy based on supply and demand, and the additional production cost is estimated in the sections above.

4 Ammonia in other industries

Ammonia is a widely used commodity that is traded and handled on a global scale. Ammonia is primarily utilized as a fertilizer in agriculture and as a refrigerant and is therefore today being handled in populated areas. Ammonia is however a toxic chemical and should be handled with care. Historically, fatal accidents involving ammonia leakage have happened. It is therefore important that safety aspects are addressed thoroughly when considering ammonia as a marine fuel.

As a substantial amount of ammonia is handled around the world, safety regulations are already in place for the use and transport of ammonia in other sectors. The shipping industry must examine how safety is addressed in other industries with large amounts of anhydrous liquid ammonia and based on this learning incorporate these measures in the early design phases of ammonia fueled ships.

Ammonia is either stored in pressurized vessels at up to 20 bar and ambient temperature or in liquid form at -33°C and atmospheric pressure. The safety risk of ammonia is mainly for pressurized storage, if leaks occur and a dangerous air concentration arises. Ammonia has a characteristic odor and is therefore easily detectable, which enables workers to get away from the leak and take appropriate actions. Ammonia is detectable at 5-50 ppm, but exposure to 700 ppm for less than one hour, does not cause major injuries.[23] This has been ammonia's biggest safety advantage. However, we do not have to rely on human detection of ammonia odors. Automated ammonia gas detection at ppm level and automated responses such as alarms, increased ventilation, line shut down etc. are standard commercial technologies allowing safe operation of ammonia handling systems.

The safety regulations regarding ammonia are related to how to avoid accidental release and how to mitigate the damage if leakage should occur.

4.1 Transport to the end-user

Large amounts of ammonia are transported around the world today by public roads, railways, ships or pipelines. Anhydrous ammonia is specified as dangerous goods and must be transported according to the legislation in place. It is classified as a toxic gas and must be properly marked and handled accordingly.

Public roads: People who transport dangerous goods on roads need to complete training and hold a valid training certificate. Training for the transport of dangerous goods is often generic and not specific for anhydrous ammonia.[24] However, the industry offers its own training programmes for drivers and other people who are involved in the transportation of ammonia.

[23] https://www.wikihow.com/Handle-Anhydrous-Ammonia#references, John Nowatzki: "Anhydrous Ammonia: Managing the risks", p 1-2, Fertilizers Europe: "Guidance for inspection of and leak detection in liquid ammonia pipelines", 2013, p. 9.

[24] IRU academy: "Transport of Dangerous Goods by Road (ADR) – Program fact sheet", 2017.

Railways: 1.5 million tons of ammonia, which equals approximately 30,000 rail tank cars, are transported in Europe each year. Only a few accidents have occurred over the last 30 years, and none of the accidents resulted in any casualties or injuries due to the release of ammonia.[25]

Shipping: Today, 170 ships are capable of carrying ammonia as cargo, 40 of which do this continually.[26] General safety measures for liquid gas carriers include actions against leakage, firefighting procedures, procedures for cargo transfer, gas freeing, ballasting and cargo cleaning, minimum allowable cargo tank steel temperature, emergency procedures and training of personnel. Specifically, for anhydrous ammonia, the ship requires toxic vapor detection.[27]

Pipelines: Large amounts of ammonia are being transported in pipelines around the world, especially in USA and Russia/Ukraine. Most of these pipelines run close to public roads or populated areas. There have been some accidents due to leakage from pipelines. Most of these were in the USA, which is the country with the largest liquid ammonia pipeline infrastructure. In the USA there have been 9 incidents, none of which were fatal.[28]

Safety measures include dangerous goods marking, proper maintenance of vessels, guidelines for loading and unloading, protective clothing and guidelines for emergency responses.[29]

4.2 Use of anhydrous ammonia in agriculture

Approximately 80% of the world's ammonia is used for fertilizer production, mainly in the form of urea or ammonium nitrate of different grades. Liquid ammonia can also be applied directly to fields. In Illinois alone, 670,000 tons of anhydrous ammonia are utilized in the agricultural sector every year. This is done without major problems, as the safety procedures applied to a large degree succeed in preventing accidents.[30]

Anhydrous ammonia is stored, transported and handled in the agricultural sector as a liquid in pressurized tanks. The handling of the equipment involves manual operations like connecting and disconnecting of pressurized vessels and moving the pressurized tank equipment. Most ammonia accidents are caused by mistakes such as filling the tank beyond recommended capacity, knocking the valve open, breaking the transfer hose, failing to bleed hose coupling before disconnecting, or in other ways not following protocol or properly maintaining equipment.[31]

In many regions additional training in the safe handling of anhydrous ammonia is offered by the agricultural industry. The training promotes safe handling of anhydrous ammonia at the farm level

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[25] European Fertilizers Manufacturers Association: "Guidance for transporting ammonia by rail", 2nd edition, 2007, p. 6.

[26] https://www.ammoniaenergy.org/articles/man-energy-solutions-an-ammonia-engine-for-the-maritime-sector/

[27] GL: "Rules for classification and construction – Ship technology", 2008, p. 99-102.

[28] Fertilizers Europe: "Guidance for inspection of and leak detection in liquid ammonia pipelines", 2013, pp. 4-6, 12-13.

[29] European Fertilizers Manufacturers Association: "Guidance for transporting ammonia by rail", 2nd edition, 2007.

[30] Mark Fecke, Stephen Garner, Brenton Cox: "Review of Global Regulations for Anhydrous Ammonia Production, Use, and Storage", 2016, p. 1, John Nowatzki. "Anhydrous ammonia: Managing the risks", p. 1, https://www.dtnpf.com/agriculture/web/ag/crops/article/2019/05/07/tips-safely-use-anhydrous-ammonia.

[31] David E. Baker: "Using Agricultural Anhydrous Ammonia Safely", 1993, p.

and contributes to protecting farmers, their families and the general public from the hazards of an accidental spill or leakage.[32] Safety measures for handling ammonia in the agricultural sector include:

- Wear protective clothes, minimum of goggles, gloves and a heavy-duty long-sleeved shirt,
- Have a container of at least 5 gallons of water ready, as water is important for first aid if skin or eyes are exposed,
- All parts of the pressurized equipment,
- Make sure the equipment is properly maintained,
- Follow guidelines for transfer procedures,
- Mark the ammonia storage vessel properly to indicate that it contains toxic gas[33].

There is one major difference between the working environment for farmers in an open field and a technician in an engine room on a ship. The farmer can work up-wind and make sure that any leakage will move away from the farmer. On the other hand, the technicians in the engine room on the ships will work according to well-defined procedures and on a regular basis, whereas the farmers carry out a wide variety of tasks, and only handle ammonia a few days a year. To mitigate the different environments and safe design standards, working procedures and professional safety training of the ship personnel is key, as it would be in the handling of other toxic materials within the shipping industry.

4.3 Ammonia as a cooling media

Ammonia has good thermodynamic qualities and is therefore efficient to use as a refrigerant. Around 360,000 metric tons of ammonia are used annually in North America in this way.[34] As this is often done in confined spaces, similar to the use of ammonia on board a ship, it is relevant to look at the use of ammonia as a refrigerant, for inspiration on how safety aspects are handled.

Ammonia accidents in refrigeration systems can have serious consequences and can cause both injuries on workers and costly property damage. However, most of the accidents that have occurred, could easily be prevented by proper maintenance of equipment.[35] If the refrigerant system is properly designed, constructed, operated and maintained, and the staff at the facility is prepared to respond correctly to leakages, ammonia can be safely used.[36]

Initiatives to prevent accidents or prepare to respond appropriately include:

- Educate personnel who operate the system and conduct emergency response drills,

[32] Fertilizer Canada: "Anhydrous Ammonia: Code of practice", 2017.

[33] David E. Baker: "Using Agricultural Anhydrous Ammonia Safely", 1993, p. 3-6.

[34] Mark Fecke, Stephen Garner, Brenton Cox: "Review of Global Regulations for Anhydrous Ammonia Production, Use, and Storage", 2016, p. 2, Walter S. Kessler: "The Good, the Bad, and the Ugly of Using Anhydrous Ammonia Refrigerant in the Process Industries", p. 2.

[35] EPA: "Hazards of Ammonia Releases at Ammonia Refrigeration Facilities (Update)", 2001, p. 2.

[36] Walter S. Kessler: "The Good, the Bad, and the Ugly of Using Anhydrous Ammonia Refrigerant in the Process Industries", p. 4.

- Use spring-loaded ball valve in conjunction with drain valve on all oil outputs as an emergency stop valve,
- Remove refrigeration oil from the refrigeration system on a regular basis,
- Provide barriers to protect equipment,
- Post ammonia warning signs,
- Regularly inspect and maintain refrigeration equipment, ammonia refrigeration piping system and emergency equipment,
- Use ammonia detector,
- Establish emergency procedures in case of power failure or ammonia release,
- Mount compressor room ventilation fan manual switch outside the compressor room.[37]

4.4 Ammonia handling

Ammonia as a marine fuel does, like other existing and alternative future low emissions fuels, pose some challenges to ensure the safety of the crew onboard the ships. However, large amounts of anhydrous ammonia are traded and handled around the world today and are not considered among the most toxic cargoes handled in shipping. This is done in various sectors, some of which have similar conditions to ammonia being utilized as a shipping fuel. In these sectors, essential safety measures include regular inspection and maintenance of equipment, training of personnel, protective clothes, warning signs and emergency procedures to mitigate damage in case of leakage.[38] It is relevant to look at these existing sectors handling ammonia, when designing the future ammonia fueled ships. However, the shipping sector has ample opportunity to integrate safety as a key measurement in the design of the new ammonia fueled fleet, as further detailed in chapter 6.

5 Ammonia marine fuel infrastructure

The use of ammonia as a marine fuel in the future will require infrastructure for bunkering and ship maintenance. It is logical to assume that the ports which have ammonia terminals now can become the foundation of the network for ammonia distribution as ship fuel in the future. It seems likely that the first ships with ammonia as fuel might be those ships that transport ammonia.

5.1 Global seaborne ammonia trade, 2019

World maritime trade in ammonia is estimated at 17.5 million tons (2019). Ammonia is transported by 71 LPG tankers, with cargo capacities from 2,500 to 40,000 tons. For ammonia transshipment, special equipment is required to maintain ammonia in a liquefied form keeping it at low temperature (-34 degrees Celsius) or under pressure.

[37] EPA: “Hazards of Ammonia Releases at Ammonia Refrigeration Facilities (Update)”, 2001, p. 3-6.

[38] Further information about regulations on ammonia handling can be found in the report “Review of Global Regulations for Anhydrous Ammonia Production, Use and Storage” by Fecke, Gamer and Cox, 2016, p. 6-9.

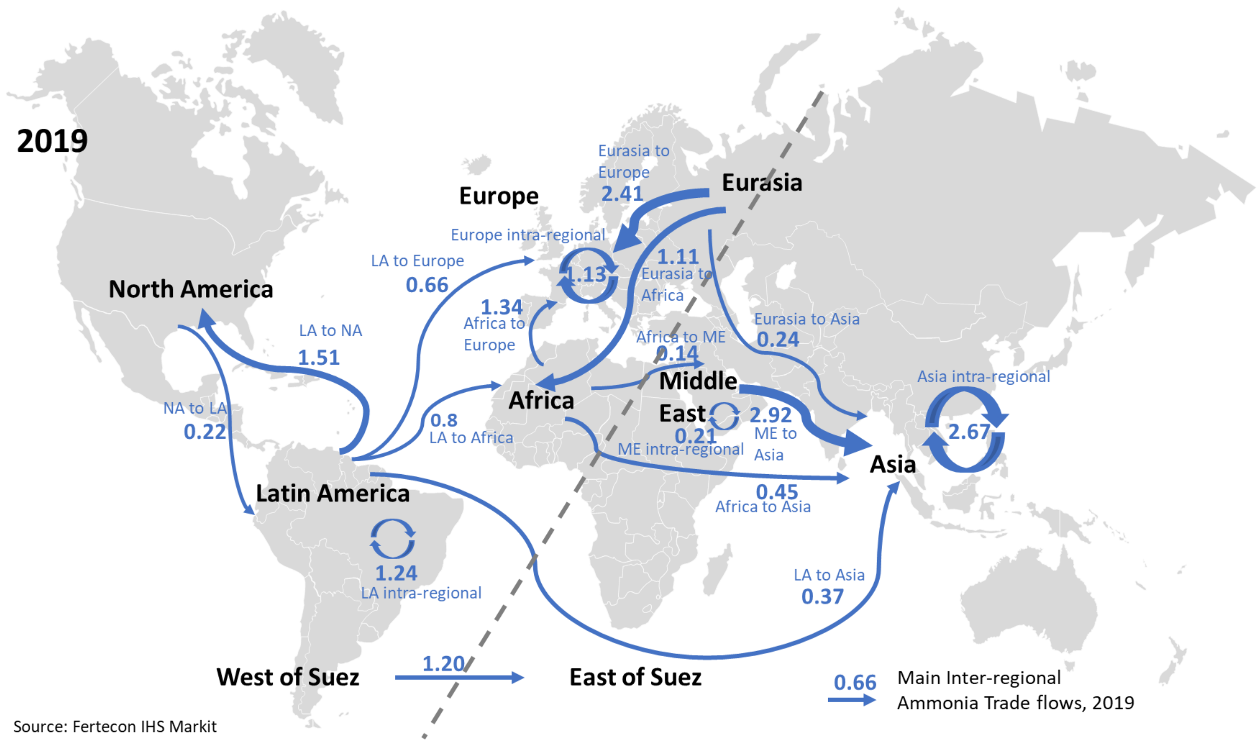

Figure 12. Map of global ammonia trade flows. Source Fertecon IHS Markit.

5.2 Existing ports with ammonia terminals

There are special ammonia terminals in 38 ports which export ammonia, and in 88 ports which import ammonia, including six ports which both export and import ammonia. Many terminals are parts of ammonia/fertilizer plants which are located at the coast of a sea or river and equipped for transshipment of fertilizers and ammonia. In other cases, the ammonia terminals are located separately from the plants and have their own ammonia storage, or they are parts of larger port complexes. Storage is usually comprised of special isothermal tanks (up to 30,000 tons) and spherical pressure storages (1,000 – 2,000 tons), special pipe and valve systems are used in a liquid ammonia discharging arm for pumping ammonia in and out of ships. The figures below show how wide-spread ammonia terminals are today, providing an excellent starting point for the infrastructure for ammonia as a marine fuel.

Figure 13. Ammonia terminals in the Baltic Sea and North-West Europe. Source Fertecon IHS Markit.

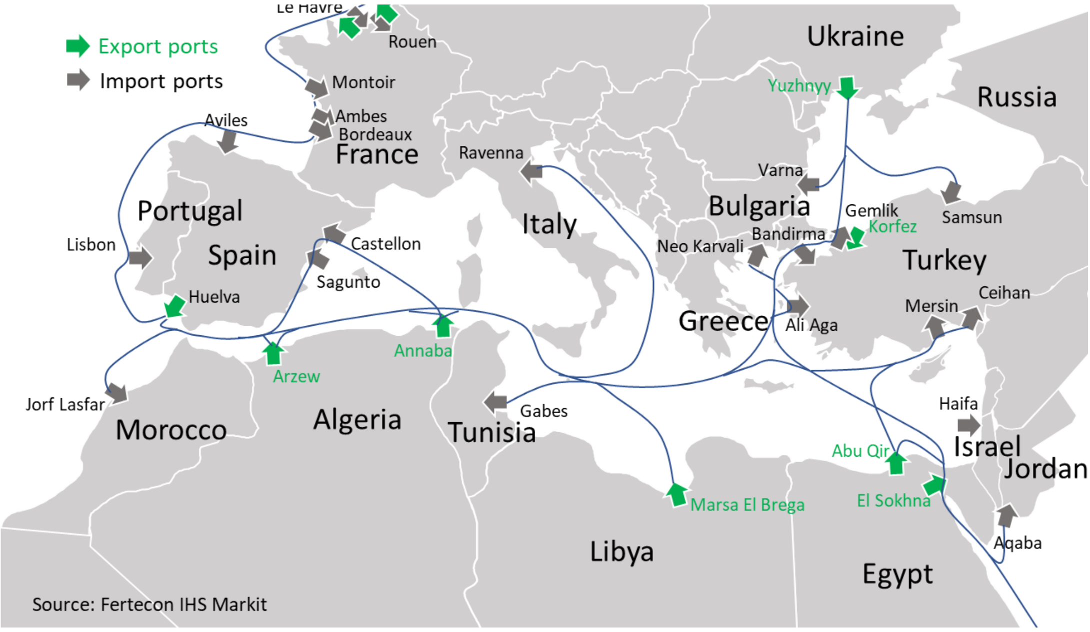

Figure 14. Ammonia terminals in the Mediterranean Sea. Source Fertecon IHS Markit.

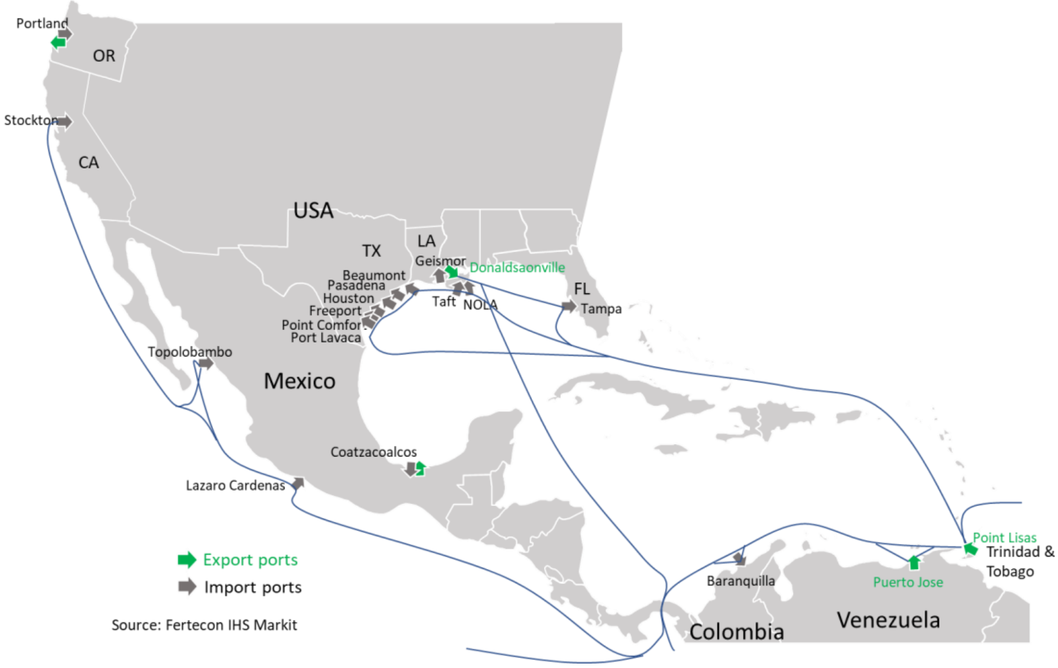

Figure 15. Ammonia terminals in the Caribbean Basin and North America (not showing the US east coast). Source Fertecon IHS Markit.

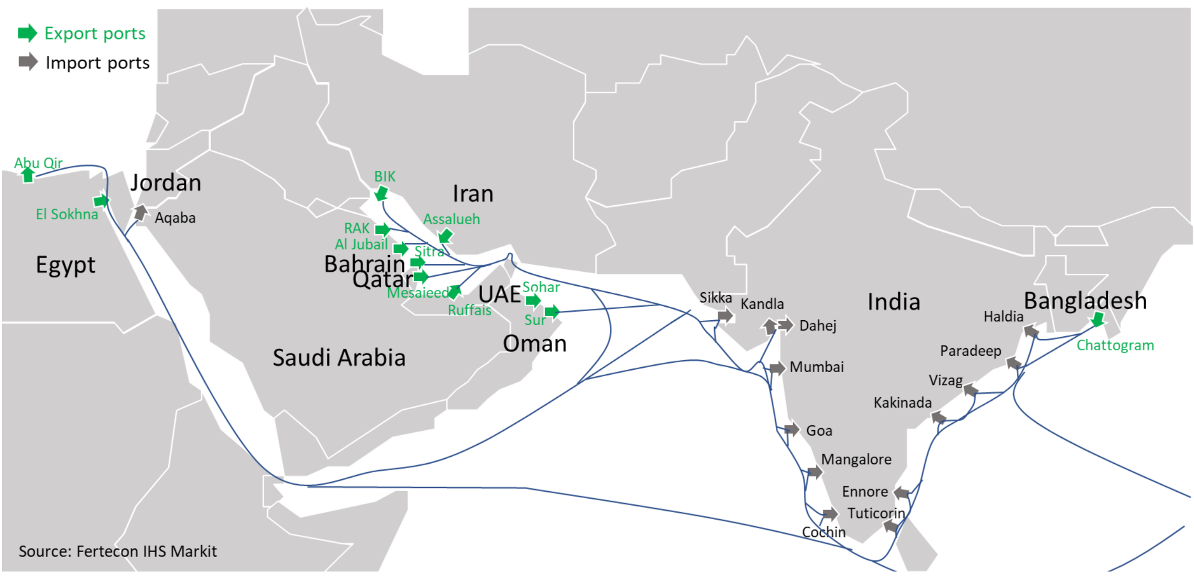

Figure 16. Ammonia terminals in the Middle East and South Asia. Source Fertecon IHS Markit.

Figure 17. Ammonia terminals in Asia Pacific and Oceania. Source Fertecon IHS Markit.

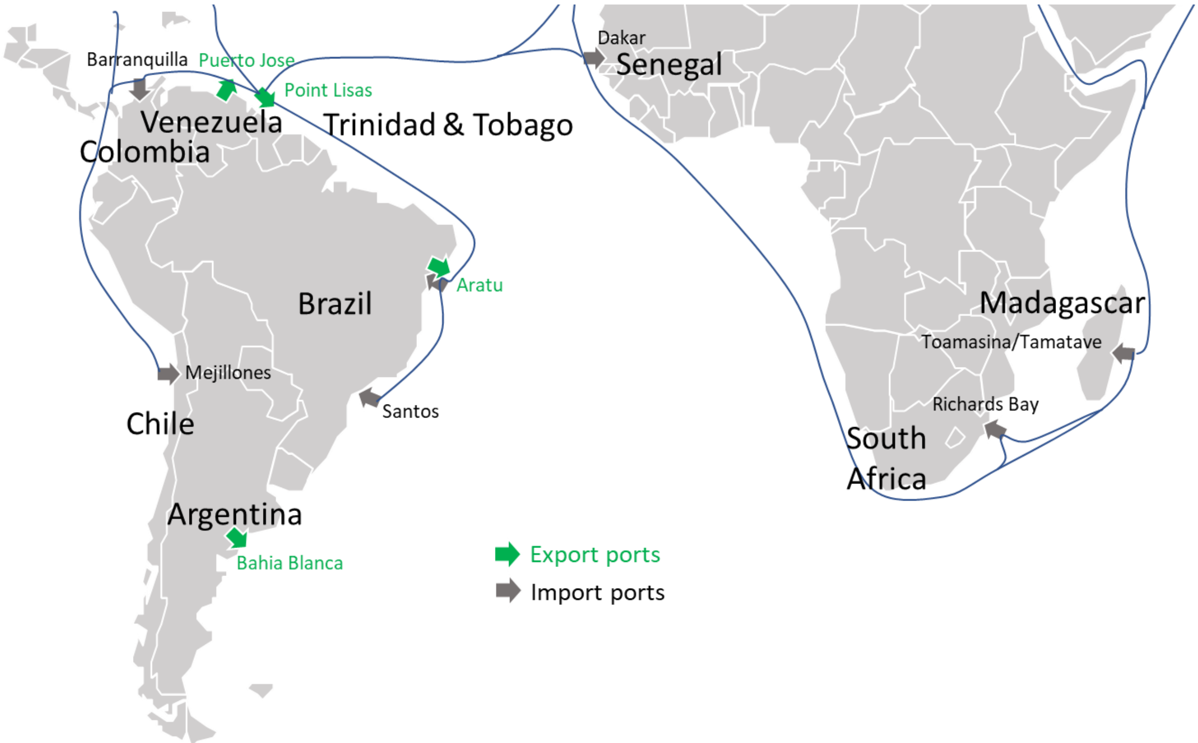

Figure 18. Ammonia terminals in South America and SS Africa. Source Fertecon IHS Markit.

5.3 Ammonia shipping, handling and storage

The many million tons of ammonia transported globally are shipped in standard semi-refrigerated and fully refrigerated gas carriers today.

Figure 19. Refrigerated gas carrier.

As the maps indicate, the cargo is loaded at the current production and exporting facilities typically located in regions with an abundance of natural gas and shipped to distributors and off-takers.

The current off-takers of ammonia are typically agricultural and industrial distributors or consumers. The ammonia carriers often unload their cargo in the dedicated chemical storage area of the receiving ports or in ammonia storage and distribution facilities. Storage tanks for liquid anhydrous ammonia are common in most of the world and are typically constructed in sizes up to 40,000 tons.

Figure 20. Refrigerated liquid ammonia storage tanks. Source: Proton Ventures.

With the currently established global grid of ammonia terminals and storage, a bunkering grid could be established quickly and cost-efficiently by converting small gas tanker vessels to bunker barges. They would be able to utilize the existing storage facilities as base stations and from there approach the vessels requiring bunkering in the vicinity. The bunkering operation itself would be very similar to when bunkering other gaseous fuels, except the main hazard would be the fuel toxicity rather than flammability, and the procedures for ammonia bunker barges need to be developed.

Figure 21. A container vessel receiving bunker from a barge while loading/unloading cargo. Source: Northstar NV.

While traditional fuels have a wide and complex range of properties, ammonia is a clean fuel consisting of only one compound, which eliminates all variations between types and qualities, thereby greatly simplifying fuel sourcing, qualification and analysis.

6 Ammonia on board

6.1 Generalities about ammonia as a marine fuel

6.1.1 Environmental regulation

The potential of ammonia as a fuel for marine engine propulsion is related to the expected fulfilment of emission regulations, as mentioned in the introductory chapter.

In 2012 the International Maritime Organization (IMO) estimated that international shipping accounted for about 2.2% of the total global anthropogenic CO2 emissions and that emissions from international shipping could further increase due to the growth of the world maritime trade[39]. In this regard, IMO's Marine Environment Protection Committee (MEPC) introduced in 2013 some measures to reduce and control GHG emissions from ships[40]:

- the Energy Efficiency Design Index (EEDI), which requires new ships to comply with minimum mandatory energy efficiency performance levels,
- the Ship Energy Efficiency Plan (SEEMP), which establishes a mechanism for shipowners to improve the energy efficiency of both new and existing ships using operational measures.

These measures, included in Chapter 4 of MARPOL Annex VI, are the first-ever mandatory global GHG reduction regime for an entire industry. Furthermore, in April 2018 MEPC adopted the resolution on Initial IMO Strategy on the reduction of GHG emissions from international shipping, as follows:

1. carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships,
2. reduce the carbon intensity, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008,
3. reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008.

Regarding the IMO target of GHG emission reduction, thanks to its being completely carbon-free, ammonia (NH3) seems to be one of the strategic fuels for the future.

In addition to being completely carbon-free, the use of ammonia as fuel can have other environmental benefits:

- Green ammonia can be obtained from green synthesis processes relying on renewable resources, with no use of fossil fuels, as explained in previous chapter 2,
- the use of ammonia can contribute further to the reduction of greenhouse gas emissions, also accounting for the prevention of methane slip which typically affects LNG fueled ships,
- differently from other fuels like methane, ammonia is not a greenhouse gas and its emissions do not tend to build up in the environment,

[39] “INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS”, Resolution MEPC.304(72)

[40] Chapter 4 of MARPOL Annex VI entitled "Regulations on energy efficiency for ships"

- ammonia is by nature a sulfur-free fuel, therefore it does not require any specific cleaning technology for SOx removal from exhaust systems.

6.1.2 Comparison of ammonia vs other fuels

The most important properties of ammonia and other marine fuels are shown in Table 6 for comparison.

	Normal Boiling Point [°C]	Pressure for storage at ambient Temperature (20 °C) [bar g]	Liquid mass density at 15°C [kg/m3]	Lower Heating Value [MJ/kg]	Energy Density [MJ/L]	CO2 by combustion [kgCO2/GJ]
HYDROGEN	- 253	--	71	120	8.5 **	0
LNG	- 162	--	450	50	22.5	56*
LPG ***	- 42	7.5 min	550	46	25.5	60
AMMONIA	- 33	7.6 min	618	18.6	12.7	0
METHANOL	65	ATM	780	19.9	15.5	70
HEAVY FUEL OIL (HFO)	>160	ATM	920 - 1010	40.5	35	80

Table 6. Comparison of physical properties of fuels[41,43]. * Methane slip not included. ** Liquid. * As propane.**

The table shows the main physical properties of some marine fuels, to which the ship investment cost is directly related.

Heavy Fuel Oil (HFO) is the traditional reference fuel in the marine industry. With its 3.5% sulfur content, HFO is not compliant with the global “sulfur cap” entered into force in 2020, requiring even stricter limits on SOx emissions. In the last decades, shipowners have started to look for alternatives to traditional HFO, rather than installing an exhaust gas cleaning system for SOx removal. Low-Sulfur Fuel Oil with a maximum of 0.5% sulfur content (so-called VLSFO) can be used as option to comply with SOx emission regulations. As an alternative, other sulfur-free fuels

[41] YARA - Anydrous Ammonia Safety Data sheet

have been adopted for marine propulsion (methanol, ethane, LNG, LPG), thanks also to the parallel development of marine diesel engine technology.

Also sulfur-free, methanol entered the scenario of alternative marine fuels in the last decades as a means of adhering to the sulfur emission regulations. Well-proven technology exists for handling and using methanol as fuel on ships in dual-fuel two-stroke diesel engines.

The amount of CO2 released by the combustion of methanol is, however, the same order of magnitude of other hydrocarbon-based fuel. A valid carbon-neutral alternative is offered by e-methanol synthesized using renewable power and bio-based carbon, which is, however, a limited resource with expected increased market price as a consequence.

LNG is another potential shipping alternative fuel that has been the subject of recent interest, mainly because of the IMO 2020 sulfur cap. LNG has a higher energy density compared to ammonia. Still, it requires cryogenic storage conditions onboard (-162°C), while ammonia can be stored onboard at nearly atmospheric pressure and refrigerated conditions (-33°C). LNG is still a carbon-based fossil fuel and the amount of CO2 released by its combustion is only moderately lower than for the traditional fuels.

Like ammonia, hydrogen is a carbon- and sulfur-free fuel that can be produced via a sustainable process. The use of hydrogen as an energy vector and as a green fuel is attractive and can be one of the drivers for the energy transition. However, considering the specific application in the marine industry, hydrogen has some disadvantages if compared to ammonia. As shown in Table 6:

- with a lower energy density than ammonia, a hydrogen-fueled ship will require higher fuel storage volumes onboard,
- hydrogen storage onboard requires cryogenic conditions (-253°C), whereas ammonia can be stored and transported under less-severe temperature and pressure conditions (-33°C at atmospheric pressure or it can be liquefied under pressure at ambient temperature),
- hydrogen is also more explosive than ammonia (Table 7).

Ammonia and LPG can be stored at similar temperature and pressure conditions. Like LPG, ammonia has a vapor pressure lower than 10 bar g at 20°C (a higher storage pressure is required in case of presence of ethane in LPG). Storage pressure increases with temperature, therefore both LPG and ammonia can be stored onboard on type-C tanks to remain liquid also at higher ambient temperature. Ammonia can also be stored onboard at nearly atmospheric pressure and refrigerated conditions, like LPG. In this case, the main advantage with respect to LNG and hydrogen is that ammonia refrigerated storage temperature (-33°C) is well above the cryogenic conditions of LNG and hydrogen (-162 to - 253°C).

	Lower Explosive Limit (vol% in air)	Upper Explosive Limit (vol% in air)
AMMONIA	15%	27%
HYDROGEN	4%	75%

Table 7. Comparison of ammonia and hydrogen flammability

6.1.3 CO2 footprint

The CO2 emissions generated by the combustion of sulfur-free alternative fuels (Table 1) is lower than HFO but still too high to ensure the achievement of the GHG reductions required by IMO, with the exception for ammonia and hydrogen, whose combustion is completely CO2-free.

Among the carbon-based fuels, burning LNG generates the lowest amount of CO2 per-MJ; conversely, HFO has the highest combustion emissions. Fossil fuel combustion also emits small quantities of nitrous oxide (N_2O) and methane (CH_4), both of which are potent climate-forcing agents (with methane and N_2O being 25 and up to 300 times more GHG-intense than CO2, respectively). Their impact as a GHG is taken into account by converting N_2O and CH_4 into CO2-equivalent. To make a complete comparison of the CO2 footprint from the various fuels, the total emissions occurring during the whole lifecycle of fuels must be considered.

An example is given by LNG: although containing less carbon per unit of energy than conventional marine fuels, from a total lifecycle point of view LNG can account only for a 15% reduction in GHG emission if compared to MGO (for dual-fuel high-pressure engine technology combined with strong upstream control of methane emissions)[42,43]. The mentioned figure of GHG reduction for LNG refers to a Global Warming Potential (GWP) over 100 years and includes upstream GHG emissions, combustion emissions and unburned fuel slip. But for different engine technologies (low-pressure engine) and shorter GWP (20 years) the use of LNG gives no benefit in lifecycle GHG emissions if compared to traditional fuels[42,43].

Referring to the upstream CO2-footprint of conventional marine fuels (well-to-hull), HFO has the lowest emission factor (19.2 kgCO2e/GJ). This is because it requires less hydrogen and energy at the refinery for processing compared to MGO and VLSFO, whose equivalent well-to-hull emission factor ranges from 22 to 22.7 kgCO2e / GJ, respectively.

Conventional ammonia carbon footprint is approximately 1.6 – 2 tons CO2/ton NH3, corresponding to 86-107 kg CO2/GJ. By also considering the CO2 emitted from combustion (74.7 kg CO2e/GJ for MGO to 76.7 kg CO2e/GJ for VLSFO to 81.2 kg CO2e/GJ for HFO[43] and zero for ammonia), it

[42] "The full picture: an assessment of shipping's emissions must be based on full lifecycle accounting" – Ammonia Energy Association – May 2020

[43] "The climate implications of using LNG as a marine fuel" – 2020 International Council of Clean Transportation

appears that conventional ammonia carbon footprint is in the same range as traditional fuels and, in case of ammonia produced in new plants, it is not worse than VLSFO. Upon application of available SCR technology (section 6.3.5) the resulting N_2O emissions will be low and similar for ammonia, conventional fuels and combustion engines in general.

6.1.4 Toxicity and safety aspects

Even if it is anticipated that ammonia carriers will be the first vessels to utilize ammonia as a fuel, the IMO International Gas Carrier Code (IGC) will have to be amended. Today it prohibits the use of cargoes identified as toxic products as fuel for the ship. Moreover, partial amendments to the section on the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) are required. For ammonia carriers, the risk of a large release to the atmosphere in densely populated port areas also needs to be considered.

Various concerns may arise when talking about the possible use of ammonia as a marine fuel. The major concerns are related to ammonia safety and toxicity issues. Ammonia is a toxic, corrosive, hardly inflammable gas with a strong characteristic odor. The odor threshold for ammonia is between 5 - 50 parts per million (ppm) of air. Repeated exposure to ammonia produces no chronic effects to the human body. However, even in small concentration in the air it can be extremely irritating to the eyes, throat and breathing ways.

The toxicity threshold depends on the time of exposure, see **Table 8**:

CONCENTRATION / TIME	EFFECT
10000 ppm	Promptly lethal
5000 – 10000 ppm	Rapidly fatal
700 – 1700 ppm	Incapacitation from tearing of the eyes and coughing
500 ppm for 30 minutes	Upper respiratory tract irritation, tearing of the eyes
134 ppm for 5 minutes	Tearing of the eyes, eye irritation, nasal irritation, throat irritation, chest irritation
140 ppm for 2 hours	Severe irritation, need to leave the exposure area
100 ppm for 2 hours	Nuisance eye and throat irritation
50 – 80 ppm for 2 hours	Perceptible eye and throat
20 – 50 ppm	Mild discomfort, depending on whether an individual is accustomed to smelling ammonia

Table 8. Ammonia toxicity exposure levels[44]

The ammonia odor has been and will continue to be an important safety precaution measure. However, in technical installations such as what will be onboard an ammonia fueled vessel, gas detection equipment covering the full relevant ammonia concentration range and coupled to automated safety protection responses will be the standard when relevant.

At present various safety studies[45] and hazard identification studies are being developed in the marine industry with the scope of defining the proper design criteria and addressing a risk evaluation for a safe ammonia-fueled ship design, preventing the hazards and mitigating the residual risks.

It is also important to consider that ammonia is not new to shipping: it is typically transported as cargo and it is common practice to use ammonia onboard as a refrigerant. All the necessary practices for safe ammonia handling onboard are already well-known in marine industries and accepted by crew and operators, including operational and safety procedures. International rules and regulations are in place covering the use of ammonia onboard. For instance, the International Code for the Construction and Equipment of Ships Carrying Liquefied Gas in Bulk (IGC Code) gives the indications for the protection of personnel operating onboard on gas carriers transporting ammonia (chapter 14.4):

- Respiratory and eye protection devices for emergency escape purposes shall be provided for every person onboard, with some minimum requirements (no filter-type; self-contained breathing apparatus 15 minutes minimum duration),
- Protective clothing to be gas-tight,
- One or more suitably marked decontamination shower shall be available on deck, depending on the size of the ship, and shall be able to operate under all ambient conditions.

The combination of solutions, devices and procedures that industry gathered about safe handling of ammonia onboard together with the experience of LNG as a fuel will be a good starting point for the development of specific guidelines for ammonia as ship fuel.

A similar approach can be followed for the evaluation of the potential environmental impact of ammonia-fueled ship. Ammonia is not a greenhouse gas, however fuel slip and other gaseous ammonia emissions that might occur during normal operation and emergency scenarios shall be kept under control. Anhydrous ammonia gas is considerably lighter than air and will rise in dry air, accelerating its dispersion. However, because of ammonia's tremendous affinity for water, it reacts immediately with the humidity in the air and may remain close to the ground, thus limiting the dispersion in the environment[46].

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[44] "Health effects of ammonia" – The Fertilizer institute

[45] "Safe and effective application of ammonia as a marine fuel", Niels De Vries, 2019

[46] OSHA website

Detailed dispersion studies and more detailed analysis will be conducted for a proper assessment of ammonia safety and environmental issues and for an evaluation of the impact on crew and operators. However, it can reasonably be said that a safe and environmental-friendly way to handle ammonia on an ammonia-fueled ship could be achieved by relying on existing emission treatment technologies.

6.1.5 Corrosivity and material selection

From a chemical point of view, anhydrous ammonia is an alkali and can combine with water to form ammonium hydroxide.

Ammonia, especially in the presence of moisture, reacts with and corrodes copper, zinc and many alloys. Only iron and steel, specific non-ferrous alloys resistant to ammonia, should be used for tanks, fitting and piping containing ammonia. Only some rubbers and polymers are compatible with liquid anhydrous ammonia, impacting the material selection for gaskets and sealing (PTFE being one possible material compatible with ammonia[47]).

Particular attention must be given to the presence of nickel: its presence in nickel alloys shall be kept below 6% to avoid the phenomenon of nickel crystalline corrosion[47].Oxygen levels of more than a few ppm in liquid ammonia can promote stress corrosion cracking in steels, which proceed very rapidly at high temperatures.

The IGC Code gives the following requirements for cargo tanks and associated pipelines, valves, fittings and other items of equipment normally in direct contact with the cargo liquid or vapor, in the case of ammonia[48]:

- mercury, copper and copper-bearing alloys, and zinc shall not be used for cargo handling ammonia and for equipment normally in contact with ammonia liquid or vapor,
- maximum nickel content in steel = 5%,
- the ammonia shall contain not less than 0.1% w/w water,
- minimum requirements for steel yield strength and post-welding treatment are indicated in IGC Code chapter 17.12.

The IGC Code also provides indications on how to minimize the risk of ammonia stress corrosion cracking (chapter 17.12).

6.2 Ammonia as a fuel

Using ammonia as a fuel is new for the shipping industry, so new systems will need to be used onboard, each with their own specific requirements and risks. But ammonia is not new as a cargo; and therefore technologies, materials and procedures are already in place and just need to be adapted and developed for this new application. It will be valuable to consider the industry's experience with other alternative fuels like LNG and methanol.

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[47] MAN Energy Solution –"Engineering the future two-stroke green-ammonia engine"

[48] IGC Code

In a general scenario of different industries competing to secure the availability of carbon-free or carbon-neutral fuels, ammonia seems to be more suitable for the big and professional users than for small ones, like trucks and private cars.

Now, in order to analyze the scenario of using ammonia as a fuel for the ships, we will consider three main aspects: the bunkering and storage of ammonia onboard, how the engine room and the engine operation is affected by this fuel and some safety aspects.

6.2.1 Bunkering and storage of ammonia onboard

The case of a vessel that is carrying ammonia as cargo is the easiest to understand. We can expect that these vessels will be the first using it as fuel, according to the previous experience with LNG, methanol and LPG. The ship adaptation will probably be limited to the installation of a dedicated NH3 fuel supply system (from now on LFSS) and to the necessary upgrading of the engine. In this case particular attention should be given to avoid any possible pollution of the cargo itself caused by pollutants coming from the engine. Therefore, the design of the LFSS should be able to secure this aspect. We will see how in the next chapter.

The ammonia availability for engine fueling, and the operations to bunker the product, are not issues for these vessels. The experience with LNG or with methanol, whose handling is in some ways more similar to ammonia (no cryogenic technologies, no boil off to get rid of and use as fuel) shows that the ship can be operated for almost 100% of the time with the alternative fuel, and lowers costs.

In the case of a vessel that is not carrying ammonia as cargo, the facilities for loading and storing it onboard need to be installed, as well as the above-mentioned LFSS and engine adaptations. Their design and safety are expected to be regulated by the IGF code, together with the description of the procedures for safe loading, storage and operation of the entire ammonia system onboard. We will analyze this in the coming section on safety.

The most cost-effective system to store the ammonia on ships with limited routes and installed power seems to be a type C pressurized tank. This tank can store the product at ambient temperature, thus not requiring any reliquefaction system. Furthermore, the type C tank is a flexible installation on the deck and can be easily integrated into a consolidated design of a commercial ship. The expected limit of applicability of type C tank is 2000 m3.

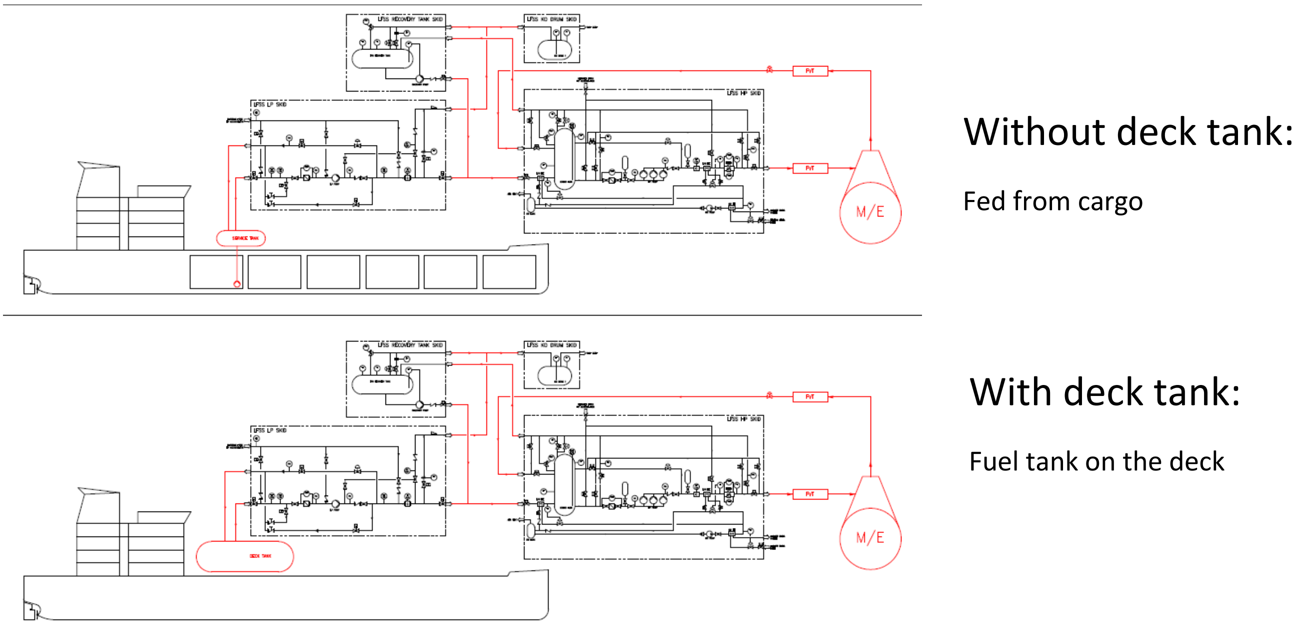


Figure 22. Alternative configurations for the ammonia fuel tank.

The tank volume is to be calculated in order to secure the full availability of ammonia for the ship propulsion. Therefore, it depends on the total installed power, the expected availability of the product in the ports the ship is calling, and on the ammonia energy density (see Table 6). Due to the energy density, the net storage volume for ammonia should be approximately 70% more than LNG and almost three times the equivalent of distillate.

For those ships that are not carrying ammonia as cargo, two specific aspects must be carefully considered: the availability of bunkering facilities in the ports and the possible impact on cargo operation time.

Today 120 ports worldwide are already equipped with facilities to import or export the ammonia. Ship to ship bunkering, where the ammonia is delivered by another ship or barge moored alongside the receiving vessel, and improved bunker hose handling will be required for the quick growth of ammonia availability. This solution is applied for LNG as well: it minimizes the investment for facilities and is flexible in providing the fuel where and when it is required.

The bunkering of ammonia is theoretically possible in parallel with cargo loading/unloading operation. But this must be authorized by the port authority. If not, this will end up in additional time in the port that is definitely a cost for the ship.

6.3 Fueling the engine with ammonia

6.3.1 Generalities about the combustion

Ammonia is a very credible option as a carbon-free or carbon-neutral fuel. But for the time being, there are limited experiences about its combustion in a reciprocating engine. The literature says that ammonia has a high auto-ignition temperature, low flame speed and limited flammability limits.

In order to be self-ignited, it requires a very high compression rate and temperature, also leading to high production of NO_x. A solution to this is to mix a second fuel to ammonia with more favorable ignition qualities (like hydrogen, to be stored onboard or to be produced onboard by ammonia cracking). Alternatively, a pilot flame can be used to start and control the combustion in the cylinder. The latter seems to be the straightforward solution to obtain complete control of the process. The dual-fuel engines with pilot flame are well-proven in the marine space and offer many advantages: reliable solution, fuel flexibility (they can be run on compliant fuels) and a very quick transition to the primary fuel in case of issues on the secondary one.

Moreover, the manufacturers offer the possibility to upgrade existing engines to this technology, thus making the conversion to ammonia possible for ships that are already in operation.

6.3.2 Generalities about the engine ancillaries and the engine itself

The use of ammonia as fuel will lead to significant changes in the engine room. Some traditional equipment will not be needed anymore, like the entire treatment for HFO (High-speed separators, heaters, booster, settling tank), and the SO_x abatement system for those ships that were using high-sulfur heavy fuel oil.

On the other hand, new systems are needed to deal with this new fuel, as well as a dedicated engine, with a direct impact on CAPEX and OPEX. The main options are listed below:

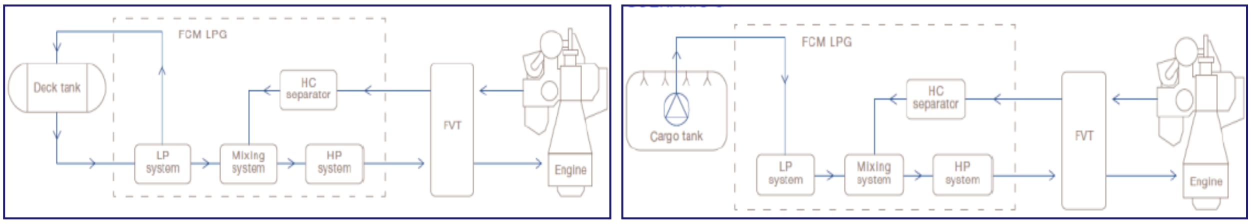
- LFSS with venting system,
- SCR post-treatment (using ammonia as a reducing agent),
- Specific engine upgrading.

Below we evaluate them in detail.

6.3.3 Liquid Fuel Supply System (LFSS)

The LFSS is the system providing the ammonia to the engine at required conditions. In order to minimize the risk of possible ammonia release in the engine room, the LFSS can be installed on the deck and connected to the engine by double-walled piping. Installation in the engine room is possible as well, but with precautions like the installation of an airlock system preventing any diffusion of ammonia in the Engine Room (ER).

Depending on the engine technology, the LFSS can have very different design. For those engines receiving the secondary fuel as a gas at low pressure, it can be similar to the low-pressure LNG supply systems. For engines receiving the secondary fuel at high pressure in liquid phase, the solution used for LPG on LGIP engines can be applied with very limited adaptations. Below a block diagram for a ship without a dedicated tank for the fuel.



LFSS for a ship with deck tank

LFSS for a ship without deck tank

Figure 23. Alternative block diagrams for the ammonia LFSS

This LFSS system implements several functions:

- It provides the fuel at the required temperature and pressure to the engine (expected 70 bar), regardless of the storage conditions,
- it segregates the fuel from the cargo securing the latter from possible pollutants coming from the engine,
- it can operate the purging when needed,
- it can handle the recovery of the product from purging and minimize the release in the atmosphere in safe conditions.

6.3.4 Ammonia engine

Many engine manufacturers are working on the development of the ammonia fueled engine. It is worth mentioning the recent updated published by MAN describing the path to have this solution available on the market[49]. The overall message is that the LGI engine family is the perfect candidate for conversion to ammonia. These engines are well-proven on the market with tens of thousands of operating hours with alternative fuels, therefore providing a reliable and well-known solution to propel the ship with ammonia fuel. The table below illustrates the ammonia engine project roadmap:

[49] “Engineering the future two-stroke green-ammonia engine”, MAN Energy Solutions, November 2019.

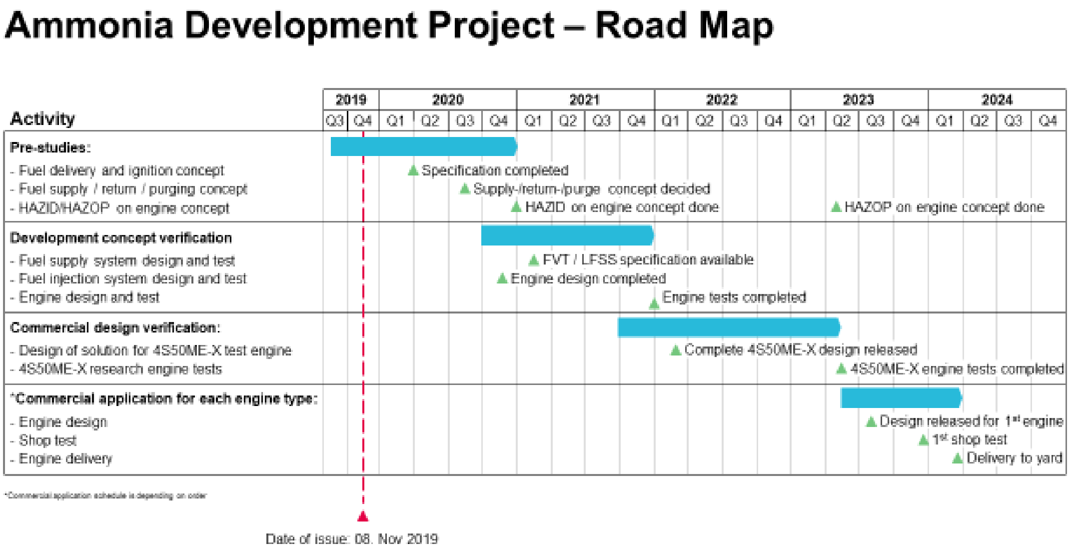


Table 9. MAN roadmap for the two-stroke ammonia engine. **Source: MAN ES.**

The LGIP engine offers a further option for fuel flexibility. The engine can be operated with any portion of gas and liquid fuel (dual fuel operation mode). In this operative mode, the amount of gas fuel is fixed and the fuel oil is added to reach the needed power output. This operation mode then allows the operator to find the best balance between CO2 reduction, costs and fuel availability. Furthermore, the existing ME C type engines can be converted to this technology. This makes the conversion to ammonia fuel possible for ships already in operation.

In terms of costs, the expected extra investment for the ammonia fueled engine in respect to the equivalent unit fueled by compliant fuel is around + 30% (engine only, storage tank and LFSS are excluded).

6.3.5 Exhaust treatment

Ammonia is being considered as a fuel is to reduce the impact of seaborne trade on the environment. Ammonia is carbon-free, thus producing no CO2 (see the concept of green ammonia in former paragraphs). It is also sulfur-free, thus producing no SO_x emissions too. The combustion is expected to produce a negligible amount of soot and particles but is not free from other pollutants: NO_x, N_2O (that is a gas with a powerful greenhouse effect and depletes the ozone in the atmosphere) and the possible slip of ammonia from the funnel. The ongoing tests about ammonia combustion in a reciprocating engine will clarify which pollutants are really produced and in which quantities.

Treatment of exhaust will be needed to reduce the nitrogen byproducts. The suitable solution will be the SCR technology, which is already mature in marine applications. If applied to the ammonia fueled engine, the ammonia itself can be used as a reducing agent, thus making the storage and handling of specific chemicals onboard unnecessary and cutting the related costs. The selection of the catalyst and SCR design to be applied for this specific engine will be made in accordance with the results of the combustion tests and the level of N_2O in the exhaust. According to Haldor Topsøe A/S, catalysts for the combined removal of NOx and N_2O from exhaust gasses are commercially available. The cost of the SCR system and the resulting exhaust levels NOx and N_2O is similar to what is achieved with SCR for conventional fuels.

6.4 Ammonia safety aspects for ship propulsion

The safe handling of ammonia has already been mentioned in this document. Some specific considerations are due in respect of the ship propulsion. These will be covered below.

While the IMO International Gas Carrier Code (IGC) prohibits the use of cargoes identified as toxic products as fuel for ships, the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) does not cover the case of ammonia. Therefore, a revision of both is needed to allow for the use of ammonia as fuel: for the time being, some preliminary activities and risk assessments were done.

The challenge will stem from adjusting the code with respect to the specific ammonia issues: lower flammability than LNG but a much higher level of toxicity. The extensive experience that the industry holds with ammonia will make it possible to implement an appropriate revision of the code.

We considered two cases: the ship that is carrying ammonia as cargo and the ship that is using it as fuel only. In both cases the installation of LFSS and the storage system on the deck is limiting the risk in the engine room mainly to the pipes from the LFSS to the FVT and to the ammonia fuel pipes on the engine. All of them will be double-walled type. This solution secures the safety of the engine room by containing any possible product leakage and, with the help of ammonia sensors, venting it to the external atmosphere when appropriate.

The technology is already well-known and applied on LNG fueled engines. It was developed in order to secure the protection against LNG flammability, and now it needs to be evaluated to address the toxicity issue. In fact, a small leakage of ammonia does not generate a real risk of fire but could diffuse inside the engine room and expose the crew to a toxic atmosphere.

Lastly, the safe release of ammonia must be considered on the ship deck. During the system purging or in the event of an emergency vent the technology is in place to safely handle the displaced ammonia, by burning it or scrubbing it to vent a clean effluent in the atmosphere. The scrubbing technology, of course, will require proper water treatment to avoid direct discharge in sensitive areas.

7 Vision and path to 2030 and 2050

An Ernest Hemingway character described himself going bankrupt in two ways - gradually then suddenly. Technological change and transitions tend to happen in the same way, what once seemed impossible and then unfeasible, becomes possible and then finally the standard. This sequence continues to be played out in major industries. Take the example of electric cars. It is within recent memory that electric cars were derided as expensive, unfeasible for practical purposes with technological drawbacks that could not be solved in any meaningful way to make their adoption widespread. Yet in 2019 automakers committed $225 billion to electrification in the coming years, and the usurping of the petrol engine by its electric counterpart in automobiles is almost taken as a given. This rapid transformation is well underway, and what has been striking about it to date has been that most carmakers have been caught flat-footed.[50] The maritime industry must not be caught in the same position.

There are ways for decision-makers in maritime to navigate these gradual changes and make sure that they are best positioned and prepared for the future. In reality, many maritime companies and businesses will not be able to realize significant benefits from such investments in the short term, but the investors who prepare for the future could realize a significant and sustained competitive advantage as a result of their foresight. In order to do so, maritime business leaders should have a basic understanding of the present and future prospects for changes that will happen, how the technology works, the risks involved, the problems that can be solved and how they should prepare to exploit the potential of ammonia as a fuel.

The work highlighted in this paper shows that a similar transition in shipping is possible and those that are bold to take action and to realize the possibilities with ammonia could gain an advantage through their early adoption and those with a longer-term outlook could see their investment pay off. There are obvious uncertainties related to how things will develop to 2050. Still, given the lifetime of vessels, a prudent investor would carefully consider the risks of continuing with business as usual. Our research reveals some key insights for shipowners that are considering preparing for a carbon-free future in the short, medium and long term:

- The use of conventional ammonia in the maritime industry provides ship operators with a viable intermediate pathway until the future green ammonia industry is built up. Ammonia could fulfil dual roles as a bridging fuel and a future zero-emissions fuel of choice.

The initial market build-up is likely to be bolstered both by demand from the nascent green ammonia industry, which is also developing for fertilizers, and for ammonia as a storage medium for transport of hydrogen which will be applied to decarbonize other industries[51] (as exemplified by the Japanese strategy for energy carriers under the SIP program[52]).

Dual-fuel engines could offer flexibility for vessel operators. A dual-fuel option could give confidence in the availability of fuel as the marine industry transitions and infrastructure is still in the process of being established. The vessel operator would also be better prepared for specific ports or emission control areas that have been introducing stricter regulations on emissions at berth by having the ability to switch to compliant green ammonia where available. It can be expected that the European Union will implement its own intra-EEA emissions standards in the shipping sector and that shipping could be added to the European Emissions Trading Scheme (EU ETS)[53]. Such a move would increase the demand for allowances, giving an advantage to any

[50] https://qz.com/1762465/2019-was-the-year-electric-cars-grew-up/

[51] The Royal Society: Ammonia: zero-carbon fertiliser, fuel and energy store

[52] http://injapan.no/wp-content/uploads/2019/02/3-SIP-Energy-Carriers.pdf

[53] https://www.lighthouse.nu/sites/www.lighthouse.nu/files/rapport_ets_eu.pdf

vessels that could utilize green fuels. Given the current rhetoric around climate change it is reasonable to expect that shipping may be included in the next EU Green Deal. Globally this pattern is repeated. China has recently introduced emission control areas (ECAs) and ambitious ports such as Los Angeles have zero emissions goals.[54,55]ECAs have been in operation for several years with ever-tightening regulations which require upgrades of vessels, increasing efficiencies and new technologies to be rolled out. Further regulatory pressure is expected on shipping operators to mitigate emissions, and with lifetimes of up to 25 years the process of retrofitting vessels to keep up with the regulation could come at considerable cost and operational risk for the vessel owner. Subsequently, vessels that are built in the proceeding decade will need to be equipped for a low carbon future. Such vessels will be operating in the period to 2050 where uncertainty is increased significantly, particularly considering aggressive targets set by certain regions identified above. There are significant risks attached to investment in a vessel that has not been created with a view to flexibility for an emission-free future, dual-fuel engines could mitigate such impact. Dual-fuel vessels may come with a higher upfront cost, but the cost of being redundant, inflexible or mothballed in a fossil-free future would be higher. From this perspective, an ammonia-powered or dual-fuel vessel could be seen as a prudent long-term play for an uncertain future.

- Conventional ammonia is currently globally available at an energy cost and life-cycle CO2 footprint similar to VLSFO but causing no CO2 emissions from the ship.
- Global infrastructure is in place with ammonia terminals in 120 ports, with the introduction of ammonia bunker barges, as seen for LNG, being the only missing step.
- Future green ammonia with essentially zero CO2 footprint will be available as Green Certificates at a moderately increased cost and provides a clear path to achieving any CO2 emission requirement which the future will impose. The physical fuel, as well as the bunkering and onboard technology, is unaffected. Setting the green fuel percentage from 0-100% becomes a desk exercise.
- Ammonia can burn in an internal combustion engine with no SOx or particulate emissions and limited N2O/NOx emissions. Engine manufacturers have stated that it is possible to remove N2O/NOx from exhaust gases using a selective catalytic reduction unit which would leave just nitrogen and water. When comparing an ammonia ICE with a conventional ICE the technical performance is similar on power density, load response and part load performance but the conventional engine would have significantly more emissions overall.

[54] https://theicct.org/sites/default/files/publications/China%20ECZ%20Policy%20Update%20vF.pdf

[55] https://www.portstrategy.com/news101/environment/us-port-moves-closer-to-zero-emission-target

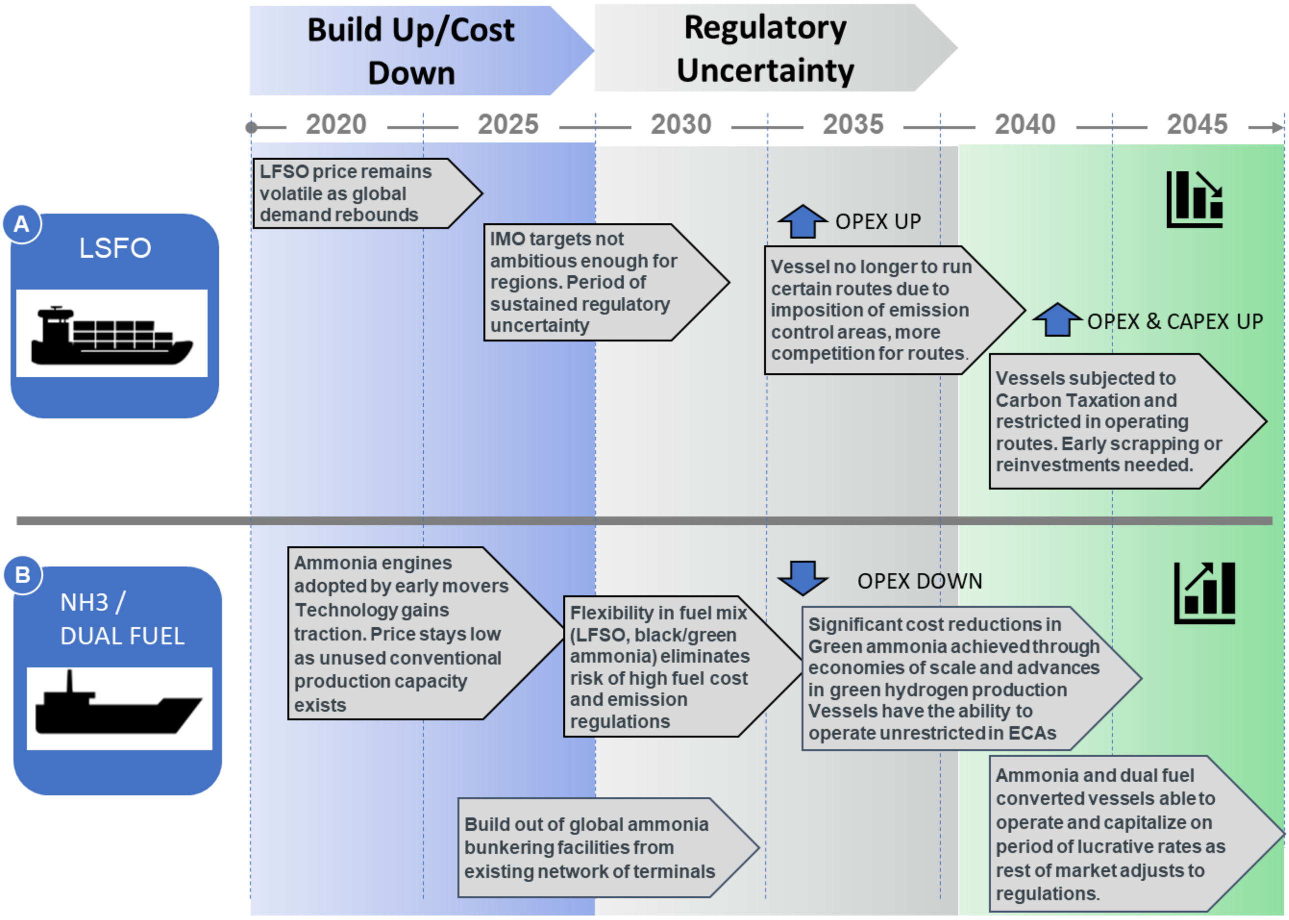


Figure 24. Vision of the path to 2050 for the VLSFO fueled ship owner and ammonia fueled ship owner respectively.

An additional risk that vessel owners need to consider is access to future finance. In the shorter-term access to green financing is becoming more prevalent, and financers are beginning to divest from investments conceived as risky from a sustainability perspective. The Poisedon principles which were established by 11 banks (inclusive of Citi, Societe Generale and ING) represent approximately $100bn in shipping finance and outline a global framework for integrating climate considerations into lending decisions to promote international shipping's decarbonization. Banks and financial institutions have begun to include an element of sustainability and environmental risk in their investment decisions. This is likely to be applied both in terms of access to preferential rates of financing and will also influencethe cost of capital.

- Prominent investors such as Blackrock, which controls $7 trillion in assets, have linked climate risk to investment risk and started divesting fossil fuel assets.[56] This decision is, importantly, not related to a moral or social conscience but based on simple risk and returns. It does not seem unfeasible that given the uncertainty in the

[56] https://www.commondreams.org/views/2020/01/21/blackrock-announcement-beginning-end-fossil-fuel-system

shipping industry it could follow a similar path given its disproportionate amount of emissions and the externalities imposed by continued use of fossil fuels.

Scorecard	
LFSO shipowner:	**Ammonia / dual-fuel shipowner:**
Period to 2050 characterized by major uncertainty: • **LFSO will remain volatile commodity due to geopolitical, economic and regulatory uncertainty.** • **Ambition of IMO may not be significant enough for regions.** • **Conventional fossil fueled vessels may be restricted to operate on certain routes unless major retrofit.**	**Certainty for long-term operation and success to 2050:** • **Conventional ammonia cost low due to surplus production capacity and low natural gas prices** • **Initial decade will be characterized by build up of global network and adoption of technology** • **Uncertainty in regulation bolsters position of ammonia vessel in period 2030-35.** • **Green ammonia cost reductions driven by economies of scale and parallel industries.** • **Ammonia vessel flexibility is profitable in later years. Customers also switch to non-fossil fuel operators.**
2050 Scorecard: • **Vessel is restricted in later years of operation. Restricted routes and ports access a potentially result in major retrofit or early scrapping of vessel.**	***2050 Scorecard:*** • **Vessel enjoys advantages in flexibility through 2035-2050, allowing more routes, competitive fuel and first-mover advantages.**

Table 10. Scorecard for the VLSFO fuel and ammonia dual fuel shipowner respectively.

Long-term projections of technology and price developments are subject to considerable uncertainty. Clarity beyond the 5-year mark is a challenging exercise, and predictions regarding both pricing and technology development have been shown to be markedly different to the reality of development in key technologies. Both the renewable energy and battery industries have repeatedly witnessed lower costs and greater technological advancement from what was projected. Therefore, it is perhaps more interesting to consider the drivers that may influence the trajectory of ammonia fueled ship's technical and economic progress over the lifetime of the vessel. In the example in Figure 24 the fortunes of a VLSFO and ammonia fueled vessel are qualitatively assessed throughout the period from 2020-2050. The scorecard is summarized in Table 10. The ammonia fueled vessel is comparatively more valuable to the vessel operator through the lifetime of the vessel. The principal reasons are due to the impact of variables that are challenging to predict.

Regulatory uncertainty is likely to be considerable up to 2050. In addition to what is mentioned above, global trade may shift from a continental to regional level as a result of the onshoring of supply chains and increasing protectionism. In such a situation regional regulation may play a more defining role in the competitiveness of vessels. Regions such as the EU have repeatedly stated that they may impose their own regulation on shipping emissions if it feels the IMO's are not ambitious enough and more emission control areas that stipulate zero requirements may become more prevalent.[57]

The above drivers could imply that an ammonia vessel could enjoy considerable advantages over a VLSFO vessel over the lifetime of a vessel. An ammonia vessel would provide the vessel owner with the flexibility to face these uncertainties. That flexibility could be translated to comparative advantage through an ability to operate whilst the LFSO vessel is restricted to more competitive and less lucrative markets. It is not unfeasible that a VLSFO-powered vessel could find it challenging to operate toward the end of its lifetime in certain areas due to for example the imposition of a carbon tax or an outright ban on the technology in certain ports.

[57] https://www.euractiv.com/section/shipping/opinion/time-to-steer-shipping-into-the-eu-carbon-market/

8 Authoring companies

Alfa Laval is today a world leader within the key technology areas of heat transfer, separation and fluid handling. Our company was founded on a single brilliant invention and innovation remains at the heart of everything we do. Alfa Laval's worldwide organization is present in almost 100 countries with 42 major production units and over 17,000 employees, with more than 3700 patents in areas that are vital to society.

Alfa Laval builds on a century-long commitment to lifetime vessel performance: we help shipowners and operators secure confident compliance with marine legislation, both through dedicated compliance technologies and by supporting the move to new fuels, we increase productivity, protect the engine, boost energy efficiency and minimize waste, contributing to higher earnings and lower lifecycle cost.

Hafnia is one of the world's leading oil product tanker owners and operators. Hafnia provides transportation of oil and oil products to leading national and international oil companies, major chemical companies, as well as trading and utility companies. Hafnia operates a fleet of 184 vessels in pools including newbuilds, of which 102 are owned or chartered-in including six owned LR2s, 27 owned and nine chartered-in LR1s, 41 owned and six chartered in MRs and 13 owned Handy vessels.

Hafnia has a strong history and reputation in chartering, operations and technical management and strives to offer customers the best integrated solution for their transportation needs. Hafnia is committed to maintaining high environmental, social and governance standards. The company has a global presence with offices in Singapore, Copenhagen and Houston and Mumbai.

Hafnia is affiliated with the BW Group, an international shipping organization that has worked in oil and gas transportation, floating gas infrastructure, environmental technologies and deep-water production for over 80 years, with six publicly listed affiliates.

Haldor Topsøe is the world leader in high-performance catalysts and proprietary technology for the chemical and refining industries. We enable companies in the chemical and oil & gas industries to get the most out of their processes and products, using the least possible energy and resources. And we are the forefront of developing sustainable technologies.

Our solutions address pressing global challenges, such as improving energy efficiency, enhancing food production for the world's growing population, and protecting our environment.

Our passion for science makes us world leaders in perfecting services, products and processes that make a positive difference in the world. We are involved in shaping the solutions and new technologies that customers will base their business on in the future.

With almost 80 years of experience in ammonia, our industry-leading solutions ensure reliable and safe operation with very low energy consumption and emissions. In the period 2000-2018, Haldor

Topsoe has designed and licensed 60 ammonia plants with an accumulated capacity of ~100,000 metric tons per day corresponding to 20% of today's operational capacity. This equals a market share of the ammonia catalyst market of around 50%.

Vestas is the energy industry's global partner on sustainable energy solutions. We design, manufacture,install, and service wind turbines across the globe, and with more than 115 GW of wind turbines in 81 countries, we have installed more wind power than anyone else. Through our industry-leading smart data capabilities and unparalleled more than 98 GW of wind turbines under service, we use data to interpret, forecast, and exploit wind resources and deliver best-in-class wind power solutions. Together with our customers, Vestas' more than 25,500 employees are bringing the world sustainable energy solutions to power a bright future.

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Siemens Gamesa Renewable Energy is a global company with more than 24,000 employees across offices in Europe, America and Asia. The company has activities of engineering, project management, testing and component production. Siemens Gamesa Renewable Energy's head office is located in Zamudio, Spain.

The company was founded as Bonus Energy in Brande in 1979 and acquired by Siemens in 2004 where it became Siemens Wind Power. Bonus was one of the most experienced Danish turbines manufacturers at the time of the acquisition, and in 1991 supplied the turbines for the world's first offshore wind farm, Vindeby. In 2017, it became Siemens Gamesa Renewable Energy in the merger between Siemens Wind Power and the Spanish renewable energy company Gamesa. Siemens Gamesa Renewable Energy is with more than 15 GW installed offshore capacity today still the market leader within offshore wind generation.

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