Public report

Institute for Sustainable Process Technology

Clean Ammonia Roadmap

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The Foundation Institute for Sustainable Process Technology (Stichting ISPT https://ispt.eu) is an open innovation network for the process industry community with partner organizations cooperating on developing and realizing sustainable process technology innovations to solve common industrial needs and contribute to the climate goals.

About this report

The Clean Ammonia Roadmap report is initiated by the Institute for Sustainable Process Technology (ISPT) and is part of the Clean Ammonia Innovation Program. This report was prepared by ISPT in close cooperation with Partners:

- Ammonia Energy Association
- Deltalinqs
- Duiker Combustion Engineers
- E.ON - Essent
- ISPT
- Horisont Energi
- HyCC
- Koole terminals
- OCI Global
- Port of Rotterdam
- Shell Global Solutions
- Zeta Energy Systems B.V.
- Ministry of Economic Affairs and Climate Policy - Netherlands Enterprise Agency (RVO)

Acknowledgement

The development and execution of this Roadmap project was a real team effort of ISPT and the Partners. It took us ten months to complete this report. We held about twenty (virtual) meetings and compiled knowledge and experience in and outside the team from relevant authorities and stakeholders. The aim was to create a fact-based overview on this new energy and hydrogen carrier and its role in the energy and industrial system for CO_2 reduction.

We are delighted to share this report with you to increase awareness and knowledge of a future low carbon and renewable energy system with ammonia as an energy carrier. The development of related large-scale applications requires safety guidelines, updates to design standards, communication and training programs.

We wish to express special thanks to the following persons from our Partners who made an important contribution to the findings, results and benefits:

Ammonia Energy Association/ Kevin Rouwenhorst; Deltalinqs/Harry van Dijk; Duiker Combustion Engineers/ Albert Lanser, Jebin James; E.ON/ Essent/Fred Hage; ISPT/ Rob Stevens, Gijs Tubben, Carol Xiao, Hans van 't Noordende; Horisont Energi/ Eivind Torheim; HyCC/ Fernanda Neira Dangelo, Willem Frens; Koole terminals/ Tamme Mekkes; OCI Global/Jan-Jaap Nusselder; Port of Rotterdam/ Mark Stoelinga, Marthe Fruytier; Shell Global Solutions/ Wouter Koopman, Shuddhank Kishor; Zeta Energy Systems/ Peter Veldman; Netherlands Enterprise Agency (RVO)/John Neef, Li Huang, David Bolsman.

Please join us.

The Authors

Executive summary

In 2022 approximately 11 Gigatonnes (Gt) of CO_2 were emitted globally as a consequence of industrial processes, which contribute to global climate change. Industrial processes will gradually become more electrified to reduce the carbon footprint to approximate zero in 2050. In addition, low carbon fuels will most likely still be required in this future decarbonized energy landscape as not all industrial processes qualify for electrification. Green hydrogen is a zero-carbon fuel that is accepted as an important energy carrier to accommodate CO_2 reduction. However, it also has some limitations due to its chemical properties. It has a relatively low energy density, which makes it less attractive for transport, storage and utilization. It also has a low ignition energy, increasing explosion risks. Hydrogen 'stored' in ammonia could help resolve these issues. Ammonia as a hydrogen carrier can be converted back to hydrogen again. Opposite to other hydrogen carriers ammonia is a non-carbon type.

Ammonia is one of the widely produced chemicals in the world and has been used in industry for over a hundred years. 80% of ammonia and its derivatives are used as feedstock for fertilizer production, thus sustaining close to half of the global food consumption. The remaining 20% is used as a building block in the chemical industry. Ammonia is currently produced by combining hydrogen with atmospheric nitrogen in a Haber-Bosch process, while hydrogen is produced from natural gas and water through steam methane reforming (about 75%) and coal (about 25%, mainly in China). This process results in about 500 million tonnes of CO_2 emissions annually. The resulting product is called grey ammonia. This type of ammonia production can be decarbonized by carbon capture and storage or utilisation (CCS/U). In that case, it is called low-carbon or blue ammonia. Green hydrogen - produced through water electrolysis from renewable electricity - can be used for conversion to renewable or green ammonia.

As the urgency for CO_2 reduction grows and geographical demand for energy sources shifts, ammonia is increasingly recognized as a promising energy and hydrogen carrier, see figure S1.

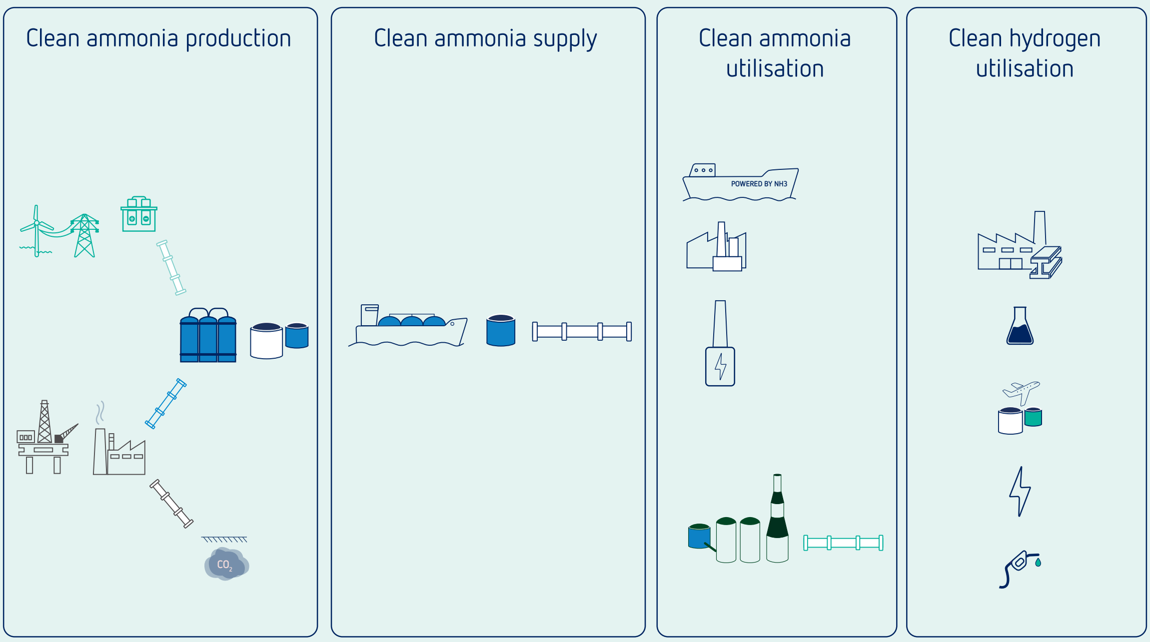

Figure S1: Clean ammonia as an energy carrier value chains

Global ammonia production and usage are expected to shift towards areas where conditions favour the production of renewable energy: areas such as North Africa, Australia, Chili and Spain. Additionally, ammonia is expected to be produced more sustainably at the traditional production sites. It will be transported from there to industrialized areas in for instance Western Europe. By now, numerous projects have been announced for low carbon and renewable ammonia production. The first clean ammonia production plants are already operational. Consequently, investment in ammonia terminals have been done and ammonia to hydrogen crackers are being built. In the meantime, though, a lot of questions on demand development and uncertainties regarding compliance still remain.

In this report from ISPT and partners from industries, the envisaged import volumes and value chains of clean ammonia as energy and hydrogen carrier, as well as challenges for society and safety aspects are addressed. It is suggested that the combined industrial cluster of the Antwerpen-Rotterdam-Rijn-Ruhr-area (ARRRA) can import and/or produce up to 25 million tonnes per annum (mtpa) of clean ammonia by 2030. This ammonia is expected to arrive in tankships, to be stored in port terminals and from there further distributed to industries. Ammonia can be used as energy carrier. It can be directly used as marine fuel. This bunkering process is expected to be centred in for example Rotterdam, the third largest port in global (fossil) bunkering volumes. Next to that, ammonia can be used as fuel in power plants. It could thus be used to complement regional or temporal electricity shortages and moreover enable baseload supply. Furthermore, imported ammonia can be converted into hydrogen for steel production, heat and power generation and mobility. Cracked ammonia can for instance be used as an aviation fuel.

The global clean ammonia market could grow to 900 mtpa, assuming that ammonia will be accepted as energy carrier and go-to fuel in the power sector and shipping industry (Figure S2). This volume still

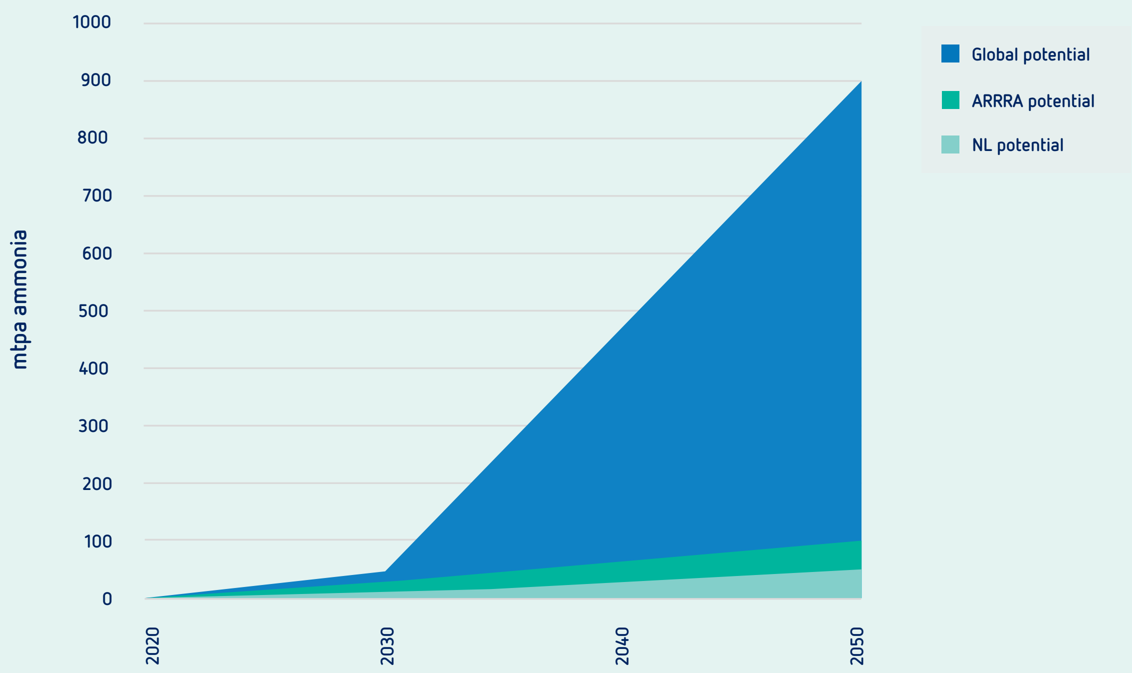

Figure S2: Potential development of ammonia demand in 2050 (additional to existing 183 mtpa ammonia as feedstock) excludes ammonia as a chemical feedstock (183 mtpa in 2021). Demand could grow to about 50 mtpa in The Netherlands and 100 mtpa in the ARRRA region in 2050.

Table S1 shows the estimated volumes of ammonia as energy carrier used for bunkering, power generation and as a hydrogen carrier for new industrial markets sustainable aviation fuel and sustainable steel. It is assumed that imports would have to cover this demand.

Table S1: Expected clean ammonia demand (excl. export) in 2030 and 2050 per industry sector

NH_3 demand (mtpa)				
2030	**Bunkering**	**Power generation**	**New industrial markets**	**Total**
Global	25	5	20	50
ARRRA	3	3	19	25
NL	1	1	10	12
2050	**Bunkering**	**Power generation**	**New industrial markets**	**Total**
Global	200	600	100	900
ARRRA	40	14	35	89
NL	20	3	20	43

Approximately 1.1 million tonnes of ammonia are expected to be used annually by 2030 for bunkering in the Netherlands. An estimated 1 million tonnes could potentially be used in retrofitted coal and gas power stations in the Netherlands alone by 2030. A suggested 10 million tonnes of ammonia could be converted into about 1.5 million tonnes of hydrogen for domestic use. New applications for ammonia are expected to take off after 2030, such as for Direct Reduction of Iron (DRI) steel production and Sustainable Aviation Fuels (SAF or e-kerosine), next to existing markets such as refineries. Meanwhile, imported or locally produced ammonia will still be used by industry as a chemical building block and for fertilizers. This currently amounts to 3.1 mtpa in the Netherlands. The ammonia volume transported from The Netherlands (and Belgium) to Germany will be an estimated 3.5 mtpa ton in 2030. This is not included in the Dutch figure.

In 2050 bunkering in The Netherlands for international shipping could grow to 20 million tonnes, depending on the pace in which the shipping industry retrofits or replaces vessels. Also, the power market and conversion to hydrogen could potentially triple from 2030 to 2050. A total of 50 million tonnes of ammonia could potentially be imported to the Netherlands and for the ARRRA region double that amount. On a global scale, the power sector could increase to 600 mtpa due to retrofitting and newly built power plants for ammonia (co-) firing in countries such as India and China. Thus, offering more flexibility in electricity supply next to renewables and other solutions with energy carriers. and storage for decarbonatization. This requires appropriate NO_x- emission control measures to be in place.

Figure S3 shows the distribution flow of ammonia as an energy carrier and hydrogen imports, exports and utilisation, including conversion form ammonia to hydrogen, in the ARRRA region for 2030. These large quantities of ammonia need to be transported to their destination by rail, barge or pipeline. Transport to the

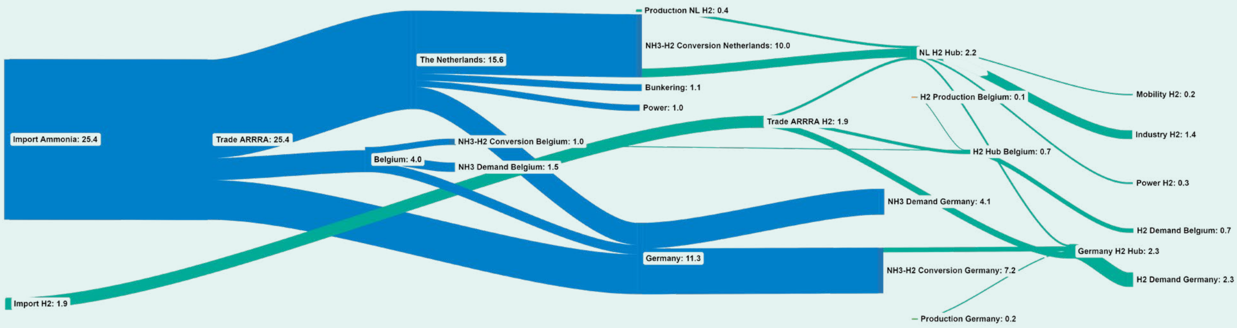

Figure S3: Sankey diagram of ammonia and hydrogen flows ARRRA region in 2030 in mtpa

hinterland in the anticipated volumes will only be practically possible with pipelines. Already 7,600 km of ammonia pipelines exist worldwide for over fifty years. During this period, eleven accidents were reported, none of these with fatalities.

An ammonia leakage has negative effects on health, safety, and environment. Ammonia is toxic in high concentrations and during a certain exposure period. The smell threshold is very low. When spilled in the environment, ammonia can be toxic for aquatic organisms. Ammonia is considered non-explosive. Furthermore, it does not sustain ignition at room temperature. The risk of ammonia fire and explosion can be reduced to a a tolerable level. Codes and standards have already been developed for ammonia because of its wide use throughout industry. Also, solid rules and regulations are already in place with strict government inspection. These standards and regulatory framework need to be updated to fit future expected quantity and application of ammonia as an energy carrier.

To ensure safety even further and to increase the capability to handle the large expected imported quantities, new technology must be developed and existing technology for storage and transportation should be upgraded. Firstly, regulations and legislation on ammonia as an energy and hydrogen carrier will be required. As of writing this roadmap report the national guidelines (PGS-12) on ammonia storage and (un)loading are being revised by experts from industry and government. Guidelines and standards are needed to ensure safe operation and maintenance of bunkering, cracking and firing of ammonia as fuel in the maritime and power sectors.

Secondly, pipelines should be further developed and implemented to handle the increase in ammonia imports and transport to customers. This should first be carried out in port areas, but after 2030 from the Netherlands and Belgium also towards Germany.

These developments require significant investments. Initiatives for deployment of low-carbon ammonia applications and integration with hydrogen value chains should be subsidized to meet growing customer demand as well as climate goals.

As can be seen in Figures S4 and S5, the steel industry has by far the highest CO_2 reduction potential per kilogram ammonia. The power and shipping sectors, however, have an even larger total CO_2 reduction potential. In the power sector renewable ammonia would replace coal and natural gas, and in the shipping sector it would replace Marine Diesel Oil. Significant conversion losses for cracking could be amply compensated by making base load operation in the energy sector more economically and energy efficient. The utilization of renewable ammonia based SAF in the aviation industry has the lowest reduction potential. In case of SAF combined with CCU this application would even rank lower.

Usage of zero-carbon ammonia as an alternative in the power sector would save about 2% of total global CO_2-emissions from coal and gas in 2050. For the Netherlands the import volumes for zero carbon ammonia in the power sector could potentially lead to 28% reduction of the attributed CO_2 emissions in power sector in 2022, in addition to renewable energy. Zero carbon ammonia bunkering for international shipping has a potential of 43% CO_2 reduction on a global scale in shipping industry. The CO_2-emission reduction potential is about 30% for the steel industry in The Netherlands, assuming DRI steel making with 50% hydrogen converted from imported ammonia. Globally the CO_2-emission reduction potential in steel making is lower -in the order of 10%- assuming higher scrap recycling, and lower DRI penetration levels. Regarding SAF, a potential CO_2-emission reduction of about 10% in aviation sector could be envisaged globally based on power-to-liquid technologies using hydrogen coming from cracked ammonia combined with direct air capture (DAC).

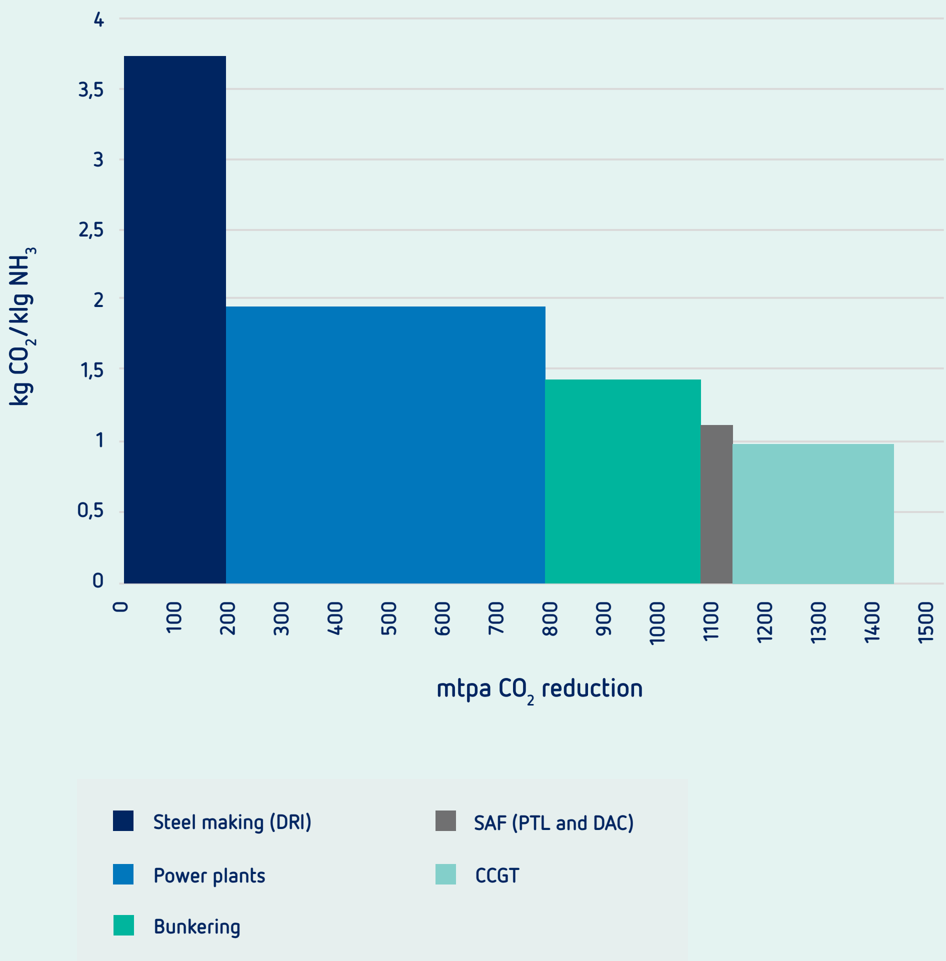

Figure S4: Merit order global CO_2 reduction based on renewable ammonia in 2023-2050

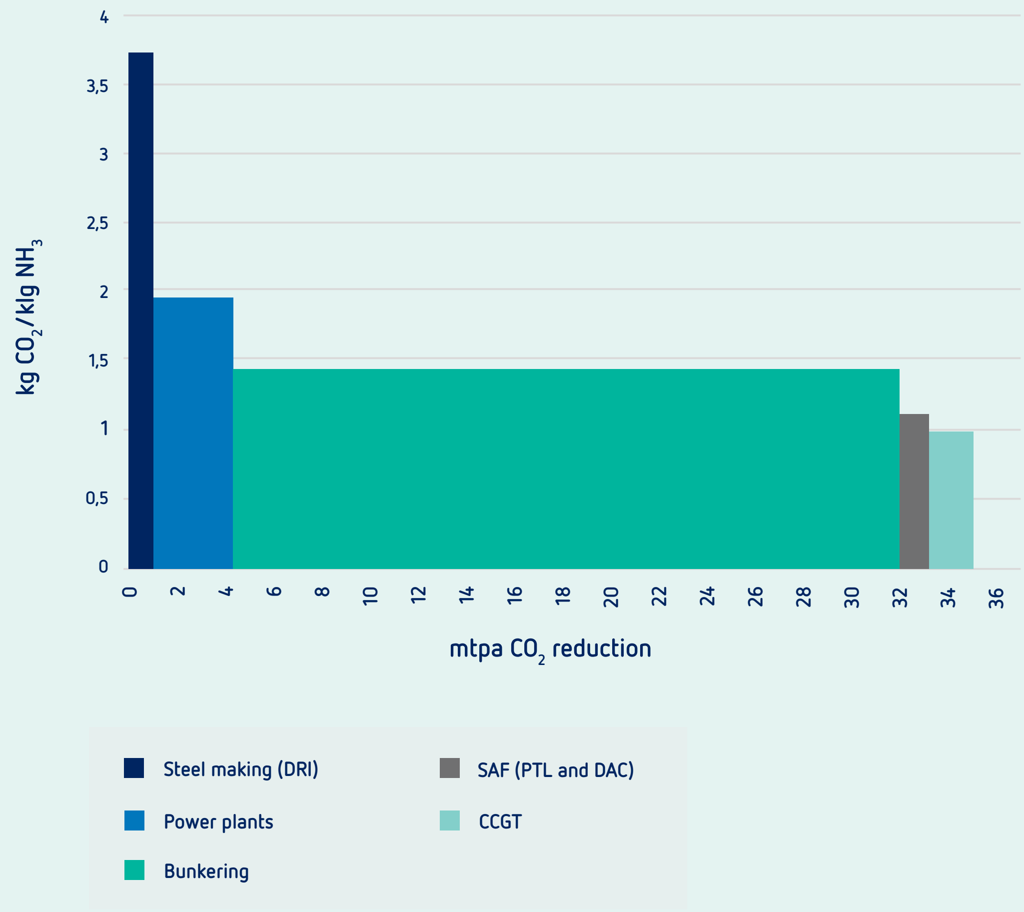

Figure S5: Merit order The Netherlands CO_2 reduction based on renewable ammonia in 2023-2025

By 2050, clean ammonia could potentially mitigate about 3% of global CO_2 emissions today, while emissions should level or even drop from 2023 onward according climate targets. In this context of CO_2 emission reduction potential, various consortia have announced the import of clean ammonia to for example the port of Rotterdam towards the end of the 2020s, resulting in substantial scale-up of ammonia storage, transport and utilisation. Thus, it is important to leverage the existing industrial knowledge on best practices for safe storage and handling of ammonia. Human capital will evidently be important, and training will be required for ammonia storage and handling. Also, a consolidated effort with enabling laws and regulations will be required for the developing and integrating value chains. This includes ammonia imports to the Netherlands, with subsequential direct ammonia utilisation, cracking to hydrogen, and transport of ammonia and hydrogen to Germany via pipelines.

In the meantime, ISPT and industry partners have decided to continue with a project to increase awareness on safety aspects and residual risks of ammonia transport via pipelines to Germany. Another recommendation is to continue with projects on nitrogen emissions (NO_x and N_2O) control in case of utilisation in the power sector.

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Introduction

Urgency of clean ammonia

In recent years the energy landscape has gone through tidal shifts. These are partly fuelled by a global policy push towards a sustainable energy system. The European Green deal, which consists of a series of policies that touch on climate, energy, transport, and taxation, aims to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Meeting these challenges necessitates large scale, high pace decarbonization. Political commitment, partnership with the private sector, adequate funding and increased technology transfer are drivers in this shift towards emission reduction. Geopolitical events further urge to reduce dependency on fossil fuels. The energy system must remain affordable, secure and sustainable. Consequently, the global production and transportation of new and renewable energy carriers will show tremendous growth in the coming decades. One of these renewable energy carriers is hydrogen.

To further reduce emissions and to meet the target of the 'EU Renewable Energy – Recast to 2030 (RED II) proposal Fit-for-55' art. 22a, 50% of the hydrogen used for conventional consumption in the EU must be 'green'. That is: produced through electrolysis with electricity from renewable energy sources such as solar and wind energy. This comes down to about 50 to 100 PJ per year in total. Hydrogen, however, is difficult to transport over longer distances and comes with storage drawbacks such as low energy density and safety risks. One solution to this challenge is to use ammonia as a hydrogen carrier. Ammonia can be produced by combining hydrogen with nitrogen from the air at high pressure and temperatures in the Haber-Bosch process. To convert ammonia back into hydrogen and nitrogen, there is a cracking process available that decomposes the ammonia over a catalyst at high temperatures and (preferentially) at normal pressures. Creating ammonia from hydrogen and back to hydrogen has a retention efficiency of 69%.

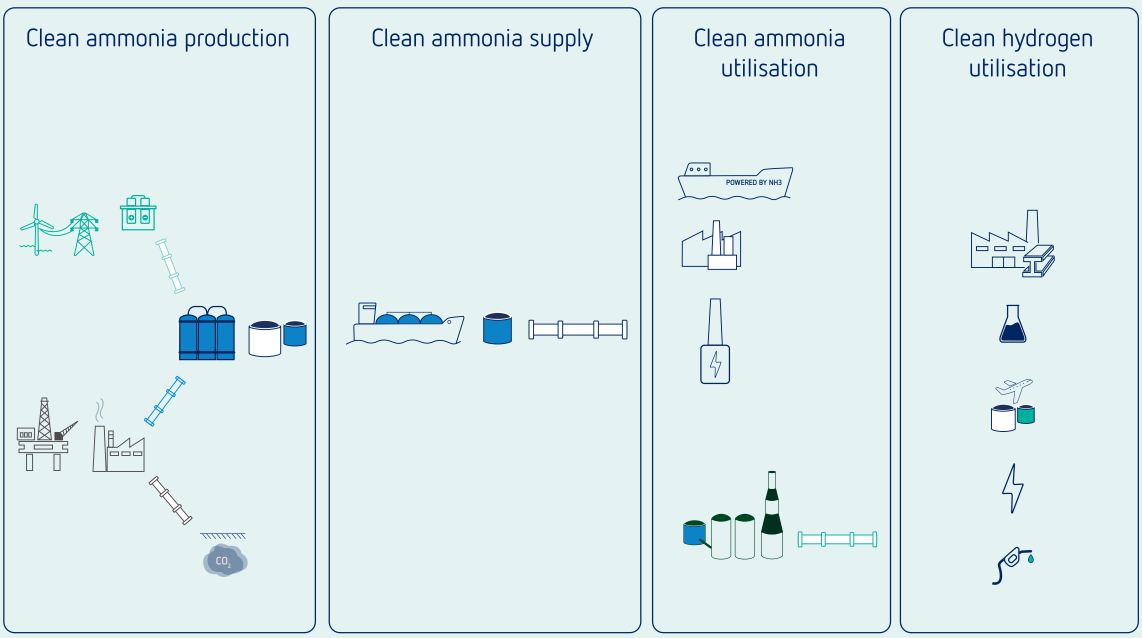

Figure 1: Clean ammonia as an energy carrier value chains

Ammonia production and utilization

Ammonia is the second most produced chemical worldwide and as such an essential global commodity. Currently, 80% of global ammonia demand finds it main application in nitrogen-based fertilizers. The remaining 20% is used for a wide range of industrial applications, such as plastics, explosives and synthetic fibres. In the context of this roadmap, the growth of clean ammonia production for chemicals outside Europe is not considered. In the context of this roadmap, only production and use for new ammonia as energy carrier outlets are being considered.

Interest has recently expanded to application of clean ammonia as a carbon-free energy carrier in future energy systems, well fitted to transport renewable energy alongside traditional industrial applications. Firstly, it can function as a clean fuel for shipping vessels. Secondly, power plants can directly be co-fired by ammonia. Lastly, ammonia is a hydrogen carrier which can be converted back into hydrogen and nitrogen through cracking.

Clean Ammonia as a hydrogen carrier can also provide a sustainable feedstock for industry. An increasingly numerous and affluent global population will lead to a substantially increasing clean ammonia demand (and thus production), now that governments around the world start committing to head towards net-zero energy related emissions. Clean ammonia has a substantial potential to mitigate and eventually eliminate the chemical industries and energy sector's carbon footprint.

As ammonia is relatively easy to transport and store compared to hydrogen, large volumes of ammonia are expected to be imported from areas with an abundance of renewable energy sources to North-Western Europe. The population and economic activity here are more concentrated and renewable energy is scarcer and more expensive.

Renewable and low carbon ammonia

Similarly to hydrogen, ammonia can also be described with the colours 'green', 'blue', and 'grey'. Most ammonia currently on the market is still overwhelmingly grey, as it is produced from fossil resources. It is produced from natural gas, through steam methane reforming followed by the Haber-Bosch process to yield ammonia. Ammonia production currently accounts for around 2% of total final energy consumption and 1.3% of CO_2 emissions from the energy system.

Renewable 'green' ammonia is defined by the use of hydrogen from renewables. Low carbon (fossil) ammonia or 'blue' ammonia is defined by using hydrogen based on Autothermal Reforming (ATR) or Steam Methane Reforming (SMR) with natural gas as feedstock combined with Carbon Capture and Storage (CCS) of which nearly all CO_2 emissions can be captured. In comparison, the CO_2 emissions without CCS are 70% of that of grey ammonia. Both types are often referred to as clean ammonia. Ammonia made with hydrogen won from methane pyrolysis or 'turquoise hydrogen' is considered here as clean ammonia as well.

Needs, drivers and enablers

Industry is keen to develop new products, technologies and services and repositioning in emerging value chains. Increased demand for hydrogen and alternative energy carriers draws attention to ammonia. Parties invest in developing new products, technologies, and services around clean ammonia. Governments also realize the potential of ammonia as an energy carrier. This asks for the development of new legislation based on new insights from society and academia.

The combination of industry interest and governmental regulation leads to new market opportunities. These in turn affect government and industry perception. These processes are influenced by the public perception of clean ammonia as an energy carrier. There is little knowledge anywhere in the world about the social acceptance of green ammonia. The public (legislative) sector, the energy market and its supply chain (technology) need to adjust to a shifting energy mix. Meanwhile, the increasing use of ammonia as energy carrier and aspects such as NO_x emissions, ammonia's toxicity and safety aspects need to be addressed and explained to stakeholders. Figure 2 visualizes this interplay between driving and restraining factors.

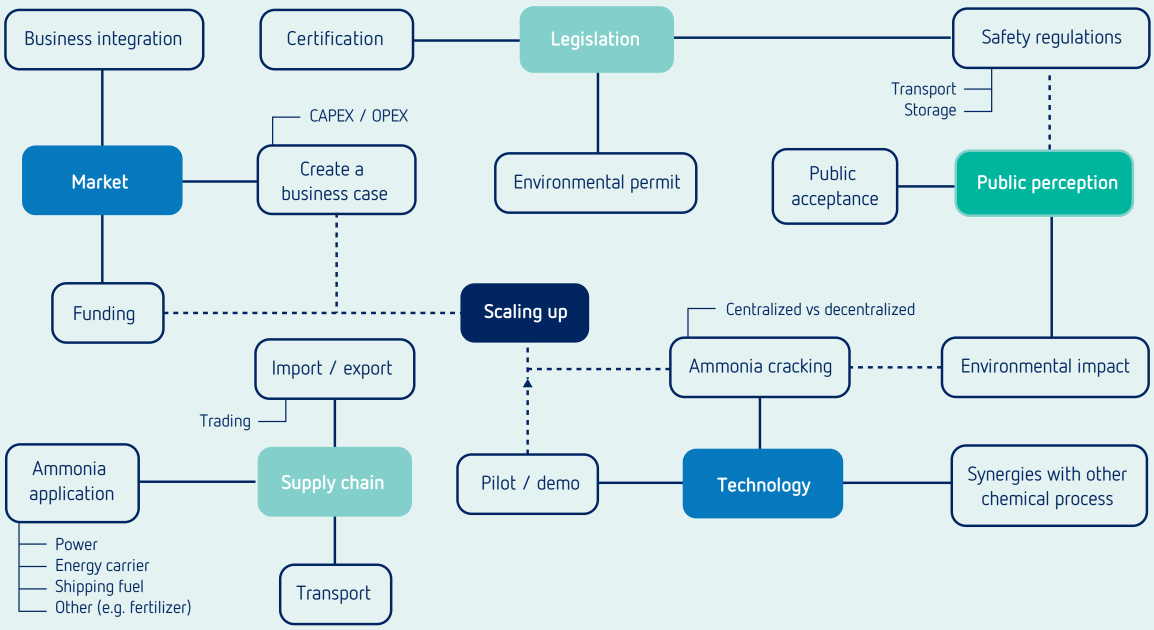

Figure 2: Needs, drivers and enablers of clean ammonia as an energy and hydrogen carrier

Ammonia is not the only possible alternative energy carrier. Table 1 compares ammonia as an energy carrier to liquified hydrogen, methanol and Liquid Organic Hydrogen Carriers (LOHC).

ISPT and industry partners in the Netherlands have explored the opportunities and challenges in this clean ammonia transition accumulating to this roadmap report. In the following chapters, the findings and expectations are discussed to gain a more realistic overview of a clean ammonia-based economy from an industry perspective.

Table 1: Pros and cons ammonia and other energy carriers

	Pros	Cons
Ammonia	• Experience with ammonia infrastructure, mature worldwide transport and storage networks • Vast experience with storage and handling • Liquid at -33 °C and atmospheric pressure • Higher energy density than hydrogen • Does not contain carbon • Can be used directly in production processes and as fuel	• Ammonia is toxic, safety measures needed for transport and storage of H_2 • Transport of cooled ammonia through road and rail is not permitted in The Netherlands • Potentially harmful emissions (NO_x and N_2O), so emission abatement required • Evaporating ammonia categorises as flammable gas. Ignition temperature and flame speed are relatively low. • Energy density is a factor 3 lower than for MDO.
Liquid Hydrogen	• Higher energy density than pressurised (gaseous) hydrogen • Does not contain carbon • Not toxic • No conversion losses compared with ammonia synthesis and cracking	• Costly and energy-intensive to store and transport - liquid at -253 °C • No infrastructure currently available, and thus only limited experience and knowledge on large-scale use • Risk of explosion due to high flammability • Factor 1.4 lower energy density than ammonia
Methanol	• No conversions – limited losses • LNG technology and possibly infrastructure can be leveraged • Methanol can be used directly in production processes and as marine fuel • Experience with production, transport and storage • Methanol can be transported by rail	• Costs for unloading H_2 from methanol carrier are relatively high • Methanol as fuel will still emit CO_2 (unless with Direct Air Capture) • Energy density is a factor 2.3 lower than for MDO • Methanol is toxic
Liquid Organic Hydrogen Carrier (LOHC)	• Methylcyclohexane (MCH): existing infrastructure can be used, experience with production, transport and storage • Dibenzyltoluene (DBT): limited experience, but relatively easy to handle • Lower hazard risk with leakage, spray, ignition and fire than ammonia and hydrogen due storage and transport at ambient temperature and pressure combined with high flashpoint[1]	• No direct applications, the carriers always have to be unloaded • Carrier has to be shipped back to pick up a new load of hydrogen, takes energy to unload, challenges in cost and safety • Lower energy density than liquified hydrogen

[1] 4th ISFEH.dot (https://hysafe.info/uploads/papers/2021/5.pdf)

Health, Safety & Environment

This section includes an assessment of the possible effects of ammonia to the environment, human health and safety. European and American databases on historical ammonia accidents in industry, rail transport and with pipelines are analysed. On this basis the most frequent causes and consequences of exposure to ammonia are identified.

Health Hazards

Ammonia creates toxicity related health hazards. The effect of ammonia vapour on the respiratory system is usually limited to the upper respiratory tract. This gas dissolves well in water and it generates strong reflexes causing someone exposed to it to immediately hold his breath. Only very high concentrations of gaseous ammonia would manage to penetrate deeper into the respiratory tract. This could damage the lungs, with possibly fatal results. Exposure to liquefied ammonia can cause caustic irritation and severe burns after skin contact.

A scenario leading to health hazards would be a rupture of a railway tank wagon, causing an ammonia cloud. Ammonia gas itself is lighter than air. In case of loss of containment, dispersion into clouds will take place due to ammonia flashing and/or evaporating from an ammonia pool. Concentration gradients will occur in the clouds, both horizontally in distance as vertically to ground level. In case of water vapour in the air (high humidity), ammonia vapours can emerge that are heavier than air. These toxic vapours can spread at ground level or in low-lying areas with poor ventilation, potentially exposing people to harmful and even lethal concentrations.

Health hazards, consequences and thresholds are presented in Figure 3. More information can be found in Annex 1. Ammonia has a Levensbedreigende Waarde (LBW Life threatening Threshold value, 30 minutes exposure) of 1500 ppm (1100 mg/Nm^3). The Level Odour Awareness (LOA) or Public Threshold Value (PGW) is much lower at around 2 ppm.[2]

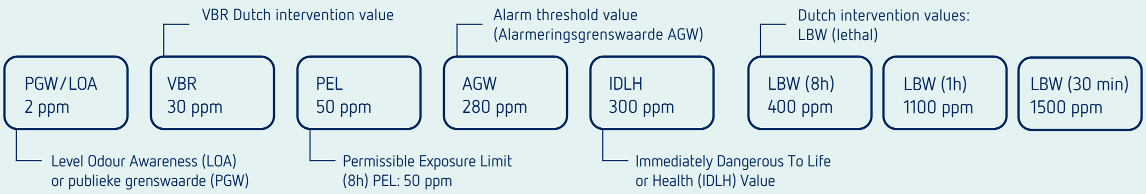

Figure 3: Ammonia in air health hazards, more information can be found in Annex 1

[2] Ammoniak-IVW-2009.pdf (https://rivm.nl)

Safety hazards

Fuels such as natural gas, hydrogen or LNG come with fire and combustion hazards. Compared to these, ammonia poses a relatively low hazard. The 2020 ammonium nitrate explosion in Beirut is associated with ammonia and could cause hesitance towards ammines. The properties of ammonia, however, differ from those of ammonium nitrate. Ammonia is non-explosive and not highly flammable. The minimum ignition energy level is 680 mJ - approximately 10,000 times larger than for hydrogen. Ammonia flames are very transparent and show low flame speed. An atmospheric boiling ammonia pool fire cannot sustain itself, as the heat of flames radiated into the pool is insufficient to sustain ignition. Only when external factors heat the pool, for example from the ground or with water, sufficient ammonia will be able to evaporate to maintain the fire. The probability of a fire or explosion could almost exclusively arise in poorly ventilated spaces. Nevertheless, there are strict safety measures in place regarding ammonia handling, based on rules and certification.

Environmental hazard

In case of spillage into surface water, high ammonia concentrations can be toxic for aquatic organisms, the soil, and air. In a comparison of ammonia with marine gas oil (MGO) by ecological receptor and environment type, a study concluded that the qualitative effects are similar.[3] The effect on aquatic organisms can be modelled in an environmental damage index (Dutch: *milieuschade index (msi)*) based on failure rates and effects.

Consequently, residual risks have to be reduced to an acceptable level. Weather conditions have significant impact on the spread of gaseous and liquid ammonia.

In case of uncontrolled combustion of an ammonia storage or shipment, significant nitric oxides (NO_x) and nitrous oxide or dinitrogen monoxide (N_2O) could be emitted. This depends on the equivalence ratio between fuel and oxygen and the wall temperature. N_2O is a greenhouse gas 298 times stronger than CO_2. As Figure 4 shows, the emission of NO and NO_2 is about 10 times higher than with methane. N_2O-emission is relevant for only ammonia combustion. The peak emission of NO_x and N_2O removal show a complementary profile in case of ammonia combustion.[4] The emissions of NO_x and N_2O are lowest close to stoichiometric mixtures. Therefore, off gas treatment, for instance through selective catalytic reduction (SCR), is necessary to meet permit requirements. Regarding cracking: when the ammonia combustion is done at lower pressures and controlled correctly, no significant NO_x or N_2O emissions are expected.

A most likely 'worst case' scenario would be a spill of ammonia from a full-bore rupture of a (bunkering) pipeline under low wind and stable weather conditions.[5] Another scenario would be a collision with a river barge tanker, causing leakage of ammonia to surface water.

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[3] Maritime-Insights-speaker-slides-Feb-2023.pdf (https://ammoniaenergy.org)

[4] Hideaki Kobayashi et al., Proceedings of the Combustion Institute, Volume 37, Issue 1, 2019, Pages 109-133, Science and technology of ammonia combustion

[5] CIW 4 2000-02 Integrale aanpak van risicos van onvoorziene lozingen - Helpdesk water

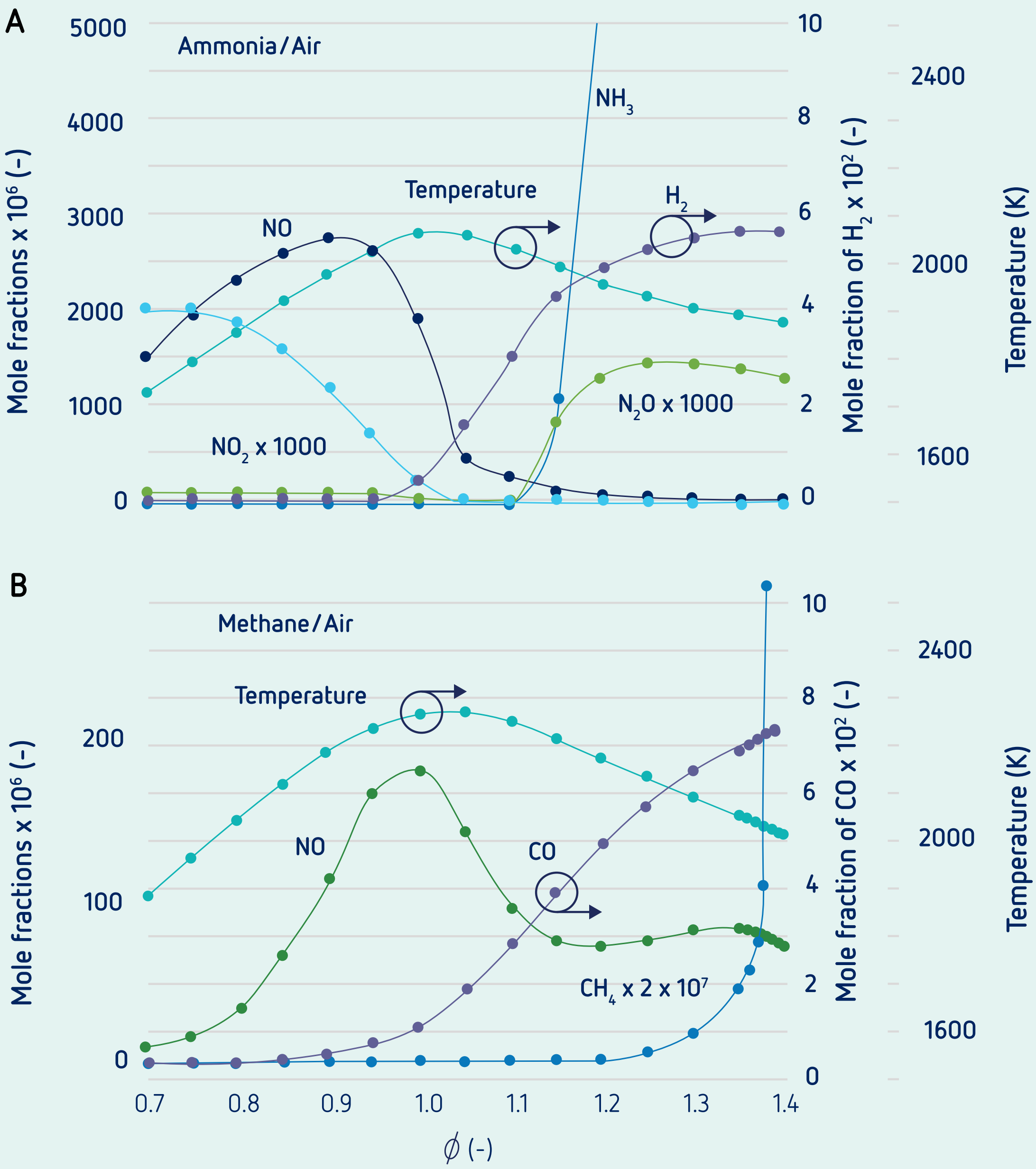

Figure 4: Emission characteristics in terms of equivalence ratio at 0.1 MPa and 40 mm downstream of the position of maximum heat release rate: (a) NH3/air; (b) CH4/air.[4]

In Japan test runs have been performed with a four-stroke marine engine running up to 80% on an ammonia fuel mix. A fully integrated set-up – including exhaust gas aftertreatment technology and fuel supply systems – produced stable operations, with N_2O emissions and ammonia slip reported as "virtually zero".[6]

[6] Maritime Consortium Successfully Completes Ammonia Co-Firing Test Using Cutting-Edge Ammonia-Fueled Engine | NYK Line

History of ammonia accidents per industry sector

Although ammonia has so far been used in substantially smaller amounts than expected for the future, ammonia is far from new to industry. Most of the ammonia was produced for direct use, and shipments were comparably small with the quantities assumed in this report. Nevertheless, these quantities are still significant and provide the opportunity to analyse historical data about ammonia related health and safety hazards. It brings the most frequent causes and most severe consequences to light. It provides a starting point to determine necessary mitigating measures for future even larger scale ammonia use.

Both the USA[7] and Europe[8] have logged all accidents concerning ammonia in their safety and health accident administration. For the USA there is the Accident Search Result Page[9] with figures from 2002 onward. Europe has its EUROPA – eMARS Accidents Search page[10] which includes data going back all the way to 1979. The eMARS has 62 registered ammonia accidents while the USA Accident Search Result Page has 82 registered entries. For an accurate representation of the health and safety situation regarding ammonia, only accidents that involved pure ammonia have been selected. The USA and EU data are analysed from three different distinctions: industry sector, cause and consequence.

Ammonia is currently used and handled for many different purposes. These can be broadly divided into eight different industry sectors: agriculture, chemicals manufacturing, handling and transportation centres, manufacturing of food and beverages, production and storage of fertilizers, production of pharmaceuticals, basic organic chemicals and the petrochemical industry. Figure 5 has categorized the

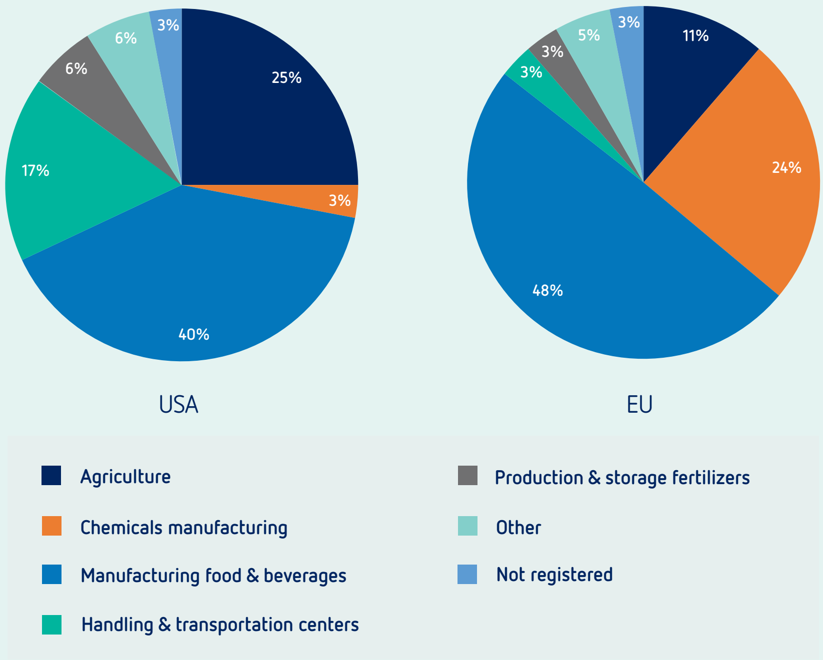

Figure 5: Accidents per industry sector

[7] https://osha.gov/help/accident-investigation
[8] https://emars.jrc.ec.europa.eu/en/emars/accident/search
[9] Accident Search Results Page | Occupational Safety and Health Administration (https://osha.gov)
[10] EUROPA - eMARS Accidents Search - European Commission

ammonia accidents per industry sector in the EU and USA. Handling and transportation centres refer to ports, airports, lorry depots and other similar locations. Figure 5 shows that in Europe, almost half of all accidents occurred in food and beverage manufacturing. In this sector ammonia is used as a cooling service. The economic advantages of ammonia refrigeration made it the coolant of choice for cold storage facilities and food processing facilities as well as the dairy and meat packing industries. Accidents were the result of ammonia spills from the cooling systems due to equipment failure, human error and external causes, see Figure 6. The data from Figure 5 show that second most US accidents are fertilizer use related (in the USA ammonia is directly applied into the soil by farmers).

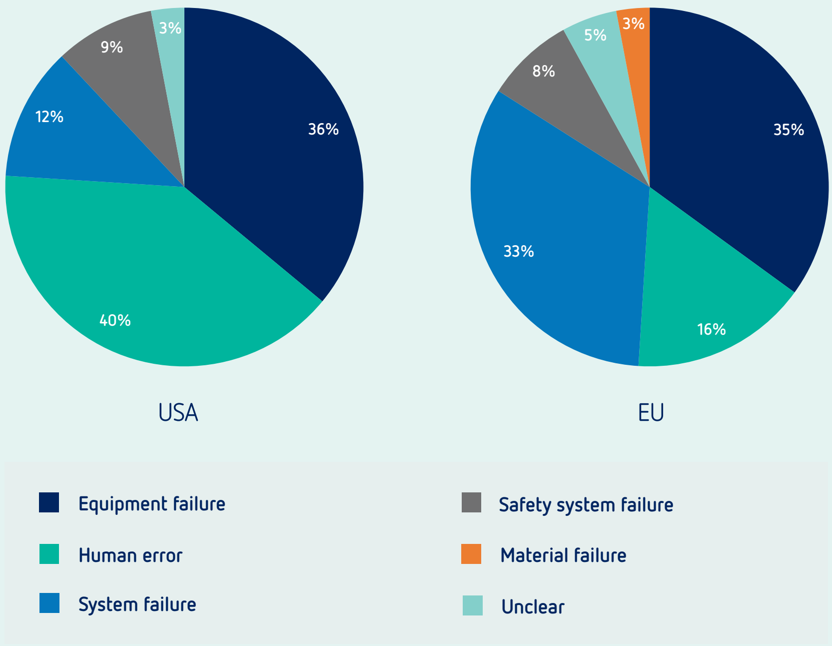

Figure 6: Causes of ammonia accidents

Root case analysis

Registered causes in the ammonia accident databases can be broadly divided into six causes: human error, material defect, equipment failure, system failure, safety system failure. The first three are responsible for over 80% of all ammonia related accidents.

Accident causes differ between Europe and the USA. In the USA human errors are more common than in Europe. Examples of human errors causing ammonia accidents are forgetting to close the door, mistaking the substance people were carrying (water instead of ammonia) or maintenance procedures carried out close to the ammonia storage. Especially in the food and beverages industry, human error (almost 50%) was a frequent cause of the accident. Accidents labelled “safety system failure”, also comprise employees not following or knowing safety protocol or having no safety protocol at all. This could also arguably be categorized under “human error”.

Equipment failure accidents can refer to a broken pump, valve, motor or other equipment. In the EU, material defects, causing 3% of accidents are mostly due to corrosion or aged asbestos pipes. This was not registered in the USA database.

Consequences

The EU health and safety accident registration form identifies four serious health, safety and environment consequence categories of ammonia accidents across all industry sectors (see Figure 5):

- More than one fatality and/or more than six injured;
- Immediate environmental damage;
- Damage to property;
- Cross boarder impact.

The data illustrated that since 1979 almost 50% of 62 reported accidents in Europe had more than one fatality and/or more than six injuries. In only four cases the environment or the property were damaged. This illustrates the critical impact of ammonia on human health and on humans in the surrounding area. Zooming in on accidents with serious human consequences, 40% was caused by human error. The most recent European fatality due to ammonia was in 2014.

The USA data list only takes human health consequence into account and made a distinction between hospitalized, non-hospitalized and fatal. The numbers show that 16% of accidents led to fatalities, 61% to hospitalization and 23% to neither.

History of accidents with ammonia transport

Railway transport

Ammonia (pressurized) is frequently transported by rail. For example, in 2020 in the Netherlands four shipments a week with one to three wagons were transported from the OCI terminal in Rotterdam Europoort to Delfzijl.[11] Similarly, ammonia shipments to Geleen take place by train. Transport by train is not without risk, as it passes densely populated areas, but as of December 2022 no accidents have taken place in the Netherlands. In December 2022 an accident did happen with an ammonia train derailment in Pirot/Stanichene, Serbia, close to Bulgarian border. This led to leakage and a resulting gas cloud with a state of emergency up to 30 km causing ammonia smells and poor visibility. Two people were reported dead and fifty-one were hospitalized with burns, damage to internal organs, heart problems, irritation of the respiratory system, eyes and skin.[12]

Shipment

Ammonia shipment overseas have been carried out for decades now. These usually involve large vessels from experienced shipowners, comparable to LNG vessels.

The novel application of ammonia as fuel introduces new safety hazards. These involve toxicity and onboard fires. Safeguards are required to reduce the risks to acceptable levels. It is therefore crucial to understand these risks and to provide proper training and knowledge dissemination.

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[11] https://railwiki.nl/index.php/Delfzijl_Industrie

[12] 51 Poisoned with Ammonia after a Freight Train derailed in Serbia – Bulgarians Must Not Leave their Homes! - https://novinite.com - Sofia News Agency

Inland shipping

Ammonia is transported from seaports inland with barges. Precautions can mitigate the risks to crew and the surrounding environment. A recent research project by Wärtisla in Finland brought to light that treating the engine room as a "gas safe space" – a safety approach employed with current dual fuel engines – is highly beneficial when designing and engineering a safe working space around an ammonia-powered engine.[13]

Ammonia pipelines

Ever since the nineteen sixties, ammonia has most frequently been transported though pipelines. Globally, more than 7,600 kilometres of ammonia pipelines are monitored. In the Netherlands, a pipeline of 3,5 kilometre operated by OCI transports ammonia from an inland harbour in Stein to the Chemelot site. Table 2 gives an overview of the existing pipelines globally. In its 70 years of existence, 11 accidents have taken place as can be seen in Table 3. So far, no human fatalities have been reported.[14, 15]

Table 2: overview of existing pipelines

Where	Length	Under/above ground	Remarks
USA	5000 Km of pipelines	Mainly underground	• Gulf Central. The 3057 km Gulf Central pipeline is the longest system and connects the major producers along the Texas and Louisiana Gulf coast with terminals in Arkansas, Iowa, Illinois, Indiana, Nebraska and Missouri. • MAPCO. The MidAmerica Pipeline System (MAPCO) extends from Northern Texas, across Oklahoma, Kansas, Nebraska and Iowa, and ends in Minnesota, all intensive agricultural areas. The total length is 1754 km. • Tampa. Another shorter system (132 km) is the Tampa Bay pipeline in Florida. • Texas: Yara is currently building a 20 km pipeline and many other projects under construction
Russia Ukraine	2424 Km (1 pipeline)	Unknown	The longest Ammonia pipeline in the world has been in operation since 1983 in Russia/Ukraine. It connects the large production facilities Togliatti/Gordlovska in Russia with the Black Sea port of Odessa in the Ukraine.
European Union	201 Km of pipeline	Aboveground and underground	25 small pipelines varying from 1.5 to 74 km (Italy) • Belgium: 2 pipelines • Germany: 3 pipelines • Italy 1 pipeline • Netherlands: 2 pipelines • France: at least 3 pipelines • Portugal: 1 pipeline • UK: 7 pipelines • Spain: 4 pipelines • Poland: 5 pipelines
Australia (Yara)	5.3 Km	Aboveground	A new pipeline less than 1 km long between Ammonia plant and TAN in 2016

13 Safety and the marine ammonia engine on Vimeo (https://vimeo.com/827453300)
14 USA (Accident Search Results Page | Occupational Safety and Health Administration (https://osha.gov)
15 Europe (EUROPA - eMARS Accidents Search - European Commission)

Table 3: History of Failure for Ammonia pipelines

Where	What happened and Cause	Barrier
Texas City, Texas, 1969	Freeze-thaw cycle in the water containing annular space of a double walled ammonia pipe	Not double wall design
McPherson, Kansas, 1973	Overpressure on a previously mechanically damaged pipe part.	Relief devices
Texas City, Texas, 1975	External corrosion as a result of mechanical damage to the pipe coating and interference in the cathodic protection in an underground pipeline	No cathodic protection as the line is not buried Regular external inspections
Ince, England, 1981	Leak developed from a small branch of a liquid ammonia pipeline that was not in continuous operation. Root cause was external corrosion due to unforeseen (rain) water entry to the pipe surface	Recirculation prevents external corrosion
Algona, Iowa, 2001	A large ammonia leak developed in a liquid ammonia pipeline as a result of maintenance work on a valve in that pipeline	Unclear
Grand Parish Louisiana, 2001	Ammonia thief drilled into a valve of the pipeline, probably to obtain Ammonia to make the drug methamphetamine	No access given to general public Pipeline fenced and located in a remote area
Kingman, Kansas, 2004	A huge leak developed after a rupture liquid ammonia pipeline. Probable cause was metal fatigue cracking in combination with previous mechanical pipe damage.	Recirculation prevents thermal fatigue
Clay County, Kansas, 2006	A 200 mm diameter liquid ammonia pipeline failed. As far as we know, the cause has not been determined yet, but seam failure is suspected	Recirculation decreasing the stresses to the welds
Mulberry, Florida, 2007	The Tampa Bay liquid ammonia pipeline near Mulberry, possibly with a diameter of 100 mm or 150 mm there, developed a leak. A boy drilled a hole in the pipeline out of curiosity.	No access given to general public Pipeline fenced and located in a remote area
Togliatti-Odessa pipeline, 2015	The leak occurred in the Ternovo district of the Voronezh region of Russia on June 21th, causing an unprecedented environmental and health disaster that has gone underreported in both Russian and international media. The leak is still under investigation	Waiting for cause
Masyutivka-Kharkiv, 2023	The 2.500km long pipeline ran through the conflict zone in the war in Ukraine, during which the pipeline had already been taken out of commission. A explosion has caused a leakage. The effects are still being researched.	Waiting for cause

Policies & regulatory framework

The transition towards a sustainable and decarbonized future requires the development and implementation of robust policies and regulatory frameworks. This chapter provides an overview of existing policies and mechanisms relevant to the current production, transport, and utilization of ammonia and hydrogen within Europe, with a particular focus on the Netherlands.

Production and origin standards

Within the European Union, the Renewable Energy Directive provides the legal framework for renewable energy. The latest revised version, knows as RED III, defines renewable hydrogen as Renewable Fuels of Non-Biological Origin (RFNBO). This could be hydrogen and hydrogen derivates, such as green ammonia. In June 2023 two Delegated Acts related to the definition and certification of renewable hydrogen were published by the European Commission. With the official publication of the RED III Directive in October 2023, these Delegated Acts have been renamed to Delegated Regulations 2023/1184 and 2023/1185.

The first Delegated Regulation 2023/1184 covers Renewable Fuels of Non-Biological Origin (RFNBO), including ammonia. It provides criteria for products that fall into the "renewable hydrogen" category and defines under which conditions a renewable fuel can be named RFNBO. This is important because the RED III Directive prescribes minimum percentages RFNBO's in both the transport fuels and in industry by 2030. It also stipulates electricity sourcing and GHG emission accounting for RFNBO including renewable hydrogen.

The second Delegated Regulation 2023/1185 covers a methodology for assessing greenhouse gas (GHG) savings, presenting a scheme to calculate the life-cycle emissions of renewable hydrogen and recycled carbon fuels to meet the GHG emission reduction threshold set in the RED II. Moreover, the RED-III itself contains two further requirements for RFNBO's: a minimum 70% GHG emission saving, and sustainability information being traded through the chain-of-custody by mass balance, which in short means that the sustainability information has to be traded together with the physical delivery of the hydrogen (so no book-and-claim).

In the context of this program both renewable and low carbon ammonia are considered, which are defined as:

- Renewable or green ammonia using hydrogen from renewable energy sources such as solar or wind (taking into account the definition of RFNBO and the criteria on additionality and temporal and geographical correlation in Delegated Regulation 2023/1184);
- Low carbon (fossil) ammonia using hydrogen based on ATR/SMR with natural gas as feedstock and with Carbon Capture and Storage (CCS) (blue hydrogen). This is also often referred to as clean ammonia. Hydrogen can be considered "low-carbon" when the GHG emissions savings are 70% or more. Also, methane pyrolysis (turquoise hydrogen) can result in low-carbon hydrogen (and clean ammonia when produced from this low-carbon hydrogen) if it meets the "at least 70% GHG emission saving" requirement. For low carbon hydrogen, the requirements of 70% GHG emission savings is defined in the decarbonization package (on which Trilogue discussions to date have not yet been finalized). This package announces the future publication of a delegated act on the GHG emission methodology for low carbon hydrogen.

Basiswet & Omgevingswet

The environmental law in the Netherlands is combined with various other laws into an Environmental Law (Dutch: Omgevingswet (Ow)) that integrates environment as well as water, spatial planning and nature. The Basisnet is subject to this Omgevingswet.

In 2021 a supply chain study on road, rail, water and pipelines in The Netherlands has been carried out. This study concludes that transport of hydrogen carriers, such as liquid hydrogen and ammonia through road, rail and water can have a big impact on risks on the main infrastructure corridors in The Netherlands (Basic Grid, Dutch: Basisnet). Rail transport is being reviewed, including a new systematic approach with focuses on increased safety of transport, infrastructure and spatial planning.[16]

PGS 12 and other Dutch safety compliances in external safety

Regarding external safety aspects of ammonia and other hazardous substances regarding pipelines the Dutch pipeline directive (BEVB) is applicable. For assets such as booster and compressor stations the Dutch external safety directive BEVI is applicable. A manual (Dutch: handleiding) on risk assessment BEVI is in place.[17]

Another guideline is the Publicatiereeks Gevaarlijke Stoffen (PGS) 12 on ammonia storage and (un)loading, which will be modified in 2023.[18] This is an aligned effort from authorities and industry with a PGS12 committee, working group and sounding board. ISPT represents the partners of the Clean Ammonia Innovation Platform in the sounding board coordinated by VOTOB.[19] The changes focus on higher volumes, review of scenarios including external impact, full containment tank design and pump type selection, next to the necessary safety measures.

A quantitative risk assessment is required as part of permitting procedures. For QRA's SAFETNL software is used for dispersion calculations to determine 10^{-6} risk contours as defined in PGS3.[20] Safety distances are indicated as 'invloedsgebied' and 'Gifwolkaandachtsgebied (GAG). 'Invloedsgebied' is defined as the distance leading to a 1% lethality rate based on probit relationships with concentration gradients and duration in the cloud. GAG is the distance at a concentration of 2,54 times that of life threatening values when exposed for 30 minutes.[21] The GAG primarily depends on initial release (flash), whereas 'invloedsgebied' also depends on the size of an ammonia pool. Of course, scenarios, failure rates and conditions have to be taken into account.

16 Ketenstudie omgevingsveiligheid van duurzame waterstofrijke energiedragers | Rapport (https://rijksoverheid.nl)
17 Handleiding Risicoberekeningen Bevi v4.3_120121.pdf (https://rivm.nl)
18 Titel (https://publicatiereeksgevaarlijkestoffen.nl)
19 The Dutch Association of Tank Storage Companies Votob
20 Guidelines for quantitative risk assessment (https://publicatiereeksgevaarlijkestoffen.nl)
21 RIVM stappenplan 6 mei 2023

Support mechanisms

Inflation Reduction Act

The Inflation Reduction Act is a US tax product for investments to meet climate goals. This legislation makes it more appealing to invest in green initiatives in the United States compared to Europe. For multinationals this creates opportunities and opens the possibility to set up new value chains in the US. For EU-based companies this poses threats to their domestic industrial assets. It will potentially lure European investors in clean ammonia technology to move to the US. The EU has therefore in return developed legislative measures that likewise promote the use of clean energy carriers. In this way, one could talk of a race to the top instead of a race to the bottom.

EU Hydrogen bank

The European Commission (EC) has set out new plans to stimulate and support investment in sustainable hydrogen production through a European Hydrogen Bank (EHB). Hydrogen is expected by the EU to contribute considerably to the EU's ambitions to end imports of Russian fossil fuels in the next few years, and ultimately to achieve climate-neutrality by 2050. This initiative is aimed at accelerating investment and bridging the investment gap for the EU to reach its ambitious REPowerEU targets of producing 10 million tonnes (mt) of renewable hydrogen domestically by 2030, on top of 10 mt of imports.

As the first final investment decisions were only taken last year and the vast majority of projects are still in the planning stage, the EHB will help address initial financial challenges in order to create an emerging renewable hydrogen market. It will also have an international dimension: to facilitate imports of renewable hydrogen to the EU.[22]

H_2 Global

H_2 Global was developed in Germany as a response to the mismatch between climate change targets and existing instruments to promote rapid reductions in CO_2 emissions in the industry, energy, heat, and transport sectors. The instrument promotes the production and use of Power-to-any renewable energy carrier (PtX) products on an industrial scale through a market- and competition based approach. Through long-term purchase contracts on the supply side and short-term sales contracts on the demand side, H_2 Global attempts to incentivize the production and use of renewable fuels.

Based on a mechanism analogue to the Contracts for Difference (CfD) approach, the difference between supply prices (production and transport) and demand prices will be compensated by grants from a public or philanthropic funding body.

The combination of these long-term purchase agreements with HINTCO as a government-backed launching customer provide the necessary investment security to unlock large-scale investments now, resulting in a catalytic effect to ramp up the hydrogen economy.

[22] Commission outlines European Hydrogen Bank to boost renewable hydrogen (https://europa.eu)

Renewable Fuel Units

In the Netherlands, a market mechanism is in place to increase the share of renewable energy in transport and to reduce of greenhouse gas emissions from transport fuels. In the Energy for Transport system, a market mechanism with "Renewable Fuel Units" (Dutch: Hernieuwbare Brandstofeenheden – HBE's) is key. Both the annual obligation and the reduction obligation are expressed in a required amount of HBEs. Companies with an obligation must ensure that they have sufficient HBE's in their account in the Energy for Transport Register (Dutch: Register Energie voor Vervoer - REV) before 1 May each year to meet the obligations.

Companies that physically supply renewable energy to transport can register their deliveries in the REV and thus create HBEs. One HBE on account in the REV represents the use of 1 gigajoule of renewable energy. In addition, an HBE stands for a greenhouse gas emission reduction to be determined annually. One HBE on account thus contributes to the mandatory use of renewable energy and to the reduction target. Companies that have to deal with the annual obligation and reduction obligation can choose. They either (1) supply renewable energy themselves and register it in the REV (entry) and use the HBEs for their own obligation, they (2) buy HBEs from other companies or (3) they apply a combination of both options.

IPCEI

Another mechanism is Important Projects of Common European Interest (IPCEI). In Dutch: 'belangrijk project van gemeenschappelijk Europees belang'. It helps to reduce dependence on natural gas and accelerates the hydrogen economy.[23] An IPCEI is an integrated European project that consists of several complementary national projects of companies and/or research institutes from various EU Member States They must have synergy and contribute to strategic European goals. In 2022, two tranches (Waves) of EU projects have been approved for funding. Most of these projects still need to pass the Financial Investment Decision, however. In the Netherlands eight projects have been granted funding. Should all these be realized as proposed, they should create approximately 1,150 MW of electrolyser capacity.[24]

Clean ammonia as an energy and hydrogen carrier specific policies

International Maritime Organization (IMO) & ETS

The maritime sector in particular is expected to become a significant driver for clean ammonia. The sector is developing international standards and agreements for safer ammonia handling. The maritime sector consumes about 300 million tonnes of fossil fuel annually to produce 12.6 EJ of energy of which 8.7 EJ for international shipping. This results in more than 1 gigatonne of Greenhouse Gas (GHG) emissions. This equals roughly 3% of the global GHG emissions.

The business landscape in maritime transport rapidly changes on Environmental, Social and Governance issues (ESG). New regulations are passed, such as the inclusion of shipping in the EU's Emission Trading System (ETS), IMO's EEXI and CII ratings, and CSRD-mandated ESG disclosures. The EU will fully

[23] IPCEIs on hydrogen (https://europa.eu)

[24] With seven projects; the eighth involves fuel cell technology

incorporate the maritime sector in the Emission Trading System (ETS) by 2026.

Customers are increasingly willing to pay a green premium. Many investors look to divest from carbon intensive assets without a clear decarbonization strategy.[25]

IMO issued a revised 2023 strategy setting a goal of net zero emissions from ships "by or around, i.e., close to, 2050". This is a major increase in the ambition level compared to the 2018 strategy, which aimed at reducing emissions from ships by just 50% with the same time horizon. A trajectory has been agreed with indicative checkpoints set at reducing GHG emissions from ships by at least 20% - striving for 30% - in 2030 and at least 70% - striving for 80% - in 2040, both in comparison to 2008 levels.[26]

There are currently no prescriptive rules for using ammonia as a fuel, so shipowners must use a risk-based alternative design process to gain approval from flag states. To ensure maximum scaling, prescriptive rules, including IMO guidelines should be updated and in place as soon as possible:

- International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)[27]
- International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).[28]

To be ready for scaling by the end of this decade, regulations, standards and safety guidelines must be prepared while technology is still under development.

[25] ESG Playbook for Shipping | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
[26] Maritime transport emissions: Commission welcomes new IMO (https://europa.eu)
[27] International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) (https://imo.org)
[28] IGC Code (https://imo.org)

Development of ammonia market demand

In this chapter we provide an estimation of the future market development for ammonia from an industry perspective as compared to figures from literature. In the first section the numbers presented are taken from prospective studies by the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA). The second section presents a model for anticipated ammonia market demand, developed by ISPT and partners. The third and fourth sections further elaborate on this per industry and market sector.

Demand development per industry sector 2030 and 2050 Outlook

Existing production and demand

Whether the current ammonia production capacity of 4.3 mtpa in the ARRRA region will remain or become (partly) replaced by imports remains unclear and subject to economics and the assumption that traditional consumption will remain the same. Part of this ammonia will be supplied as building block to the chemical industry, whereas the ammonia derivates (fertilizers) are sold locally or exported. For this reason and because of the focus on clean ammonia as an energy carrier, existing production is not considered in the imports outlook in this study.

Current hydrogen demand stems from fertilizer plants, chemical industry, refineries and the food industry. The present grey hydrogen supply can be replaced by locally produced or imported green/blue hydrogen or converted from clean ammonia and is included in the projections in this report.

Ammonia bunkering as shipping fuel

The maritime sector is one of the difficult to abate sectors. Methanol is a drop-in fuel that can be used for bunkering of seagoing and inland vessels. In the long run clean ammonia is could be favorable thanks to its decarbonization potential.

For 2030 1 mtpa ammonia from the Port of Rotterdam CDG scenario is projected, with a 50% methanol-ammonia distribution, see Annex 3. For other national ports we assume 10% of this figure. Regarding relevant Belgian and German ports and for simplicity, the same figure is adopted as for Rotterdam.

For 2050, 29% (MJ/MJ) ammonia in the fuel mix with methanol, LNG and biofuels is assumed in the global fuel demand for bunkering based on EIA projections. 300 mtpa Marine Diesel Oil (MDO)[29] needs to be decarbonized globally. This amounts to 200 million tonnes of ammonia. The Port of Rotterdam ranks third in bunkering worldwide. This amounts to 10 mtpa MDO. In The Netherlands a total of 20 mtpa ammonia is suggested, based on this figure taking into account an annual growth at 4%, the above fuel mix and an additional 10% for the other ports. For simplicity reasons the same figure is adopted for the total relevant Belgian and German ports.

[29] Zero shipping, 2022

Power generation potential for ammonia firing

We envisage that ammonia-to-power could become an important market to meet climate goals. Ammonia as a fuel can replace coal in coal-fired power plants and natural gas in combined cycle gas turbines (CCGT). Clean ammonia utilization will enable sufficient electricity generation in regions with shortages in renewable energy supply and enables base load demand in industry. Ammonia can just like other fuels be used for grid-balancing in a highly solar PV and wind-based electricity grid.

For coal-fired thermal power plants, country-specific replacements of coal have been determined. On average, it is assumed that about 86% of coal-based electricity will be replaced by a combination of nuclear power, hydropower, geothermal power, solar PV, and wind in combination with energy storage. The remaining 14% is assumed to become replaced by 50% solid biomass and 50% ammonia on an energy content basis. In the case of coal-fired power plants, ammonia can reduce the carbon footprint by co-firing a mixture of up to 60% ammonia by energy content. The transition to 50-60% ammonia co-firing is expected by the 2030s, and 100% ammonia firing is targeted for the 2040s. By 2050, it is suggested that about 300 mtpa ammonia as pure fuel will be required globally to replace coal as a fuel in thermal power plants.

Natural gas based electricity generation is assumed to transition for 87% to a combination of natural gas and CCS, biogas, nuclear power, hydropower, geothermal power, solar PV, wind, in combination with energy storage. This is also based on country-specific scenarios. The remaining 13% of electricity generation is assumed to transition to ammonia as a power fuel. This could be either as pure fuel (100%) or as a mixture with for example hydrogen at 30-50% ammonia blends on an energy basis. By 2050, it is suggested that about 300 mtpa of ammonia will be required globally for gas turbines.

For The Netherlands the power sector could potentially grow from 1 mtpa in 2030 based on two (retrofitted coal-fired) power plants and 10 CCGT's, co-firing (33%) ammonia, to about 3 mtpa in 2050. In total global ammonia-to-power can potentially consume 600 mtpa (4,5 EJ) of clean ammonia for closing the decarbonization cycle of the power sector on a 50% / 50% basis for coal-fired power plants and gas turbines. This represents about 2% of the global energy consumption through coal and natural gas.[30]

Conversion to H_2 and new industrial markets

Hydrogen demand is expected to increase thanks to climate goals, new industrial markets, and emerging applications. These applications include:

- sustainable aviation fuel (SAF or e-kerosine);
- steel making through direct reduction of iron (DRI) combined with electric arc furnaces. (EAF);
- high-temperature applications including furnaces and steam generation;
- ammonia as reductor for circular carbon production.

In this report only the SAF and steel making industries are discussed.

[30] World Energy Outlook 2022 (https://windows.net)

Additional imports of hydrogen to ARRRA are needed, apart from local supply. It is, however, expected that not all hydrogen can be imported either in compressed, liquid or LOHC form. It could be more economically attractive to import ammonia as hydrogen carrier and convert it through cracking back to hydrogen again. This could for example be done for steel making and sustainable aviation fuel (SAF) production. Production of SAF and steel in other regions, using locally produced clean/green hydrogen and subsequent shipment to Europe could possibly show better economics. However, due to geopolitical reasons, to be partially self-supportive in energy supply and industrial production is very attractive. Another argument to keep these industries here in The Netherlands is the superb infrastructural connection with the European hinterland. Thanks to ammonia imports, base load operation will become possible, as storage of clean ammonia is relatively easy. This is expected to drive the business cases for both DRI and SAF. This round-trip hydrogen supply (hydrogen to ammonia and back to hydrogen) is needed for base load demand based on for instance 50% full load hours renewables.

Based on EIA targets, the SAF contribution to annual kerosene consumption could grow from 10% in 2030 to 30% in 2050. The global aviation market outlook shows a growth form 375 in 2020 to 500 mtpa kerosine in 2050 of which the Schiphol share in 2020 was around 1%. The SAF could be biogenic and as e-fuels, e.g., 50% e-fuels. As a first guess, half of the required hydrogen would be imported as ammonia to The Netherland and the other half produced locally or imported as liquified hydrogen or LOHC. Potentially, the locally produced SAF could be shipped to other countries or transported to Germany instead of crude oil today.

According to the IEA, in 2050 19% of total steel production will rely on different DRI-EAF technologies.[31] These include gas- and coal-based DRI with and without CCUS and electrolytic hydrogen-based DRI (e.g. as being developed by the HYBRIT project.[32] Also here, the assumed hydrogen supply for domestic DRI is 50% directly from local produced and imported hydrogen and 50% from clean ammonia converted to hydrogen.

Another industrial application is the (partial) utilization of ammonia or hydrogen in furnaces and steam boilers. The resulting increase in demand is included in the projections, but not substantiated in this report. Apart from hydrogen-based reduction of iron, use of ammonia as a direct reductant is also an option. This would omit the cracking process and the conversion losses related to it. The use of ammonia for conversion of iron ore into top sponge iron has been demonstrated on lab scale, but needs further research, validation, and upscaling.[33] Ammonia-based direct reduction (ADR) is kinetically (at 700 °C) as effective for producing green iron as hydrogen direct reduction (HyDR). Direct use of ammonia could save CAPEX and 10-25% of energy for cracking.

Ammonia can also potentially be used as reductor in electrochemical processes for circular carbon production, replacing fossil carbon. One example is converting ammonia to nitrate at the anode while CO_2 is reduced to ethylene at the cathode. Ethylene is an important platform molecule and this route could

31 Global crude steel production by process route and scenario, 2019-2050 – Charts – Data & Statistics - IEA

32 HYBRIT | SEI - taken from https://ammoniaenergy.org/wp-content/uploads/2022/10/AEA-Presentation-FINAL-no-notes.pdf

33 Ammonia: efficient hydrogen carrier and green steel enabler | Max-Planck-Institut für Eisenforschung GmbH (https://mpie.de)

replace high-temperature naphtha crackers. This process requires renewable electricity supply and is still in a low technology readiness level.

Mobility sector

Mobility as sector for hydrogen fuelled electrical vehicles could grow in the next decades. Growth depends on regulations, economics, and technology. Part of the hydrogen could originate from imported ammonia converted to hydrogen, once local supply is insufficient or unattractive. This assessment lies, however, beyond the scope of this study.

Import ambitions for ammonia and hydrogen

The potential for the ammonia and hydrogen import markets development have been projected, based on the model, assumptions, and figures from the previous sections. Table 4 summarizes the clean ammonia demand. It is assumed that this demand needs to be imported, i.e. 12 mtpa to The Netherlands and 25 mtpa to ARRRA in 2030. In 2050 this could quadruple. On a global scale the total ammonia production capacity necessary for use as energy and hydrogen carrier could grow to 900 mtpa. This is roughly a factor 2,5 higher than IRENA and IEA forecasts.

Table 4: Clean ammonia demand (excl. export) in 2030 and 2050 per industry sector

NH_3 demand (mtpa)				
2030	**Bunkering**	**Power generation**	**New industrial markets**	**Total**
Global	25	5	20	50
ARRRA	3	3	19	25
NL	1	1	10	12
2050	**Bunkering**	**Power generation**	**New industrial markets**	**Total**
Global	200	600	100	900
ARRRA	40	14	45	89
NL	20	3	30	53

In the Dutch figures, the ammonia volumes for transport from The Netherlands (and Belgium) to Germany are not included. It is suggested that ammonia transit to Germany will grow to about 3.5 mtpa ton in 2030. This is lower than the projected 9 mtpa according to Port of Rotterdam, due to suggested demand per industry sector and the assumption of German import of ammonia to the North-Western ports and to a lesser extent also export from Belgium to Germany. The distribution of import and transport for 2050 is not indicated as there are too many uncertainties involved.

Clean ammonia offtake for shipping fuel and power generation are expected to grow fast. The envisaged clean ammonia offtake in new industrial markets and applications is predominantly for cracking to hydrogen and producing sustainable aviation fuel and sustainable steel and high temperature applications.

To summarize, the global market and import volumes for the ARRRA region and the Netherlands are given in Table 5 for clean ammonia and in Table 6 for clean hydrogen. The Dutch figure of 16 mtpa also integrates transport from the Netherlands to Germany. Rounded figures are presented for 2050 compared with Table 4.

Table 5: Projections for clean ammonia import excluding existing demand as chemical feedstock

NH_3 import mtpa	2020	2030	2050
Global	18	50	900
ARRRA	1	25	100
NL	0,7	16	50

Table 6: Projections for clean hydrogen imports excluding existing demand as chemical feedstock

H_2 Import mtpa	2020	2030	2050
Global	0	Not determined	Not determined
ARRRA	0	2	20
NL	0	0.4	8

In Figure 7 and 8, the market trend is graphically illustrated for ammonia as an energy carrier. In 2050 for The Netherlands the bunkering market for international shipping could grow to 20 million tonnes. The power market and conversion to hydrogen could triple. In total, 50 million tonnes of ammonia could potentially be imported to the Netherlands and in ARRRA region double this volume. The global clean ammonia market could grow to 900 additional million tonnes per annum. This is under the assumption that ammonia will be used as fuel on a large scale in the power sector and shipping industry.

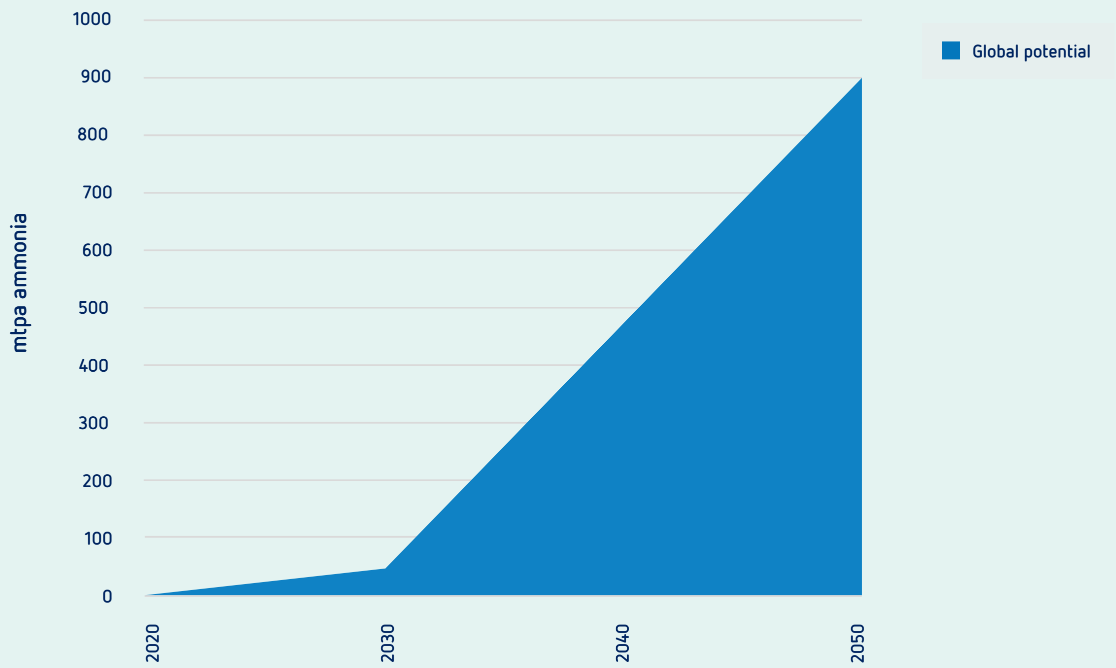

Figure 7: Illustration of market trend for ammonia as energy carrier in 2050 on a global scale (additional to existing 183 mtpa ammonia as feedstock)

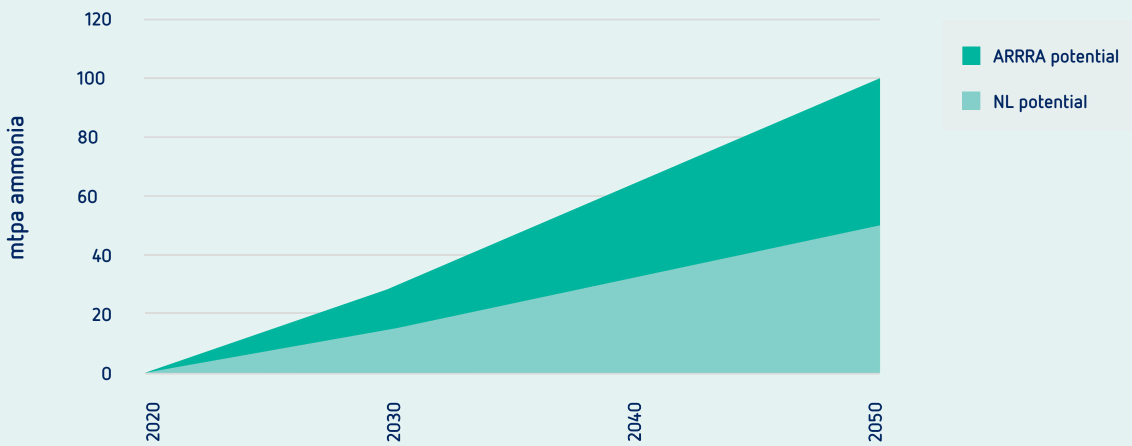

Figure 8: Illustration of market trend for ammonia as energy carrier on ARRRA and NL scale

Model for 2030 Outlook

A model for ammonia and hydrogen demand flows in The Netherlands, Belgium and Germany is prepared in this study, providing examples of imports to The Netherlands, Belgium and Germany (Nordrheinland-Westfalen, Niedersachsen). This regards the potential growth of the ammonia and hydrogen value chains for 2030. The model illustrates the integration of hydrogen and ammonia and the three countries involved with imports, exports and local production, demand and conversion. The suggested figures indicate the urgency for assets and infrastructure development for several value chains during the years to come.

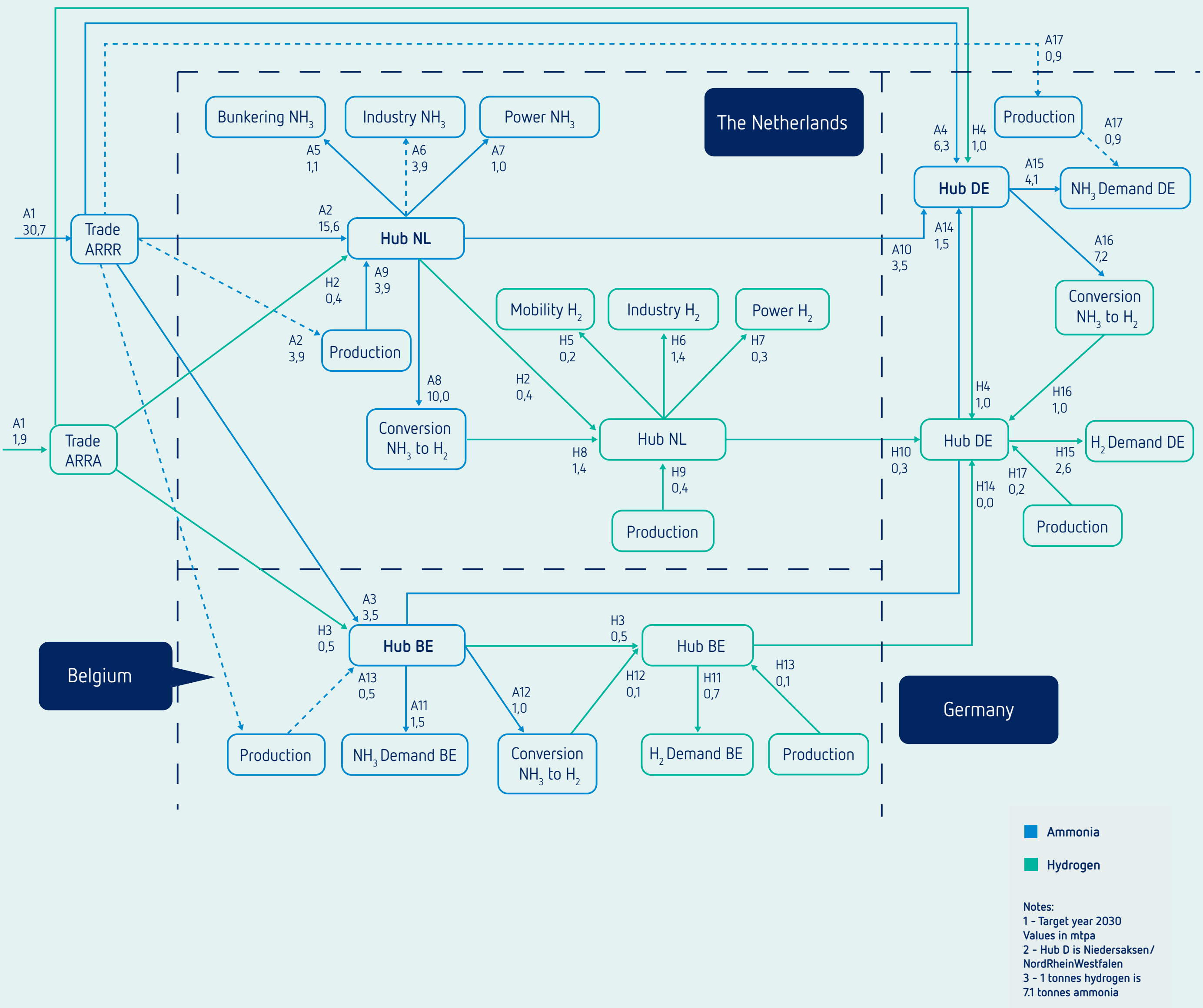

Figure 9: Ammonia and hydrogen trade model in ARRRA

Literature

Global IRENA, IEA

The usage of clean ammonia is driven by decarbonization incentives and the potential applications of innovations. A projection from the International Renewable Energy Agency (IRENA) in 2022 estimated the transition towards an ammonia economy to lead to an increased global clean ammonia market of up to 688 mtpa. Today's market is around 183 mtpa and is expected to grow at a rate of 2-3% annually, resulting in demand in 2050 of 333 mtpa. This implies about 355 mtpa will be required for clean ammonia. As global trade flow in 2022 was only 18 mtpa, a fast growth pace of trade, infrastructure, and storage is required.

According to the IEA Ammonia Technology Roadmap (2021) and Sustainable Development Scenario, the 2050 production capacity for current applications will grow from 185 to 226 mtpa, with net zero emissions (CO_2). The forecast for use as energy carrier is 335 mtpa for shipping and power generation.[34] This results in a total ammonia production of 561 mtpa by 2050, which is slightly lower than the IRENA forecast.

According to IRENA, of the total clean ammonia production by 2050, 566 mtpa would be sourced from renewable sources, whereas the remaining 122 mtpa is expected to come from fossil sources with CCS. The combined capacity of all renewable ammonia projects announced so far is around 15 mtpa by 2030 and around 71 mtpa by 2040. These projects rely solely on electrolysis, which already relates to more than 10% of the estimated 566 million tonnes of green ammonia production by 2050 in the 1.5°C scenario.[35]

Renewable ammonia manufacturing is predicted to become competitive from 2030 onwards, depending on policies and legislation. Clean (and more importantly, green) ammonia is expected to be able to compete with alternative energy sources as prices are predicted to drop.[36] Promising locations for large scale green ammonia production have supplies of solar and/or wind energy. Examples are Australia, Chile, and Morocco. To meet global demands and to facilitate trading, current ammonia infrastructures will have to be expanded drastically. Furthermore, from 2025 onward clean ammonia production is expected to dominate all new ammonia production capacity.

The first new applications of ammonia as an energy carrier are expected to be commercialized around 2025. These consist of - but are not limited to - the use of ammonia as feedstock for retrofitted gas turbines, furnaces, or internal combustion engines. In the IRENA figures power generation is limited to Japanese government policies. Other countries have not been included.

The IRENA 1.5°C scenario predicts the largest chunk of market growth to come from the maritime sector. This market is expected to grow towards 197 million tonnes ammonia by 2050, with an additional 127 million tonnes of demand of ammonia as a hydrogen carrier.

[34] https://www.iea.org/reports/ammonia-technology-roadmap/executive-summaryExecutive Summary – Ammonia Technology Roadmap – Analysis - IEA

[35] IRENA. (2022). Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn.

[36] According IRENA, in 2022 ammonia is approximately USD 720 per tonne, but is expected to drop to USD 480 per tonne by 2030 and USD 310 per tonne by 2050 for the best solar and wind locations.

Table 7: Decarbonized 2050 ammonia targets in mtpa. Source: IRENA / Ammonia Energy Association.

2050 mtpa Ammonia	Green/Renewable (IRENA, 2022)	Blue/Low carbon (IRENA, 2022)	Total (IRENA, 2022)	Total (IEA, 2021)
Existing markets/ feedstock			333	226
Energy carrier			355	335
Total	566	122	688	561

Regional hydrogen and ammonia development in NL, D, B

Ammonia is already being produced in Western-Europe, with in total 4.3 mtpa in the ARRRA region. In the Netherlands the total annual production quantity is 3.1 mt. OCI in Geleen produces 1.2 mtpa, while Yara Sluiskil produces approximately 1.9 mtpa. Germany produces 0.8 mtpa at Yara Brunsbüttel. This company imports an additional 3 mtpa for use at Yara Rostock (2.6 mtpa), the larger Nordrheinland-Westfalen region (0.15 mtpa) and other German users (0.2 mtpa). Belgium produces approximately 0.4 mtpa at Yara Tertre.

A recent study by Berenschot and TNO presents the development of hydrogen carrier imports and production in three scenarios. The third scenario is the most ambitious and relevant for this study. The 2035 forecasts include imports of hydrogen carriers to The Netherlands and ammonia transport to Belgium (red stacks) and Nordrheinland-Westfalen in Germany for conversion to blue and green hydrogen. Imports come as ammonia, Liquid Organic Hydrogen Carrier (LOHC) or as liquified hydrogen. The import figures amount to about 40 mtpa.[37] This is slightly higher than suggested in this roadmap.[38]

In 2022 Port of Rotterdam and Oxford Economics developed some long term scenarios for the development of transshipment in the Port of Rotterdam.[39] The most progressive scenario is called Connected Deep Green CDG, see Annex 5. It is in line with climate goals. For 2030, it predicts about 2 mtpa for hydrogen-equivalents demand in the port and its hinterland. This demand could be met primarily through import of 11 mtpa ammonia (1.7 mtpa hydrogen-eq), of which 1 mtpa ammonia for bunkering, 9 mtpa ammonia converted to 1.2 mtpa hydrogen and the remainder for short sea shipping. In addition, 0.2 mtpa liquid hydrogen and 0.1 mtpa LOHC-hydrogen-ea. are assumed to be imported.

In another study, Port of Rotterdam and seventeen industrial partners investigated the feasibility of centralized and decentralized configurations with terminals and crackers. This study concludes that it would be technically feasible, also from a safety point of view, to build and operate 1 mtpa capacity ammonia crackers with state-of -the-art technology. The lowest CAPEX would involve a single large-scale cracker, as this would be more efficient than a decentralized approach for production, storage and transport.[40]

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[37] Not clear whether ammonia or hydrogen-equivalents is used as unit

[38] Assuming that this is expressed as ammonia for option 3 in 2035 eindrapport-volumes_-modaliteiten-en-veiligheid-waterstofrijke-energie-dragers.pdf (https://berenschot.nl)

[39] Havenscenario's - waterstof en -dragers, Port of Rotterdam, Oxford Economics, 2023

[40] Large-scale ammonia cracker to enable 1 million tonnes of hydrogen imports via port of Rotterdam | Port of Rotterdam

For 2050, imports of hydrogen-equivalents are estimated at about 17 mtpa. A large part will be destined for transit. The suggested breakdown is 7 mtpa of liquid hydrogen, 8 mtpa of ammonia hydrogen-eq, 1 mtpa of LOHC, 2 mtpa for e-methanol (hydrogen-eq) and local green hydrogen production (including North Sea) growing to 2 mtpa. Accordingly, the ammonia import is 47 mtpa.

Compared to existing literature, the outlook in this report assumes the ammonia market as energy carrier to become a factor 2.5 larger than reported by IEA and IRENA. Ammonia imports from other regions for transshipment will become important, affecting demand in the ARRRA region. The power sector specifically represents a high potential. We forecast that ammonia converted to hydrogen can offer an opportunity to decarbonize the steel industry and aviation. Shipping is expected to play a large role in the Netherlands.

Value chains

Ammonia is a global commodity that is part of a global value chain. This section provides an overview of the value chains, based on forecasted demand and supply as discussed in the 2030 Outlook model in the previous section. Furthermore, an indication of expected additional investments in assets required for deployment up to 2030 is given. This representation mainly focuses on the ARRRA region and the Netherlands in particular, and depends on local and regional utilization, logistical routes, and exports to the hinterland.

The value chain analysis also comprises hydrogen as ammonia is also expected to be cracked into hydrogen. Existing value chains with ammonia and hydrogen as feedstock for industry are not included.

The value chains are visualized as a set of assets to be developed to meet forecasted supply and demand in 2030. Related potential investments are expressed in terms of sizes and numbers of estimated assets needed. The CAPEX and OPEX estimates are not part of this study. Assets that have been considered include:

- Dual-fuel sea going vessels
- Terminals with storage tanks
- Bunkering facilities at terminals
- Bunkering (sea going) vessels
- Ammonia-to-hydrogen crackers
- Coal & gas power plants
- Gas turbines combined cycle (GTCC) Retrofitting or new power plants
- Internal combustion engine powerplants (ICE)
- Transport modalities:
    - Sea going vessels
    - Pipelines
    - Inland vessels
    - Rail wagons

Due to safety reasons, pipelines are the preferred transportation modality. For illustration purposes, rail transport and inland shipping are presented in the following value chains, but these modalities are not preferred regarding the large volumes and safety risks involved.

Ammonia utilisation value chain

The Figure 10 shows the value chains of imported ammonia in The Netherlands. Ammonia is shipped to the import terminal in the ports and hence transported though pipelines to customers in the shipping, power and industry sectors. For illustration also railways transport is shown but due to large volumes and safety reasons this is not considered. The use case of ammonia in cracking plants will be further explored in the hydrogen value chains.

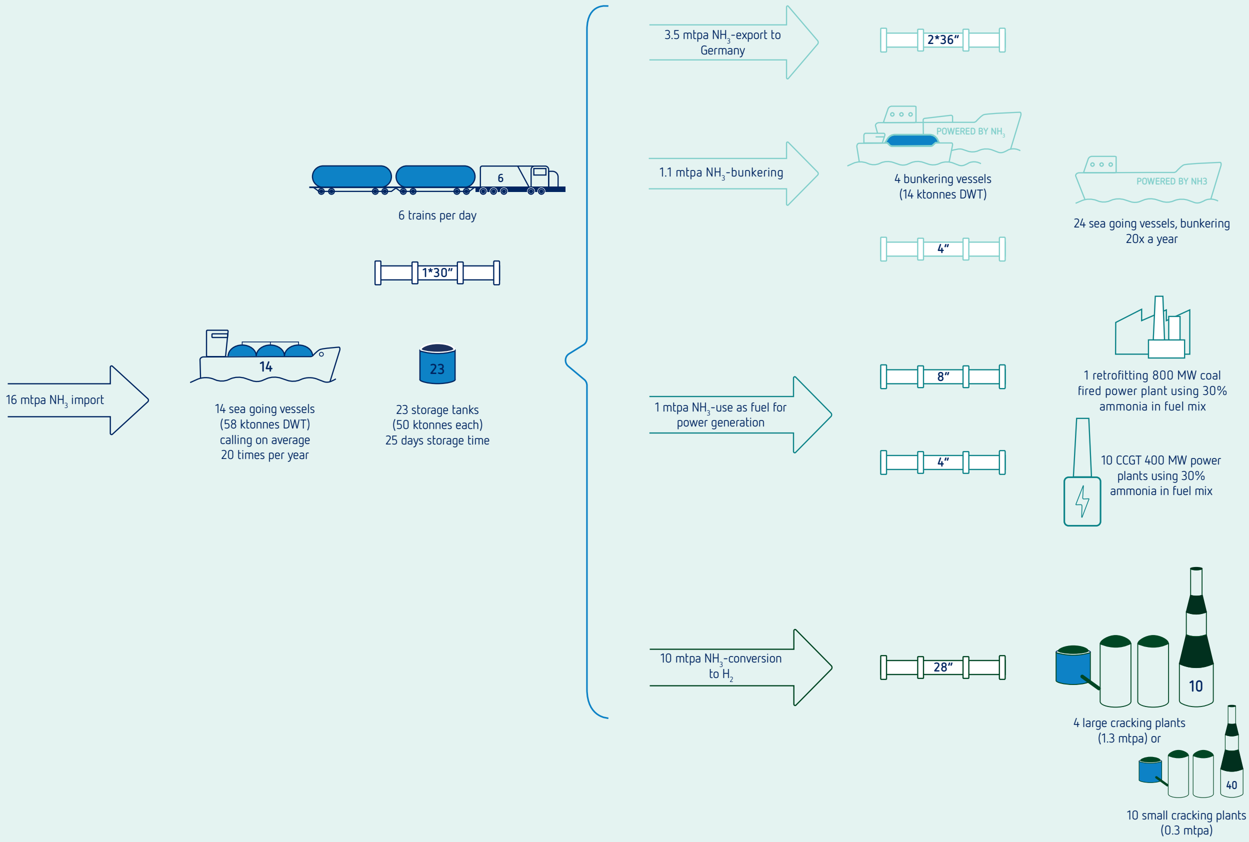

Figure 10: Clean ammonia as energy carrier in the Netherlands (2030)

Hydrogen utilization value chain

Hydrogen can be used in refineries and chemical industry as a feedstock and as an energy carrier in steel making, mobility and the power sector. The figure below shows the various value chains according the 2030 outlook model.

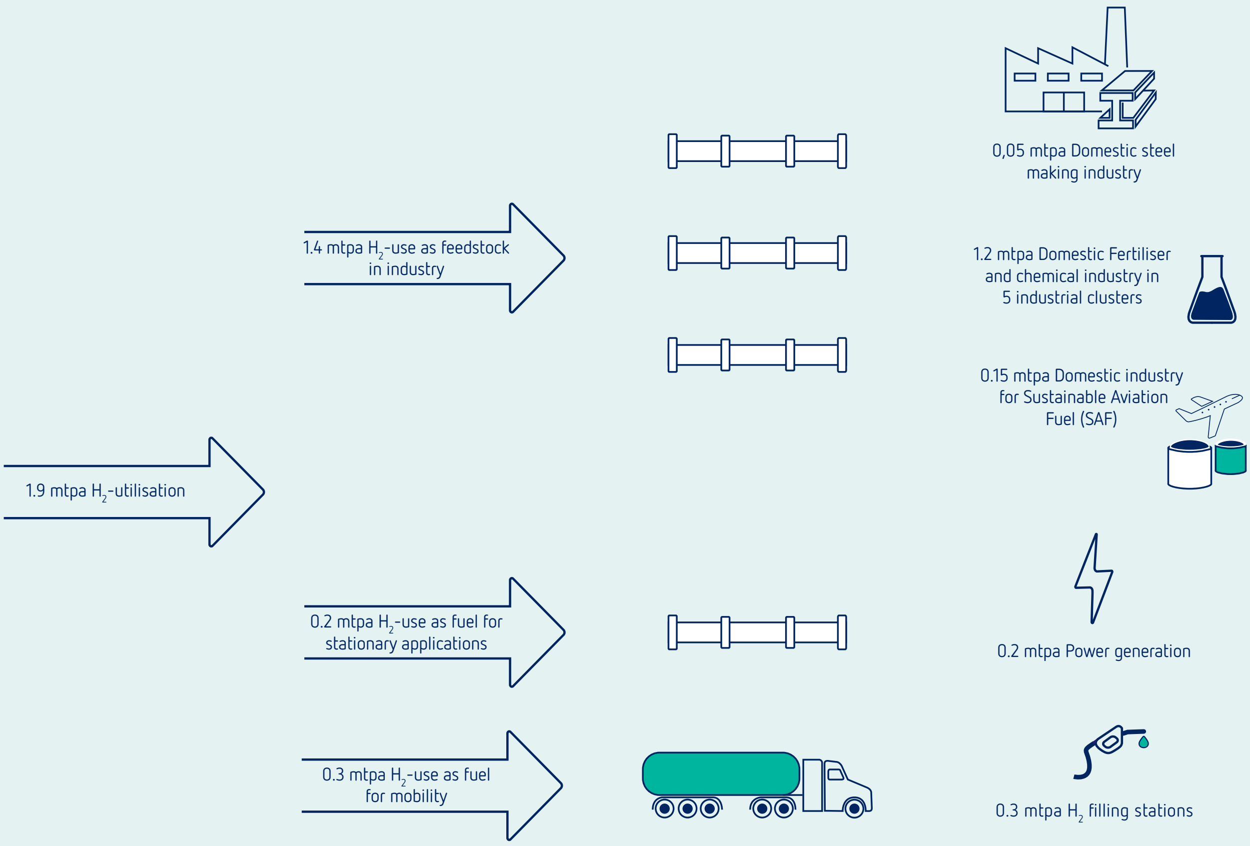

Figure 11: Hydrogen from clean ammonia as hydrogen carrier in the Netherlands (2030)

Integration of ammonia and hydrogen value chains

The hydrogen supply to The Netherlands can be from clean ammonia cracking, hydrogen production and import of hydrogen (liquified, gaseous or LOHC). Figure 12 shows the integration of the corresponding value chains and the suggested throughputs and asset investments.

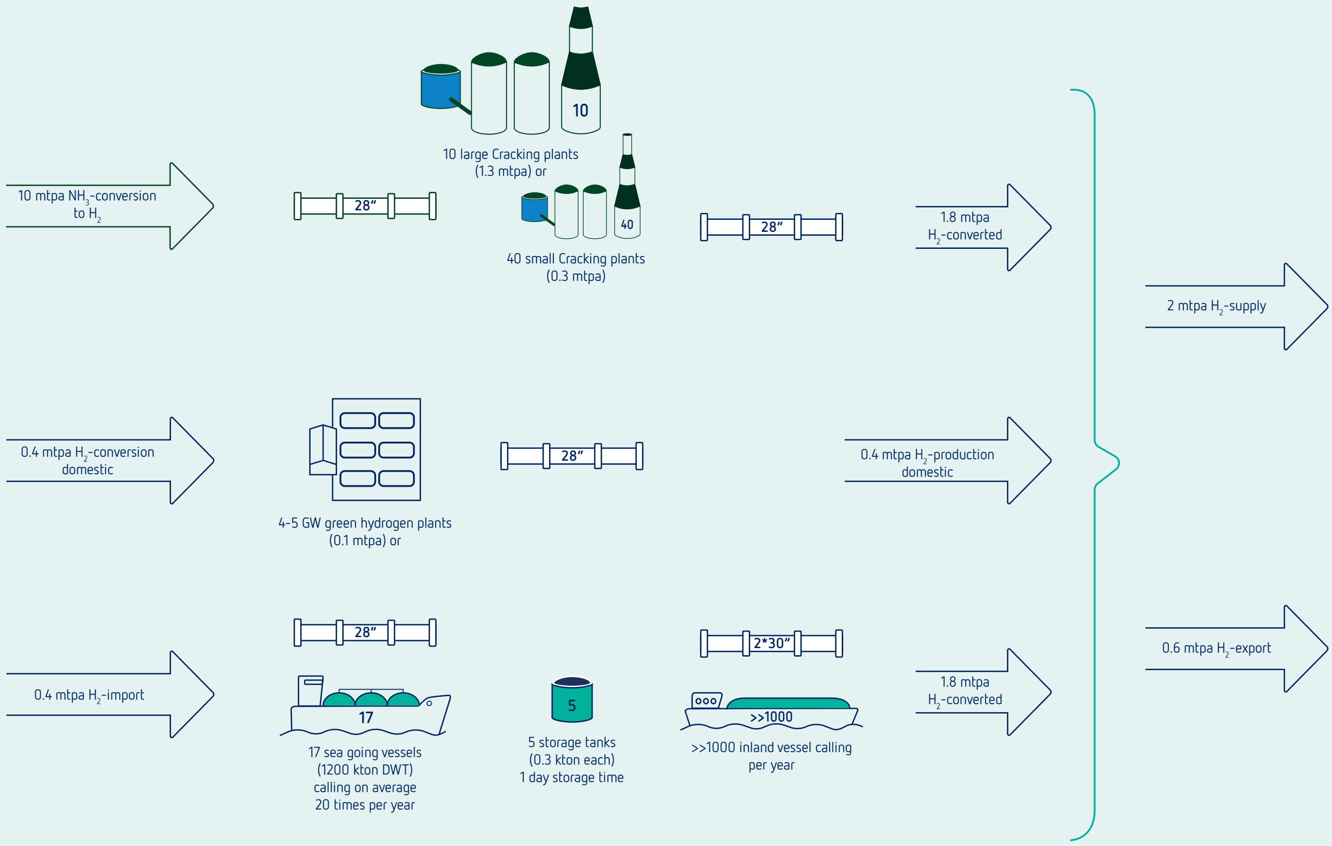

Figure 12: Import, utilisation and export of hydrogen from clean ammonia cracking and hydrogen production and import in the Netherlands (2030)

Use cases

Dutch industry expects a sharp increase in use of ammonia as an energy carrier in the coming years. This chapter summarizes and visualizes the ammonia value chains to fit the ARRRA 2030 scenario.

Import and export

Ammonia will partly be produced in and shipped from regions with abundant green energy supply, such as Arabia, North Africa and Spain. Australia is another contender. Large scale green energy initiatives are under development there. One of these is the AREH project in which BP participates for 40%. This project is expected to produce up to 9 million tonnes of green ammonia annually. This ammonia is projected to arrive at least partly in the ARRRA region.

Part of the energy imports will come in the form of (liquid) hydrogen, part as ammonia. Ammonia and hydrogen will be shipped to Antwerpen, Terneuzen, Rotterdam, Eemshaven Wilhelmshafen and Brunsbüttel among other ports. Amsterdam harbour/Velsen is assumed to only import hydrogen or LOHCs due to local restrictions.

Not all hydrogen is expected to be imported, though. In order to maintain a degree of independence, some of the hydrogen demand will be fulfilled locally. To produce green hydrogen in the ARRRA region is, however, relatively expensive. Today ammonia is produced locally, but this can be (partly) replaced by imported clean ammonia. Not all imported ammonia and hydrogen will be destined for local use. The Netherlands in particular is expected in 2030 to export large quantities of ammonia and hydrogen to the hinterland through for example the Delta Rhine Corridor pipeline to industrial clients in Germany Nordrheinland-Westfalen and Baden Würtemberg. Import from ports in the North of Germany will be possibly through pipelines connected to Yara Rostock and potentially other companies in the region. Based on projections made in the previous chapter, the imports of ammonia and hydrogen in the ARRRA region for 2030 are visualized in Figure 13.

Ammonia use

Figure 13 shows the flow of ammonia to various uses in the ARRRA region. It. reemphasizes the regional interconnectivity with regard to ammonia and hydrogen imports and exports.

In The Netherlands a portion of the ammonia imports in 2030 are destined for bunkering. With the potential of ammonia as marine fuel, bunkering with ammonia at Antwerp and Rotterdam is expected to grow in line with existing bunkering capacities.

The use of ammonia as direct fuel for (retrofitted) power stations to create electricity and heat is explored by NUON. It has already been applied in practice in Japan. The potential of ammonia in coal fired power plants and gas fed turbines is therefore realistic. Imported ammonia will still be used as feedstock for existing applications. Ammonia can be locally converted into nitric acid or ammonium nitrate.

Alternatively, it is used in the chemical industry for acrylonitrile production. Acrylonitrile is produced from propylene, ammonia, and oxygen for the production of polymers. ISPT currently works on electric cracking[41] to substantially reduce emissions for propylene production from propane. If this is combined with clean ammonia, substantial CO_2 emission reductions become within reach. OCI, AnQore and Elix Polymers announced that green ammonia would be utilized for green acrylonitrile production in the Netherlands.[42] Fortescue Future Industries and polymer manufacturer Covestro announced a partnership for green polymer production.

Figure 13: Suggested imports of ammonia and hydrogen in mtpa in ARRRA region, 2030

One other major component of the prospective ammonia value chain is conversion to hydrogen. As Figure 14 shows, a major share of ammonia imports will end up in conversion to hydrogen.

[41] https://ispt.eu/programs/electric-cracking/

[42] https://ammoniaenergy.org/articles/green-ammonia-for-polymers-econitrile/

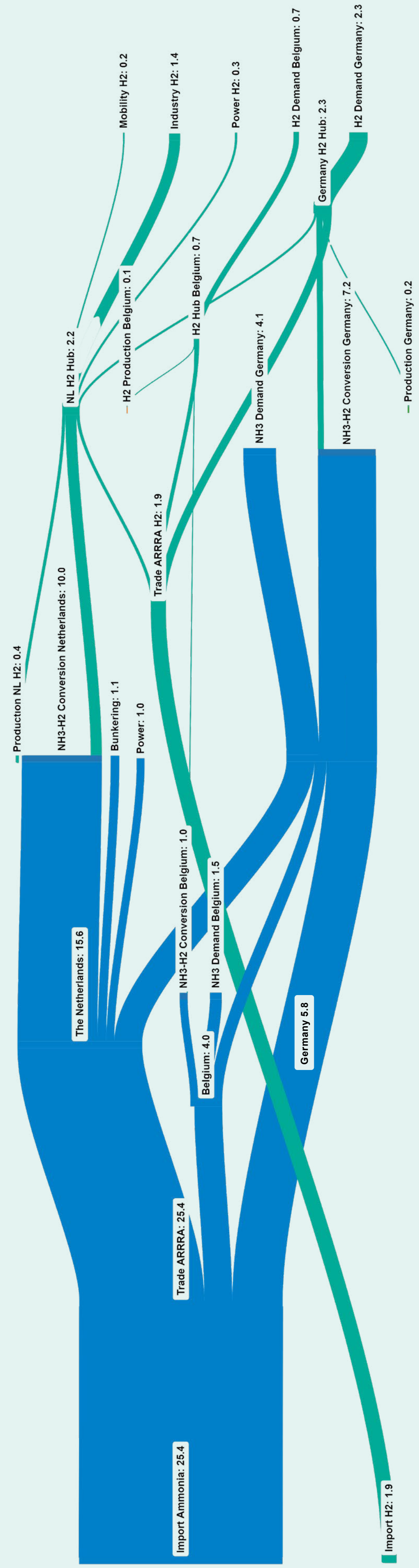

Figure 14: Sankey diagram of imported ammonia and its use 2030.

Technology pathways

Overseas ammonia transport

Intercontinental ammonia transport typically takes place by ship. An estimated total of 18-20 million tonnes of ammonia are traded in this way annually.[43] This represents about ten percent of global ammonia demand.

For this purpose, fully refrigerated carriers were deployed, just like with LPG. This implies that current LPG carriers can be reused as ammonia carriers. Typical carriers have a capacity of 30,000-80,000 m^3, equivalent to 20-55 kt of ammonia capacity.

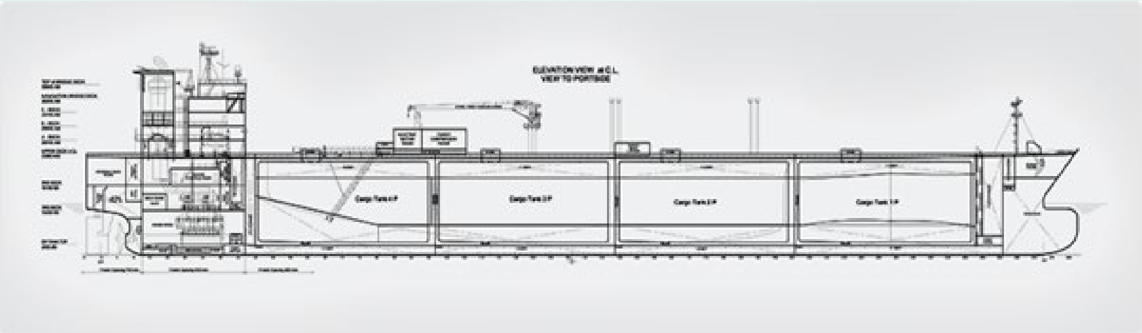

Figure 15: Fully refrigerated LPG carrier (84,000 m^3 or 57.3 kilotonnes ammonia capacity over 4 tanks, or 14.3 kilotonnes ammonia per tank). Total ship length 229 m.[44]

Ammonia storage

Ammonia (un)loading terminals are globally distributed as shown in Figure 16. These facilities have a capacity of several dozens of kilotonnes. Smaller ammonia storages are widely available in the United States, where ammonia is directly used as a fertilizer. The United States houses more than 10,000 ammonia storage locations[45].

A typical ammonia import terminal has a capacity in the range 30 to 50 kilotonnes of ammonia. The liquid ammonia is then stored at -33°C and near ambient pressure, as shown in Table 8.

Table 8: Ammonia storage types.[46]

Type	Capacity	Temperature	Pressure
Refrigerated storage	4.5-50 kt-NH_3	-33°C	ambient
Semi-refrigerated storage	0.5-2.7 kt-NH_3	0°C	3-5 bar
Pressurized storage	<1.5 kt-NH_3	20-25°C	16-18 bar

[43] Hatfield, O. (2020). A review of global ammonia supply. In NH_3 Energy Conference.

[44] ICE Marine Design. (n.d.). Gas carriers. Retrieved January 30, 2023, from https://icedesign.info/services/proprietary-designs/gas-carriers/

[45] Papavinasam, S. (2014). Oil and Gas Industry Network. In Corrosion Control in the Oil and Gas Industry (pp. 41–131). https://doi.org/10.1016/B978-0-12-397022-0.00002-9

[46] Rouwenhorst, K. H. R., Van Der Ham, A. G. J., Mul, G., & Kersten, S. R. A. (2019). Islanded ammonia power systems: Technology review & conceptual process design. Renewable and Sustainable Energy Reviews, 114. https://doi.org/10.1016/j.rser.2019.109339

Figure 16: Ammonia loading terminals and ammonia unloading terminals.[47]

Modern refrigerated ammonia storage tanks are so called full containment tanks, as presented in Figure 17. These tanks have double walls, a suspended roof and insulation on the outside. The tank is erected on piles on a concrete slab foundation to prevent the ground from freezing which could cause cracking. For new large storages, the outer shell and roof of double wall tanks will be constructed in concrete to mitigate risks from outside impact. This is included in pending PGS12 recommendations. Ammonia storages are kept at low temperatures by a system in which part of the ammonia in the storage tank evaporates (boil-off), which is then compressed and cooled. Upon depressurization the ammonia evaporates and cools the remaining ammonia.

Intermediate-scale ammonia storage tanks of 0.5 to 2.7 kilotonnes ammonia operate under semi-refrigerated conditions at 0°C and 3-5 bars. Such tanks have the spherical shape of a so called Horton sphere. Small-scale ammonia storage tanks of typically below 1.5 kilotonnes operate under pressurized conditions: 20-25°C and 16-18 bars. These storage tanks have the shape of a nurse tank or an ISO tank.

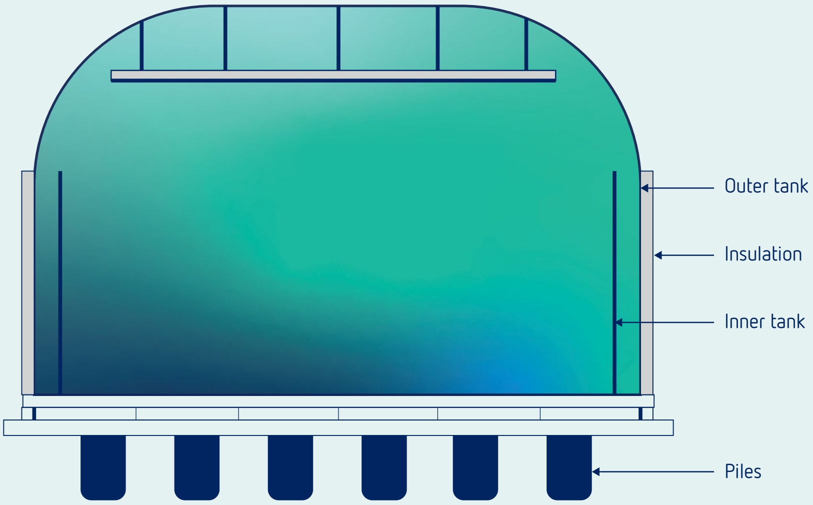

Figure 16: Full containment ammonia tanks.[48]

[47] IRENA, & Ammonia Energy Association. (2022). Innovation Outlook: Renewable Ammonia. Abu Dhabi. https://doi.org/978-92-9260-423-3

[48] Pattabathula, V., Nayak, R., & Timbres, D. (2014). Ammonia Storage Tanks. Ammonia Know How. Retrieved January 30, 2023, from https://ammoniaknowhow.com/ammonia-storage-tanks/

Ammonia transport by barges

Inland ammonia transport over water is done with barges which a capacity of up to 3 kilotonnes. Liquid ammonia transport by barge occurs under pressurized conditions at temperatures above 5°C and at elevated pressures. An ammonia barge as shown in Figure 18 has a total capacity of approximately 900 tonnes ammonia.

Figure 18: Ammonia barge with a capacity.[49]

Ammonia rail transport

Liquid ammonia rail transport takes place under 5 to 12 barg pressure, at temperatures above 5°C[50]. Typical wagon volumes are 50 to 110 m^3 (maximum fill level of 88%), which equals approximately 26 to 58 tonnes of ammonia. A typical train with 20 wagons of 95 m^3 (50 tonnes) transports 1000 tonnes of ammonia.

Ammonia pipelines

Ammonia can be transported by pipelines in gaseous and liquid form. Gas pipelines of typically 16 to 40 inches diameter are less economic because of the much lower density.

In Europe ammonia pipelines are typically restricted to industrial cluster areas, with typical pipe lengths below ten kilometres.[51] Typical capacities of such pipelines range from 120 to 14,000 tonnes of ammonia daily. About 1.5 megatonnes of ammonia is transported annually in the Midwest of the US through 3,220 kilometres of pipelines with 6 to 16 inches diameter.[52] Similarly, a 2424 kilometres long pipeline used to pump 3 to 5 megatonnes of ammonia per annum from Tolyatti in Russia to Odesa in Ukraine [4].

Refrigerated liquid ammonia pipelines (-33°C and 2-5 bargs) are typically only operated for distances below five kilometres, as the refrigeration infrastructure would become very costly for transport over larger distances. Pressurized liquid ammonia pipelines operated at ambient temperature and 15 at 22 barg are typically used for longer distances. Pumps are used to keep up the required pressures over long distances and to prevent ammonia evaporation.

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[49] CNI. (n.d.). 02 x $715m^3$ Bullet Tanks on an NH_3 Carrying Barge (FACO). Retrieved January 30, 2023, from https://cnipvc.com/projects/02-x-715m3-nh3-carrying-barge-faco/

[50] EFMA. (2007). GUIDANCE FOR TRANSPORTING AMMONIA BY RAIL. Retrieved from https://cefic.org/app/uploads/2018/12/Transporting-Ammonia_ByRail-by-EFMA-2007-GUIDELINES-_ROAD-SUBSTANCE.pdf

[51] Fertilizers Europe. (2012). Guidance for inspection of and leak detection in liquid ammonia pipeline.

[52] Acker, M. (2021). Pipeline Transportation of Ammonia – Helping to Bridge the Gap to a Carbon Free Future. In Ammonia Energy Conference 2021 (pp. 1–9). Retrieved from https://ammoniaenergy.org/wp-content/uploads/2021/11/AEA-Ammonia-Pipeline-Transportation-MEA-11-4-2021.pdf

Ammonia cracking

Ammonia can be converted to hydrogen and nitrogen in an ammonia cracker. Ammonia is first vaporized and then passes a heat exchanger before entering the actual ammonia cracker. Ammonia crackers typically contain oxide-supported Ni catalysts, Fe-Co catalysts, or oxide-supported Ru catalysts. The crackers operate at 600-900°C and at 10 to 80 bars pressure. Hydrogen is typically purified using pressure swing adsorption (PSA). Downstream hydrogen compression may be required to meet the pipeline pressure. The burners are typically fed with a mixture of feed ammonia and recycled hydrogen & nitrogen mixtures from the hydrogen purification stage. A typical process overview is shown in Figure 19. The hydrogen production capacity lies in the range of 10 to 500 tonnes hydrogen per day. The energy efficiency ranges from 85 to 90%.

In a feasibility study commissioned by the Port of Rotterdam Authority and 17 companies from the region it was shown that there are several proven techniques available that can be used on a large scale. A central large-scale cracker will result in lower costs than a decentralized approach, due to economies of scale and more efficient storage and transport of the hydrogen.[53]

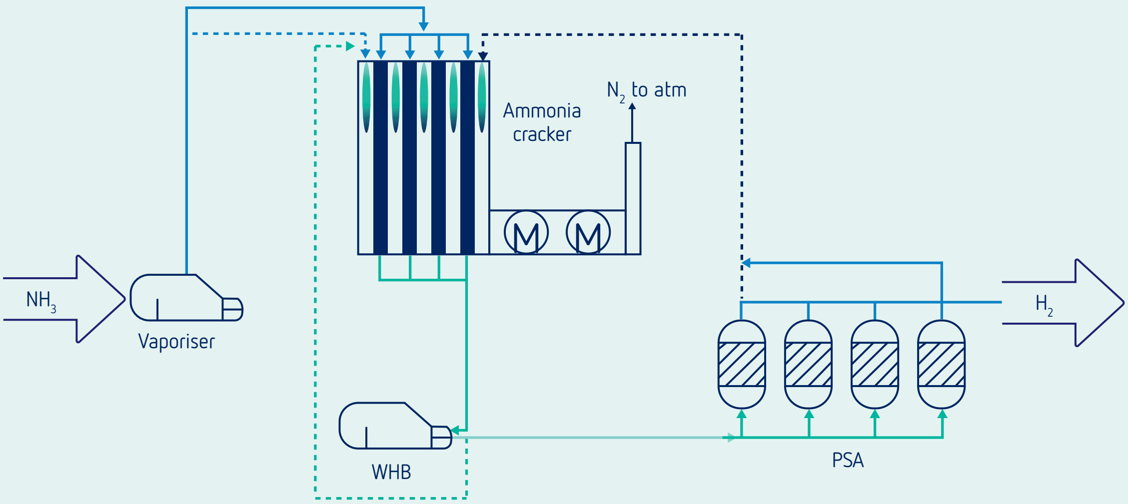


Figure 19: Ammonia cracking schematic. WHB: Waste heat boiler. PSA: Pressure swing adsorption[54].

Ammonia as shipping fuel (bunkering)

Ammonia is considered a main option to decarbonize international shipping next to alternatives such as methanol and biofuels. Given a ship's lifetime of twenty to thirty years, newly built ships are often already built with 'ammonia-ready' fuel storages. Engine manufacturers such as MAN ES and Wärtsilä are developing two and four stroke ammonia-fed maritime engines. These are expected to be commercialized

[53] Study: Ammonia cracker realistic and safe method for large-scale hydrogen imports | Port of Rotterdam

[54] Pach, J. (2022). Ammonia Cracking: Design and Safety Considerations. In Ammonia Energy Conference 2022 (pp. 1–32). Retrieved from https://ammoniaenergy.org/wp-content/uploads/2022/10/AEA-Presentation-FINAL-no-notes.pdf

by 2024 or 2025, for newly build engines as well as for retrofits. A pilot fuel such as oil is likely required for ammonia-fed two-stroke engines, for instance to improve the compressibility of the mixture.

The engines for various fuels are developed from the same basic architecture, allowing conversion to an ammonia-fed engine. Multi-fuel operation is also considered, as low carbon fuels may not always be available in the early stage.

In a NoGASP study two main machinery configurations were assessed as part of the feasibility phase – an ammonia-electric propulsion system with four-stroke main engines and an ammonia-mechanical solution with a two-stroke main engine. The two-stroke option prevailed due the lower fuel consumption, reduced emissions and a more simple safety concept.[55] Ammonia Solid Oxide Fuel Cell (SOFC) applications might also become feasible, but these are still at low Technology Readiness Levels.[56]

NO_x emissions are mitigated through exhaust gas recycling and a deNO_x system. Ammonia slip catalysts may also be required to mitigate emissions.

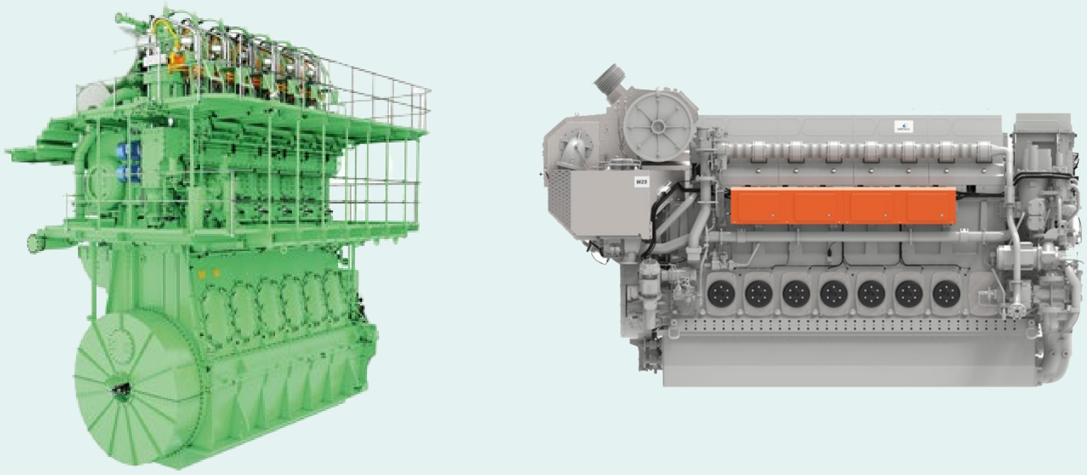


Figure 20: Left: MAN ES two-stroke engine (Photo MAN). Right: Wärtsilä multi-fuel four-stroke engine (Photo Wärtsilä).

Ammonia as fuel for gas turbines

Ammonia can be used to replace natural gas in gas turbines used for baseload electricity generation or as a peaker plant. The fuel cost is relevant for baseload electricity generation. It is less significant in peaker plants, where maintenance is the dominant cost factor.[57]

Ammonia can be used as a direct fuel or it can be partially cracked to hydrogen and nitrogen before entering the combustion chamber. A key challenge for ammonia-fed gas turbines is NO_x generation during

[55] Nordic Green Ammonia Powered Ships (NoGAPS) | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

[56] https://marinelink.com/news/first-test-ammonia-fuel-cell-system-a-506258 - Viking Energy with ammonia-driven fuel cell – Eidesvik Solid Oxide Fuel Cell (SOFC) 4 Maritime | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

[57] Cesaro, Z., Ives, M., Nayak-Luke, R., Mason, M., & Bañares-Alcántara, R. (2021). Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants. Applied Energy, 282(A). https://doi.org/10.1016/j.apenergy.2020.116009

combustion.[58] Small-scale gas turbines of around 40 MW can operate with pure ammonia, one of these turbines can be seen in Figure 21.

Mitsubishi Heavy Industries aims to commercialize this technology by 2025. Large-scale gas turbines in the hundreds of MW range are likely to require typically 30% ammonia cracking for optimal performance. For the cracking process, the exhaust heat from the gas turbine can be used, thereby improving overall energy efficiency.

Figure 21: Mitsubishi Heavy Industries H-25 Series 40 MW gas turbine.

Ammonia fired powerplant

Ammonia can be applied to replace coal and other hydrocarbons in thermal power stations to fuel steam generation boilers or to generate high temperature heat. JERA from Japan, one of the world's largest energy companies, aims to operate one of its 1 GW coal-fired power plants with 20% ammonia co-feed in 2024.[59] The replacement will not have a significant effect on NO_x emissions. If all Japanese coal-fired power plants would operate with 20% renewable ammonia co-feed, CO_2 emissions could be reduced by about 40 megatonnes.[60]

The Netherlands currently emits about 178 megatonnes CO_2 equivalents annually. Using coal as fuel will be prohibited here from 2030 onward.[61] Ammonia, possibly in combination with other feedstocks such as solid biomass, could be used to sustain baseload power generation beyond 2030.

58 Kobayashi, H., Hayakawa, A., Somarathne, K. D. K. A., & Okafor, E. C. (2019). Science and technology of ammonia combustion. Proceedings of the Combustion Institute, 37(1), 109–133. https://doi.org/10.1016/j.proci.2018.09.029

59 Atchison, J. (2022). JERA targets 50% ammonia-coal co-firing by 2030. Retrieved January 31, 2023, from https://ammoniaenergy.org/articles/jera-targets-50-ammonia-coal-co-firing-by-2030/

60 Stocks, M., Fazeli, R., Hughes, L., & Beck, F. J. (2022). Global emissions implications from co-combusting ammonia in coal fired power stations: An analysis of the Japan-Australia supply chain. Journal of Cleaner Production, 336, 130092. https://doi.org/10.1016/j.jclepro.2021.130092

61 Rijksoverheid. (2018). Kabinet verbiedt elektriciteitsproductie met kolen. Retrieved January 31, 2023, from https://rijksoverheid.nl/actueel/nieuws/2018/05/18/kabinet-verbiedt-elektriciteitsproductie-met-kolen

Ammonia for high-temperature heating applications

Ammonia burners based on Duiker Combustion Engineers technology are already operated. Their Stoichiometry-Controlled Oxidation (SCO) technology is based on two-stage combustion (see Figure 22), resulting in NO_x emissions as low as 50-80 ppmv (at 3 vol.% O2 in dry flue gas). Further NO_x emission reduction to below 5 ppmv NO_x can be achieved through a selective catalytic reduction (SCR) $DeNO_x$ system typically used in nitric acid plants.

Principle

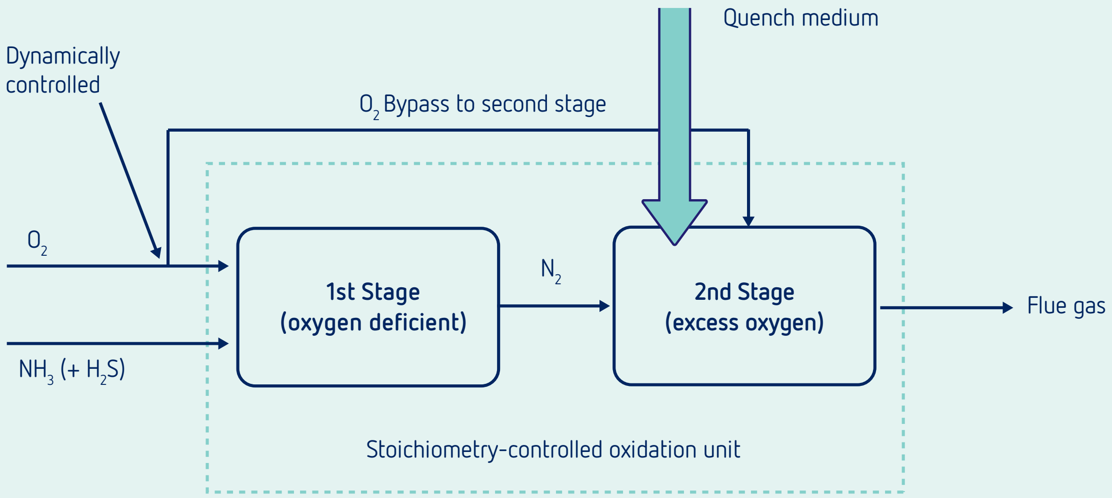


Figure 22: Stoichiometry-Controlled Oxidation (SCO) technology. Courtesy Duiker Combustion Engineers.

Merit order and CO_2 reduction

CO_2 reduction potential

In reality, CO_2 reduction with clean ammonia can be attained by either low carbon or by renewable ammonia. For simplicity reasons, 100% CO_2 emission free use of renewable ammonia is considered alongside low carbon plus CCS. No emissions upstream according to a life cycle assessment have been taken into account. This approach is considered acceptable for such a merit order.

Various value chains can be envisioned for the use of ammonia as energy and hydrogen carrier, namely coal-fired power plants, (combined cycle) gas turbines (baseload and peaker, CCGT), international shipping, and hydrogen production and utilisation. Regarding hydrogen utilisation, steel industry with direct reduction of iron combined with electric arc furnaces (DRI-EAF) and shipping have been considered. The hydrogen supply is to a large extent imported as ammonia and locally converted to hydrogen.

Ammonia production and CO_2 reduction

The two large ammonia producers in The Netherlands have a name plate capacity of 3.1 million tonnes of ammonia and a total maximum emission of about 5.7 million tonnes-CO_2 per annum. This leads to a carbon intensity of about 1.8 tonnes-CO_2/tonnes-NH_3 depending on the fuel/feedstock ratio.[63] The current fossil-based ammonia production can be replaced with zero-carbon ammonia production and clean ammonia imports. The CO_2 emissions originate mainly from steel methane reforming (SMR), producing hydrogen from natural gas upstream of the Haber-Bosch process with exothermic ammonia synthesis. The actual reduction potential is lower, as roughly 40% of emissions is currently already captured before the ammonia loop and converted to urea as fertilizer, used in greenhouses to stimulate growth and applied as AdBlue for diesel engines. The remaining 60% for CCS for the ammonia fertilizers not requiring CO_2 as feedstock results in about 1.2 mtpa-CO_2/t-NH_3 or in other words a reduction potential of 0.6 mtpa-CO_2/t-NH_3 or 1.9 mtpa-CO_2.

Taking into account Yara's announced plans to transport 0.8 mtpa-CO_2 for permanent storage to Norway from 2025 onward[63], a net emission of 1 mtpa-CO_2eq remains. Further CO_2 emissions for hydrogen production from Steam Methane Reforming may be feasible with hydrogen burners combined with up to more than 95% capture rates process CO_2. This is not commercially operated yet, and therefore not included in these figures. In case the non-urea capacity were to be replaced with zero-carbon ammonia, this would amount to about 2.9 million tonnes-CO_2 reduction per annum. Thus, replacing existing fossil-based ammonia production capacity with imported zero-carbon ammonia or local production of urea and ammonia combined with CCS is a matter of certification of renewable / low carbon hydrogen/ammonia and economics.

[62] https://pbl.nl/sites/default/files/downloads/pbl-2019-decarbonisation-options-for-the-dutch-fertiliser-industry_3657.pdf

[63] https://yara.com/news-and-media/news/archive/news-2022/major-milestone-for-decarbonising-europe/

CO_2 reduction potential of ammonia as energy and hydrogen carrier

The CO_2 reduction potential can be calculated. The first parameter for this is the carbon intensity for each energy carrier. This is divided by the required ammonia input, derived from the total global aggregated energy consumption. The Lower Heating Value of ammonia is also taken into consideration. The resulting figures do not consider differentiation for regions, lifetime of equipment, (new) technologies nor efficiency.

Table 9: CO_2 reduction potential for ammonia as feedstock, energy carrier and hydrogen carrier.

Market-product	CO_2 reduction potential (renewable ammonia)	CO_2 reduction CCS (low carbon ammonia)	Current situation and assumptions
Converted ammonia to hydrogen in steel making (DRI-EAF)	3.7 t-CO_2/t-NH_3 [64, 65]	3.0 t-CO_2/t-NH_3 (80% CCS)[67]6	35 EJ/a fuel globally, 2600 mtpa-CO_2eq direct emissions globally[67] and global steel market 2000 mtpa.[68, 69] In The Netherlands Tata Steel produces 7,5 mtpa steel with around 6 mtpa and 4 mtpa through Vattenfall Power Velsen[70]
Ammonia-fired power plants replacing coal	1.9 t-CO_2/t-NH_3	1.1 t-CO_2/t-NH_3 (e.g. 60% CCS)	13.9 mtpa-CO_2eq emissions for 17.15 TWh power, at 46% LHV efficiency [71]
Ammonia production Haber Bosch with hydrogen from SMR	1.8 t-CO_2/t-NH_3	0.6 t-CO_2/t-NH_3	8.5 to 10 kg-CO_2/kg-H_2 with 70% as feedstock and 30% as fuel
International shipping using ammonia instead of MDO	1.4 t-CO_2/t-NH_3[72]	N/A	8.7 EJ/a fuel globally, 667 mtpa-CO_2eq-emissions globally[73]
Synthetic Aviation Fuels (as e-fuel/kerosine)	22.3 t-CO_2/t-NH_3 (Renewable ammonia cracking and Direct Air Capture)	0.7 t-CO_2/t-NH_3 (60% CCS)	12 EJ/a fuel globally, 712 mtpa-CO_2eq emissions globally[74]
Gas turbine (CCGT)	1.0 t-CO_2/t-NH_3	0.95 t-CO_2/t-NH_3 (95% CCS for baseload, N/A for peaker plants)	22.3 mtpa-CO_2eq emissions for 70.44 TWh/a power, at 60% LHV efficiency[75]

64 Based on 24 ton CO_2/kgH_2, acc hydrogen_insight_brief.pdf (https://rmi.org)

65 According the authors, the CO_2 reduction potential can be different form this figure depending on the technology, the conversion losses, the assumption on CO_2 per ton steel and whether only the blast furnaces are considered or also other processes. As a result, the range may be between 2 and 5 ton CO_2/ ton ammonia.

66 jrc119415_iron_and_steel_decarbonisation_brief.pdf (https://europa.eu)

67 Iron and Steel – Analysis - IEA

68 1,8 CO_2 per ton steel acc Climate change policy paper (https://worldsteel.org)

69 Reported figures lead to 117,5 GJ and 1,3 million tonnes CO_2 per ton crude steel. To the opinion of the authors, the application of these figures should be with care to calculate the CO_2 reduction from DRI as these figures include scrap metal as raw material besides iron ore. Using scrap metal as raw material has a much lower CO_2 footprint than virgin steel and for example, 60% scrap metal can be used as feedstock leading to around 50% lower CO_2 emissions. Also, it is not clear whether indirect emissions from firing steel gases for electricity generation are included in the steel sector CO_2 footprint. Furthermore alternative routes will have an impact on waste gases and may disrupt the opmitmal heat integration.

70 Emissies naar lucht op Nederlands grondgebied; stationaire bronnen (https://cbs.nl)

71 https://rvo.nl/sites/default/files/2022-

72 Confirmed by 3,206 kg CO_2 per kg MDO acc Fourth Greenhouse Gas Study 2020 (imo.org) divided by a factor 2,3 for LHV MDO/NH_3

73 https://iea.org/reports/international-shipping

74 https://iea.org/reports/aviation

75 05/CE_Delft_210338_Emissiefactor_Elektriciteit_Fossiele_Bronnen_DEF.pdf

Steel making has the highest emission reduction potential, despite conversion losses of ammonia conversion to hydrogen. Coal-fired power plants and unmitigated SMR fossil hydrogen production also have a high emission reduction potential, followed by international shipping, gas turbines and Synthetic Aviation Fuels (SAF).

For SAF the CO_2 sources and (renewable) heat and electricity are relevant. Theoretically, there is a 100% CO_2 reduction potential with Direct Air Capture (DAC), whereas with 60% carbon capture in refineries 40% will still be emitted. Of course the use of low carbon or renewable hydrogen or ammonia determines the eventual CO_2 reduction potential. Alternatively, substantial CO_2 emissions can be mitigated by CCS/CCU.

CO_2 reduction merit order

The merit order for decarbonization through ammonia based on the figures in Table 9 is shown in Figure 23. The CO_2 reduction potential is divided in a low carbon (CCS) share in mitigation as well as net CO_2-emissions, which will also be mitigated in case of renewable ammonia.

CCS is assumed to be unfeasible for Combined Cycle Gas Turbine power plants used as peaker plants and for maritime and aviation applications. As coal-fired power plants will not be allowed to use coal in The Netherlands by 2030, it is thus assumed that CCS capacity will not be introduced for this application either.[76]

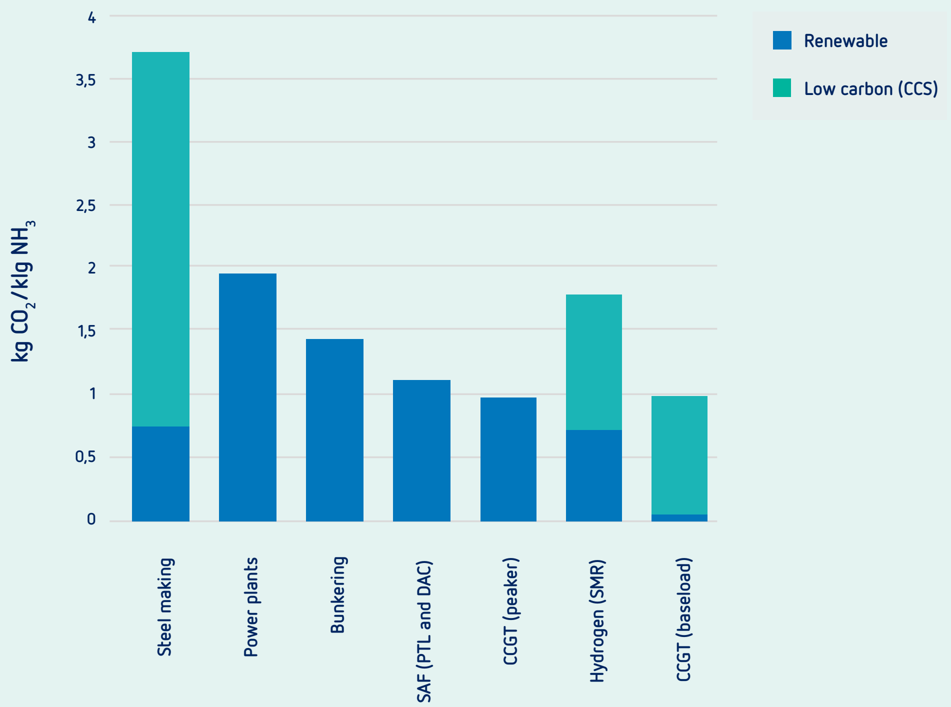


Figure 23: Merit order for ammonia decarbonisation potential (renewable and low carbon)

[76] https://rijksoverheid.nl/actueel/nieuws/2018/05/18/kabinet-verbiedt-elektriciteitsproductie-met-kolen

It should be noted that other factors are also relevant. These are alternative, lower cost pathways to mitigate emissions, such as electricity generation by solar PV and wind. Direct electrification is, however, unlikely for international shipping or aviation before 2050. Furthermore, increased use of ammonia as peaker fuel for grid balancing will emerge in a grid with high renewables penetration. This cannot be accounted for as replacement of fossil assets. Thus, ammonia or other pathways with CCS / CCU will be a matter of politics, certification and economics.

Figures 24 and 25 present the merit order for CO_2 emission reduction in the utilisation phase, based on global and domestic renewable ammonia application for the period 2023 to 2050. The CO_2 reduction potential refers to Table 9 figures and excludes CO_2 reduction during hydrogen/ammonia production. The CO_2 reduction figures are obtained from multiplication of the potential with the suggested ammonia volumes for imports and utilization. The steel sector and the power sector are by far the most important industries to obtain CO_2 reduction. The utilization of Renewable ammonia based SAF in the aviation industry through Direct Air Capture (DAC) has the lowest ranking. It would be even lower in case of SAF combined with CCU.

An important part of the CO_2-emission reduction in the Netherlands could be attained in the shipping industry through ammonia bunkering. The actual reduction would, however, be attained in international waters and in ammonia production regions.

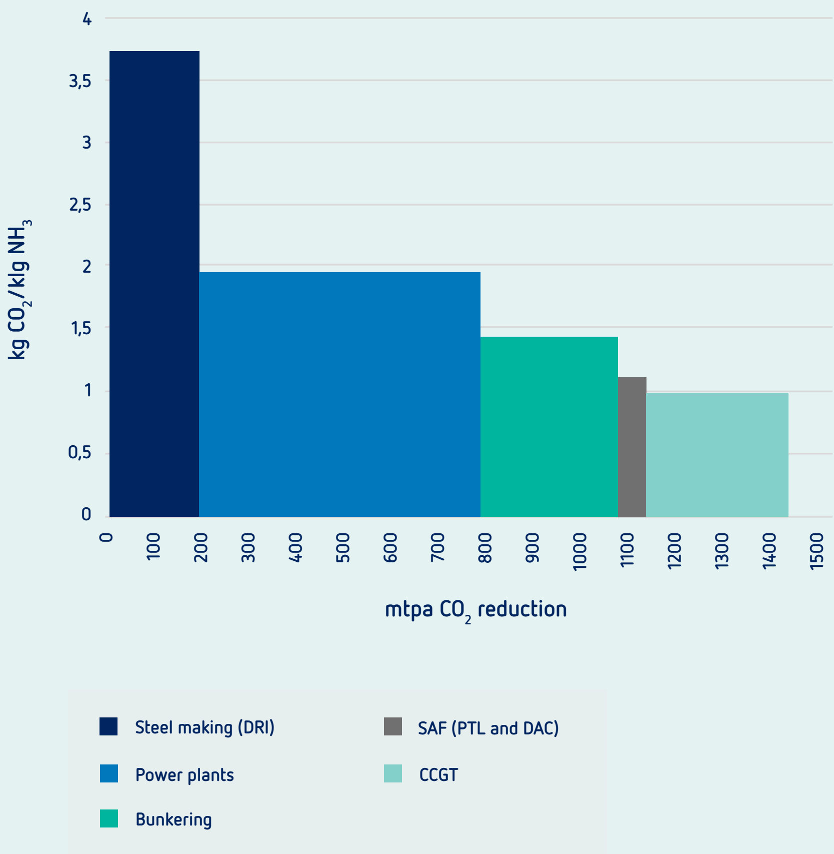


Figure 24: Merit order global CO_2 reduction based on renewable ammonia in 2023-2050

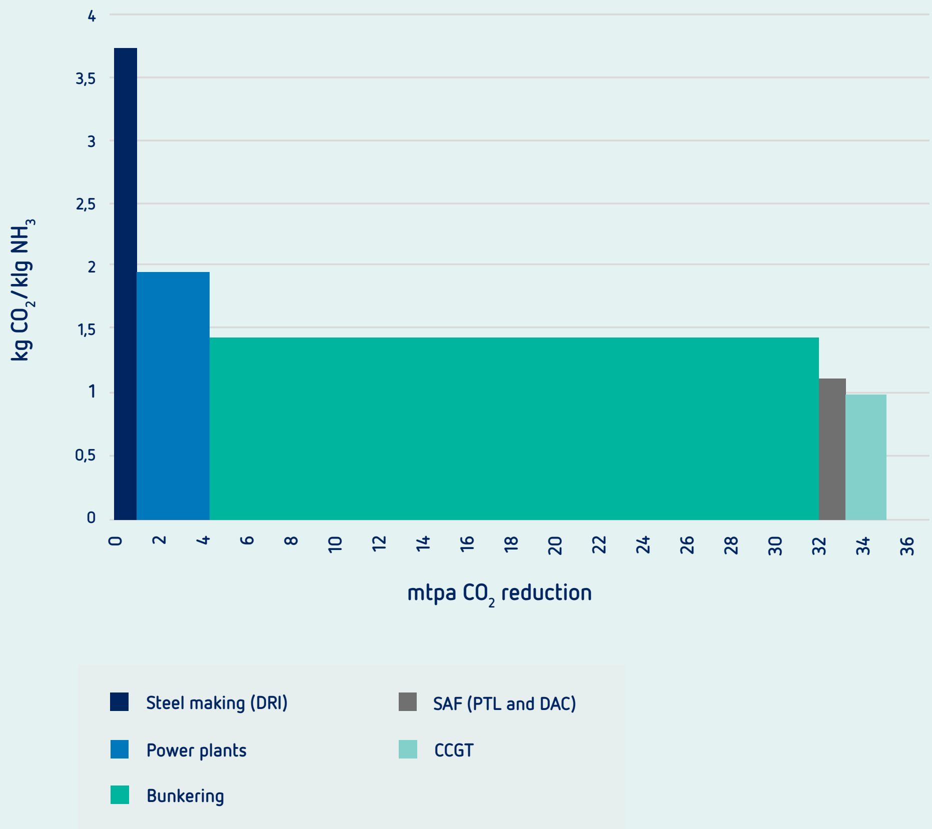


Figure 25: Merit order The Netherlands CO_2 reduction based on renewable ammonia in 2023-2050.

Zero-carbon ammonia as fuel in the power sector could save about 2% of global CO_2-emissions in 2050 from all emissions from power plants and gas turbines together firing coals, oil and gas today. For the Netherlands the suggested import volumes for zero carbon ammonia in the power sector would lead to 28% reduction of the attributed CO_2 emissions in the power sector from 2022 to 2050, based on 7% from gas-fired and 21% reduction from coal-fired power plants, the remainder to meet zero emissions replaced by renewables energy. Zero carbon ammonia bunkering for international shipping suggests a potential of 43% CO2 reduction globally in shipping industry. The CO_2-emission reduction potential is about 30% for the steel industry in The Netherlands, assuming DRI steel making with 50% hydrogen converted from imported ammonia. Globally the CO_2-emission reduction potential in steel making could be lower -in the order of 10%- assuming higher scrap recycling, more use of other abatement technologies than DRI, and taking into account the remarks in Table 9. Regarding SAF, a potential CO_2-emission reduction of about 10% in aviation sector could be envisaged globally, based on power-to-liquid technologies using hydrogen coming from cracked ammonia combined with DAC. The total CO_2 reduction thanks to 900 mtpa of clean ammonia utilization as energy and hydrogen carrier would be about 3% of the total CO_2 emission (37 mtpa) globally.[77]

[77] CO_2 Emissions in 2022 – Analysis - IEA

Conclusion

Industry expects clean ammonia use as an energy carrier to grow significantly. This paves the way for alternative value chains next to utilization as fertilizer and as a chemical building block. Large quantities of ammonia are expected to be imported to the Netherlands and transported to the hinterland to be used in power plants, in the maritime sector and as an hydrogen carrier in industry. Ammonia transit to Germany could reach about 3,5 mtpa, whereas ammonia converted to hydrogen could attain a volume of about 2 mtpa in 2030. For 2050 there are too many uncertainties to make assumptions.

Ammonia-to-power could become an important market to meet climate goals, especially in regions of Asia which mainly use coal. Clean ammonia can supplement renewables to accommodate sufficient electricity generation to balance the grid. Ammonia imports are needed in regions with a renewable energy shortage or to enable industrial base load demand. It is assumed that about an additional 600 mtpa of clean ammonia will be needed in 2050. This equals the replacement of about 2% of global coal and natural gas consumption.

The shipping industry is one of the difficult to abate sectors. Methanol is a drop-in fuel that can be used for bunkering of seagoing and inland vessels, but in the long run clean ammonia will be a better alternative thanks to its decarbonization potential. It is assumed that about 200 mtpa of clean ammonia can be utilized for bunkering in 2050.

Its conversion potential towards hydrogen opens up possibilities for a more efficient international trade flow of renewable energy, for example to produce sustainable aviation fuels and steel. These global markets could potentially add-up to about 100 mtpa of ammonia in 2050. The Netherlands has a promising position for shipping fuel and initial growth of hydrogen demand. The ammonia utilization for bunkering will be the dominant application, with up to 20 mtpa of ammonia in 2050 after taking-off from around 1 mtpa in 2030. This of course depends on the pace in which the shipping industry manages to retrofit or replace vessels.

The figure of up to 20 mtpa is also envisaged for conversion to hydrogen to enable DRI green steel production and sustainable aviation fuels in 2050 which could doble the initial capacity in 2030. It is assumed that part of production to meet domestic demand will remain in Western-Europe for geopolitical reasons and to enable base load operation. The power sector in The Netherlands could grow from 1 mtpa in 2030 to about 3 mtpa in 2050, based on for example a 1 GW (retrofitted coal-fired) power plant and 10 CCGT.

The global market for new ammonia outlets could grow from non-existing now to 50 mtpa in 2030 and to 900 mtpa in 2050, even excluding ammonia as a feedstock. This makes the global market for ammonia as a fuel for maritime transport and for stationary power a factor two bigger than present ammonia production volumes for all current markets using ammonia as a feedstock. For The Netherlands this growth from 2030 to 2050 is estimated at 12 mtpa to about 43 mtpa. This would mean imports of fourteen times the present nominal capacity of the two ammonia plants in The Netherlands.

To further ensure safety and to increase the handling capability for expected ammonia imports, new and existing technologies will have to be developed. Regulations and legislation on ammonia as energy and hydrogen carriers are needed. Presently, the national guidelines (PGS-12) on ammonia storage and (un) loading are revised by experts from industry and authorities. Guidelines and standards are also needed to ensure safe operation and maintenance during bunkering, cracking and firing of ammonia as fuel in the maritime and power sectors. Secondly, pipelines should be extended to handle increased ammonia imports and distribution. Initiatives for deployment of low-carbon ammonia applications and integration with hydrogen value chains should receive support from authorities to meet the growing demand from customers and the climate goals.

The power sector and shipping are by far the most important industry sectors to attain massive CO_2 reduction. The contribution of CO_2 reduction as a result of the DRI-EAF steel making process is the highest in merit order, but lower than the total volume to be achieved by the power and bunkering markets. The utilization of renewable ammonia SAF in the aviation industry has the lowest priority.

Zero-carbon ammonia in the power sector would save about 2% of global CO_2-emissions from power plants and gas turbines together. Zero carbon ammonia bunkering for international shipping suggests a potential of 43% in global CO_2 reduction in shipping emissions due to bunkering of ammonia.

Clean ammonia based SAF could lead to a potential CO_2-emission reduction of about 10% globally due to use of clean ammonia. By 2050, ammonia can potentially mitigate about 3% of global emissions, assuming emissions will level or drop from 2023 onward.

For the Netherlands, the suggested import volumes for zero carbon ammonia in the power sector lead to 28% reduction of the attributed CO_2 emissions. The utilization of ammonia derived hydrogen for DRI steel making shows a reduction potential of 10% of the CO_2-emissions in steel industry in The Netherlands and 7% globally. Various consortia have already announced the import of clean ammonia to The Netherlands towards the end of the 2020s. This will result in a substantial scale-up of ammonia storage, transport and utilization. Thus, it is important to leverage the existing industrial knowledge on best practices for safe storage and handling of ammonia. Human capital will be important and training will be required for ammonia storage and handling. Also, a consolidated effort with enabling laws and regulations will be required for the integration of value chains with aspects such as ammonia cracking to hydrogen and hydrogen pipeline transport to Germany.

In the meantime, ISPT and industry partners have decided to continue with a project to increase awareness on safety aspects and residual risks of ammonia transport via pipelines to Germany. Another recommendation is to continue with projects on NO_x and N_2O emission control in case of utilization in the power sector.

Annex 1 Ammonia health hazards

Table A1: Ammonia health hazards

Hazard	Exposure	Effect	Consequence	Remarks	Ref.
Toxic	Exposure to persons				
	Skin				
		Irritation	Injury	Direct contact with liquid ammonia	
		Burns	Fatality	Freezing/ dehydration/burning of human tissue	
	Respiratory	Smell	Complaints	Dutch intervention values: Voorlichtings-richtwaarde VBR 21mg/m^3 or 30ppm	78
			Complaints	Level Odour Awareness (LOA) 1,7 mg/m^3 (2,4 ppm), publieke grenswaarde (PGW) 1,4 mg/m^3 (2ppm)	
			Complaints	Odor threshold : 5 ppm to 50 ppm	79
		Irritation	Irritation	Simple thresholds: smell 30ppm; 100ppm irrritates the nose	80
			Irritation	Permissable Exposure Limit (8h) PEL: 50 ppm	81
			Irritation	VBR to AGW: 30ppm to 140ppm (10min) and 280ppm (8h)	8
		Lung damage	Injury/ Fatality	1000-10000ppm severe injury to death (function of duration)	10
			Injury	Alarm threshold value (Alarmeringsgrenswaarde AGW) 200 mg/m^3 (10min) to 99 mg/m^3 (8h) or 280ppm 140ppm	8
			Injury	400ppm tolerable for 30min	10
			Injury	Between 300 -500 ppm, unbearable	9
			Fatality	1900mg/m^3 (10 min) to 280 mg/m^3 (8h) or 2600ppm and 400ppm	8
			Fatality	Immediately Dangerous To Life or Health (IDLH) Value 300ppm	11
			Fatality	2500ppm (30 min) and LC50 4000-10000ppm	9
			Fatality	for QRA LBW 1495mg/m^3 or 2100ppm (1h)?	10
	Eye	Eye damage	Injury	700ppm	9
Environment	Aquatic organism	Toxic	Fatality	High solubility 540g/l	
	Greenhouse warming		Climate change	N_2O	
	Nitrogen deposition	Biodiversity		NO_x, NH_3	
	Acid rain			NO_x + OH converted to HNO_3	

[78] Ammoniak-IVW-2009.pdf (https://rivm.nl)

[79] M.-Kent-Anderson - Ammonia Safety a global perspective, 2017

[80] DNV, Ammonia-bunkering-of-passenger-vessel-Concept-quantitative-risk-assessment, 2021

[81] US NIOSH

Table A2: Ammonia safety hazards

Hazard	Exposure	Effect	Consequence	Remarks	Ref.
Fire	Exposure to persons	Pool/jet fire	Fatality	High ignition energy 680mJ (Methane 0,3mJ, gasoline 0,8mJ coal ~4mJ), LEL 15% UEL 28%, not likely	
				Transparent flames	
				Cold NH_3 pool will not burn in a sustainable way due to insufficient heat radiation (for evaporation) to pool	82
Explosion	Storage tanks/ containers		Fatality	15-33% vol ammonia to air auto-ignition 680°C, not likely	
				Only for heat exposed tanks, in combination with external heat from e.g. fire	11
	Buildings		Fatality	Poorly ventilated spaces, not likely	
Release	Cloud dispersion/ respiratory	lung damage	Fatality	Probit function depending on frequency, concentration and duration	83
				Gaseous ammonia is lighter than air but with higher humidity can be heavier than air	
				In present Dutch legislation no external safety distances imposed, to be changed?	84
			Complaints	See toxic	
			Irritation	See toxic	
			Injury/ Fatality	See toxic	

[82] https://Final-Report_External-safety-study-bunkering-of-alternative-marine-fuels-for-seagoing-vessels_Rev0_2021-04-19.pdf
[83] https://ammonia-bunkering-of-passenger-vessel-Concept-quantitative-risk-assessment.pdf
[84] https://publicatiereeksgevaarlijkestoffen.nl

Annex 2 Main properties and conversion factors

Table A3 : Main properties and conversion factors of ammonia and other hydrogen carriers

Energy carrier		Ammonia pressurised	Ammonia cooled	Liquified Nat. Gas	MDO/ MFO[85]	Liquified H_2	Methanol
LHV	MJ/kg	18.6	18.6	52.0	42.8	120.0	19.9
Temp	°C	25	-33	-162	25	-253	25
Pressure	Bara	10	1	1	1	1	1
Density	kg/Nm^3	602	683	710	850	73	790
Energy density	MJ/Nm^3	11,199	12,706		36,380	8,757	15,725
Same energy							
Normalised	Nm^3/Nm^3	0.88	1	2.24	2.86	0.69	1.24
Normalised	kg/kg	1	1	2.8	2.3	6.5	1.1

In case of ammonia and hydrogen as energy carrier conversion factors need to be adopted.

- For direct utilization a stochiometric factor 5.6 (kg/kg) is applicable to go from ammonia to hydrogen-equivalents. Based on equal energy content this factor is 6.5 (kg/kg).
- The cracking efficiency is 79% (kg/kg) leading to 7.1 kg ammonia per kg of hydrogen.
- The roundtrip efficiency going from hydrogen to ammonia and back to hydrogen is 67%, assuming 86% (kg/kg) ammonia synthesis efficiency and cracking efficiency 79% and 2% transport losses. Thus, 8.5 kg//kg ammonia per kg of hydrogen is needed.

The losses for clean hydrogen production (except cracking) and transport are not included in the above factors:

- Losses in electricity consumption for water electrolysis;
- Heat and compression losses for CCS;
- Fuel losses for shipping.

85 Oil Fuel Properties - Global Combustion

Annex 3 Assumptions for modelling ammonia market demand and import

General

In this study, the following assumptions have been made:

- Existing ammonia production and usage in traditional industry is not taken into account
- The global energy system will be based on renewables in line with 2030 and 2050 climate goals and scenarios from IPPC, IEA, IRENA. Several sources suggest that the future energy system with generation, transport and distribution, and utilization will be much more flexibility due to volatility in renewables, energy storage when there is no wind/solar, expected congestion
- For The Netherlands, ARRRA, Europe, import of energy carriers is needed due to increased demand arising from climate goals and shortage in regional renewable electricity production and limited means of flexibility, demand load management and energy storage.
- In this study the technical potential for ammonia import, transport and demand as energy/hydrogen carrier is investigated.
- Both ammonia and hydrogen market demand are considered as energy carriers as these are related through conversion (cracking) of ammonia to hydrogen.
- Ammonia as hydrogen carrier is supplemented to hydrogen import volumes to match hydrogen demand.
- Mobility as market for hydrogen converted from ammonia is beyond the scope of this study.
- Time horizon is 2030 and 2050.
- The ammonia and hydrogen import, transport and demand is determined on three scales: for The Netherlands, ARRRA and Globally.
- In the model the Hub Netherlands comprises the Port of Rotterdam, Port of Amsterdam, (Gronigen Seaport (Eemshaven) and Nort Sea ports (Vlissingen and Terneuzen). The demand is located in the industry clusters in these ports and Chemelot in Limburg.
- In the model the Hub Belgium comprises the ports of Antwerp, Gent and Zeebrugge and related industry clusters.
- In the model Germany is considered as a Hub D with Niedersachsen (NS) and Nord-Rhein-Westfalen (NRW), including Niedersaksen port of Wilhelmshafen, Brunsbuttel, (Bremerhafen, Hamburg) and industry clusters in NRW.In the model Germany is considered as a Hub D with Niedersachsen (NS) and Nord-Rhein-Westfalen (NRW), including Niedersachsen ports of Wilhelmshafen and Brunsbuttel, and Bremerhafen, Hamburg.
- The Netherlands, Belgium and Germany are considered.as one region as Antwerp-Rotterdam-Rhein-Ruhr-Area (ARRRA). The North-Western Ports in Niedersachsen in Germany are added, but for sake of simplicity still ARRRA is referenced.
- Clean hydrogen production is considered, so both green and blue.
- Hydrogen can be imported through shipments as liquid hydrogen and as LOHC. In this study it is assumed that all hydrogen will be imported as liquid hydrogen.
- The annual growth of ammonia production as feedstock is assumed to be 2%. The annual growth of bunkering, steel making industry and aviation fuel is assumed to be 4%.

2030 Outlook

- Import with ammonia and hydrogen is calculated with mass balances using a simple input-output model (Excel) for time horizon 2030.
- The reported 2030 figures are for indication only as multiple solutions are possible. Justification of data used in the forecasts are based on.
- The model is fitted for import, conversion and demand in order to meet the mass balances
- Clean ammonia production is produced outside Europe (e.g. Africa, South America, Australia or Middle East). Therefore, it is assumed that the local production is replaced by imported ammonia.
- No import of compressed hydrogen through pipelines is considered.
- No connections, no supply from Eastern and Southern Europe are considered
- Import of ammonia and hydrogen to ARRRA is the result of demand minus production including conversion form ammonia to hydrogen.
- The ammonia and hydrogen export from Belgium and The Netherlands to Germany is positive.
- Ammonia and hydrogen import to Germany is in the same order of magnitude as the import to Belgium and The Netherlands.
- Pipelines are at least 50% oversized relative to nominal capacity to consider future demands
- The resulting import figures are used to determine the needs for assets development for different value chains.
- Input data to the model is based on assumptions for market demand, literature, recent announcements from private companies, interviews with partners.
- Regarding input data for 2030 market demand in The Netherlands a breakdown per industry sector and per region is assumed.
- For Belgium and Germany assumed 2030 market demand is not differentiated due to simplicity.
- The supply of ammonia and hydrogen for import is through sea-going vessels. The origin and sourcing of ammonia is not part of this study.
- The import of ammonia represents demand as energy carrier and demand as feedstock. The import of ammonia as feedstock is a separate position for the production of fertilizers and other chemical products. The focus in this study is on import of ammonia representing demand as energy carrier.
- The existing domestic ammonia production as feedstock is assumed to be fully replaced by import.
- New markets demand will develop like shipping, sustainable aviation fuel (SAF) and steel making. We expected that domestic demand and production capacity for SAF and steel making is not significant in 2030 due to pricing and short time for deployment.
- It is suggested that power generation can be another major off-taker of (imported) ammonia. This is not part of other studies.
- For conventional power generation we assume the same parc with retrofitted or replaced/new (converted) coal-fired power plants and Combined Cycle Gast Turbines (CCGT).

2050 Outlook

- For time horizon 2050 an outlook based on global demand per industry sector has been estimated. This has been factorized to ARRRA and Netherlands
- The idea is that EU policy is to be partially self-supportive so part of the regional production of hydrogen, SAF and steel will remain domestic.
- For 2050 figures, we assume that power generation will become a dominant market to meet the climate goals. Starting point is that globally, the present installed power will be partially phased out up to 2050. Part of the load will be replaced by renewables, nuclear and natural gas with CCS, depending on country fuel mix. For the remaining power demand, the dispatch will be for coal fired power plants around 50% of the fuel will be biomass and 50% ammonia. For CCGT this is 100%.
- For the Netherlands the import is based on Port of Rotterdam scenario import is 47 mtpa NH_3 with a factor 2 for other ports. Fort ARRRA a factor 2 is assumed for Belgium and Germany.

Annex 4 Drivers and Enablers for clean ammonia

The following topics have been mentioned by the partners in the kick-off of this Roadmap project, see also Figure 3.

Ammonia synthesis and demand

- Overseas production from renewables or using NG and CCS
- Produce NH_3 more efficiently
- NH_3 synthesis optimization
- Intermittency of energy sources
- Other methods
- Green ammonia synthesis
- Optimizing for intermittency of wind and solar
- Alternative synthesis methods (i.e. competitors to Haber-Bosch)
- NH_3 demand
- Shipping fuel
- Fuel to power plants
- Fuel for mobility
- Industrial demand

Cooperation in value chains

- Gate keeping - impact of NH_3 operations for serving companies (fuel/storage/conversion)
- Joined forced on knowledge development (H_2 storage and feedstock)
- Cooperation in value chain (within the harbour)
- Integration between H_2 production and the ammonia process
- Pressure, integration of system and equipment
- Energy/process to produce N2
- Electrolyser technology
- Energy requirements
- Create an overview of what is being done (opportunities to collaborate?)
- Full value chain
- as both feed and carrier
- Focus on innovative applications: Ammonia to power/heat/H_2/shipping/mobility (small scale)
- Local transport (port to hinterland)
- Scale, intermittency of energy supply, integration with offshore H_2 production, CAPEX/OPEX
- Inland shipping/logistics and permitting (restrictions to transport for NH_3 - safety)
- Roadmap/overview
- What is already there and being done

- Communication of feasible value chain
- Identification of NH_3 volumes based on real scenarios/cases (feasibility) and what does it mean regarding safety etc.
- Context of applications, when to use what (mix/H_2/NH_3/other fuels)
- Merit order supported by business cases
- Map IRENA Innovation Outlook NH_3 to NL
- What is needed through full value chain to realize ammonia as energy carrier - would include NH_3 end-uses in this as well

Ammonia cracking

- Large scale storage and cracking
- Profitability of decentral cracking
- Cracking technology development
- NH_3 cracking
- Technology
- Scale-up
- Energy efficiency
- De-risk cracking technology
- Safety standards
- Business case
- Large scale cracking
- Hardware (have commercial cracking installation available)
- Funding for building pilot/demo cracking plant
- Understanding scale, timelines, cost, scale-up challenges, energy efficiency, etc.

Communication, safety, public acceptance

- Public acceptance of NH_3 storage and transport
- Safety and regulations
- Social acceptance in port area (NIMBY), Education
- Legal challenges
- Communicable story/overview/roadmap of what NH_3 will be in the NL
- Addressing bottlenecks and opportunities
- Influence public perception of NH_3 positively
- Improve/smoothen environmental permitting process
- Health and safety
- Public perception

Annex 5 Port of Rotterdam Decarbonisation Scenarios

The forecast of the development of hydrogen and ammonia flows in 2030 and 2050 in the Connected Deep Green (long-term) port scenarios.[86]

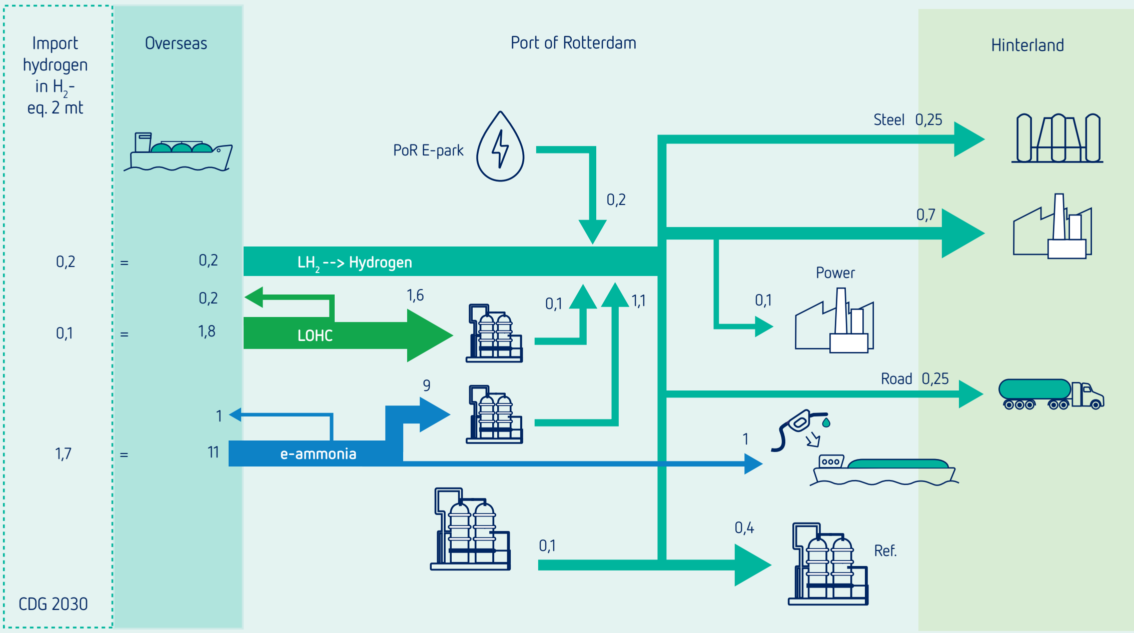


Figure A5.1 The forecast of the development of hydrogen flows in 2030 in the Connected Deep Green (long-term) port scenario.

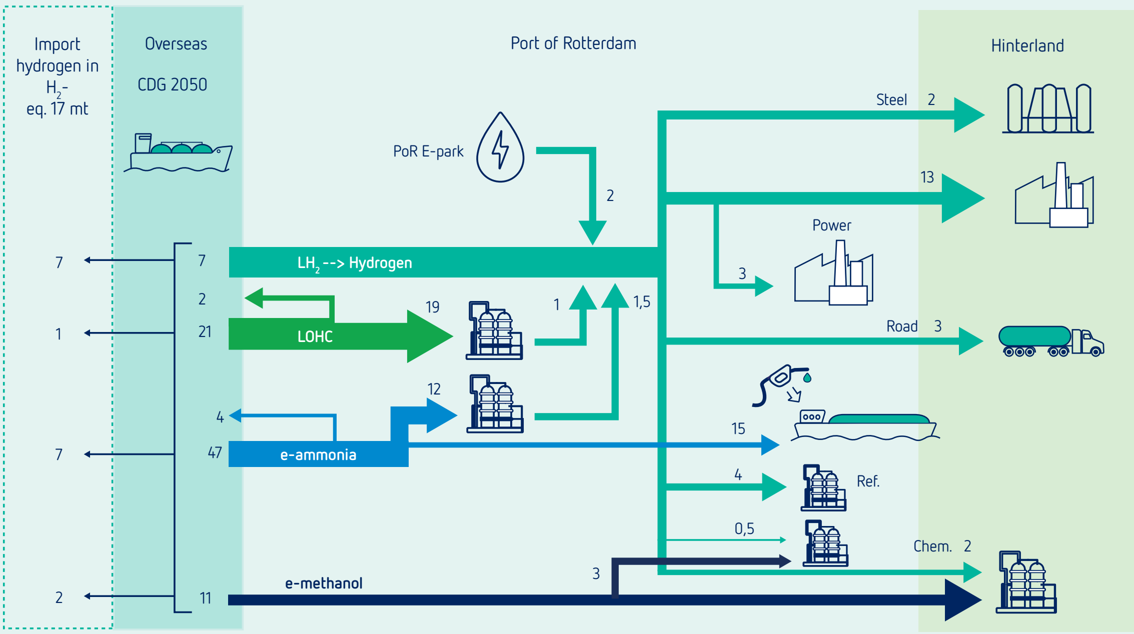


Figure A5.2 The forecast of the development of hydrogen flows in 2050 in the Connected Deep Green (long-term) port scenario.

86 Havenbedrijf Rotterdam presenteert toekomstscenario's 2050 | Port of Rotterdam (https://portofrotterdam.com/nl/nieuws-en-persberichten/havenbedrijf-rotterdam-presenteert-toekomstscenarios-2050)

Annex 6 Recent announcements

In the Netherlands, several clean ammonia projects have been announced to anticipate on the expected large quantities of green ammonia that will be imported to the Netherlands in the foreseeable future. This list is not exhaustive, but is a selection of new developments to give an overview of activities already happening.

- Koole Terminals developing a multi-million ton per annum ammonia-import terminal and storage facility in the Port of Rotterdam
- OCI is to expand the ammonia-import terminal in Rotterdam (tripling transit capacity) to first 1 mtpa and later to 3 mtpa of ammonia.
- Yara Sluiskil & Orsted to produce green ammonia in the Netherlands through Haddock 100MW green hydrogen project
- Air Products & Gunvor developing a green liquid hydrogen import terminal in Rotterdam
- OCI investing in blue ammonia
- Uniper & Vesta Terminals to retrofit and expand an existing Vesta Terminal in Vlissingen to store green ammonia. Set to become the first green ammonia hub in North-West Europe.
- As green ammonia could steer 1/3 of the shipping fuel demand, the TU Delft has recently started the AmmoniaDrive project focussing on the application of green ammonia in the maritime sector.
- OCI teaming up with NortH_2 to develop integrated green ammonia and methanol value chains using green hydrogen the joint venture will supply. NortH_2 is an offshore wind-to-hydrogen electrolysis project being developed in the Eemshaven area by Equinor, RWE, Shell, Gasunie, and Eneco that could have as much as 4 GW of hydrogen electrolysis by 2030.
- Magnum Power Plant Eemshaven examines three applications of ammonia at the plant: producing and transporting low- or zero-carbon ammonia, storing excess power as ammonia, ammonia storage and combustion as fuel.
- Air Liquide announces the construction of an industrial scale ammonia (NH_3) cracking pilot plant in the port of Antwerp, Belgium.[87]
- Yara export terminal in Brunsbüttel ad the terminal in Rostock can increase the imported volumes as of summer 2023. In total Yara would be able to deliver 3 mtpa of clean ammonia, which meets the Yara production capacity in Rostock.[88]
- Saudi Arabia's flagship green hydrogen production facility at NEOM has reached financial investment decision (FID). An equal joint venture between ACWA power, Air Product and NEOM green Hydrogen Company's mega-plant will integrate up to 4GW of solar and wind energy to produce up to 600 tonnes per day of carbon-free hydrogen by the end of 2026.[89]

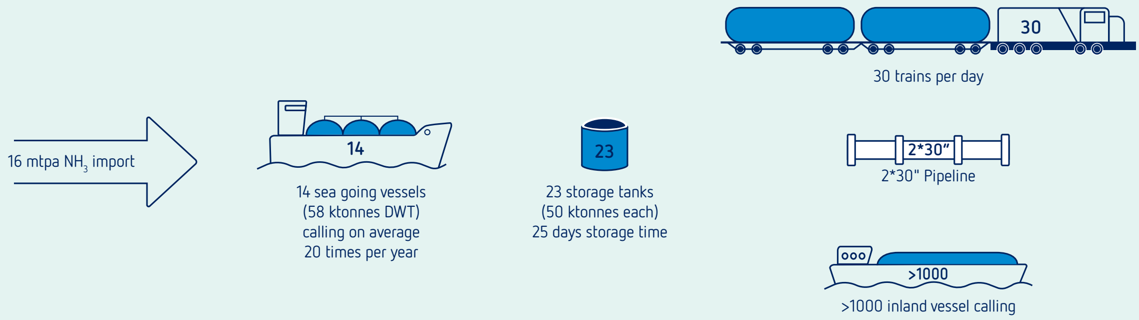
[87] Air Liquide paves the way for ammonia conversion into hydrogen with new cracking technology | Air Liquide

[88] Yara is speeding up the hydrogen economy in Germany | Yara International

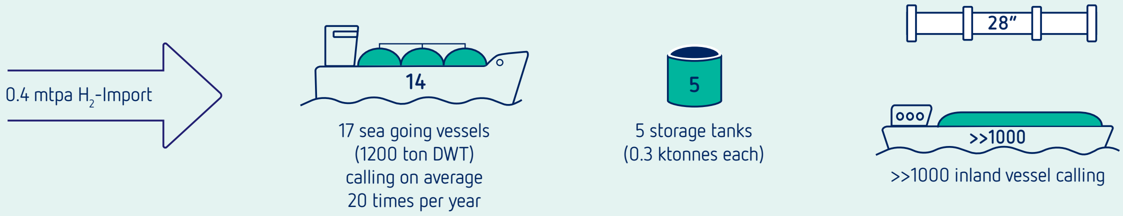
[89] Hydrogen Council on LinkedIn: NEOM Green Hydrogen Company completes financial close at a total..

Annex 7 Value chains

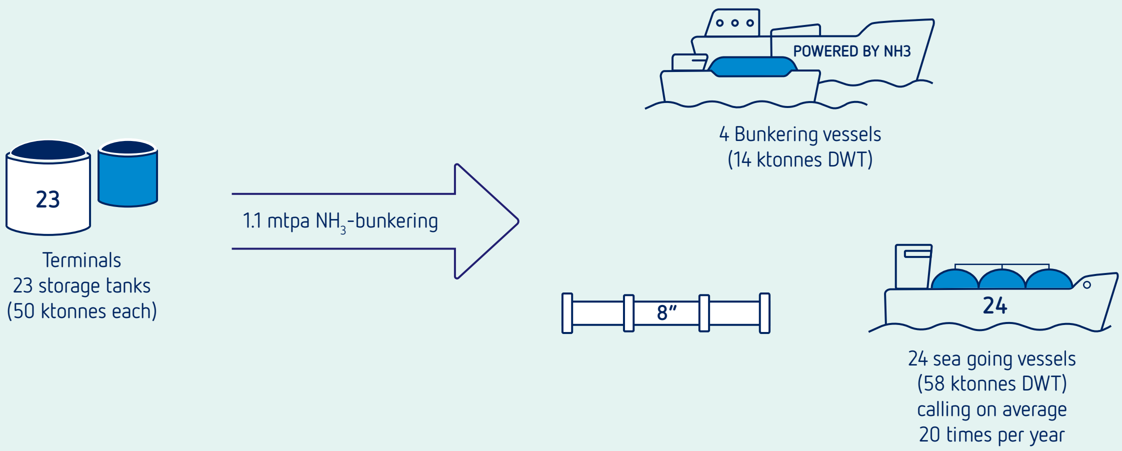
Import of ammonia



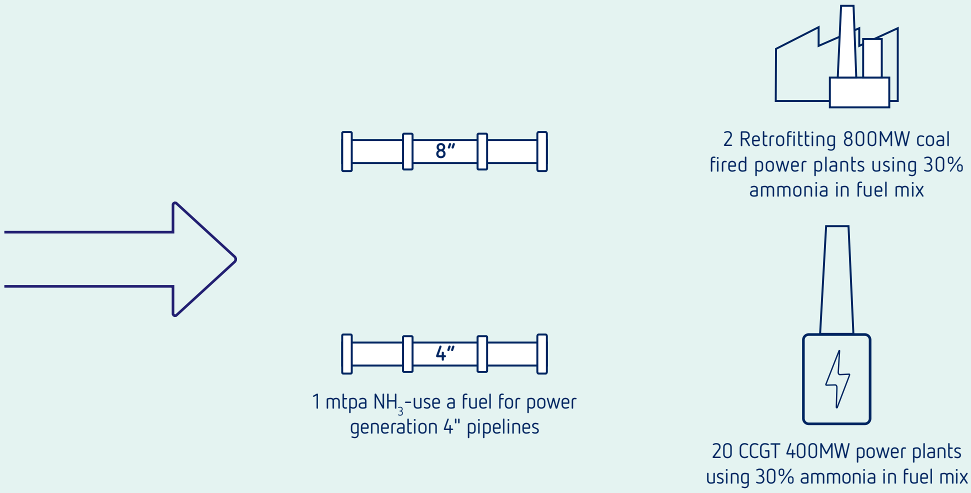
Import of Hydrogen



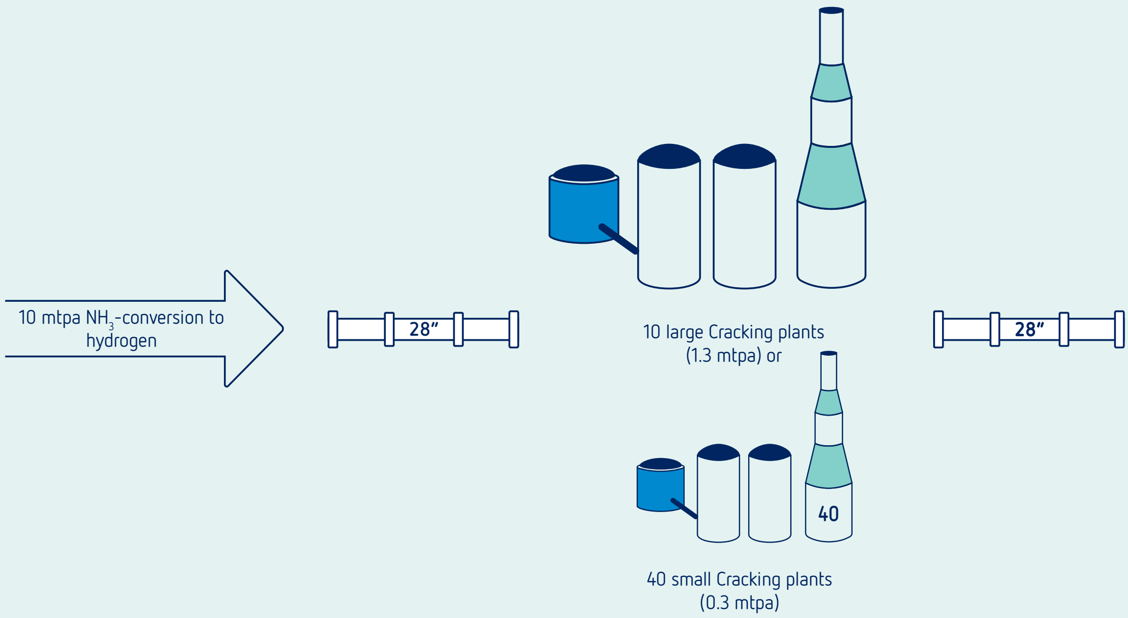
Ammonia value chain for bunkering of sea going vessels



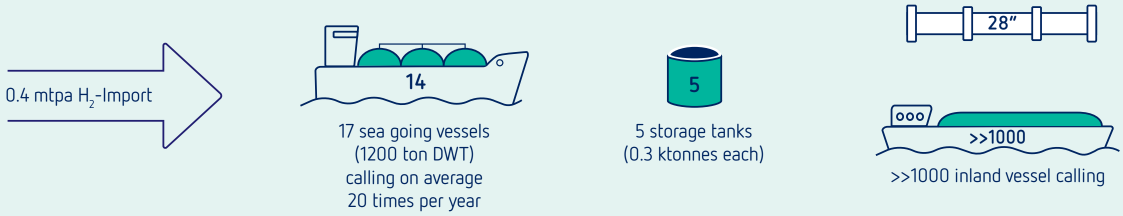
Ammonia value chain for use of power generation



Ammonia conversion value chain



Ammonia utilisation value chain



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