MAGPIE

SMART GREEN PORTS

Gaps and developments

Ammonia supply chain for future demand

D3.6 – GAPS AND DEVELOPMENTS AMMONIA SUPPLY CHAIN FOR FUTURE DEMAND

GRANT AGREEMENT NO.	774253
START DATE OF PROJECT	1 October 2021
DURATION OF THE PROJECT	60 months
DELIVERABLE NUMBER	D3.6
DELIVERABLE LEADER	Zero Carbon Shipping
DISSEMINATION LEVEL	PU
STATUS	V0.2
SUBMISSION DATE	30-03-2023
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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774253.

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Modification Control

Version #	Date	Author	Organisation
V0.1	20-03-2023	Thomas Butler	Zero Carbon Shipping
V0.2	30-03-2023	Thomas Butler	Zero Carbon Shipping

Release Approval

Name	Role	Date
Zenaida Mourão	Peer Reviewer	21-03-2023
Peter Mollema	Peer Reviewer	21-03-2023
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Executive Summary

The adoption of low-carbon fuels in European ports could exponentially progress Europe on its path to Net Zero. As hubs for global trade and homes to energy demand and supply, the impact of decarbonising the port ecosystem can go far beyond its geographical area. Low-carbon ammonia could play a significant role, but only if the supply chain is understood and gaps identified and closed. This report is a stepping stone on that journey.

Through evaluation of ammonia sources, routes to market and future off-takers we have mapped the supply chain, with a focus on the Port of Rotterdam as a case study. Our analytical models and interviews with key stakeholders have identified the gaps and developments that we have explained through the report.

Our findings were that for almost every gap – the ultimate solution was regulation. It remains the resounding pre-requisite to establishing an ammonia supply chain, but only when drafted well. Both 'facilitating' and 'incentivising' regulation is needed, but should be carefully considered with market participants. Pescriptive regulation of a fast-developing technology could hinder progress. Consideration could be given to exagerating the incentivisation of new low-carbon fuels disproportionately compared to energy saving technology – in an effort to accelerate progress to the end goal of a zero-carbon fuel.

We also found the promise of commercial-scale zero-carbon fuels, such as green ammonia, help yet hinder. This end-goal is vital, but intermediate steps, such as blue ammonia, could be encouraged to help progress.

1. Introduction

There is unlikely to be a single low-carbon fuel of the future and ammonia is well-placed to play a significant role. It's competition faces challenges: biofuels are short of sustainable feedstock, liquified hydrogen is a nascent technology, methanol remains a carbon-based vector and e-methanol is widely forecast to be more expensive than green ammonia.

However, ammonia has it's own challenges to address – notably its toxicity and low-carbon production. Demonstration projects and well-written regulation are key to expanding the proven, yet high-carbon, value chain of today. We will explore this below.

1.1 Report methodology

The purpose of this document is to map the value chain of ammonia from source to end use as a low-carbon vector, highlighting gaps and developments that must be addressed. The ambition is to accelerate a breakthrough in the supply and use of ammonia within ports.

Analytical models and expert interviews will form the basis of sections on supply and demand. Expert interviews are used for sections on operations and infrastructure. Findings and knowledge disseminated will feed into Work Package 9: Masterplan for European Green ports and Work Package 5, Demo 4: Ammonia bunkering demonstration. This report will be revisited in a second phase during months 48-54 of MAGPIE.

The report is split into four sections: supply, operations, infrastructure, and demand. How these sections interrelate on the value chain is visualised in figure 1 below.

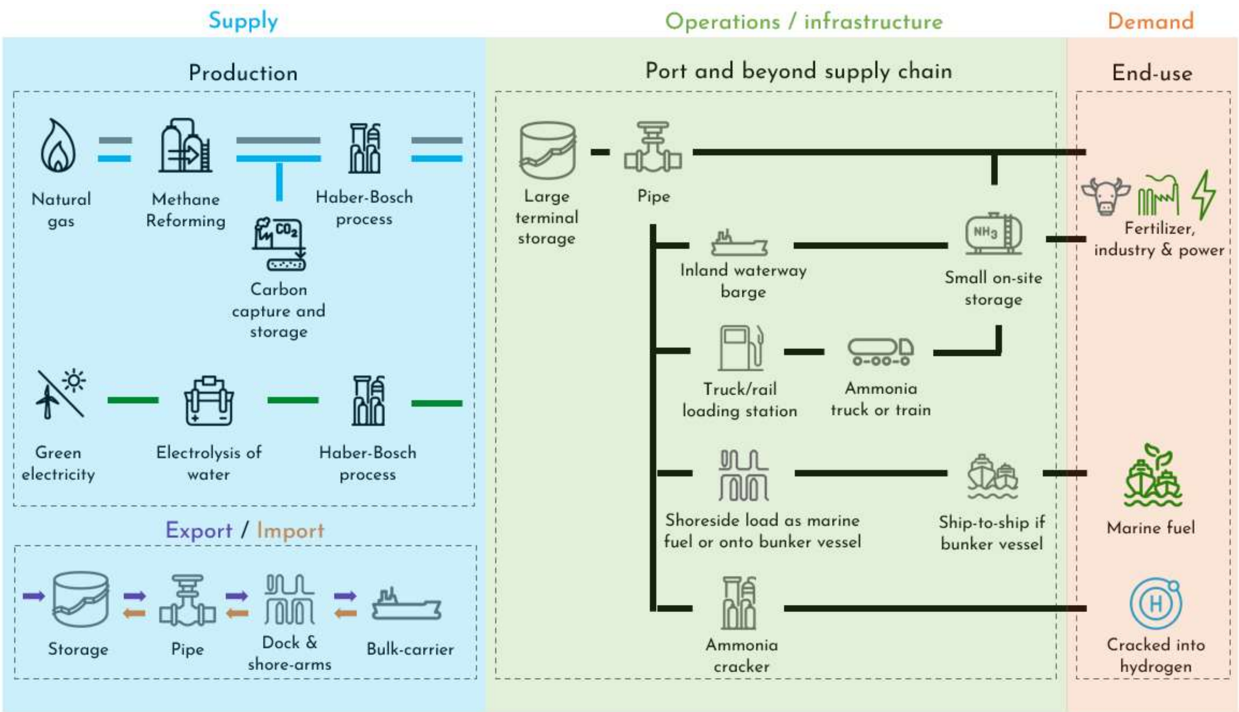

Figure 1: a simplified value chain diagram for ammonia

1.2 What is ammonia?

Ammonia is a compound of nitrogen and hydrogen with the formula NH_3. It is a gas at standard ambient pressure and temperature, with a boiling point of -33°C; efficient storage requires it to be under pressure or at low temperature.

It neither contains carbon nor necessarily produces carbon during its manufacture. However, its production is an energy intensive process, and its environmental impact heavily depends on its method of production.

Today, approximately 70% of ammonia is used to manufacture fertilizer and 30% for industrial applications including the manufacture of plastics[1].

In the future, ammonia holds potential as a hydrogen carrier and zero or lower-carbon fuel. It can be converted into useful energy directly via spark ignition or fuel cell, or indirectly via dissociation into hydrogen (sometimes referred as cracking). Its key advantage over hydrogen is its higher energy density and liquefaction temperature – aiding transport and storage. Ammonia is seen as the most technologically advanced method for the carriage of hydrogen by vessel.

Perhaps more than any other factor, ammonia's toxicity has and may continue to hinder its adoption as a future fuel and energy carrier. Nevertheless, a depth of industry experience to date and careful future management can mitigate risks.

1.3 Ammonia safety

Ammonia is produced naturally from the breakdown of organic matter – in the environment and within the human body. Exposure at these very low levels is not considered to pose a risk to health. However, at high concentrations it is highly toxic. Ammonia is hydroscopic, seeking water from the nearest source. The high moisture content of eyes, skin and lungs puts them at the greatest risk.

Ammonia has a pungent smell that humans can detect at approximately 3-5ppm, which can act as an early warning system. Irritation to the eyes, nose and throat can be expected from 2 hours exposure to 50ppm or immediately at 700ppm. Above 1,500ppm humans will experience pulmonary oedema, coughing and laryngospasm. Concentrations of 2,500-4,500ppm can be fatal in 30minutes whilst 5,000-10,000ppm is rapidly fatal due to airway obstruction[2].

When ammonia is released, it combines with humidity in the air to form a vapour cloud. This vapour cloud can travel long distances at ground level posing significant risk to populations in the vicinity of the release. Safety procedures at European ports will help to mitigate the risk. A release on-board a vessel poses a greater challenge. Just small concentrations of ammonia into the sea are sufficient to kill marine life.

The effects of large spills of ammonia on people and ecosystems are still relatively unknown and based on limited case studies. One potential gap in the supply chain is the challenge of testing large spills considering the toxicity.

[1] IEA, 2021, Ammonia Technology Roadmap, available here
[2] Public Health England, 2015, Ammonia Toxicological Overview, available here

Ammonia does not burn readily thanks to its narrow flammability range, high ignition temperature and low laminar burning velocity. The risk of an ammonia fire is lower compared to other fuels.

2. Supply

This section will explain the categorisation of ammonia, its availability, emissions, the challenges it faces as a lower-carbon fuel and identification of gaps in the supply chain. Our modelling then predicts geographical sources, pricing and timeline for use.

2.1 Production process

Grey, blue or green ammonia?

Ammonia production involves two main steps: firstly, isolating hydrogen via methane reforming or water electrolysis and secondly, reacting it with nitrogen to produce ammonia. The production pathway determines its informal classification as grey, blue, or green – although in each case the product is the same. Certification and legislation may categorize ammonia differently in each country, but this informal grouping does help to explain the production process. A simple process diagram is shown in figure 2.

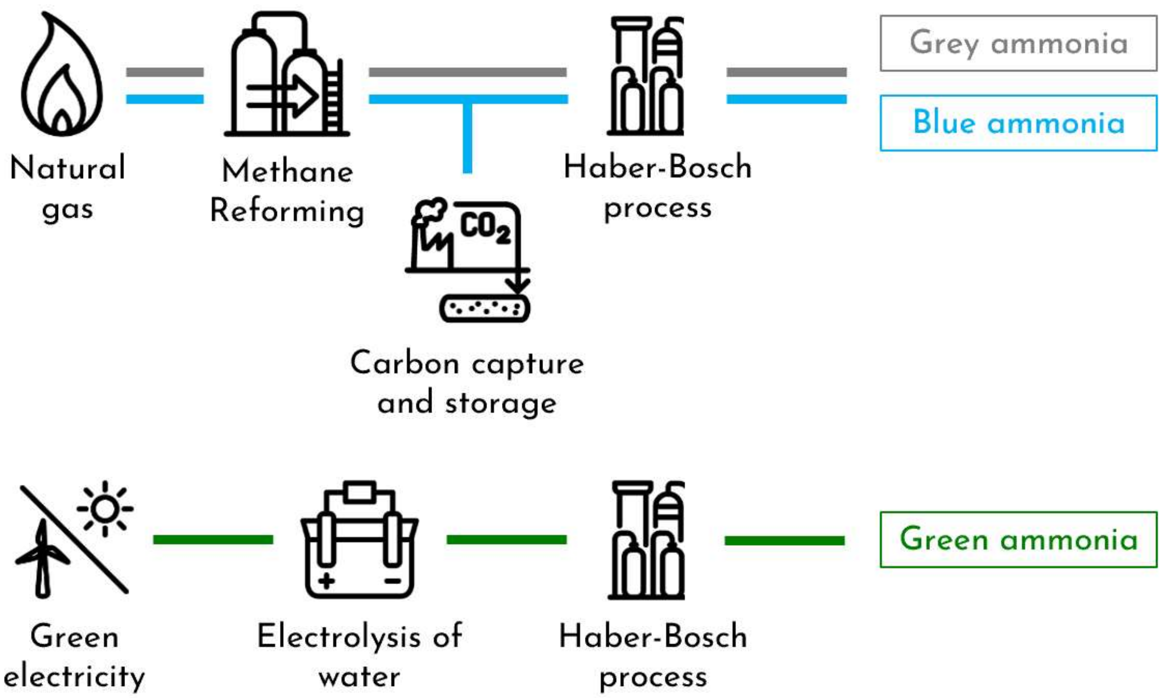

Figure 2: Key processes of grey, blue, and green ammonia production

Grey

Except for a fraction of a percentage, all ammonia produced today obtains its hydrogen from fossil fuels. 40% of the energy input to produce ammonia is consumed as feedstock, the rest as process energy, mainly heat. Approximately 72% comes from natural gas through methane reforming, 22% from the gasification of coal and the rest naphtha and heavy fuel oil[3].

This grey ammonia (sometimes referred to as brown) is hugely energy intensive and consequently produces twice as much carbon dioxide per tonne than steel production does. If the ammonia industry was a country, it would be the 16th largest emitter in the world. Therefore, the decarbonization of today's ammonia industry is critical to achieving greenhouse gas emissions targets[4].

Blue

The hydrogen content of blue ammonia is generated by conventional methane reforming but combined with carbon dioxide capture and storage (CCS). Whilst it will not be 100% CO_2 free, it will likely come close. CO_2 capture rates of new CCS technologies approach 100% and upstream methane leakage is gaining greater focus.

No blue ammonia is produced today. However, the two parts (grey ammonia and CCS) are both operational. Carbon capture is not new, there are 30 operational facilities globally with the majority in the USA where natural gas is abundant[5]. However, for perspective: global CO_2 emissions in 2021 were 33 billion tonnes[6] with CCS capturing just 40 million tonnes. Commercial barriers prevent greater uptake – but progress to scale up the industry is now being made.

Green

Green ammonia, or electro or e-ammonia, takes hydrogen from water electrolysis where hydrogen is split from oxygen using electricity. The Haber Bosch process reacts this hydrogen with atmospheric nitrogen to produce ammonia. Provided that the energy source is renewable, the end product can be 100% emission free, however the high temperatures required make this challenging.

Less than 0.04% of hydrogen production in 2021 came from electrolysis and no green ammonia is produced today. However, this is forecasted to change[7].

Availability

Ammonia is produced, shipped, and consumed globally today. However, almost all this ammonia is categorized as grey. Lower-carbon ammonia, in the form of blue and green, is expected in the next few years.

Around 185 million tonnes of grey ammonia is produced annually, with 20 million tonnes traded and transported by ship[4]. As a hydrogen carrier or low carbon energy source, this report has ruled out grey ammonia because its price and emissions are higher than those of low-sulfur fuel oil. Exceptions may be warranted for a transition step, for example testing new technology ahead of lower and zero-carbon supply.

[3] IRENA, 2022, Innovation Outlook: Renewable Ammonia, available here
[4] IEA, 2021, Ammonia Technology Roadmap, available here
[5] Global CCS Institute, 2022, Global Status of CCS 2022, available here
[6] IEA, 2021, Global Energy Review, available here
[7] IEA, 2022, Global Hydrogen Review 2022, available here

No blue ammonia is produced today. Its availability will depend on the development of carbon capture utilization and storage.

No green ammonia is produced today. Its availability will track the cost competitiveness of renewable energy generation, green hydrogen production and the incentives for lower-carbon fuels. There have been many project announcements and feasibility studies, but so far, no FID for plants with any appreciable scale. No production at scale is expected for several more years.

Availability of ammonia versus alternative fuels

It is widely accepted that there will not be a single low-carbon fuel of the future. There will be competing fuels for each demand segment, and their commercial availability will impact their adoption. For example:

Biofuels (e.g., bio-diesel, bio-methane and bio-methanol) are the most established lower-carbon fuel competitor and offer comparable emissions reductions to ammonia and are commercially available today. However, demand will exceed supply. Availability is limited as biomass harvesting must be balanced with natural regeneration to be sustainable. Interestingly, estimates of biofuel availability have been falling over recent years and regulations have become stricter.

E-methanol, produced from renewables, is less toxic than ammonia and similarly relies on renewable electricity build out and the development of electrolyser technology to become commercially available. Additionally, it requires a low-carbon source of CO_2. E-methanol is forecast to be more expensive than green ammonia which could hinder its adoption (Figure 25).

Liquified Hydrogen is a nascent technology and faces technological challenges to become commercially available.

Green production challenges

It's often quoted that electrolysers could run only when there is excess renewable generation. However, this raises two significant challenges for green hydrogen. Firstly, it gives a highly variable and unpredictable production profile which is difficult to manage for offtakers. This is especially relevant during the early years of production when storage capacity is limited. Secondly, running electrolysers on 100% renewable energy means they may not run for significant lengths of the day due to the variability of wind and solar. The IEA estimates that capex is in the range of $500-1400/kWe for alkaline electrolysers, $1100-1800 for PEM and $2800-5600 for SOEC[8]. Our high-level modelling shows that capex may be in the region of 50-70%+ of the total green hydrogen production cost. The unit cost will be dramatically increased if these assets sit unutilized when renewable resource is too low.

Moreover, Ammonia synthesis is carried out at elevated temperatures (over 375°C) and pressures (over 100 bar). Reaching this temperature and pressure from ambient is energy intensive and thus benefits significantly from constant operations. Some synthesis assets have suggested it could take them three days to restart operations fully should operations have to shut down.

[8] IEA, 2022[2], Electrolysers: technology deep dive, available here

Therefore, the need for some dispatchable energy to complement renewables is apparent. It may be necessary initially to expand the definition of 'green ammonia' or term a new phrase that allows production plants to balance their energy supply with non-renewable power and fuel e.g., gas with carbon capture.

Price

Grey ammonia prices show correlation to the natural gas price. A recent price history is shown in figure 3 below.

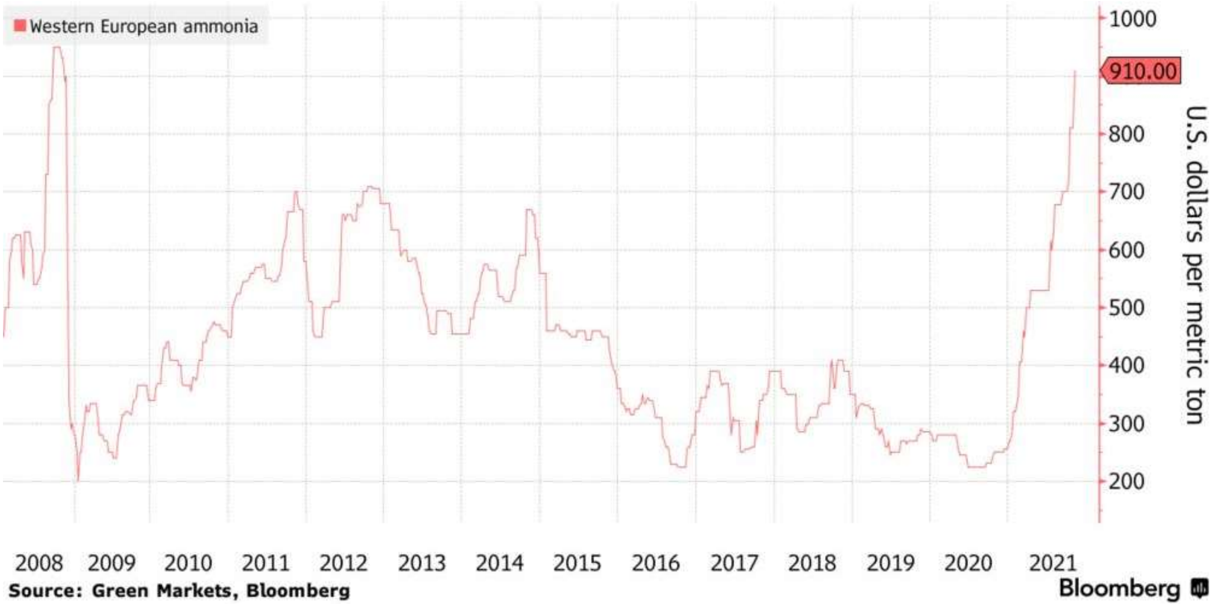

Figure 3: Grey ammonia price history, Western Europe

The cost of green or blue ammonia is dependent on the cost of hydrogen, evaluated under WP3.3. Our high-level modelling shows ammonia produced using $2/kg blue or green hydrogen may be in the region of $500, whilst $4/kg hydrogen may produce $900 ammonia. Hydrogen could be significantly more expensive – especially in the near-term, raising the cost of low-carbon ammonia further.

Emissions

Production of ammonia via unabated fossil fuels (grey) is highly energy intensive and thus emits significant GHG emissions. Capturing most of these CO_2 emissions (blue) or production via electrolysis with renewable power (green) creates a lower-carbon fuel.

Encouraging progress is being made on green and blue ammonia production methods. The below chart (figure 4) forecasts how ammonia's full value chain emissions stack up versus competing fuels for marine shipping.

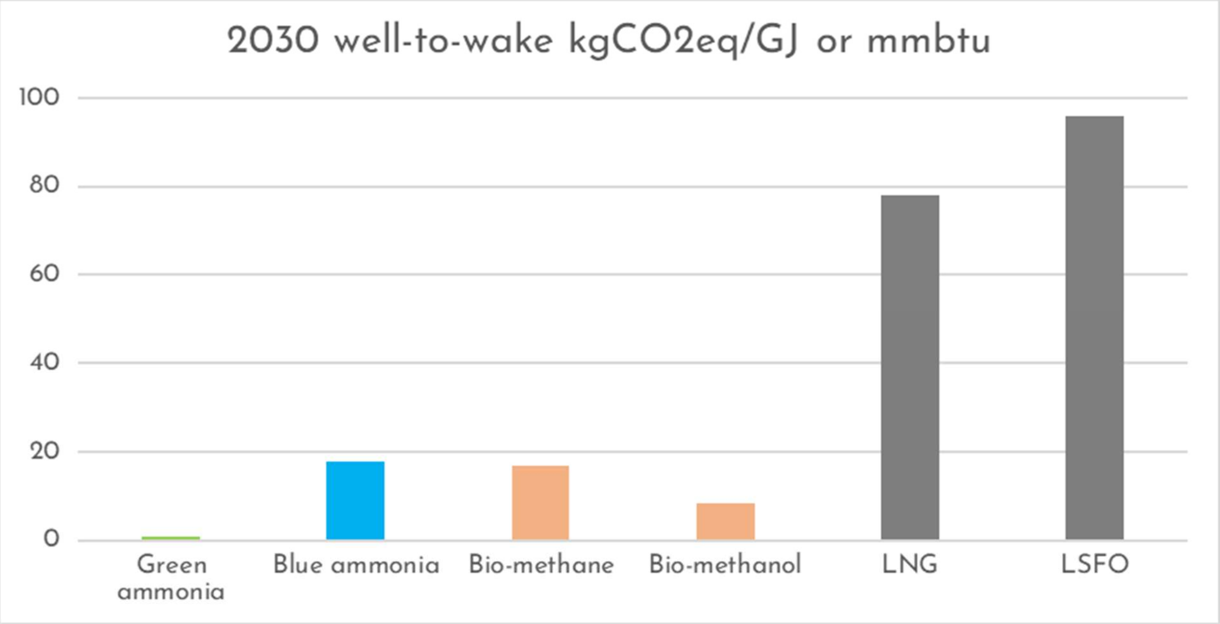

Figure 4: well-to-wake shipping emissions by fuel [9]

2.2 Imported or domestic production?

Domestic sources

The additional processing of hydrogen into ammonia utilizes more energy. Where hydrogen can be used directly, it is more efficient to do so. As such, we expect ammonia to only be produced where it is directly required (e.g., fertilizer or in the future, marine fuels), where incentivized (e.g., displacement of coal for power) or when transporting long distances. As such, we expect ammonia production within Europe may be limited. Nevertheless, we see opportunities where ammonia could be sourced domestically:

Blue

Production of blue hydrogen requires access to natural gas supply and geologically suitable sites for the storage of carbon captured. Europe is short gas, importing via pipeline and LNG. However, progressive governmental schemes in countries with domestic production and access to carbon storage sites, notably Norway and the United Kingdom, may see some of the first blue hydrogen produced globally. However, we forecast this hydrogen to be consumed domestically rather than converted into ammonia. If this policy support continues and projects ramp-up, it is possible that conversion to ammonia grows in attractiveness.

Green

A massive build-out of renewables in Europe may create periods of surplus generation during

[9] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022[2], Preparing Container Vessels for Conversion to Green Fuels, available here

periods of high availability. This excess capacity could run electrolyser projects and potentially ammonia production. However, as discussed earlier, it is challenged by a need for significant storage capacity to maintain a manageable offtake profile by a capex that is too big an expense to not run plants relatively constantly. Should capex costs reduce over time, this may become less of an issue.

Production of green hydrogen and subsequently ammonia requires ample land, renewable potential, and governmental support. Whilst reasonable renewable potential exists, the build out of renewables in Europe may be delayed. The time it takes to secure licensing for renewables dwarfs the construction period for building wind, solar and electrolysers. The EU is making efforts to accelerate the permit-granting process and the impact of this will be critical. If renewable build-up is delayed, hydrogen and ammonia production projects seeking PPAs from renewables will have to compete with customers looking to decarbonise their electricity supply. Because of the energy loss during conversion, it could be argued that new renewable electrons are better used to decarbonise electricity supply. Ultimately, this will be a decision made by governments whilst projects are subsidized. For example, in the UK the Electrolytic Allocation Round 2022 saw additional scoring for electricity supplied by new generation assets rather than existing ones – to "avoid negative impacts on wider decarbonisation".

Import sources

Potential import sources are mapped in figure 5. The USA could become a major exporter of low-carbon hydrogen, transported to Europe as ammonia. Cheap domestic natural gas (see figure 6) and approximately 70% of the world's carbon capture capacity combine with production tax credits under the Inflation Reduction Act of up to $3/kg h2 are the main reasons. Other countries with significant natural gas resource could follow suit, for example Qatar. However, to date there are very few planned projects. Import sources for green is evaluated in section 2.3 below.

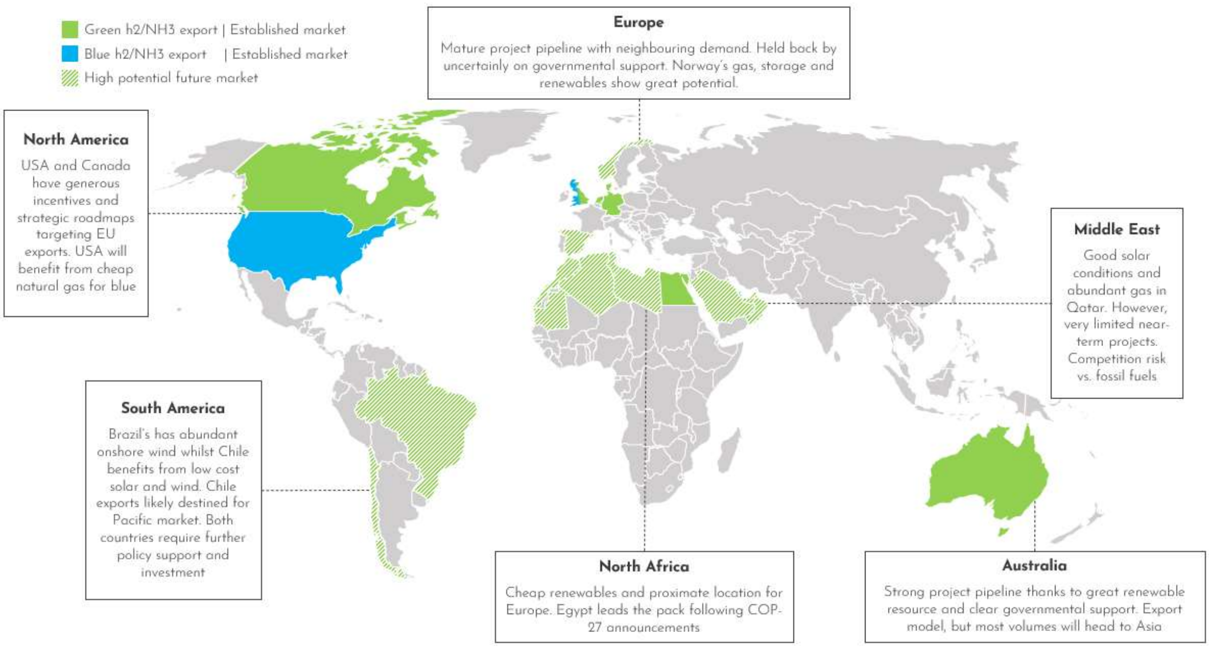

Figure 5: a high-level view of potential ammonia exporters for supply into European ports

Figure 6: historic price differential between European and US gas prices

2.3 Green ammonia supply costs for the Netherlands in the mid-term

We use the EWI global PtX Cost Tool to calculate and compare the supply costs of green ammonia. The tool determines production and supply costs from 113 origin countries worldwide to a destination country for two different cost scenarios (baseline and optimistic), featuring cost developments until the year 2050. For this report, we modify the EWI Global PtX Cost Tool introduced by Moritz et al., 2023 by incorporating the Netherlands as the destination country. A short but insightful description of the PtX Cost Tool is also found in D3.2.

Figure 7 shows the green ammonia supply costs to the Netherlands by origin country. The costs are calculated for the baseline cost scenario in 2030. We assume that the origin countries supply a quantity of 3 Mt ammonia per year to the Netherlands which equals the historic production capacity of the Netherlands[10] [11]. The figure reveals that production costs account for the largest share of supply costs. Although gaseous at standard conditions, ammonia can be liquefied at a temperature of -33°C, which requires significantly fewer cooling expenses than methane liquefaction at -162°C or the liquefaction of hydrogen at -253°C. In the liquid state, ammonia can be transported in large quantities by ship. Compared to the production costs, the transport costs of ammonia account for less than 10% of the supply costs. The share of transport costs in supply costs increases with increasing distance to the Netherlands. From the perspective of transport costs, it can be concluded that neighboring regions such as France or Denmark are advantageous for the import of green ammonia due to short transport distances. However, considering the share of production costs shows that more distant countries with higher RES potentials and lower capital costs can reduce their geographical disadvantages, such as Morocco, Qatar, UAE, and Chile, or

[10] OCI, 2021: Investor presentation, available here
[11] Yara, 2020: Yara, the company, available here

Canada. The four most economic origin countries for green ammonia supply are European countries close to the Netherlands or the Netherlands themselves. Norway is the most economical supplier of green ammonia. Domestic ammonia production in the Netherlands is the second most economical supply option. The Netherlands has significant and economical wind onshore and offshore RES potentials located on the North Sea coast. Therefore, despite being a relatively small country with a high population density, the Netherlands could produce green ammonia domestically at low costs. However, the ammonia production potential in the Netherlands is limited to about 100 Mt ammonia per year[12]. In the mid-field of the ten most economic origin countries are countries from the MENA-Region. Morocco has large and low-cost wind and solar energy potentials, and Qatar and the United Arab Emirates have particularly low-cost solar energy potentials. Moreover, ammonia can be imported from Chile and Canada. Both countries have significant and low-cost wind resources.

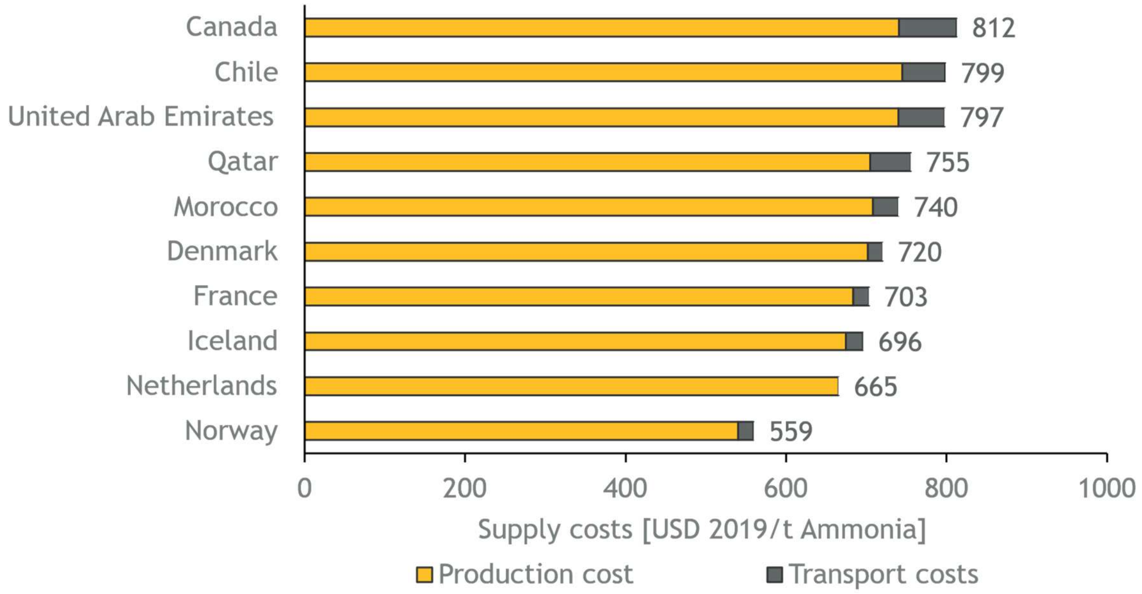

Figure 7: The 10 most economically viable origin countries for green ammonia supply to the Netherlands

Figure 8 shows a global overview of the deviation between the supply costs from an origin country to the Netherlands from the domestic production costs in the Netherlands. Countries from which importing green ammonia is more expensive than domestic production are colored in red, and countries from which import is less expensive than domestic production are colored blue. Countries are colored grey if not featured in the data or have a production potential of less than 3 Mt per year.

[12] Moritz et al., 2023: Moritz, Michael; Schönfisch, Max; Schulte, Simon: Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities. In International Journal of Hydrogen Energy 48 (25), pp. 9139–9154. DOI: 10.1016/j.ijhydene.2022.12.046.

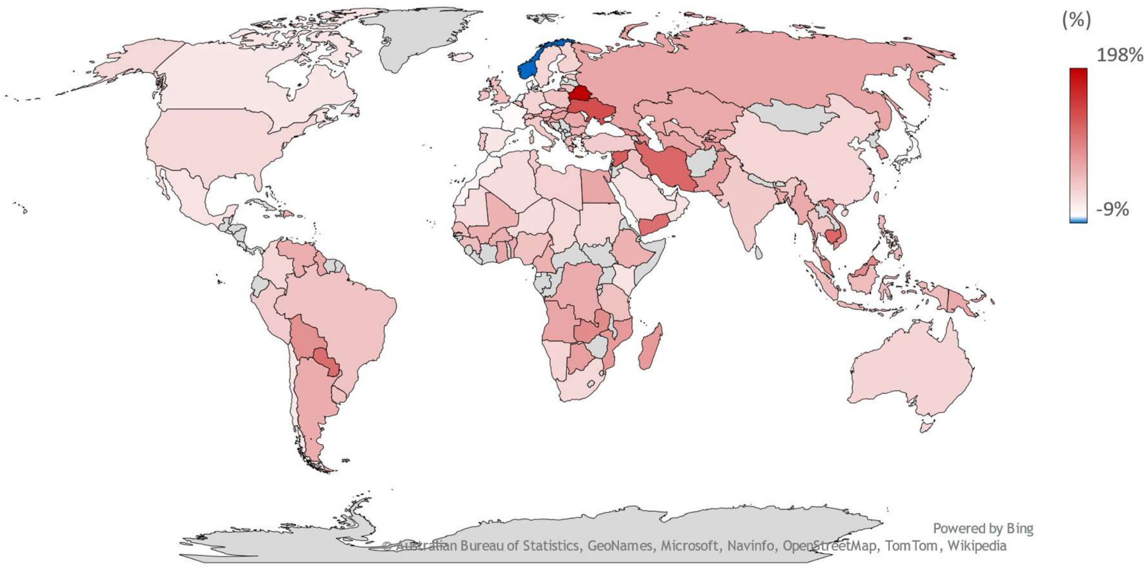

Figure 8: Deviation of supply costs from the origin country compared to production costs in the Netherlands

Norway is the only country that can supply 3 Mt ammonia per year below the domestic production costs of the Netherlands. Supply costs from Norway are -16% below domestic production costs. Countries that have limited (max. 22%) higher supply costs compared to domestic production in the Netherlands are European countries (Iceland +5%, France +6%, Denmark +8%,), MENA countries (Morocco +11%, Qatar +14%, United Arab Emirates +20%), Chile +20%, and Canada +22%. The cost comparison results show that the supply costs vary greatly depending on the country of origin. This variation is mainly due to differences in production costs, which are influenced by country-specific RES potentials and weighted average costs of capital.

The EWI Global PtX Cost Tool calculates supply costs based on RES potentials, technology costs, and weighted average costs of capital. To what extent a single origin country will supply a particular destination country does not depend only on economic conditions. Long-term commitments and contracts between origin and departure countries are valued tools to establish trading in renewable energy commodities such as green ammonia. With some of the ten most economical supply countries determined in our analysis, agreements on trade in hydrogen-based energy commodities are already planned or have been signed. These include agreements between the European Union or members and Canada, Chile, UAE, Qatar, Morocco, or Norway. These agreements can secure and reinforce the market ramp-up of green energy commodities on the path toward climate neutrality.

Production costs for conventional ammonia based on grey hydrogen are highly dependent on the price of natural gas and range from 300 to 700 USD/t ammonia in Europe[13] [14]. Compared to the grey ammonia production costs of 500 USD/t, the supply costs of green ammonia are 25% to 65% higher, depending on the origin country. Accordingly, a cost gap must be closed for green ammonia to become competitive. Based on Europe's all-time high natural gas prices in 2022, green ammonia could have already been competitive against

[13] Bartels, 2008, A feasibility study of implementing an Ammonia Economy, available here
[14] Boulamanti & Moya, 2017, Production costs of the chemical industry in the EU and other countries: Ammonia, methanol and light olefins, available here

conventional ammonia. In the medium term, natural gas prices are expected to decrease to historical levels[15], potentially increasing the cost gap between grey and green ammonia again.

In conclusion, imports from Norway and the domestic production of green ammonia might be the most economic option. However, as the future demand for green ammonia and for green hydrogen is still to be determined, there is a crucial question about whether the demand can be covered by these two supply options alone. If not, numerous countries near the Netherlands, from the MENA Region, and from North and South America could provide economically feasible supply options for green ammonia for a cost premium of less than 20% compared to domestic production costs in the Netherlands.

[15] EWI, 2022: Institute of Energy Economics at the University of Cologne, Scenarios for the Price Development of Energy Commodities, available here

3. Operations and Infrastructure

Whilst ammonia is produced, transported, stored, and used today, hurdles lie in its path to be used as a lower-carbon fuel. This section aims to highlight those gaps in the supply chain to ensure they receive the attention and funding they require.

3.1 Ammonia value chain

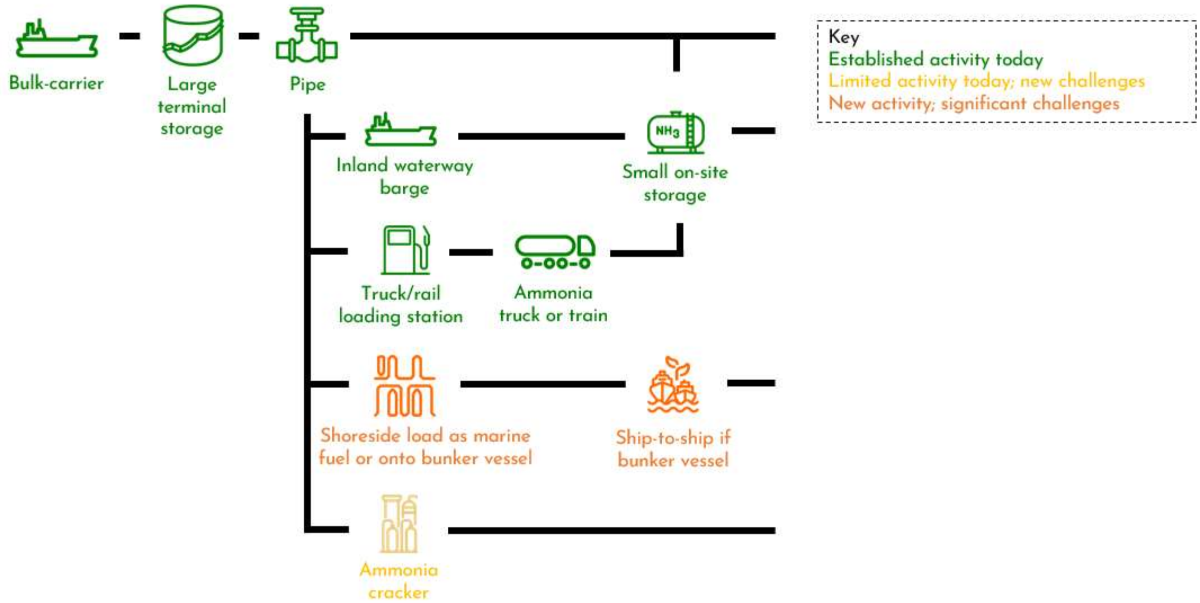

Figure 9: Status of operations and infrastructure within the ammonia value chain

Bulk-carrier transport of ammonia

20 million tonnes of ammonia is transported by ship today[16]. We estimate that 50% is transported on mid-sized gas carriers with capacity around 30,000 – 45,000m3. We also estimate that around 25% is transported on large gas carriers from 45,000 – 70,000m3 in size with the balance on small gas carriers under 30,000m3.

This established activity is well understood but will have to scale up enormously – requiring significant growth in the gas carrier fleet. Bigger ships are possible but will likely require a switch from prismatic to membrane tanks as the forces applied as the ship rolls would otherwise be too great.

For perspective, Japan has drafted a roadmap that plans to grow the country's demand for ammonia as a fuel to 3 million tonnes a year by 2030[17]. Currently, 1 million tonnes is used a year for fertilizer – with none used as a fuel. 235,000 tonnes are imported with the rest

[16] IEA, 2021, Ammonia Technology Roadmap, available here

[17] Kiko Network, 2021, Hydrogen and ammonia co-firing in the power sector, available here

produced domestically. Using a mid-sized carrier of 45,000m3, their current import demand requires just 8 deliveries a year. If Japan imported all 3 million tonnes proposed for fuel, it would take 111 deliveries. To achieve 20% ammonia blend with coal across all the major utiliies' coal power plants would require 20 million tonnes – or 740 deliveries.

Storage

Ammonia contains more hydrogen than pressurized or liquified hydrogen itself and can comparatively be stored in inexpensive containers. To store ammonia it is either liquified under pressure (10 bar at 25°C) or refrigerated (boiling point -33°C). Large shore and ship tanks typically use refrigeration which is cheaper and safer, whilst trucks and rail use pressurized bullet tanks or similar.

Shore

Ammonia storage capacity at the production plant is sized based on ensuring sufficient storage to prevent unnecessary curtailment of the ammonia synthesis plant (subject to frequency of shipping, time to fill ships, inventory in receiving terminals and serve weather windows), ensuring sufficient inventory to fill an ammonia transport ship is key. The total production plant storage quantity is then split into an economically and safe number of tanks considering economies of scale and tank size limitations subject to seismic and plot restraints. Ammonia import terminals storage capacity is generally sized to accommodate offloading of a transport ships inventory.

Shore tanks are already of reasonable scale, typically no bigger than 45,000MT. As comparison, the largest floating roof tank is approximately 156,000MT, holding crude oil (Ras Badran, Egypt). Growth is expected with recently constructed tanks in Antwerp (BASF) and Qatar (QAFCO) are approximately 50,000MT. 70,000MT tanks are under construction in Saudi Arabia (NEOM GH2) and Texas City (GCA). Pressurized bullet tanks, Horton spheres and pressure vessels are typically sized up to 2,000MT.

A high-integrity ammonia storage tank should be double-walled. The primary container uses low-temperature carbon manganese steel. Insulation is typically applied in the annular space between the walls, whilst the outside container must be protected from ice which could cause heaving. The tank should sit on an elevated, piled concrete base to protect against frost heave, and surrounded by a dike in case of release. A minimum of two pressure relief vales and vacuum relief valves allows for safer maintenance. A vaporizer and emergency shut-off valve in the supply line to protect against low-low and high-high pressure scenarios respectively. There should be a separate standalone access tower. Only proven compressors should be used for refrigeration, with emergency power access. Three independent level and pressure indicators, multiple earthing bosses, a flare, wind direction indicator and emergency lighting are among the other requirements. Careful attention in design should be paid to possible extreme weather events and seismic activity. A full hydrostatic test of the tank (for at least 1 week) should be taken alongside acoustic emission tests before use. The acoustic emission test should also be carried out after first fill of ammonia and on a regular basis. This is not an exhaustive list and is only provided for an appreciation of the variety of safety considerations applicable.

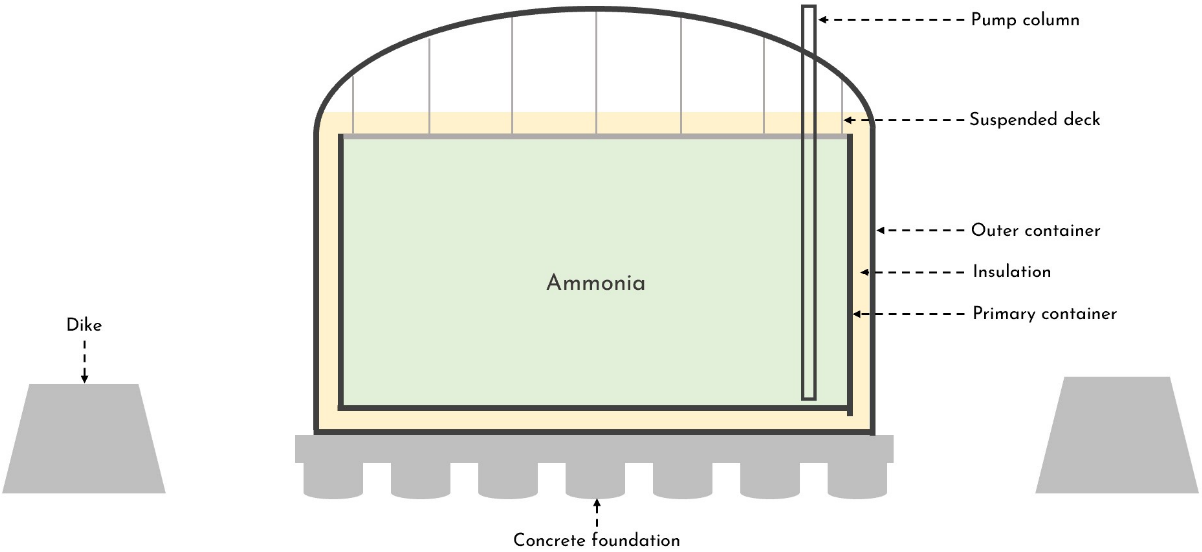

Figure 10: simplistic drawing of an ammonia storage tank

Figure 11: QAFCO's two 50,000 tonnes net capacity single-wall refrigerated ammonia storage tanks

The volume of storage required to meet the estimated demand scenario in the Port of Rotterdam (figure 12, referencing figure 23) is significant. This is a gap in the current supply chain and is expensive to complete. Therefore, parties may wish to consider the economies of scale savings possible through shared storage.

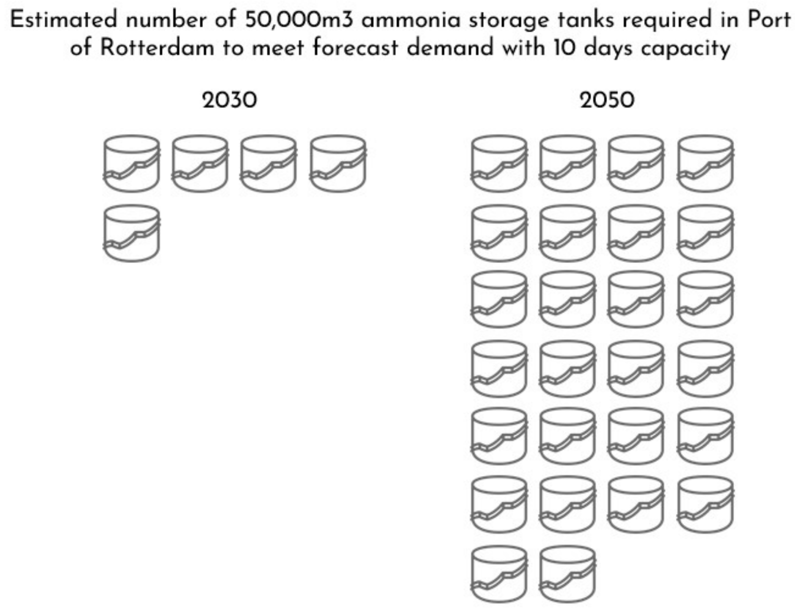

Figure 12: Visualisation of potential ammonia storage capacity in Port of Rotterdam

Floating

Some ports may look to floating storage rather than shore infrastructure to increase the distance to population. Existing or new gas carriers could be utilized. Large gas carriers are a similar size to the largest shore tanks (as detailed above). However, personnel on-board have limited evacuation opportunity compared to land and any leak at sea may have an immediate impact on marine ecosystems.

Furthermore, some early-stage research and development is on-going for a floating storage with regasification capability for transfer via pipeline to shore as a gas.

Small on-site storage

Smaller customer sites may choose to utilise bullet tank storage rather than the larger shore tanks mentioned above. This may be quicker, cheaper, and flexible for small volumes. These tanks are already commonly used for LNG. Ammonia could be stored for longer durations in bullet tanks than LNG because of the higher liquefaction temperature limiting the boil-off gas.

Pipeline

Ammonia pipelines have been operating for decades. In the USA over 5000km of mild carbon steel pipeline deliver around 2 million tonnes of ammonia per year. The longest ammonia pipeline runs between Russia and Ukraine at 2424km in length. In Europe only short pipeline systems are in operation today, the largest being 74km in Italy[18].

Ammonia in pipelines is transported under pressure in liquid form and provides an efficient and cost-effective route to end users.

Ensuring safety standards is critical ahead of the likely ramp-up in ammonia transportation by pipeline. Nine incidents have been cited in literature, with causes of: external corrosion (2), malicious acts (2), overpressure (1), maintenance work (1), metal fatigue cracking (1), seam failure and unforeseen free-thaw cycle (1)[18]. As such, safety must consider accidental and malicious acts of people as well as more engineering issues as corrosion.

Pipeline routing from storage to end-user will have to be carefully considered by ports considering the existing density of people and operations. For example, the Port of Rotterdam has significant existing operations and infrastructure to build around.

Inland waterway barge

Notable amounts of ammonia traverse waterways via barge in the USA today, primarily along the Mississippi River. Europe's inland waterways also see ammonia transportation by barge. Scaling up would be required to meet low-carbon demand.

Truck and rail

Ammonia is also already transported by truck and rail. Quantities are limited by this method.

Marine fuels bunkering

No ammonia bunkering operation has occurred today. This report will feed into an ammonia bunkering demonstration in the Port of Rotterdam under Work Package 5, Demo 4. This pilot project aims to identify and address the challenges.

Ammonia is frequently transferred between terminal and ship across European ports today. Bunkering of ammonia could be a largely similar operation but delivered into a fuel tank rather than storage tanks. However, risks associated with ammonia will necessitate additional safety provisions.

Of conventional fuel bunkering, LNG is the closest comparison. Likely routes to supply marine vessels include:

- In port, by shoreside terminal using fixed infrastructure
- In port, by barge or trucks
- In secure anchorage, by bunker barge

Shoreside loading may be restricted in some locations due to the risk to local population from possible release of ammonia. Concurrent bunkering with cargo operations is challenging due to the risk to shoreside operators. Losing the opportunity for simultaneous operations will have a commercial impact on vessel owners.

[18] Fertilizers Europe, 2013, Guidance for inspection of and leak detection in liquid ammonia pipelines, available here

Ammonia bunkering by bunker barge at a bunkering anchorage may decrease risk to local population by adding distance. However, operations at sea will be exposed marine conditions. If the secure anchorage is at some distance from the port, the potential for floating storage could be considered.

Larger transfer quantity can introduce greater risk and hence additional safety restrictions.

Ammonia has poor combustion characteristics which necessitates the use of a pilot fuel such as diesel. The quantity required is 5-15% for two-stroke engines and up to 30% for four-stroke engines[19]. Ships will have to ensure access to both ammonia and a pilot fuel.

Deep dive: bunkering patterns

Ammonia's utilisation as a marine fuel is challenged by its energy density - approximately 3 times the tank volume is required compared to fuel oil for the same range. However, many ships currently have ranges considerably longer than their actual trip length to allow them to take advantage of differences in fuel prices between ports. It is estimated that the top 20 bunker ports in the world provide over 90% of all bunkers to shipping. Bunkering is highly concentrated at the moment, but could this change with ammonia?

Commonly the bunker capacity of a vessel is such that the vessel can sail at design speed uninterupted for 30-40 days. However, as most vessels sail slower than design speed the range in practice is even larger. As a result, most containerships only bunker once per round trip in the cheapest port; commonly as do large bulkers and tankers sailing predominantly between two areas. Even short sea ships, sailing tramp along the European coast, will often pick-up bunkers along the way if cheaper.

With alternative fuels it is expected that this behaviour will change, especially for fuels with much lower densities such as ammonia, hydrogen and electricity from batteries. Owners will have to weigh up the reduction of cargo capacity to accommodate larger fuel tanks, or a reduction in range.

Depending on respective operations, new ranges could emerge. Some may remain large enough to allow bunkering optimisation, but others having to bunker by necessity after each trip or en-route.

Figure 13 provides an overview of how shipping ranges change when varying marine fuel and holding volume constant[20].

[19] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023, Ammonia emissions reduction position paper, available here
[20] TUDelft, 2023, Andrew Snaathost, Alternative marine energy carrier impact on ship powering and the environment, available here

	Range	Bulk carriers (km)	Tankers (km)	Container ships (km)
Fuel Oil	100%	38,163	30,174	26,914
Methanol	42%	16,206	12,813	11,429
LNG	40%	15,417	12,190	10,872
Hydrogen	12%	4,448	3,517	3,137
Ammonia	28%	10,690	8,452	7,539
Batteries	1%	457	361	322

Figure 13: Ship ranges by fuel type, holding storage volume constant

We theorise that should ammonia, or alternative low-carbon / lower energy density fuels, be adopted, that the current dominance of top bunker ports may be reduced. Although this may also be impacted by factors such as existing ammonia infrastructure in the port or concerns for safety.

In the second phase of MAGPIE 3.4, we will be investigating trade patterns, fuel use and vessel properties to identify how a switch to ammonia would impact the vessel operations. The investigation will allow only for limited adaptation of the vessel especially draft and size restrictions together with potential to lengthen or widen the vessel to allow for more storage of ammonia. To limit the scope the focus will be on vessels visiting the EU regularly. Ammonia cluster sizes will be used as a proxy for price variation to see if new bunker ports could emerge amongst the existing ammonia hubs.

We will present findings on the trade patterns, fuel use and vessel properties. They will be presented under phase two of Work Package 3, Task 4, and will also be relevant for Work Package 3, Task 6 models to be developed.

Ammonia cracker

After storing the product in the port there are three potential routes for handling the NH3. Onwards transport as NH3, direct use in the port as bunkering fuel, or cracking the NH3 to H2 for use in the port or onwards transportation. This paragraph focusses on the cracking process. The NH3 cracking process essentially comprises of four steps illustrated by a simple schematic in figure 14 and described below.

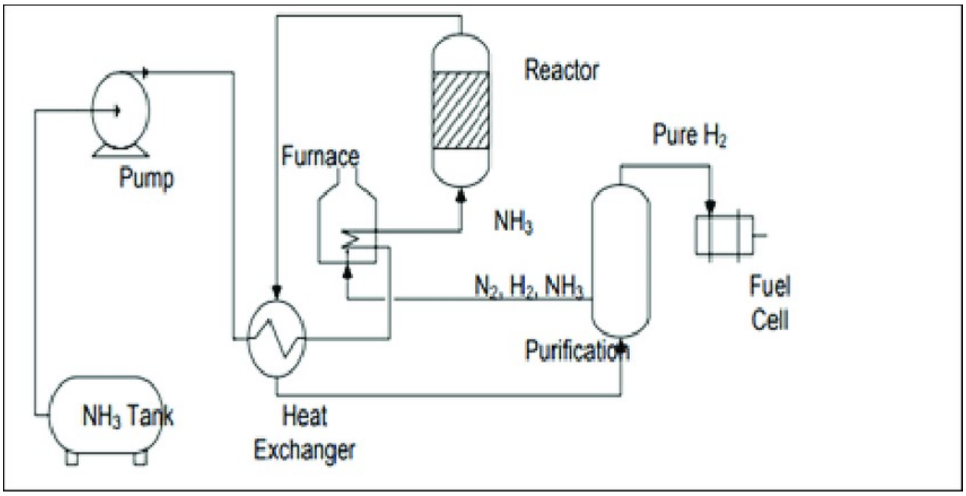

Figure 14: simplified flow diagram of NH3 cracking

Ammonia evaporation and preheat

Liquid ammonia feedstock (99.5 wt% pure) from storage is pumped to the ammonia evaporation and preheat section. Ammonia needs to be vapourised before being fed to the cracking furnace. Ammonia is preheated using energy contained in the cracked gas product.

Ammonia cracking

Ammonia cracking is a catalytic endothermic process i.e., one where energy needs to be supplied, to break the bond between N-H but also to ensure that the feed is at reaction temperature. Pre-heated vapourised ammonia is routed to the cracking furnace (with catalyst-containing tubes) where fuel is fired to provide the required additional energy. In order to have no CO- 2 emissions from the process, on cannot use external sources of fuel. Therefore, the possible choices are NH3 feed, cracked product gas, PSA tailgas and purified H2 product. There is no make-up of catalyst to the process. The catalyst is loaded at the start of the process (start of run or SOR) and needs to be replaced at the end of life (end of run or EOR). The EOR is typically marked by the maximum process operating temperature acceptable by the process equipment at which the required process yields can be obtained.

Heat recovery from cracked gas

Cracked gas from the furnace consists of N2, H2 and unconverted NH3. This hot gas stream needs to be cooled before being purified. Heat is extracted from this stream into the process feed stream.

The cracked gas stream may be washed to recover unconverted NH3 by routing the water-NH3 containing stream to a distillation column. Ammonia is recycled to the cracker feed to improve the overall process conversion.

Purification of cracked gas

Cooled cracked gas is routed to a PSA (Pressure Swing Adsorption) Unit to separate H2 with the desired product purity. The tail gas (that containing the rest of the components as well as some (approx. 10-15%) H2 in the feed to the PSA) is routed to the cracker as fuel gas. Product H2 gas may be compressed to the process operating pressure.

Cracking at large scale is still in development. Whereas each individual step in the process is technically proven, large scale crackers for Ammonia have not been built. It is anticipated that quick scale up will be realised if the market demand increases. For now there are several projects announced, including in the ports of Brunsbüttel, Antwerp or Rotterdam

The resulting Hydrogen can be fed into the local, regional or national pipeline network

Advantages:

As NH3 is a common chemical a lot of the infrastructure is already in place. Although cracking is a new step in the value chain it can be relatively quickly implemented. Crackers can ramp up and down with the demand and balance the pipeline systems. Manufacturing in remote locations and transport to and from the ports is actively being developed at the moment.

Disadvantages:

NH3 is a toxic chemical with large environmental impact in case of incidents. Large capital layout is required to design and build the installation, but per kg of H2 produced over the design life of the plant these costs represent only a fraction of the total H2 price.

Recommendations:

Regulation and specifications for handling and storing NH3 need to be up to date to enable safe processes.

3.2 Existing infrastructure

Existing ammonia terminals and production in Europe

Ammonia's toxicity may influence port developments unevenly, driven by local, regional and country-level judgement of ammonia. Ports with existing ammonia infrastructure may be faster to adopt ammonia as a low-carbon fuel versus ports to whom it would be a new chemical.

To this effect, Europe is already home to over 40 ammonia terminals (figure 15). Of the top 15 busiest ports in Europe, by cargo tonnage, two-thirds have an ammonia terminal within the port itself or in close proximity. Notable ammonia absentees include the ports of Amsterdam, Algeciras and Marseille, the 4th, 5th and 8th largest.

It is additionally worth noting that there does not appear to be a notable lack of ammonia infrastructure in ports with large, proximate populations.

Figure 15: blue dots indicate locations of existing ammonia storage terminals in Europe (compiled from DNV & industry sources)

This logic can also apply to the ports and regions where ammonia production plants already exist (figure 16).

Figure 16: location and production capacity of ammonia plants in the European Union and Norway[21]

Potential to convert LNG shore infrastructure

It is possible to convert LNG terminals to ammonia, but it is neither simple nor cheap. It is likely to offer saving versus building new but may be more costly than expanding existing ammonia's terminals where it is possible to do so.

Pre-investment would maximise re-use of equipment and offer cost-savings versus conversion and replacement. This pre-investment would likely include, but is not limited to, stronger fabrication and foundations for the storage tanks, toxicity management in the process control system and different materials for items such as seals and gaskets. Without pre-investment storage tanks will likely be limited on capacity and cycle speeds, replacement of the process control system and new seals and gaskets.

Each part of the import terminal system would need to be specifically evaluated. For example, the boil-off gas system may require minimal pre-investment or conversion cost. On

[21] DECHEMA, 2022, Perspective Europe 2030, Technology options for CO_2 emission reduction of hydrogen feedstock in ammonia production, available here

the other hand, pumps may need to be completely replaced to handle ammonia's liquid density 1.5x that of LNG.

Additionally, LNG terminals would have to re-permit their sites for use of ammonia. This could be challenging considering they have not been located with consideration to the additional environmental and social risks of ammonia.

Another consideration is the additional energy consumption of an ammonia terminal versus LNG. Increased power will be required for pumping due to ammonia's energy density being 1.5x higher than LNG. If cracking is included, then this adds substantial heat demand. If this is not procured from sustainable paths it undermines the conversion.

Thus, conversion of LNG infrastructure will come at a cost to terminal owners. Whilst this cost can be reduced through pre-investment, owners will bear the risk that the shift to ammonia doesn't happen. However, it can be argued that ammonia poses the most promising use of LNG infrastructure in a decarbonised world – when compared to alternatives:

Conversion of LNG infrastructure for use with liquid hydrogen does not appear possible. To manage the required liquid temperature of -253°C for hydrogen versus -162°C for natural gas would require complete replacement of tanks, pumps, vaporisers, boil-off gas system, vents/flares, piping etc. Pre-investment is either not possible or uneconomical. It is a novel concept and will require a lengthy research and design period.

Methanol is already well understood and may be able to utilise the storage tanks with minimal expenditure. Elements such as piping, valves and vents would all likely benefit from pre-investment. The boil-off gas system would become redundant. However, it is still a carbon-based vector.

LOHC may require similar adjustments to infrastructure and the additional challenge of scaling up dehydrogenation.

Potential to convert ships to use ammonia as a marine fuel

Ammonia-fuelled vessel design will require holistic design changes versus vessels running fuel oil today. This includes storage tanks, bunker station, fuel supply system, ventilisation system, engine and more. In contrast, LNG-fuelled vessels already have many of these gas fuel handling systems and would require a far less radical design overhaul. Still, significant safety mitigations will also need to be developed, for example: ventiliation, restriction of access, separation of bunker station from accomodation, water curtain in bunker station, double walled piping and more.

The storage tank system will likely form the majority of the cost and be the key design consideration considering ammonia's lower energy density. Ammonia requires approximately 3 times the tank volume to deliver the same energy output as fuel oil. This will generally come at the expense of either range or cargo capacity. This isn't just a sticking point for ammonia, other green fuels will see similar challenges – see figure 13.

The optimisation of ammonia storage on-board may depend on the vessel type. Tankers could potentially utilise ISO Type-C tanks on deck limiting the reduction in cargo volume, whilst vessels without free deck space, e.g. container ships, would benefit from the greater space-volume efficiency of membrane or prismatic tanks built into the hull. Safety studies will conclude what is feasible.

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping[22] analysed that the optimal ammonia tank location for a 15,000 TEU container vessel is below the accomodation where the fuel oil tank would typically be located, but its larger size reducing cargo capacity by 4%. The fuel oil tank would be moved between cargo holds. This is shown in figure 17 below. For an LNG conversion, the LNG tank is already typically located where the proposed ammonia tank would sit and could be made ammonia-ready.

Figure 17: designs for a 15,000 TEU container vessel.

Top is fuel oil only. Bottom is dual-fuel ammonia and fuel oil.

However, this is only possible for a new-build. A ship converting to ammonia would install the ammonia tanks across three cargo bays to obtain the same range; a 7% reduction in cargo capacity. This is shown in figure 18 below.

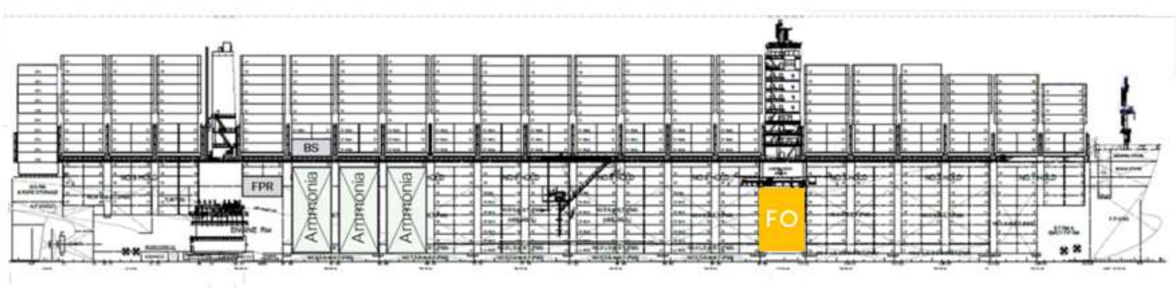

Figure 18: designs of the 15,000 TEU container vessel converted to run on ammonia

Conversions not only reduce the cargo capacity, but cost more than new-builds. When considering both aspects, the analysis showed that it is economical to construct the vessel

[22] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022², Preparing Container Vessels for Conversion to Green Fuels, available here

dual-fuel from new-build provided owners anticipate switching from fuel oil to ammonia within 8 years of operation. If switching after 8 years, it's economical to make no preparations (there is no value in semi-preparing the vessel). For LNG, the switch point is also 8 years of operation, but more preparations can be made at the new-build stage considering it requires a gas system either way.

Thus, vessel owners will need confidence of ammonia's establishment as a competitive marine fuel within 8 years to consider a new-build ammonia-ready vessel. Acceleration of ammonia's adoption would require some transfer of risk from vessel owners to the state.

4. Demand

This section considers the demand sectors, timeline for adoption, forecast volumes and the gaps in the supply chain that need to be addressed. We deep dive on the Port of Rotterdam demand.

4.1 Demand segments

For this report, we have categorized the demand for ammonia into five segments: fertilizer, industrial demand, power generation, marine fuels and as a hydrogen carrier, as visualised in figure 19 below.

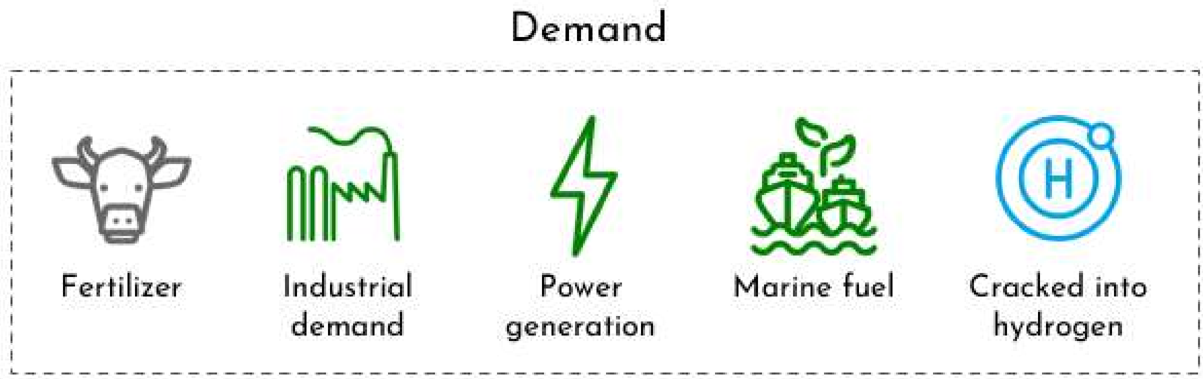

Figure 19: ammonia demand segments

Deep dive: direct use for power in marine propulsion

Despite its toxicity, ammonia is considered by many as an effective hydrogen carrier and future fuel for sea-going vessels, mainly because of its promise of being a cost-effective, carbon-free and relatively energy-dense fuel. However, choosing ammonia as a sustainable shipping fuel does not yet solve the question of how it is used as a fuel, or in other words, how the energy stored in ammonia can be converted into useful (mechanical or electric) power on board ships. Engine manufacturers are currently developing diesel-ammonia dual-fuel marine ICEs as a solution to this question. The fuel cell community is at the same time advocating ammonia-fuelled fuel cells (FCs).

From our market research, we are not aware of any dual-fuel ammonia vessel ordered today. This is not surprising considering that ammonia-diesel dual-fuelled engines and ammonia powered fuel cells are not expected to be operational before 2024 as per figure 20.

With only testbank demonstrations reported to date, and not always for full scale marine engines, the timeline may be delayed. When overlaying issues relating to the toxicity of ammonia, full scale implementation could be delayed until the 2030s.

However, it is expected to be even later than that as only testbank demonstrations have been reported to date and not always for full scale marine engines. With the additional issues relating to the toxicity of ammonia, full scale implementation of ammonia powered vessels is not expected before 2035-2040.

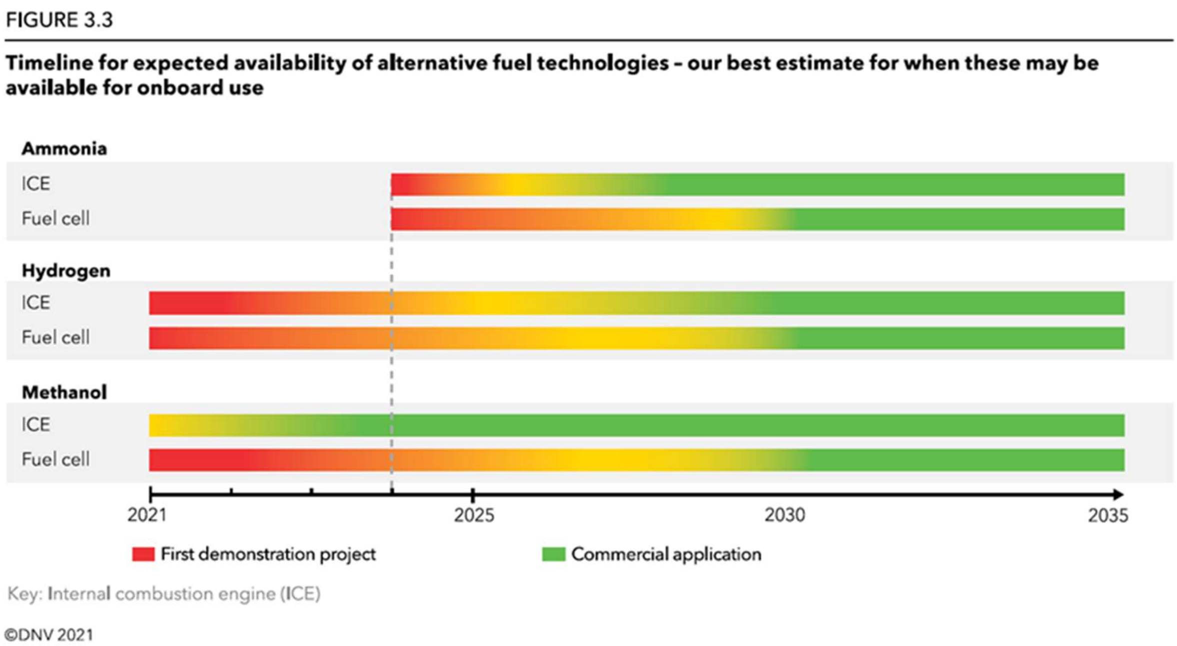

Figure 20: timeline for ammonia, hydrogen and methanol combustion engines and fuel cells[23]

Besides the use of ammonia in an internal combustion engine (ICE) in combination with diesel, which is a first step, research has also started on the use of ammonia in an ICE in combination with a fuel cell. The project, AmmoniaDrive, starts in April and will simulate and investigate this solution in marine operations. As can be seen in the figure below, any ammonia driven ICE will also require selective catalytic reduction (SCR) to stay below NOx limits. An advantage here is that an SCR also requires ammonia for its operation, so this can be taken directly from the bunkers, instead of dealing with additional tanks and systems for this purpose.

[23] DNV, 2021, Maritime Energy Transition Outlook of 2021, available here

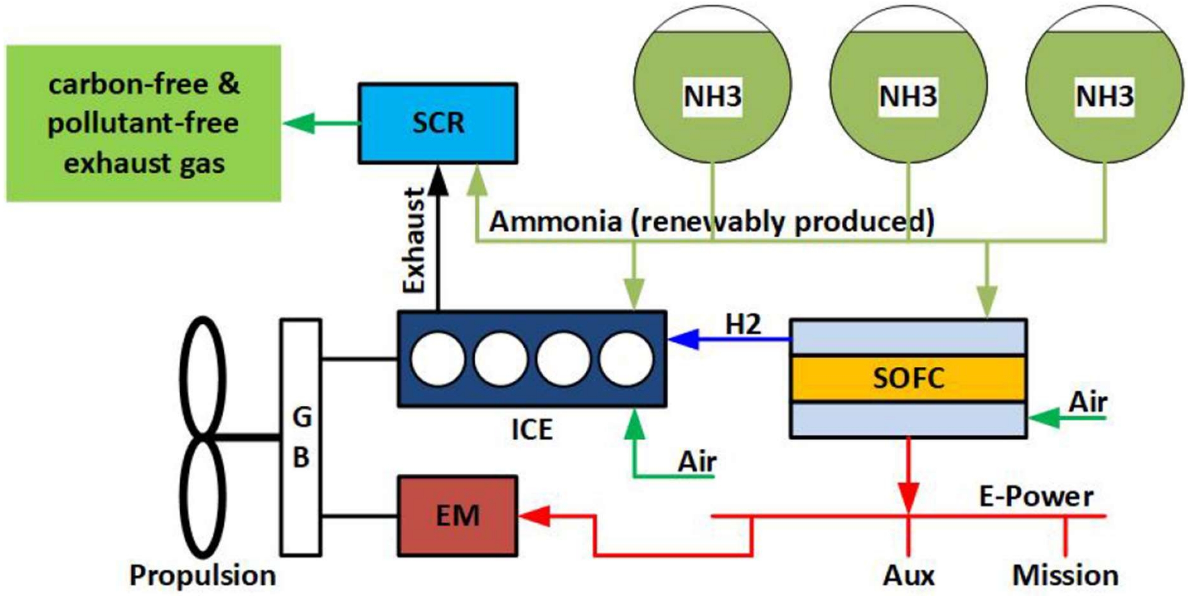

Figure 21: AmmoniaDrive's study of internal combustion engine combined with fuel cell

Deep dive: business case for ammonia powered port-based workboats

Ammonia is being explored as a potential fuel for dredgers and workboats as part of efforts to reduce greenhouse gas emissions in the maritime sector. We forecast the earliest potential introduction of ammonia-powered dredgers and workboats in the Port of Rotterdam to be 2028, due to the current technology readiness level of ammonia power sources (marine engines and ammonia fuel cells).

The demand for ammonia from port-based workboats may then increase rapidly. An optimistic forecast being 250 tonnes in 2028, 400 tonnes in 2029 and 500 tonnes in 2030. This is based on our estimation that the average dredger and workboat in the Port of Rotterdam has a total installed power of over 20MW and a 50% substitution rate in internal combustion engines.

However, this demand forecast assumes enough incentivisation to make low-carbon ammonia affordable commercially. This could be applied at the state level, or even locally. Within the Port of Rotterdam, an incentive is already in place to use greener fuels on board workboats. Every fuel has a 'Milieu Kosten Indicator' (MKI, translates to English as Environmental Cost Indicator) which is lower when the environmental impact of a fuel is lower (CO_2, NOx, Particulate Matter). When contractors tender for projects within the Port of Rotterdam, they get a notional discount on their bid calculated as the total MKI rating of their bid (as a result from the fuel type and quantity) multiplied by an amount of money per MKI point for the chosen fuel solution. This yields a 'Milieu Kwaliteits Waarde' (MKW, translates to English as Environmental Quality Value). In 2023, an MKW value of 2 euro per MKI point is commonly being applied. This does not yet result in an economically viable business case in combination with the ammonia fuel costs (figure 7) plus cost of bunkering. To enable an economical transition to this new technology, we estimate that a minimum MKW value of 10 euro per MKI point may be required (assuming no other separate incentivisation).

Providing support to Port Authorities to fund increased MKW valuation is one option to spur adoption amongst port-based workboats, when the technology and supporting regulation facilitates ammonia's adoption.

4.2 Demand forecast

Global demand

It's impossible to accurately forecast demand for ammonia into new segments - there remain far too many uncertainties around its adoption considering price, safety and technology. Many entities have attempted it nevertheless – but with wildly different results. For example, forecast demand for marine fuels has varied from zero to 900 million tonnes!

Nonetheless, a perspective on scale is important. Therefore, we have included a view from the International Renewable Energy Agency which combines several demand estimates for each and uses the median. It is also conveniently not dissimilar to our categorization. This is shown in figure 22 below.

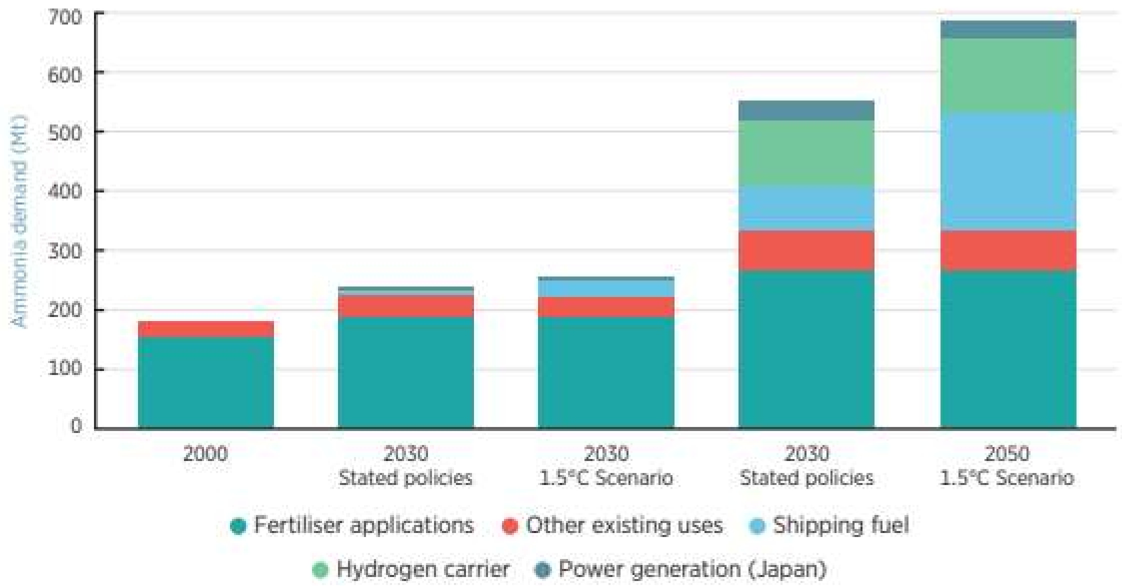

Figure 22: An ammonia demand forecast by segment from IRENA[24]

[24] IRENA, 2022, Innovation Outlook: Renewable Ammonia, available here

Port of Rotterdam demand deep dive

Figure 23 shows a forecast value chain for the Port of Rotterdam in 2030, drawing out imports, a high-level value chain and demand segments.

In 2030, 9.5million tonnes of ammonia (1.5million tonnes of hydrogen equivalent) is forecast to be imported by vessel. The biggest driver is power generation consuming almost half. The remainder will go into marine fuels, industry and be cracked into hydrogen.

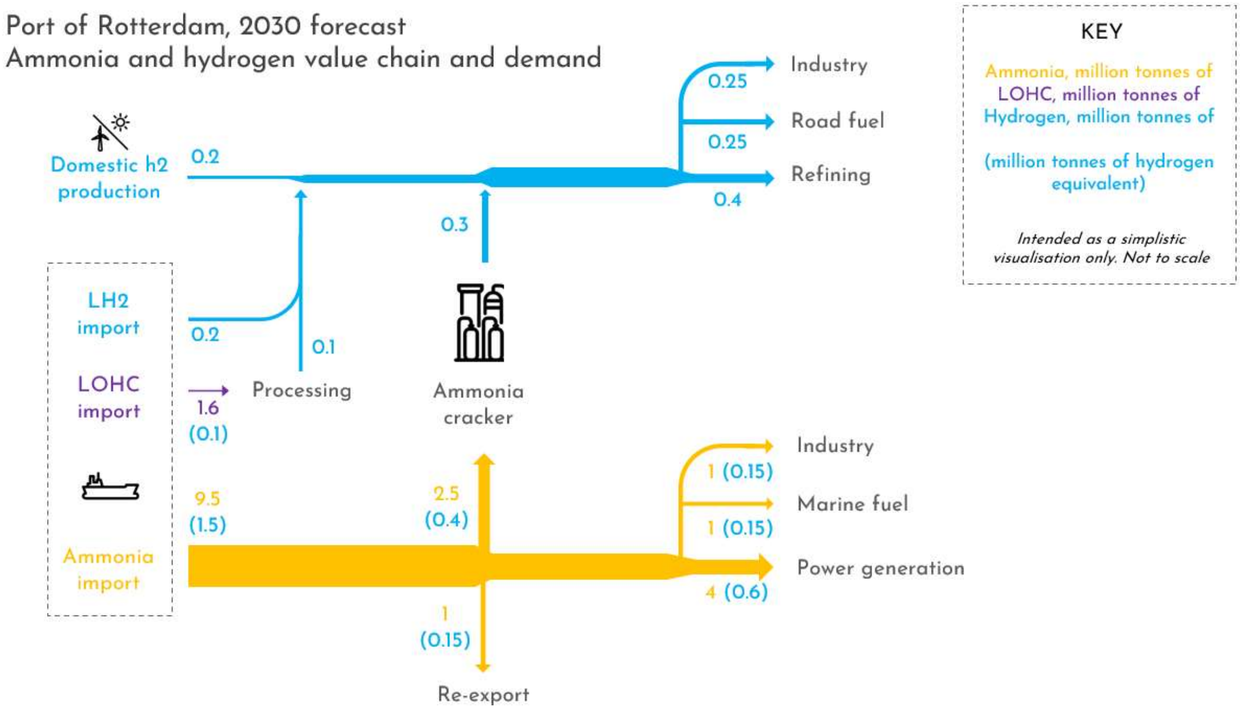

Figure 23 – forecast ammonia and hydrogen imports, demand and value chain for the Port of Rotterdam in 2030 (provided by the Port of Rotterdam)

By 2050, the ammonia value chain in the Port of Rotterdam is forecast to grow significantly to 47million tonnes imported. Marine fuel becomes the biggest consumer. This is shown in figure 24 below.

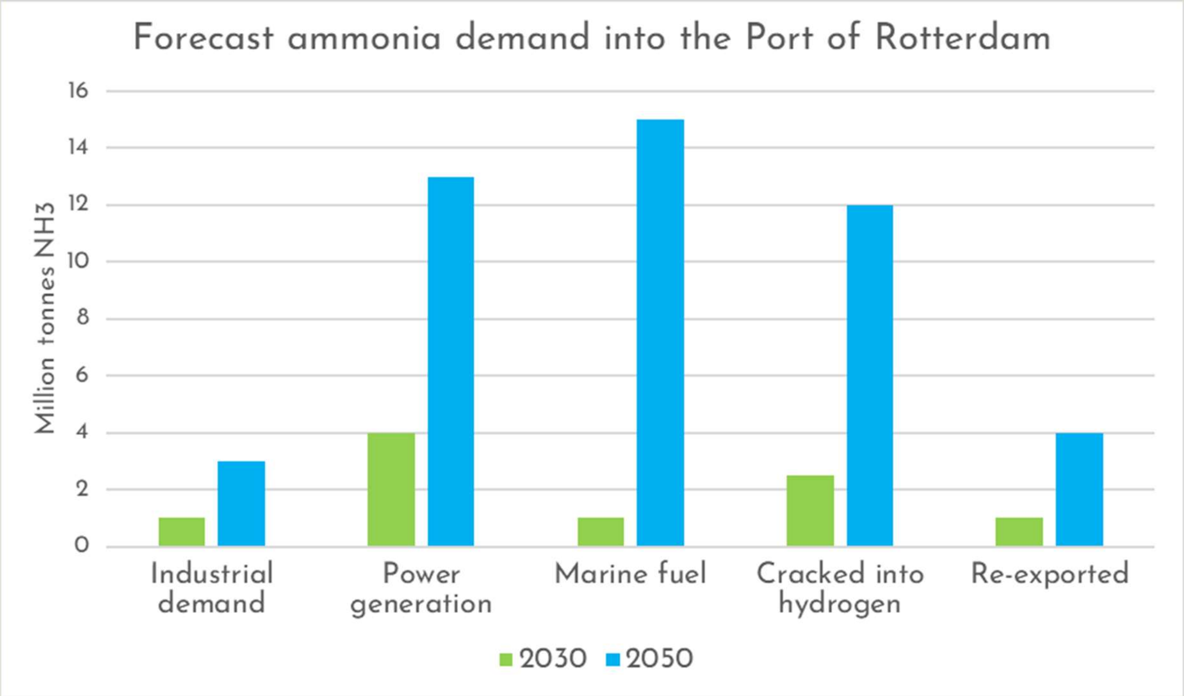

Figure 24 – forecast ammonia demand into the Port of Rotterdam by segment in 2030 and 2050 (provided by the Port of Rotterdam)

4.3 Challenges to be addressed to stimulate demand

Commercial challenges

Price

Ammonia will cost significantly more than fossil fuels today. However, it holds potential to be highly competitive versus alternative low-carbon fuels. Significant incentives will need to be put in place to stimulate demand. Perhaps the most simplistic and effective is a global price on carbon.

Figure 25 shows how a global price on carbon could impact the fuel production costs of ammonia, alternative low-carbon fuels and traditional fossil fuels.

Figure 25 – Effect of carbon pricing on various fuels[25]

Committed volumes for marine fuels

Ship engines with the capability of burning ammonia will be dual fuel with diesel and LSFO. This will serve the need for pilot fuel, as well as giving ship owners a back-up should ammonia be unavailable. It also allows owners to burn the cheapest fuel.

Resultingly, ship owners may be unwilling to sign-up to longer duration take-or-pay contracts. On the other hand, suppliers often require these contracts to build a business case and obtain debt financing. To enable a value chain for marine fuels some party will have to accept this risk. It may be that governmental entities are well placed to do this to drive faster decarbonisation.

The impact this can have was seen with LNG bunkering. Despite LNG offering 20-30% lower greenhouse gas emissions versus conventional fuels[26], when energy equivalent prices exceeded marine gasoil and low sulphur fuel oil at the back-end of 2021 shippers reverted to the cheaper fuel. Our tracking of several LNG bunker vessels operating in Europe shows very little activity since this date, suggesting only a small volume of take-or-pay contracts. This eventually exposes suppliers to significant losses and may discourage them from taking such risks again without additional guarantees or support.

Regulatory challenges

New regulation is a prerequisite for the adoption of ammonia as a lower-carbon fuel; having to both incentivise and facilitate. This section outlines the critical gaps that exist today and offers several considerations when drafting – obtained from discussions with players across the value chain.

[25] Mærsk Mc-Kinney Møller, 2022, Maritime Decarbonization Strategy, available here
[26] Sphera, 2021, 2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel, available here

'Facilitating' regulation will be needed to govern how ammonia is used, for example: its safe handling, storage, combustion, and personnel training. Without this, any incentives would be futile.

'Incentivising' regulation will be needed to encourage industry, power generators and ship owners to switch from cheaper fossil fuels.

Marine fuels regulation deep dive

Global regulation for shipping falls under the remit of the International Maritime Organisation (IMO). The below regulations (figure 26) need to be updated or drafted in order to facilitate and incentivise ammonia as a low-carbon fuel.

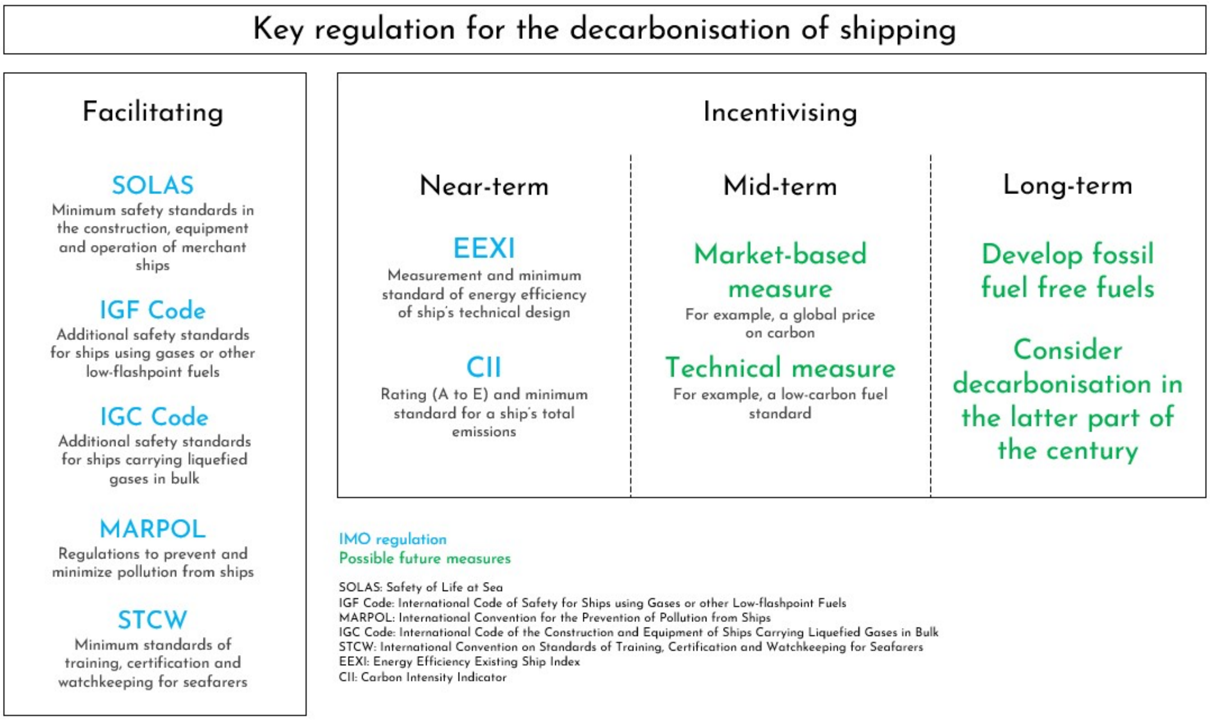

Figure 26 – key regulation for the global decarbonisation of shipping

Regulation drafting considerations:

1. **Global versus regional**

In a global business, regulation is best applied globally. A ship owner adopting ammonia to reduce its emissions under one region's regulation shouldn't be disadvantaged against its competitors in another region with less strict regulation.

As indicated previously, Ammonia is well suited for long distance "deep sea" routes. As such vessels will cross regions of different regulation making it difficult for regional regulation to have its desired effect.

However, the IMO's strategy falls short of the Paris 1.5°C trajectory. As such, it is widely expected that the EU will implement regulation to speed up the decarbonisation journey. Whilst beneficial to the plant, EU legislation should be careful to avoid creating a 'two-tier' global fleet, where new vessels run lower carbon fuels in Europe – costing a premium, and older vessels continue to burn cheaper conventional fuels elsewhere. This would disadvantage the economies of EU countries.

2. Well-to-wake emissions for shipping

Today, IMO regulations focus on tank-to-wake, or operational, greenhouse gas emissions from shipping. The EU is also proposing some tank-to-wake regulations in the Fit-for-55 package. However, this approach ignores significant emissions before the fuel reaches the tank and thus can wrongly influence behaviour.

It is vital that emissions from the entire fuel lifecycle are considered instead. Life cycle assessment (LCA) is the most comprehensive evaluation of environmental impact but is bespoke and complex. Well-to-wake offers a good balance – covering all emissions in a standardised and simplified approach.

3. Not just CO2

N_2O has 300 times the warming power than CO_2, whilst methane is 80 times more potent. To avoid replacing CO_2 emissions with gases with a greater impact to global warming, all greenhouse gas emissions should be targeted within regulation.

4. Danger of prescriptive measures

It's all new. Prescriptive measures assume that the way we do things today will be the same in the future. Prescriptive regulation might unwittingly hinder development.

5. Benefit of 'multipliers'

Goal based regulation, for example enforcing a reduction in GHG emissions of x%, allows industry players to find and adopt the most cost-effective measures in a 'free market' scenario – avoiding being too prescriptive.

However, it does not necessarily progress industry towards the 'ultimate goal' of moving to a zero-carbon fuel, such as green ammonia. For example, shippers may find that adopting efficiency measures such as sailing at a slower speed, is more cost effective than using ammonia.

To really accelerate the transition to ammonia, regulators could consider disproportionally incentivising use of ammonia. A reduction is emissions from using ammonia could be worth double that of energy efficiency measures for example. This doesn't restrict compliance options but incentivises those that progress shipping on its journey to the 'ultimate goal'.

6. Green corridors and first movers

Establishing a whole new industry, globally, all at once is a mammoth task. Incentivising first movers and specific locations could help. In this regard, the ammonia value chain may be influenced by the speed individual European ports adopt it as a lower-carbon fuel.

Provided sufficient policy support in the region, first movers may be ports with significant proximate potential customers. For example, Wilhelmshaven has been a focal point for ammonia import to access significant demand in Germany. In January 2023, bp announced plans to evaluate the construction of an industrial-scale ammonia cracker and repurposed oil/gas facilities to transport hydrogen. Uniper have proposed "Green Wilhelmshaven" an ammonia import terminal and 1GW electrolysis plant. Other proposed import terminal locations with proximate ammonia demand include Rotterdam, Brunsbuttel and Antwerp.

5. Next steps for Task 3.4

In Months 48-54 of MAGPIE Task 3.4 will be revisited. We suggest progressing 4 areas:

1. Update with the latest projects, figures, developments etc. (ZCS & PoR lead)
2. Provide a scenario-based case study analysis for the Port of Rotterdam
   - Develop (three) demand scenarios for the Port of Rotterdam (PoR lead)
     - Low (for example, limited IMO progress halts use as a marine fuel, minimal governmental subsidy etc.)
     - Medium
     - High (significant carbon price, facilitating regulation for ammonia quickly implemented, all demand sectors adopt ammonia etc.)
   - Model how Port of Rotterdam demand is optimally be supplied for each scenario (EWI lead)
     - Utilisation of the PtX cost tool to evaluate import/export, price, green vs. blue etc.
   - Examine how Port of Rotterdam infrastructure could look for each scenario (PoR lead)
     - Cost-benefit analysis of infrastructure options
3. Evaluate how the bunkering market landscape may change for ammonia as a marine fuel (as described in section 3) (TUD lead)
4. Further review of deployment of ammonia by transport modes other than vessels (VOO lead)