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RELAUNCHING AMMONIA

FROM FERTILIZER TO ENERGY CARRIER IN NORTHWEST EUROPE

CIEP PAPER 2023 | 02 UPDATED

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RELAUNCHING AMMONIA

FROM FERTILIZER TO ENERGY CARRIER IN NORTHWEST EUROPE

UPDATED VERSION

Following discussions of the publication with stakeholders from the sector, we have made the decision to upload a new version of the paper 'Relaunching Ammonia: From Fertilizer to Energy Carrier in Northwest Europe'. Regrettably, certain errors in the initial publication came to our attention only post-publication. In our commitment to maintaining high standards of research we have rectified these discrepancies in this updated version.

ADDENDUM FOR THIS UPDATED VERSION

Some inaccuracies were found in the ammonia terminal dataset, including closed terminals and duplicate entries under different names. In accordance with these corrections, on page 10, line 26, the phrase "Presently, there are 18 ammonia terminals…" has been revised to "Presently, there are 13 ammonia terminals…" to align with the corrected data.

Outdated information was found in the ammonia production capacity dataset. The previous version included ammonia plants in Ince, Billingham and Severnside, all of which are now closed. Additionally, an error was made during the data cleaning process: The capacity of the ammonia plant in Hull is approximately 810 t/d, not 8100 t/d as previously indicated. In accordance with these corrections, on page 20, an updated version of figure 1 has been added.

On page 21, an updated version of figure 2 has been added. The previous version depicted air separation for nitrogen production, which is commonly associated with the production of ammonia when electrolysis is utilized for the production of hydrogen. However, in case hydrogen is produced through steam methane reforming, nitrogen is typically produced within the reforming process itself rather than through additional air separation.

On page 22, an updated version of figure 3 has been included. The previous version contained a mistake, illustrating ammonia sulfate as a derivative from ammonia nitrate, whereas ammonia sulfate directly originates from ammonia. In the updated version, ammonia sulfate is not depicted.

On page 32, changes have been made to address the errors in the terminal dataset. Specifically, on line 2, the phrase 'There are currently 18 ammonia terminals in operation in Northwest Europe..' has been updated to 'There are currently 13 ammonia terminals in Northwest Europe..' On line 3, the phrase 'These terminals have a storage capacity ranging from 1,500 to 44,000 tonnes', has been removed. Furthermore, an updated version of figure 7 has been added. The previous version included terminals in Vlissingen, Terneuzen, Willebroek, Immingham and Ince, all of which are currently closed or were duplicated in the dataset but under different names. Additionally, Gonfreville has been renamed Le Havre in the figure.

On Page 33, changes have been made to address rounding errors and an inaccuracy in the text. Specifically, on line 5, '67 Mt' has been changed to '68 Mt' to rectify a rounding error. On line 7, the phrase '..more than half the current total world production (120 Mt)..' has been revised to '..more than a third of the current total world production (183 Mt)..'. On line 10, the value '33 Mt' has been corrected to '34 Mt'. Additionally, within the footnote on page 33, the value '67 Mt' has been corrected to '68 Mt'.

On page 75, an updated version of figure 16 is added. The previous version contained the same error as figure 3 on page 22, which was addressed earlier in this note.

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EXECUTIVE SUMMARY

In the past century, ammonia has been one of the pivotal synthetic molecules in our society. Ammonia serves as the primary feedstock for nitrogen fertilizer, making it essential for global food production. Yet its large-scale production and utilization has come at a cost, resulting in substantial carbon emissions and environmental challenges.

Recently, the molecule has garnered renewed attention as a promising hydrogen carrier for the international trade of low-carbon energy. Its superior volumetric energy density compared to hydrogen, facilitates more convenient transport and storage. Beyond its potential as a hydrogen carrier, for some applications ammonia is a promising low-carbon fuel.

The energy sector's growing interest in ammonia is largely driven by the ability to leverage the pre-existing infrastructure of the nitrogen fertilizer industry. The production, transportation, storage and use of ammonia has a century-long history, with transportation across long distances by ship, rail, truck and pipeline spanning multiple decades. The current infrastructure, knowledge and expertise provide a strong foundation for ammonia's role in the energy sector.

This paper examines the changing role of ammonia in Northwest Europe, and how the existing ammonia ecosystem in the region may be leveraged to facilitate ammonia's integration as an energy carrier and low-carbon fuel. The paper addresses multiple facets, including the current ammonia industry in Northwest Europe, ammonia's potential as an overseas energy carrier, inland transportation and storage, its potential role as a fuel, and the implications for the ammonia market in the region.

THE CURRENT AMMONIA INDUSTRY IN NORTHWEST EUROPE

Europe boasts a substantial fertilizer industry, comprising more than 120 production sites, the majority of which are concentrated in the northwestern part. Most ammonia production in Northwest Europe happens within fertilizer production complexes. Currently, practically all ammonia produced in Europe is made from natural gas. While the ammonia plants in Northwest Europe rank among the least polluting worldwide, the fertilizer industry there still contributes significantly to carbon emissions in the region. To further reduce these in future, plants in the region look into three primary strategies: the continual modernization and improvement of the carbon efficiency of existing installations, the integration of Carbon Capture and Storage (CCS) technology, and the production of ammonia from renewable energy sources.

The energy crisis of 2022 has been extremely challenging for the Northwest European fertilizer industry. High European gas prices, at some point up to 8-10 times those in competing regions, impeded the Northwest European fertilizer industry's ability to compete with global rivals. A significant chunk of the production capacity in Northwest Europe was temporarily curtailed, and some production sites permanently closed. Should high natural gas prices persist, and should Europe intend to prevent further loss of industry, a strategic reassessment is necessary to maintain the competitiveness of the European fertilizer industry. From a strategic perspective, it might be wise to prioritize domestic ammonia production, considering its expected central role in the future Northwest European economy, including the energy sector.

AMMONIA AS AN OVERSEAS ENERGY CARRIER

As Northwest Europe shifts towards a low-carbon energy system, it is expected to remain reliant on overseas energy imports to satisfy its needs. Hydrogen and hydrogen carriers are deemed to play an important role. Numerous (theoretical) options exist for transporting low-carbon energy or hydrogen overseas. However, thanks to its well-established infrastructure, extensive knowledge base and technological maturity, 85 per cent of global hydrogen export projects focus on ammonia as the carrier for overseas transportation. In contrast to alternative energy carriers, ammonia is already a globally traded commodity. There is an annual global seaborne trade of approximately 20 Mt of ammonia, which accounts for roughly 10 per cent of global production.

As the European Union is the biggest importer of ammonia in the world, it boasts considerable import infrastructure. Presently, there are 13 ammonia terminals in Northwest Europe. Nevertheless, substantial expansion will be required if ammonia is to play a significant role in overseas energy transportation. In general, expanding existing infrastructure proves to be easier, quicker and more cost-effective than constructing entirely new terminals. Also, the regulatory compliance is likely to be less cumbersome, as the existing terminals have already been approved for ammonia usage. The permitting process in the European Union, known for its complexity, can form a significant obstacle to the construction of new ammonia import terminals, alongside safety concerns and public approval. Moreover, key European ports, such as Hamburg, Antwerp and Rotterdam, grapple with space constraints. Repurposing old infrastructure offers a partial solution for mitigating space limitations. For instance, bulk liquid storage facilities that currently store different substances, like

LPG, can be repurposed to accommodate ammonia storage. Converting existing LPG or LNG terminals to serve as ammonia import facilities is also a promising possibility. These facilities already possess the requisite land area, location and jetties suitable for ammonia terminals.

AMMONIA INLAND TRANSPORTATION AND STORAGE

In the European public debate, it is commonly assumed that ammonia should primarily serve as a hydrogen carrier for overseas energy transportation, with conversion occurring near the receiving port. While converting ammonia at ports offers advantages, like economies of scale, available infrastructure, and proximity to hydrogen demand, there are reasons to consider refraining from immediate ammonia-to-hydrogen conversion upon arrival, or skipping conversion altogether. For strategic reasons, hinterland countries in Northwest Europe might want their own ammonia storage and conversion facilities. Space limitations at ports can be a limiting factor for conversion in port areas. Additionally, ammonia's higher boiling temperature and greater volumetric energy density make it easier to transport and store than hydrogen. Lastly, direct use is often preferred, when possible, to avoid the energy penalty of conversion.

For inland transportation of large volumes of ammonia, pipelines are often regarded as the most cost-effective and safe way of transportation. Globally, approximately 8,000 km of pipelines are operational. Europe has about 25 ammonia pipelines. In contrast to the ammonia pipelines in United States, those in Europe are typically short, covering distances of only 1-12 km. In Northwest Europe, the primary emphasis for new low-carbon fuel infrastructure is on hydrogen. However, the Delta Corridor project expresses great interest in the development of a long-distance ammonia pipeline, linking the Port of Rotterdam in the Netherlands to North Rhine-Westphalia in Germany. The construction of ammonia pipelines, by either repurposing old gas infrastructure or building completely new ones, could enhance the resilience of the future Northwest European energy network by diversifying the variety of energy carriers within the system.

As Northwest Europe shifts towards a low-carbon energy system, energy storage will become even more important than it is today. Ammonia is a promising low-carbon option for energy storage. Nevertheless, when used on a large scale, its toxic properties present challenges related to safety, the environment and public perception. However, over the years the fertilizer industry has accumulated the expertise necessary to thoroughly deal with these challenges.

Ammonia can be stored in various ways, both aboveground and underground. While underground storage is uncommon and demands further research to better understand associated issues and risks, aboveground ammonia storage is widely practiced around the world. Refrigerated aboveground storage tanks have a capacity of up to 50,000 tonnes of ammonia, equivalent to 260 GWh of energy, similar to the energy content in a hydrogen-filled salt cavern. Unlike hydrogen storage in salt caverns, ammonia storage in tanks boasts a wealth of global experience. To meet the future Northwest European energy storage needs, aboveground ammonia storage tanks can provide a valuable supplement to underground hydrogen storage facilities.

AMMONIA AS A LOW-CARBON FUEL

When it comes to its direct use as a fuel, for most applications ammonia is not the first fuel of choice, due to its toxicity, complex combustion characteristics and technological immaturity. Nevertheless, ammonia is seen as a promising clean fuel for ships and for power plants. Although some engineering problems have yet to be solved, for both applications prototypes have successfully been developed and the first industrial-size implementations are expected in the coming years.

The Amsterdam-Rotterdam-Antwerp (ARA) region is well-positioned for a role in the global ammonia bunker market. The Port of Rotterdam is the largest bunkering port in Northwest Europe, and in 2021, it ranked as the world's second biggest bunkering port. Its strategic location within the global trading network, its substantial oil cluster, deep water port and nearby demand centres, which has granted it a leading position in the contemporary bunker market, are expected to be valuable for the ammonia bunker market as well. Part of the extensive energy infrastructure in the Port of Rotterdam can be adapted for ammonia bunkering purposes. Moreover, the Port already has established ammonia infrastructure, including a terminal and storage facilities. These existing facilities can be repurposed to facilitate ammonia bunkering as well. However, in the future ammonia bunker market, it remains to be seen how ports in Northwest Europe will compare with other bunkering ports that have similar advantages, but also access to cheap renewables.

A substantial number of coal and gas-fired power plants in Northwest Europe are still relatively young, and those are good candidates to be retrofitted to (co-)fire low-carbon ammonia or hydrogen. Co-firing allows for a gradual transition to these fuels. Currently, Europe focuses on hydrogen co-firing, which makes sense for locally produced hydrogen. However, when hydrogen is imported as ammonia, it might be more practical to burn ammonia directly. Currently, the strict REACH regulation remains a barrier to widespread use of ammonia in the energy sector of the European

Union. For ammonia to play a substantial role in the energy sector, it is fundamental to strike a good balance between regulation, promoting chemical safety and environmental protection, while at the same time realizing the potential benefits of using ammonia as a clean energy carrier.

CHANGING MARKET DYNAMICS IN NORTHWEST EUROPE

The shifts in global ammonia production, driven by carbon emissions reduction efforts, and growing demand from the energy sector, are bound to transform the Northwest European ammonia market. Key fertilizer producers such as Yara, BASF and OCI, which currently dominate the ammonia market in the region, are facing a shifting business landscape. New low-carbon ammonia projects, developed by consortia involving energy and industrial gas companies, are emerging worldwide. Although currently most ammonia is used at the location where it is produced, the numerous newly announced ammonia export and import initiatives indicate a potential shift towards more globally traded markets in the coming decade.

Due to high gas prices and the growing interest in renewable energy-based ammonia production, Northwest Europe is expected to shift from domestic ammonia production to relying more on ammonia imports for both fertiliser and energy needs. This shift challenges the Northwest European nitrogen fertilizer producers, and asks for a reinvention of their business models to remain competitive.

Coastal nitrogen fertilizer producers, with access to global ammonia markets, can potentially expand imports, shift to fertilizer production from imported ammonia and use their import platform to supply the energy sector. Landlocked producers might struggle to compete or reinvent themselves. Producers that formerly focused on international markets might shift their focus to the domestic markets, as they benefit from a degree of protection through trade tariffs and can capitalize on their proximity to the market. There is a possibility that a growing proportion of fertilizer production relocates near the new ammonia production sites in third countries[1], especially if the RFNBO obligations for 2040, as stipulated in the RED III regulation, proof unattainable. Ultimately, the sector's transformation and survival will largely depend on the geographical location of production facilities, the availability of necessary infrastructure and the regulatory frameworks in place.

The existing interconnectedness between world food and energy markets may intensify due to the growing use of ammonia in the energy sector. Increasing ammonia demand from the energy sector has the potential to significantly impact the struc-

1 Non-EU countries

ture, pricing and bargaining power of the various buyers and sellers in the international ammonia market. Ammonia demand in the energy sector directly competes with agricultural sector demand, posing a potential challenge to food security. With Northwest Europe and other high-income regions embracing ammonia in the energy sector, it is essential to seriously consider its potential impact on both global ammonia markets and food security.

1 INTRODUCTION

Ammonia (NH3) is a versatile molecule that has both been glorified and vilified over the years. In its essence it is an inorganic compound, comprising of one nitrogen atom and three hydrogen atoms. At room temperature (20 °C) and at standard atmospheric pressure (1 bar), ammonia is a toxic, colourless gas with a distinct sharp smell. In the natural environment, ammonia plays a role in the nitrogen cycle and is produced in soil through bacterial processes. It is also naturally produced through the decomposition of organic matter, which includes plants, animals and animal waste.[2]

Since the invention of the Haber-Bosch process at the beginning of the 20th century, ammonia has played a critical role in the development of modern society. The Haber-Bosch process has been the first industrial method to connect hydrogen (H_2), extracted from methane, with nitrogen (N), extracted from the air, using an iron metal catalyst under high pressures and temperatures, to produce synthetic ammonia on a large scale.[3] Ammonia is a key ingredient for synthetic nitrogen fertilizer, which has fundamentally changed agricultural practices around the world. For most of human agricultural history, an increase in food production could only be provided by an increase in land use, putting a clear cap on the maximum amount of people that could be supported by the earth. The Haber-Bosch process provided a way to circumvent this 'rule of nature', as nitrogen fertilizer served as a replacement for the formerly necessary increase in land use, saving millions of lives at the time.[4] Currently about half of the world's population would be threatened by food shortages, were it not for ammonia-based fertilizer.[5] It is no overstatement to say that the modern world cannot exist without ammonia synthesis. Hence, it has been hailed by some as the single greatest invention of the 20th century. Besides its role in fertiliser production, ammonia is a key feedstock in rubber, plastics, pharmaceuticals, textiles, refrigeration, explosives and various other products.

Although the contribution of ammonia to the modern world has been immense, it has come at a cost. Since World War I, ammonia nitrate (mixed with TNT) has been

2 Britannica (2023). Nitrogen Cycle. Available at: https://www.britannica.com/science/nitrogen-cycle
3 Smil (2004). Enriching the Earth, Fritz Haber, Carl Bosch, and the Transformation of World Food Production. Available at: https://mitpress.mit.edu/9780262693134/enriching-the-earth/
4 BBC (2017). How Fertiliser Helped Feed the World. Available at:
5 Ritchie (2017). How Many People Does Synthetic Fertilizer Feed? Available at: https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed/

used in explosives, causing millions of deaths around the world.[6] Furthermore, ammonia production is a highly energy intensive process, accounting for approximately 2 per cent of total final energy consumption globally.[7] Presently, almost all ammonia is produced using fossil fuels. Global ammonia production is estimated to be around 183 million tonnes, accounting for about 1.3 per cent of global carbon emissions.[8,9] Lastly, there are serious environmental concerns that come with the use of fertilizer. On average, only about half of the applied fertilizer is effectively absorbed by crops. The remaining fertilizer ends up polluting (drinking) water or gets broken down by microbes in the soil, releasing nitrous oxide emissions in the air.[10]

Recently, despite significant challenges, ammonia has once again taken the spotlight in a more positive manner. While for the last hundred years ammonia has been valued for the nitrogen portion of the molecule, currently there is an increasing interest in the hydrogen portion of the ammonia molecule, as a result of the energy transition. Ammonia is often mentioned as a promising hydrogen carrier[11] for the international trade of low-carbon energy. Its more favourable volumetric energy density in comparison with hydrogen, makes it easier to transport and store. In addition to its potential as a hydrogen carrier, ammonia holds promise as a clean fuel, suitable for addressing challenges in maritime shipping and the power sector.

Low-carbon hydrogen[12] is a central pillar of the European Commission's energy strategy. Hydrogen can potentially fulfil a 'systemic function' in the future energy system, accommodating intermittent renewable electricity in hard-to-abate sectors.[13] In the REpowerEU plan, the European Commission has set extremely ambitious tar-

6 Gibbens (2020). The Deadly History of Ammonium Nitrate, the Explosive Linked to the Beirut Blast. Available at: https://www.nationalgeographic.com/science/article/deadly-history-ammonium-nitrate-explosive-linked-to-beirut-blast

7 IEA (2021). Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

8 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

9 IEA (2021). Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

10 MIT Climate Portal (2021). Fertilizer and Climate Change. Available at: https://climate.mit.edu/explainers/fertilizer-and-climate-change#:~:text=Crops%20only%20take%20up%2C%20on,nitrogen%20they%20get%20from%20fertilizers.&text=Much%20of%20the%20applied%20fertilizer,nitrous%20oxide%20into%20the%20atmosphere.

11 A substance or material that can effectively transport or store hydrogen.

12 Hydrogen produced with low carbon emissions, from renewable energy with electrolysis, or natural gas combined with carbon capture and storage technology.

13 Clingendael International Energy Programme (2019). From an invisible to a more visible hand? Hydrogen and electricity: towards a new energy system backbone. Available at: https://www.clingendaelenergy.com/inc/upload/files/CIEP_Paper_2019_2B_web.pdf.

gets for hydrogen production (10 million tonnes) and import (10 million tonnes).[14] Currently, about 85 per cent of the current export-oriented low-carbon hydrogen projects worldwide, plan to ship ammonia instead of hydrogen or other hydrogen derivatives.[15] Various organizations in Europe are preparing to set up new or expand existing ammonia sea terminals and storage facilities.

One of the main reasons ammonia has captured the attention of the energy sector, is the possibility to leverage the existing infrastructure of the nitrogen fertilizer industry. Ammonia has been produced and used for over a century and transported over long distances by ship, rail, truck and pipeline for multiple decades. As ammonia's potential role expands to applications in the energy sector, the existing ammonia infrastructure, knowledge, expertise and industry can serve as a launching pad for venturing into these new areas. This paper will examine the changing role of ammonia in Northwest Europe[16] and how the current ammonia ecosystem can be leveraged to facilitate ammonia's integration as an energy carrier and low-carbon fuel in the region. For the structure of this paper, the logic of the current value chain and the potential use as an energy carrier is followed.

This paper proceeds as follows:

- Chapter 2 briefly discusses the current ammonia industry in Northwest Europe, looking at production and demand, followed by a broad overview of the effects of the 2022 energy crisis on the industry.
- Chapter 3 considers the potential role of ammonia as an overseas energy carrier for Northwest Europe, by examining current ammonia trade, terminals and the specific characteristics of the region.
- Chapter 4 discusses current practices and future possibilities of inland transportation and storage of ammonia in Northwest Europe.
- Chapter 5 explores ammonia's potential role as a fuel in the Northwest European maritime bunkering and power sector.
- Chapter 6 examines the changing ammonia market dynamics in Northwest Europe, looking into the consequences for the supply chain and the growing interrelation of food and energy markets.

14 European Commission (2022). REPowerEU Plan. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

15 Wood Mackenzie (2022). What Role Will Ammonia Play in Global Hydrogen Trade? Available at: https://www.woodmac.com/news/opinion/what-role-will-ammonia-play-in-global-hydrogen-trade/

16 In this paper Northwest Europe covers the following countries: Belgium, Denmark, France, Germany, Netherlands, Norway and the United Kingdom.

2 THE CURRENT AMMONIA INDUSTRY IN NORTHWEST EUROPE

Europe has a sizeable fertilizer industry, with more than 120 production sites spread out over the region. Throughout the supply chain, the industry employs almost 75,000 people and has a turnover of about 9.5 billion euros.[17] Currently, ammonia production is often tailored for captive use, with production plants primarily situated at or near fertilizer production facilities. Most of the facilities are located near harbours at the sea or rivers, providing an entry to markets worldwide. Most of these production sites are concentrated in Northwest Europe.

In 2014 (the most recent year for which data was found), Germany was the country with the biggest ammonia production capacity in Northwest Europe. Germany had a total capacity of about 3.4 million tonnes per year, produced by 5 plants, followed by the Netherlands with about 2.7 million tonnes by 2 plants, and France with a capacity of 1.5 million tonnes by 4 plants.[18] The map in figure 1 shows the clusters of ammonia capacity in Northwest Europe.

2.1 TYPE OF PRODUCTION AND DEMAND

Natural gas serves as the primary feedstock and energy source for global ammonia production, with approximately 75 per cent of all ammonia being derived from this source. [19] China, the world's largest ammonia producer, is somewhat of an outlier in this respect, as it predominantly uses coal as a feedstock for its ammonia production. Virtually all ammonia in Northwest Europe is produced using natural gas, both as a feedstock and an energy source. This is primarily due to an era of relatively cheap gas in the region. Natural gas (CH_4) possesses the most optimal carbon-hydrogen ratio (1:4) among all hydrocarbons. Carbon emissions of coal-based fertilizers can be up to four times higher compared to using natural gas as the raw material.[20]

The main technology used to produce hydrogen from natural gas is Steam Methane Reforming (SMR). In a second step, via the Haber-Bosch process, the hydrogen is

17 DECHEMA (2022). Perspective Europe 2030 Technology Options for CO2-emission Reduction of Hydrogen Feedstock in Ammonia Production. Available at: https://dechema.de/dechema_media/Downloads/Positionspapiere/Studie+Ammoniak.pdf

18 CEPS (2014). Composition and Drivers of Energy Prices and Costs in Energy-Intensive Industries: The Case of the Chemical Industry – Ammonia. Available at: https://cdn.ceps.eu/wp-content/uploads/2014/01/Ammonia.pdf

19 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

20 Yara (2022). Climate Roadmap 2030. Available at: https://www.yara.nl/globalassets/2220875-yara-climate-roadmap-brochure-juni-2022-lr.pdf/

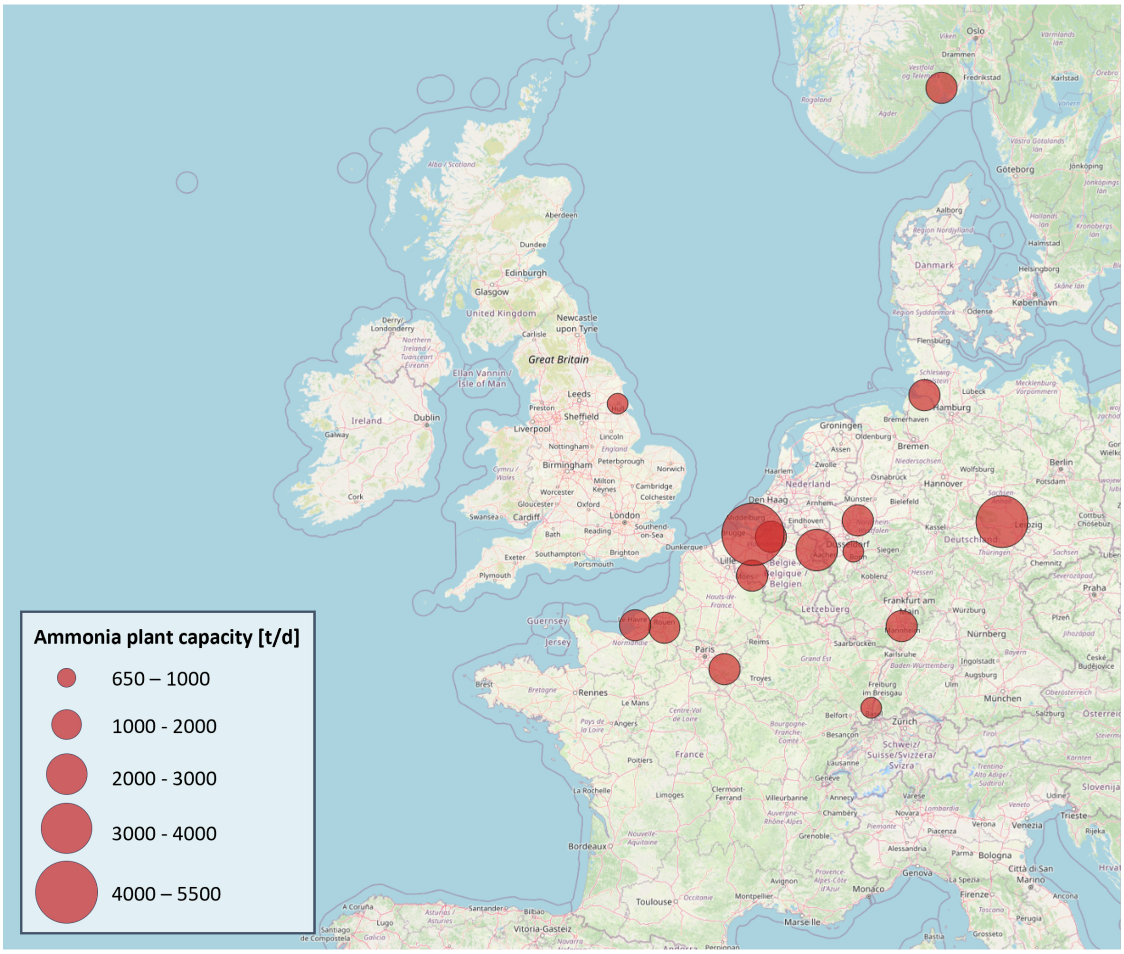

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FIGURE 1: AMMONIA PRODUCTION FACILITIES IN NORTHWEST EUROPE

COMPILED BY CIEP, BASED ON CONVERSATIONS WITH STAKEHOLDERS AND DATA SOURCES: EUROPEAN COMMISSION (2007). LARGE VOLUME INORGANIC CHEMICALS – AMMONIA, ACIDS, AND FERTILISERS. AVAILABLE AT: HTTPS://EIPPCB.JRC.EC.EUROPA.EU/SITES/DEFAULT/FILES/2022-03/LVIC-AAF.PDF

YARA (2020). PRODUCTION CAPACITIES BY SEGMENT. AVAILABLE AT: HTTPS://WWW.YARA.COM/SITEASSETS/INVESTORS/057-REPORTS-AND-PRESENTATIONS/OTHER/2020/PRODUCTION-CAPACITIES-BY-SEGMENT-SEPTEMBER-2020-PDF.PDF/

fixed with nitrogen, which is separated from the air, to produce ammonia (see figure 2). The Haber-Bosch process has been around for more than a hundred years. Over the years, the process has undergone significant optimization. Initially, around 100 GJ of energy was required to produce a tonne of ammonia. Presently, the energy consumption in the most efficient plants in Northwest Europe is close to the practically achievable minimum of 27 GJ per tonne of ammonia.[21] Currently, China is a significant global exporter of nitrogen fertilizer produced from coal. Because production processes in Northwest Europe are relatively low in carbon emissions, an increased share of production and export by Northwest Europe in the world market could contribute to a reduction in overall global carbon emissions.

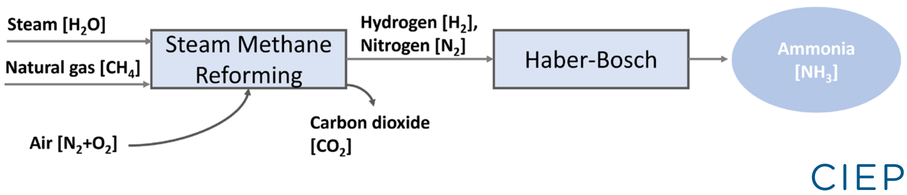

FIGURE 2: CURRENT COMMON INDUSTRIAL AMMONIA PRODUCTION METHOD

Synthetic ammonia has a wide range of potential applications, but it is primarily used in the fertilizer industry, accounting for 80 per cent of global usage (see figure 3). It forms a crucial connection between the nitrogen in the air and the crops we cultivate.[22] It can either be directly used as plant nutrition, or as a feedstock to produce a variety of mineral nitrogen fertilizers. Some of the most common nitrogen fertilizers are urea, ammonium nitrate, ammonium sulphate and UAN. Apart from being used in the fertilizer industry, ammonia is used as a feedstock and intermediate for chemicals, explosives, fibres, plastics, refrigeration, pharmaceuticals, pulp, paper, mining, cleaning and more.[23]

21 Yara (2022). Climate Roadmap 2030. Available at: https://www.yara.nl/globalassets/2220875-yara-climate-roadmap-brochure-juni-2022-lr.pdf/

22 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

23 European Commission (2007). Integrated Pollution Prevention and Control. Available at: https://eippcb.jrc.ec.europa.eu/sites/default/files/2022-03/LVIC-AAF.pdf

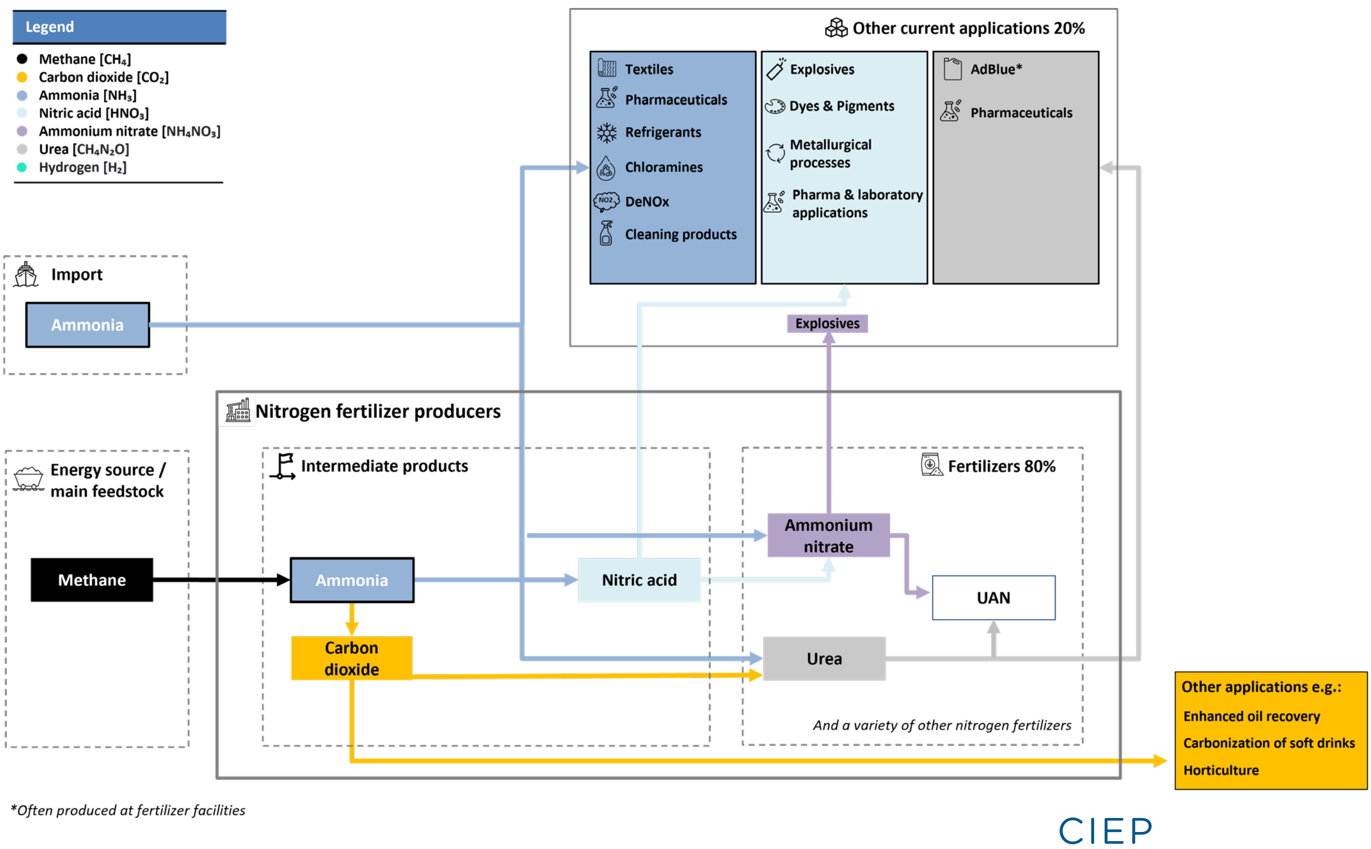

FIGURE 3: CURRENT AMMONIA SUPPLY CHAIN IN NORTHWEST EUROPE

Even though significant efficiency steps have been made, ammonia production stays an energy intensive process. To reduce carbon emissions in the production process in future, three main strategies are employed: further modernization and improvement of the carbon efficiency of existing installations, implementation of Carbon Capture and Storage (CCS) technology, and the production of ammonia from renewable energy sources. Currently, various low-carbon ammonia production initiatives are being set up in Northwest Europe. Some examples are:

- Yara in collaboration with Lantmännen, who aim to introduce the first fossil-free fertilizers in 2023 in Sweden, derived from renewable ammonia produced from hydropower. They anticipate achieving an 80-90% reduction in carbon emissions.[24]
- Orsted and Yara, who are developing a project for green ammonia production in the Netherlands. The aim is to replace fossil-based hydrogen with hydrogen produced via electrolysis from offshore wind energy at Yara's Sluiskil factory in Zeeland, starting from 2024/2025. A 100 MW electrolyser will be used and is expected to produce approximately 75,000 tonnes of low-carbon ammonia per

24 Yara (2022). Yara and Lantmännen Sign First Commercial Agreement for Fossil Free Fertilizers. Available at: https://www.yara.com/corporate-releases/yara-and-lantmannen-sign-first-commercial-agreement-for-fossil-free-fertilizers/

year, equal to about 10 per cent of the capacity of the biggest ammonia plant in Sluiskil.[25] If this is all used as a feedstock for fertilizer, it would be sufficient to fertilize half a million hectares of agricultural land, which is equivalent to the total arable area of the Netherlands.[26]

- The 'Barents Blue plant' in Norway, which intends to use natural gas from the Barents Sea to produce ammonia via the Auto Thermal Reforming (ATR) process. The installation will be equipped with CCS technology and is expected to be the first large-scale low-carbon ammonia production facility in Europe, producing approximately 1 Mt of ammonia per year. It is projected to save about 2 Mt of carbon emissions annually, starting from 2026.[27]
- The HØST PtX Esbjerg ammonia plant in Denmark, which is currently being developed close to the port in Esbjerg. The project is expected to produce about 600,000 tonnes of low-carbon ammonia per year for fertilizer production or fuel for the maritime industry, using a 1 GW electrolyser. The final investment decision is planned for 2025 and the plant is expected to enter full operation in 2029.[28]

2.2 THE EFFECT OF THE ENERGY CRISIS OF 2022 ON THE INDUSTRY

The year 2022 has been an extremely challenging year for the fertilizer industry in Northwest Europe. The lion's share of variable fertilizer production costs are the costs of natural gas. In the EU, rising gas prices resulted in an increase in nitrogen fertilizer prices of 149 per cent between September 2021 and September 2022.[29] Since the end of 2021, when energy prices began to rise in Europe, ammonia and fertiliser production sites in the region have experienced periodic closures or reductions in production. Waves of production curtailment coincided with the peaks of natural gas prices during the autumn of 2021, and the spring and summer of 2022 (see figure 4).[30] After prices reached the highest level at the end of August 2022, about 70 per

25 Smart Delta Resources (2021) Orsted and Yara Develop Project for Green Ammonia Production. Available at: https://www.smartdeltaresources.com/en/orsted-and-yara-develop-project-green-ammonia-production-0#:~:text=%C3%98rsted%20is%20the%20largest%20offshore,conventional%20cars%20off%20the%20street.

26 Yara (2022). Climate Roadmap 2030. Available at: https://www.yara.nl/globalassets/2220875-yara-climate-roadmap-brochure-juni-2022-lr.pdf/

27 Horisont Energi. Barents Blue Europe's First Large-Scale Clean Ammonia Plant. Available at: https://horisontenergi.no/projects/barents-blue/. Last accessed on 25.09.2023

28 HØST PtX Esbjerg. Green Ammonia Made in Denmark. Available at: https://hoestptxesbjerg.dk/about-ptx/#:~:text=H%C3%98ST%20PtX%20Esbjerg%20is%20an,of%20e.g%20infrastructure%20and%20agriculture. Last accessed on 25.09.2023

29 European Commission. Ensuring Availability and Affordability of Fertilisers. Available at: https://agriculture.ec.europa.eu/common-agricultural-policy/agri-food-supply-chain/ensuring-availability-and-affordability-fertilisers_en Last accessed on 25.09.2023

30 European Commission. Ensuring Availability and Affordability of Fertilisers. Available at: https://agriculture.ec.europa.eu/common-agricultural-policy/agri-food-supply-chain/ensuring-availability-and-affordability-fertilisers_en Last accessed on 25.09.2023

cent of all ammonia production capacity in Europe was curtailed in the subsequent month. A month later this had already somewhat improved, but curtailment stayed at 50 per cent.[31] The production plants that typically remained operational, were those with the highest energy efficiency or logistical advantages, which made them less vulnerable to higher gas prices.[32]

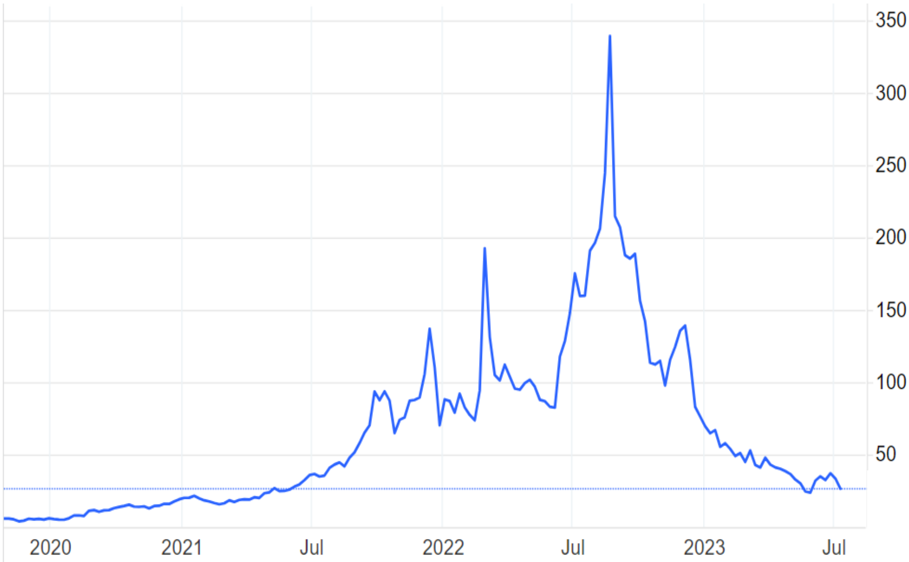

FIGURE 4: NATURAL GAS PRICES EU, AT THE TITLE TRANSFER FACILITY (TTF)

SOURCE: TRADING ECONOMICS, EU NATURAL GAS. AVAILABLE AT: HTTPS://TRADINGECONOMICS.COM/COMMODITY/EU-NATURAL-GAS. LAST ACCESSED ON 02-10-2023

The declined ammonia production was partly replaced by imports, as it was significantly cheaper to import the chemical than to make it domestically. Even though, at times, more than half the ammonia production capacity was curtailed during the summer, the nitrogen fertiliser production in Europe in August was only 23 per cent below the average in previous years, because of the increased flow of ammonia imports (see figure 5).[33]

31 Bloomberg. Europe's Nitrogen Industry Faces New Threats After Reopening. Available at: https://www.bloomberg.com/news/articles/2022-12-07/europe-s-nitrogen-industry-faces-further-risks-as-plants-restart Last accessed on 25.09.2023

32 Yara (2022). Climate Roadmap 2030. Available at: https://www.yara.nl/globalassets/2220875-yara-climate-roadmap-brochure-juni-2022-lr.pdf/

33 European Commission. Ensuring Availability and Affordability of Fertilisers. Available at: https://agriculture.ec.europa.eu/common-agricultural-policy/agri-food-supply-chain/ensuring-availability-and-affordability-fertilisers_en Last accessed on 25.09.2023

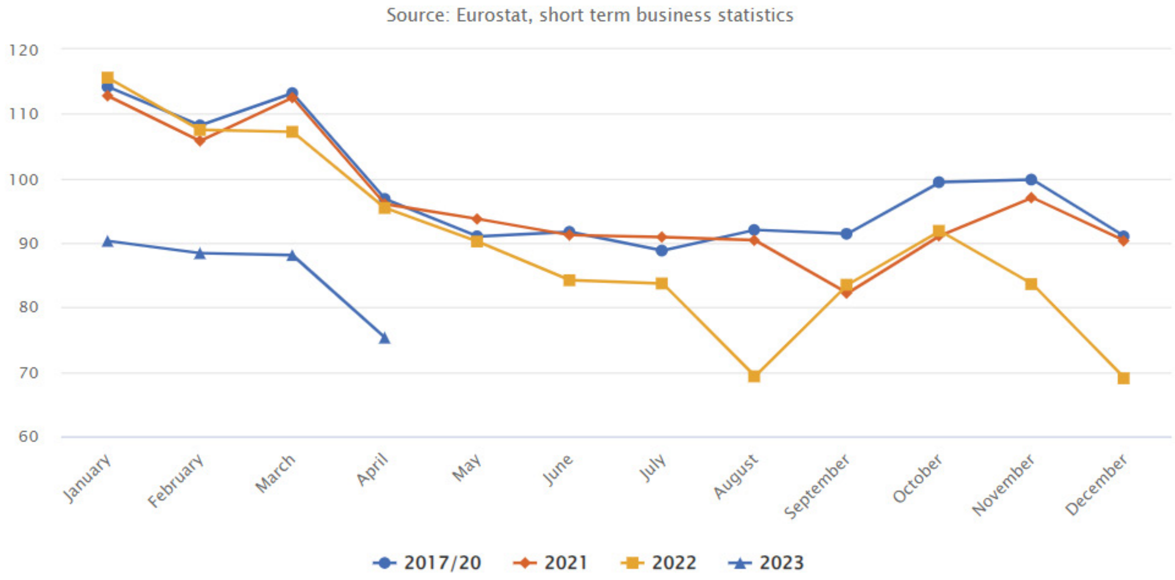

FIGURE 5: MONTHLY INDEX OF PRODUCTION IN VOLUME OF FERTILISERS AND NITROGEN COMPOUNDS (EU-19)

SOURCE: EUROPEAN COMMISSION. ENSURING AVAILABILITY AND AFFORDABILITY OF FERTILISERS. AVAILABLE AT: HTTPS://AGRICULTURE.EC.EUROPA.EU/COMMON-AGRICULTURAL-POLICY/AGRI-FOOD-SUPPLY-CHAIN/ENSURING-AVAILABILITY-AND-AFFORDABILITY-FERTILISERS_EN. LAST ACCESSED ON 25.09.2023

With European gas prices 8-10 times higher than gas prices in rival countries and regions, the Northwest European fertilizer industry has not been able to compete on the global market.[34] As a result of the high natural gas prices, on 24 February 2023, the chemical giant BASF announced it will permanently close one of its two ammonia plants at its flagship facility in Ludwigshafen in Germany.[35] If the situation persists, it is likely BASF will not be the last fertilizer producer to permanently close a production facility in Europe. Although natural gas prices have declined from their record high of 338 Euro/MWh in August 2022 to approximately 40 euro/MWh in April 2023, they remain well above the average levels of 10-20 Euro/MWh observed in the decade preceding the war. Furthermore, there are reasons to worry about Europe's second winter without flows from Russia, its former biggest supplier. During the previous winter, Europe was fortunate to benefit from mild weather conditions and exceptionally low Chinese LNG demand. However, as we approach the upcoming winter season, the conditions remain uncertain.[36]

34 Fertilizers Europe (2022). Europe's Fertilizer Industry Victim of EU's Energy Chaos. Available at: https://www.fertilizerseurope.com/wp-content/uploads/2022/08/Fertilizers-Europe-Press-release_Europe-fert-industry-victim-of-EU-energy-chaos-1.pdf

35 C&en (2023). BASF is Cutting Back at its Main Site in Germany. Available at: https://cen.acs.org/business/finance/BASF-cutting-back-main-site/101/web/2023/02

36 WAtoday (2023). LNG Exporters Face Sinking Prices as Fuel Shortage Fears Fade. Available at: https://www.watoday.com.au/business/companies/lng-exporters-face-sinking-prices-as-fuel-shortage-fears-fade-20230418-p5d1at.html

The fertilizer industry is a significant component of the Northwest European economy. It plays a fundamental role in the production of food, and the sector is of key importance, strengthening Northwest European strategic autonomy. The high gas prices and uncertainty about the future, threaten general European industrial competitiveness and the survival of the European fertilizer industry.[37] Furthermore, on the medium- or long-term, ammonia will likely be produced using renewable electricity, which often is also cheaper and more abundant outside of Europe. Europe has been losing industry to regions with cheaper energy or labour for decades, in a globalized and cooperative world these developments do not necessarily have to be problematic. However, current geopolitical tensions threaten to decrease globalization and cooperation around the world, increasing the importance of self-sufficiency of critical chemicals.

In 2020, Europe already imported 30 per cent of its total domestic consumption of inorganic nitrogen.[38] If Europe wants to prevent losing a larger share of its nitrogen fertilizer industry in future, and not increasingly rely on import to fulfil demand, it might need to rethink how to create an environment in which the European fertilizer industry can compete. From a strategic standpoint, it seems wise to ensure a certain level of domestic production. Especially as ammonia is also expected to play a role in the energy sector, and with that to make an even greater and more crucial contribution to the Northwest European economy of the future.

37 Euractiv (2023). A Strong Domestic Fertilizer Industry Crucial for EU. Available at: https://www.euractiv.com/section/agriculture-food/opinion/a-strong-domestic-fertilizer-industry-crucial-for-eu/

38 Euractiv (2023). A Strong Domestic Fertilizer Industry Crucial for EU. Available at: https://www.euractiv.com/section/agriculture-food/opinion/a-strong-domestic-fertilizer-industry-crucial-for-eu/

3 AMMONIA AS AN OVERSEAS ENERGY CARRIER

Northwest Europe has a long history of importing large amounts of energy to fuel its domestic economy, despite significant domestic production, including oil and gas from the North Sea and until recently gas from Groningen. Norway is currently the only net exporter in Northwest Europe. All other countries in Northwest Europe depend to a greater of lesser extent on imported coal, oil, gas or electricity to satisfy in their domestic energy needs. Northwest Europe is not an outlier in this respect, the European Union as a whole imported more than half (57.5 per cent) of its energy demand in 2020.[39]

A transition to a system dominated by renewable energy is likely to change production and trade dynamics. While renewable energy production is generally less location-dependent than fossil fuel production, as the first exporters of low-carbon molecules enter the market, the global trade in renewable energy may initially be more concentrated . Furthermore, renewables require substantially more land area per unit of produced energy than fossil fuels. Hence, even in a low-carbon energy system, where energy production becomes less location-dependent, Northwest Europe may still face challenges in fulfilling its energy requirements solely through domestic production. At times, the situation may arise that we will generate surplus electricity which could be exported to neighbouring regions, while we simultaneously face a shortage of low-carbon molecules that would have to be imported.

If domestic production fails to meet the demand, there are two potential outcomes: either energy imports will be necessary to sustain current industrial activity, or a process of deindustrialization or reindustrialization may be required. Some people argue it is inevitable that Europe will lose its energy intensive industry, because energy costs will be lower elsewhere. Energy intensive industry, or parts of the value chain, moving to regions with high renewable energy potential is a serious possibility. However, energy prices are not the only reason why industrial clusters are located at a certain place. Industry also requires access to (skilled) labour, capital, raw materials, infrastructure, ideas, (world) markets, demand centres and a stable political climate, most of which Northwest Europe is well equipped to provide. Although a rise in energy

39 Clean Energy Wire (2023). Germany, EU Remain Heavily Dependent on Imported Fossil Fuels. https://www.cleanenergywire.org/factsheets/germanys-dependence-imported-fossil-fuels#:~:text=In%202020%2C%20the%20European%20Union,the%20previous%20year's%2067%20percent.

costs should not be underestimated, it is too simplistic to declare the end of European industry based on a potential competitive disadvantage regarding future energy prices. Moreover, with the renewable energy potential of the North Sea, Northwest Europe also has something to offer future industries.

Overseas low-carbon energy imports are important to Northwest Europe, as it is expected to stay an energy short region in future. To satisfy future low-carbon energy demand, the European Commission has set extremely ambitious targets for hydrogen import (10 Mt), in its RepowerEU plan for 2030. [40] Industrial ports in countries such as the Netherlands, Belgium and Germany, are well-situated to provide a hydrogen corridor to the rest of Europe. Even if only a fraction of the target is realized, a large percentage of the European hydrogen imports will likely come ashore in Northwest Europe.

There are various (theoretical) possibilities to transport low-carbon energy/hydrogen over long distances. Liquified hydrogen, Liquified Organic Hydrogen Carriers (LOHC), ammonia and methanol, belong to the most promising low-carbon energy carriers for overseas transportation. However, they all come with their own unique set of advantages and disadvantages with regards to energy density, safety, technological maturity, experience, existing infrastructure, costs and their potential for direct application (see table 1).

Although discussions and research often revolve around determining a 'winner' based on technological efficiency, it is important to recognize that energy systems cannot always be designed to be maximally technologically efficient. In addition to technological efficiency, economic, social, and political interests also play significant roles in the development of energy systems. Furthermore, Northwest Europe is not a greenfield, energy supply history will also determine systemic choices. Especially in the early stages, it is plausible that multiple low-carbon energy/hydrogen carriers will coexist in the energy system, as their unique characteristics may cater to specific economic, political, or social needs.

Out of all export-oriented hydrogen projects around the world, currently 85 per cent focuses on ammonia as an overseas carrier, which has led to an increasing interest in ammonia import in Northwest Europe.[41] The global interest in ammonia for overseas

40 European Commission (2022). REPowerEU Plan. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

41 Wood Mackenzie (2022). What Role Will Ammonia Play in Global Hydrogen Trade? Available at: https://www.woodmac.com/news/opinion/what-role-will-ammonia-play-in-global-hydrogen-trade/

	Compressed hydrogen	Liquified hydrogen (cryogen)	Ammonia (liquified)	LOHC (MCH)	Methanol
Volumetric energy density	Compressed at 70 Mpa: 5.6 MJ/L	9.1 MJ/L	15.6 MJ/L	5.66 MJ/L	15.8 MJ/L
Gravimetric energy density (LHV)	120 MJ/kg	120 MJ/kg	18.8 MJ/kg	7.35 MJ/kg	22.4 MJ/kg
Existing infrastructure	No specific infrastructure available (parts of the current gas network can be repurposed	Almost no infrastructure available	Decent amount of infrastructure available	Conventional chemical and oil infrastructure can be used	Some infrastructure available
Safety risks	Limited	Explosion risk	Highly toxic	Limited	Limited
Technological maturity/ experience	Experience with production, transportation and storage	Limited experience	A lot of experience with production, transportation and storage	Limited exprience however, not overly complicated to scale up	A lot of experience with production, transportation, storage and burning
Direct application of carrier	Power generation, steel industry, chemical process industry, refineries, transport fuel, heating	Chemical process industry, transport fuel, steel mills etc.	Fertilizer, chemical process industry, maritime fuels, power generation and potentially in industrial furnaces	Unknown, conversion necessary	Chemical feedstock, fuel for cars, trucks, buses, ships, fuel cells, boilers and cook stoves (but emits CO2)

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TABLE 1: CHARACTERISTICS OF DIFFERENT ENERGY/HYDROGEN CARRIERS

energy transportation is primarily due to its favourable volumetric energy density, the extent of existing infrastructure, knowledge and technological maturity, compared with other potential energy carriers.

3.1 CURRENT TRADE AND OVERSEAS TRANSPORTATION

As mentioned, ammonia is already a globally traded commodity and has been transported over significant distances by ships, trains, trucks and pipelines for decades. There is an established network of ports, pipelines and storage facilities dedicated to facilitating ammonia trade around the world. Current ammonia transportation infrastructure is predominantly meant for the fertilizer industry. As the industry grows, the existing infrastructure and the experience with handling ammonia in global transportation, provide a perfect basis for understanding future costs, performance and potential safety issues. If ammonia takes on a new role in the global economy as an energy carrier and a potentially versatile fuel, the existing transportation infrastructure will need to be scaled up significantly. Contrary to most other low-carbon energy carriers, the need for innovation in ammonia transportation is limited, and building on existing infrastructure is considerably easier than starting from scratch.

Worldwide, there are around 200 terminals in more than 120 ports which have the capability to import or export ammonia (see figure 6).[42] These terminals are equipped with specialized storage tanks, and the majority is designed for imported ammonia. Only a small fraction are cargo export terminals. Although the majority of the ammonia produced globally is used directly on-site as a feedstock for nitrogen fertilizer, about 20 Mt of ammonia is transported by ship on a yearly basis. This volume accounts for approximately 10% of global production.[43]

Worldwide, about 170 ships have the ability to transport ammonia, 40 of these ships are solely dedicated for ammonia transport.[44] These ships typically carry up to 60,000 tonnes of ammonia, which equals an energy content of about 313 GWh.[45] As a comparison, an LNG ship of the same size is able to carry about 750 GWh of energy, so to replace the energy delivered by one LNG carrier, more than two ammonia carriers are needed.[46]

According to the IEA, in 2019, the main ammonia exporting regions were Russia, Trinidad and Tobago and the Middle East, with 24, 23 and 15 per cent of global export respectively. In this same year, the biggest importer was the European Union (24 per cent) followed by India (14 per cent) and the United States (13 per cent).[47]

Ammonia exporting regions are often rich in energy resources such as natural gas or coal. As mentioned in chapter 2, costs of ammonia production depend largely on the costs of energy, which enables these regions to produce ammonia in a relatively cheap way. A similar trend is expected for a future dominated by low-carbon ammonia, as production is likely to take place in renewable energy abundant regions.

Although not as rich in energy resources as Russia or Trinidad and Tobago, Northwest Europe has had some considerable gas resources of its own, and for many years it has benefitted from relatively cheap Russian gas supplies. Besides access to a substantial agricultural market and a skilled labour force, cheap gas has been one of the incentives for the development of the ammonia production industry in Northwest Europe.[48]

42 S&P Global Commodity Insights. Green Ammonia – Maritime. Available at: https://commodityinsights.spglobal.com/contact-us-product.html?productName=info-green-ammonia-maritime. Last accessed on 16-10-2023.

43 IEA (2019). Ammonia Technology Roadmap. Available at: https://www.iea.org/reports/ammonia-technology-roadmap

44 Brown (2019). Renewable Hydrogen for Sustainable Ammonia Production. Available at: https://www.aiche.org/sites/default/files/cep/20190826-53a.pdf#page=22

45 Ammonia 18.8 MJ/kg (LHV) - 5.22 MWh/tonnes – 313 GWh/per ship (60,000 tonnes)

46 LNG 45 MJ/kg (LHV) - 12.5 MWh/tonnes – 750 GWh/per ship (60,000 tonnes)

47 IEA (2019). Ammonia Technology Roadmap. Available at: https://www.iea.org/reports/ammonia-technology-roadmap

48 Fertilizer Europe (2023). Energy Cost. Available at: https://www.fertilizerseurope.com/industry-competitiveness/energy-cost/

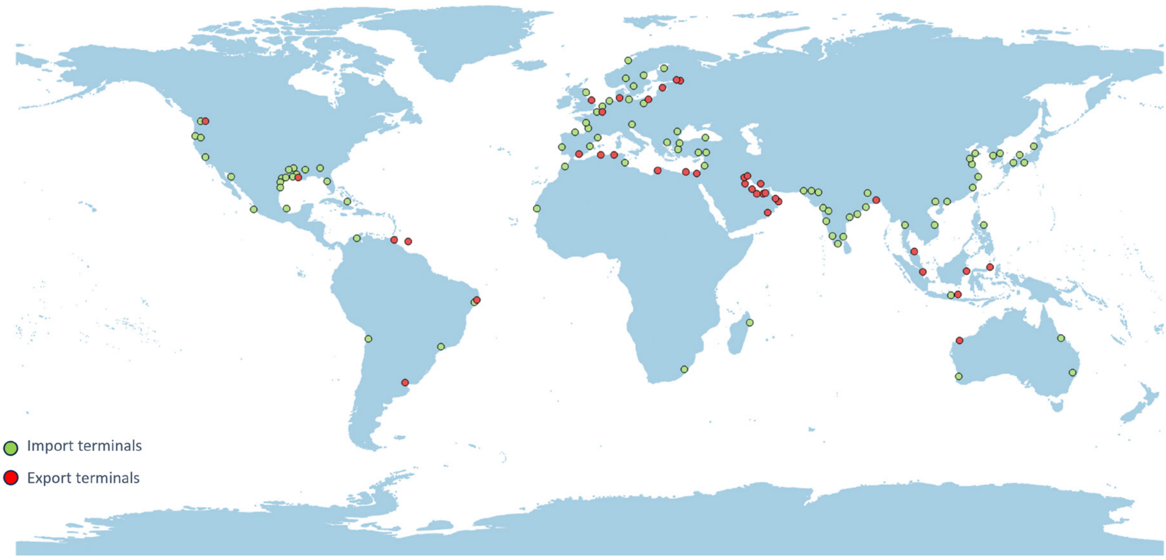

FIGURE 6: GLOBAL AMMONIA TERMINALS 2021[49]

COMPILED BY CIEP, DATA SOURCE: S&P GLOBAL COMMODITY INSIGHTS. GREEN AMMONIA – MARITIME. AVAILABLE AT: HTTPS://COMMODITYINSIGHTS.SPGLOBAL.COM/CONTACT-US-PRODUCT.HTML?PRODUCTNAME=INFO-GREEN-AMMONIA-MARITIME. LAST ACCESSED ON 16-10-2023.

In 2020, the ammonia consumption in Europe was approximately 19 Mt. Europe produced 17 Mt domestically, imported 4 Mt and exported 2 Mt of ammonia.[50] As mentioned in chapter 2, in 2022, the elevated energy prices in Europe led to a significant increase in ammonia imports, replacing domestic production, because producers were compelled to curtail their manufacturing activities. In August 2022, imports of ammonia and ammonia fertilisers increased with 34 per cent compared to the average between 2019 and 2021, while throughout 2022, exports of ammonia and nitrogen fertilizer dropped by 69 and 59 per cent respectively, compared to the previous year.[51]

49 This map only serves as an illustrative representation.

50 IEA (2022). Production, Consumption and Trade of Ammonia in Selected Countries and Regions 2020. Available at: https://www.iea.org/data-and-statistics/charts/production-consumption-and-trade-of-ammonia-in-selected-countries-and-regions-2020

51 European Commission. Ensuring Availability and Affordability of Fertilisers. Available at: https://agriculture.ec.europa.eu/common-agricultural-policy/agri-food-supply-chain/ensuring-availability-and-affordability-fertilisers_en. Last accessed on 25.09.2023

3.2 TERMINALS IN NORTHWEST EUROPE

There are currently 13 ammonia terminals in Northwest Europe, as shown in figure 7.[52] Although sizeable import capacity is already available in Northwest Europe, it will need to increase substantially if ammonia will indeed play a role in overseas energy transportation (see box 1 for an example).

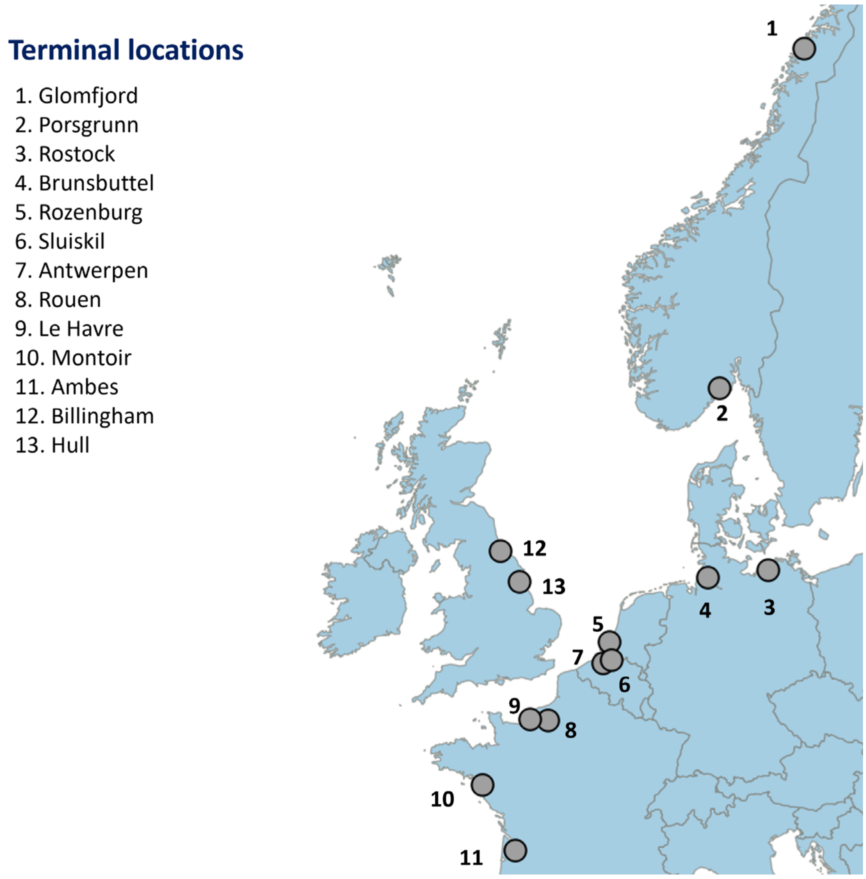

FIGURE 7: AMMONIA SEA TERMINALS IN NORTHWEST EUROPE

CIEP

COMPILED BY CIEP, BASED ON CONVERSATIONS WITH STAKEHOLDERS AND DATA SOURCE: DNV. ALTERNATIVE FUELS INSIGHTS: AVAILABLE AT: HTTPS://AFI.DNV.COM/MAP. LAST ACCESSED ON 10-10-2023

52 DNV. Alternative Fuels Insight. Available at: https://afi.dnv.com/map. Last accessed on 29.09.2023

Box 1: Putting the European Commission's hydrogen import target in perspective

The European commission aims to import 10 Mt of low-carbon hydrogen by 2030. To simplify, let us assume 85 per cent will be imported as ammonia (based on current hydrogen export projects). This would imply that about 68 Mt of ammonia would have to be imported in 2030 (based on an optimistic conversion loss of 20 per cent).[53] This is more than a third of the current total world production (183 Mt) and more than three times the present-day global ammonia trade (20 Mt). In 2019, Northwest Europe imported about 2.4 Mt ammonia.[54] Let's say half the future European import volumes (34 Mt) will reach the shores in Northwest Europe. This would imply ammonia imports in Northwest Europe would need to increase by a factor 14 compared to the levels observed in 2019. This would raise an array of new safety concerns and require a lot of space in the already space constrained harbours of Northwest Europe, especially as long as the fossil fuel infrastructure is still in use.[55]

Besides the challenge of increasing the import capacity, it remains to be seen if the targeted amount of low-carbon hydrogen will be available for import to Europe by 2030. Hydrogen Europe estimates that only about 5 Mt will be available for import to Europe around that time.[56] However, this estimate is also subject to great uncertainty, as the current Memoranda of Understanding (MOUs) with exporting countries only cover 2.8 Mt and most of these projects have not yet reached a final investment decision.[57]

Ammonia terminals are located in most major ports in Northwest Europe, such as Antwerp, Immingham, Rostock and Rotterdam. The considerable experience and existing infrastructure in Northwest Europe are an advantage for increasing ammonia

53 The energy content of hydrogen = 33.33 MWh/t. The energy content of ammonia = 5.22 MWh/t. Based on a 20% conversion loss, this means 79.8 Mt of ammonia is necessary to produce 10 Mt of hydrogen. As it is assumed 85% of the 10 Mt hydrogen target will be imported as ammonia, 68 Mt of ammonia would need to be imported by the EU in 2030.

54 Nation Master. Find Market Sizing and Trends on any sector, in any country. Available at: www.nationmaster.com. Last accessed on 29.09.2023

55 TNO (2023). Transport Gevaarlijke Stoffen Voor Energietransitie Vraagt Nu Om Nieuw Veiligheidsbeleid. Available at: https://www.tno.nl/nl/newsroom/2023/03/transport-gevaarlijke-stoffen/

56 Hydrogen Europe (2022) Clean Hydrogen Monitor 2022. Available at: https://hydrogeneurope.eu/clean-hydrogen-monitor-2022/

57 Erasmus Commodity & Trade Centre (2023). CommodipHy: The Commodification of Ammonia and the Role of Rotterdam as a Global Pricing Centre. Available at: https://www.eur.nl/en/erasmusctc/media/2023-03-commodiphy-research-report-march-2023

import capacity in the region. Currently various new ammonia import projects have been announced, containing both ideas for expansion of existing terminal infrastructure and plans to build completely new terminals. Some examples are:

- The announced modification of *Yara's* ammonia terminals in Brunsbüttel in Germany. The expansion will be completed by the end of 2023, enabling up to 3 Mt of ammonia imports per year.[58]
- *OCI's* final investment decision for the first phase of its ammonia import terminal expansion in the Port of Rotterdam in the Netherlands. The initial increase in throughput will be from approximately 400 Kt per year to 1.2 Mt per year, which can be achieved with relatively low-cost upgrades (estimated to cost less than 20 million) to the existing infrastructure. It is expected to be ready at the end of 2023.[59]
- A newly planned ammonia import facility at The Port of Immingham by *Air Products* and *Associated British Ports,* intending to import ammonia and convert it to hydrogen for hydrogen fuel mobility purposes.[60]
- A technical feasibility study by *Uniper* on building ammonia import infrastructure with a capacity of 2.5 Mt per year in Wilhelmshaven, which would be combined with an industrial-scale ammonia cracker. They estimate this project should be able to provide more than 10 per cent of Germany's hydrogen demand in 2030.[61]

In general, the expansion of existing infrastructure is easier, faster and cheaper than building completely new terminals. Throughput can often be increased over a short timespan with relatively low-cost adjustments, and adhering to regulations will likely be less of a burden in case approval of the existing terminals has already been given.

In Northwest Europe, the permitting process for new ammonia import terminals can form a significant obstacle. Dealing with regulatory complexities to ensure compliance with national, regional and local legislation can be extremely time-consuming and requires expertise in understanding and fulfilling the necessary regulatory obliga-

58 Yara (2023). Yara is Speeding up the Hydrogen Economy in Germany. Available at: https://www.yara.com/news-and-media/news/archive/2023/yara-is-speeding-up-the-hydrogen-economy-in-germany/

59 OCI (2022). OCI N.V. to Expand Port of Rotterdam Ammonia Import Terminal to Meet Emerging Large-Scale Low-Carbon Hydrogen and Ammonia Demand in the Energy Transition. Available at: https://www.oci.nl/news/2022-oci-nv-to-expand-port-of-rotterdam-ammonia-import-terminal/

60 Ammonia Energy Association (2022). Air Products Targets Ammonia Imports at UK Port. Available at: https://www.ammoniaenergy.org/articles/air-products-targets-ammonia-imports-at-uk-port/#:~:text=Air%20Products%20and%20Associated%20British,industrial%20and%20heavy%20transport%20sectors.

61 Ammonia Energy Association (2022). Air Products Targets Ammonia Imports at UK Port. Available at: https://www.ammoniaenergy.org/articles/air-products-targets-ammonia-imports-at-uk-port/#:~:text=Air%20Products%20and%20Associated%20British,industrial%20and%20heavy%20transport%20sectors.

tions. Adhering to strict environmental and safety regulations, often requires extensive studies and the implementation of proper mitigation measures to guarantee the safety of workers, nearby communities and the environment. Also, gaining public acceptance can be challenging, due to concerns for community health and well-being.[62]

Furthermore, several major ports in Europe, including Hamburg, Antwerp and Rotterdam, encounter limitations in terms of available space. This could potentially hinder the expansion of existing ammonia terminals, or the construction of new terminals within these ports. This issue becomes even more significant if ammonia-to-hydrogen conversion facilities also need to be situated in these harbours, given that conversion capacity requires a substantial amount of space.[63]

Repurposing old infrastructure can help to reduce space constraints. For example, bulk liquid storage facilities that previously stored other substances, such as LPG, might be adaptable for ammonia storage. Furthermore, besides expanding existing ammonia terminals or building completely new ones, converting existing LPG or LNG terminals to import ammonia also belongs to the realm of infrastructural possibilities. These facilities already possess the necessary land area, location and jetties suited for ammonia terminals.

To address the significant decline in Russian pipeline gas supply in 2022, European member states, Germany in particular, have been signing contracts to setup several new LNG import terminals.[64] These primarily consist of floating Storage and Regasification Units (FSRUs), but they also include fixed onshore terminals.[65] Natural gas is expected to continue to play an important role in the energy sector in the years ahead. However, fixed onshore LNG terminals have a potential lifespan of 20-40 years.[66] To prevent potential early retirement or low utilization rates in future, it would be wise to build new fixed onshore LNG terminals with the flexibility to be converted into low-carbon fuel import terminals later on.

62 NRC (2023). 'Er is in Rozenburg al Zoveel Gaande. En nu Komt er Ook Nog Waterstof', Zeggen Bewoners. Available at: https://www.nrc.nl/nieuws/2023/03/08/er-is-in-rozenburg-al-zoveel-gaande-en-nu-komt-er-ook-nog-waterstof-zeggen-bewoners-a4158997

63 TNO (2023). Transport Gevaarlijke Stoffen Voor Energietransitie Vraagt nu om Nieuwe Veiligheidsbeleid. Available at: https://www.tno.nl/nl/newsroom/2023/03/transport-gevaarlijke-stoffen/

64 Fraunhofer (2022). Conversion of LNG Terminals for Liquid Hydrogen or Ammonia. Available at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2022/Report_Conversion_of_LNG_Terminals_for_Liquid_Hydrogen_or_Ammonia.pdf

65 Economist (2022). How Europe Plans to Cope as Russia Cuts Off the Gas. Available at: https://www.economist.com/graphic-detail/2022/06/01/how-europe-plans-to-cope-as-russia-cuts-off-the-gas

66 Brauers, Braunger and Jewell (2021). Liquefied Natural Gas Expansion Plans in Germany: The Risk of Gas Lock-in Under Energy Transitions. Available at: https://www.sciencedirect.com/science/article/pii/S2214629621001523

While LNG infrastructure is occasionally labelled as 'ammonia ready,' this concept can be somewhat misleading, as certain components will undoubtedly require replacement to ensure compatibility with ammonia. However, repurposing some of the most expensive components of LNG terminals is feasible, if considered in the initial design. The feasibility, advantages and cost savings of repurposing LNG terminals for ammonia usage are case-dependent and impossible to accurately generalize. Nevertheless, according to a literature study carried out by Fraunhofer, components worth approximately 70 per cent of the initial LNG terminal investment can be repurposed for an ammonia terminal, if a future conversion to ammonia is considered in the design.[67] Repurposing a terminal exclusively designed for LNG will be more costly. Among other components, the storage tank might need to be replaced, accounting for approximately 50 per cent of the Capital Expenditure. While Europe (Germany in particular) is developing new LNG infrastructure to ensure short- and medium-term energy security, it would be prudent to take into consideration possible future repurposing of this infrastructure for low-carbon energy carriers already in the design phase.

67 Fraunhofer (2022). Conversion of LNG Terminals for Liquid Hydrogen or Ammonia. Available at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2022/Report_Conversion_of_LNG_Terminals_for_Liquid_Hydrogen_or_Ammonia.pdf

4 AMMONIA TRANSPORTATION AND STORAGE

When considering the future role of ammonia in the energy sector, there is a common assumption in the public debate in Europe that ammonia should primarily serve as a hydrogen carrier for overseas transportation. The conversion to hydrogen would take place at or near the harbour where it is received. After conversion, the hydrogen can be added to the hydrogen network.

Several advantages come with converting ammonia at the location where it is received, including the anticipated economies of scale, the presence of existing infrastructure, such as storage tanks and pipeline entry points, and proximity to hydrogen demand centres. Consequently, it is not surprising that this location is often regarded as the most logical choice for a conversion facility. Numerous announced ammonia terminal projects also include conversion plants in their design. However, there are several reasons why it might be interesting to refrain from immediate ammonia-to-hydrogen conversion upon arrival, or skip conversion altogether.

First, as reaffirmed by the 2022 energy crisis, energy infrastructure continues to be a matter of national security. Presently, the Netherlands holds a crucial position as an oil entry point for Belgium and for the German state of North Rhine-Westphalia, thanks to its strategic location at river deltas, which connect international waters with Northwest Europe. The Netherlands wishes to continue its energy hub function in a future low-carbon energy system. The Dutch government has already signed MOU's with Namibia, Chili, South Africa, Canada, Uruguay, Oman, Morocco, Iceland, Spain, Portugal, Brazil, Denmark, Indonesia, Japan, Norway, Saudi Arabia, Uruguay, United Arab Emirates, the United States and Australia for low-carbon hydrogen trade, which is likely to be imported as ammonia.[68] However, the sudden loss of Russia as primary gas supplier to Europe has been a wake-up call for the whole continent, especially for Germany, whose industry greatly depended on cheap Russian gas. Security of supply once again plays a dominant role in European energy strategy. The Netherlands will probably continue to be an important energy entry point for Germany in future. Nevertheless, the German government might prioritize domestic storage and conversion facilities, to increase Germany's ownership of critical energy infrastructure and reduce reliance on other countries for its energy supply.

68 Nationaal Waterstof Programma. Internationale Samenwerking. Available at: https://www.nationaalwaterstofprogramma.nl/kennisbank/2543118.aspx?t=Internationale-samenwerking. Last accessed on 02-10-2023

Second, converting ammonia to hydrogen on a large scale requires substantial land area. According to TNO, the projected German hydrogen demand (based on the Hy3-study) arriving at the Port of Rotterdam by 2030/2035, would require an ammonia conversion capacity equal to the capacity of 25 of the largest SMR hydrogen production facilities currently in operation in the Netherlands.[69,70] It is unlikely there will be enough space available in 2030/2035 in the port area, particularly considering that a significant portion of the fossil fuel energy system will still be operational. Just like Rotterdam, most of the other important Northwest European harbours are also struggling with space constraints. Simply a lack of space can form an obstacle to ammonia conversion in the ports where it is landed ashore.

Third, ammonia is often easier to transport and store due to its higher boiling temperature (-33 °C compared to -252.9 °C for hydrogen) and higher volumetric energy density (12.7 MJ/L compared to 8.49 MJ/L for liquid hydrogen).[71] Economically it often makes more sense to transport and store ammonia instead of hydrogen, making ammonia a good candidate for strategic and commercial energy storages. Therefore, in various cases, it might be more cost-effective to have more distributed conversion facilities, further on in the supply chain. Nevertheless, it's important to acknowledge that transportation and storage of ammonia comes with additional toxicity and safety risks.

Fourth, besides its current role as a feedstock, there are various energy applications where ammonia could potentially be used directly. According to the IEA, the conversion of ammonia to hydrogen has an efficiency of approximately 70-80 per cent, depending on the required hydrogen purity. [72] In a best-case scenario, still 20 per cent of the energy content is lost. More research on cracking catalysts and reactors is necessary to improve efficiency. Nevertheless, in order to circumvent the inevitable energy penalty that comes with the conversion to hydrogen, direct use is preferred where possible.

Therefore, ammonia might play a more diverse role than just functioning as a hydrogen carrier for overseas energy transportation, in the Northwest European energy

69 TNO, Julich en Dena (2022). Hy3 – Large-Scale Hydrogen Production from Offshore Wind to Decarbonise the Dutch and German Industry. Available at: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2022/Hy3_Large-scale_Hydrogen_Production_from_Offshore_Wind_to_Decarbonise_the_Dutch_and_German_Industry.pdf

70 TNO (2023). Transport Gevaarlijke Stoffen Voor Energietransitie Vraagt nu om Nieuwe Veiligheidsbeleid. Available at: https://www.tno.nl/nl/newsroom/2023/03/transport-gevaarlijke-stoffen/

71 Aziz, Wijayanta and Nandiyanto (2020). Ammonia as Effective Hydrogen Storage: A Review on Production Storage and Utilization. Available at: https://www.mdpi.com/1996-1073/13/12/3062

72 IEA (2022). Global Hydrogen Review. Available at: https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

sector, in the next decade. This makes it interesting to look at inland transportation, storage and possible direct energy applications of ammonia.

4.1 INLAND TRANSPORTATION

Ammonia is usually transported overland as a pressurized liquified gas by trucks, trains and pipelines. Also, a substantial volume of ammonia is transported through countries by inland waterways. For larger volumes, pipelines are often regarded the most cost-effective and safe way of transportation. Pipelines have an excellent safety record and are in general considered to be a low-risk method to transport ammonia. Ammonia pipeline transportation is therefore common around the world. Globally about 8,000 km of pipelines are currently in operation.[73] The longest pipeline (2,424 km) in the world runs from a production site in Tolyatti in Russia to the coastal city of Odessa in Ukraine.[74] However, this pipeline was damaged on 5 June 2023 and is currently out of service.

One of the most extensive ammonia networks is located in the United States, where ammonia is directly used as a fertilizer. In the United States there are more than 5,000 km of pipelines connecting the Gulf of Mexico to the Midwest.[75] Approximately 1.5 Mt of ammonia is annually transported in the United States.[76]

Europe has about 25 ammonia pipelines. Contrary to the United States, European ammonia pipelines usually only span short distances, typically 1-12 km.[77,78] Most ammonia is produced within fertilizer production facilities, where it is either directly used as a feedstock, or transported to nearby industrial areas. With a few exceptions, such as a 74 km pipeline in Italy, in Europe, long distance transportation of ammonia primarily takes place by train, amounting to approximately 1.5 million tonnes annually.[79] For relatively small volumes, transportation by train can make sense. However,

73 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

74 Fertilizers Europe (2013). Guidance for Inspection of and Leak Detection in Liquid Ammonia Pipelines. Available at: https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Guidance_for_inspection_of_and_leak_detection_in_liquid_ammonia_pipelines_FINAL_01.pdf

75 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

76 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf?rev=50e91f792d3442279fca0d4ee24757ea

77 Elishav et al., (2021). "Chapter 5 - Storage and Distribution of Ammonia" in Techno-Economic Challenges of Green Ammonia as an Energy Vector (eds Agustin Valera-Medina & Rene Banares-Alcantara) p. 85-103. Available at: https://doi.org/10.1016/B978-0-12-820560-0.00005-9.

78 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf?rev=50e91f792d3442279fca0d4ee24757ea

79 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf?rev=50e91f792d3442279fca0d4ee24757ea

there are serious safety hazards and capacity constraints when transporting large volumes of ammonia by train, truck or barges, bisecting densely populated areas. In the Netherlands, for example, transportation of ammonia by train is discouraged and minimized by government policy.[80]

To increase transportation capacity in densely populated Northwest Europe, pipeline transportation seems to be the most promising candidate. The costs of new ammonia pipelines depend on the location, length, diameter and flow-rate. However, ammonia pipeline transportation costs are only a fraction of ammonia market value.[81] Ammonia is usually transported through pipes as a liquid instead of a gas. Therefore, the diameter of ammonia pipelines is relatively small compared to gas pipelines. Pipes or tanks for ammonia can be made of various materials, of which carbon steel is most commonly used. Ammonia pipeline transportation is expected to be cheaper than hydrogen pipeline transportation, due to the higher volumetric energy density of ammonia, and the lower costs of pumping liquified ammonia, compared to the necessary compression of gaseous hydrogen.[82]

While the primary focus in Northwest Europe for new low-carbon fuel infrastructure is on hydrogen, there is specific interest in the construction of a new long distance ammonia pipeline from the Port of Rotterdam in the Netherlands to North Rhine-Westphalia in Germany, as part of the Delta Corridor project (see figure 8). In the early planning phase, the Delta Corridor was intended for hydrogen, CO_2 and propene, currently however, also ammonia is being considered as a candidate. The pipeline network is planned to go into operation in 2026.[83] This would allow transportation of ammonia to industrial clusters in Moerdijk, Chemelot, Geertruidenberg and North Rhine-Westphalia (including Cologne, Gelsenkirchen and surrounding areas). In these clusters, ammonia could be stored, used as a feedstock or fuel, or converted into hydrogen. In future, the Delta Corridor could also connect with industrial clusters in Belgium and deeper into Germany.

80 TNO (2023). Transport Gevaarlijke Stoffen Voor Energietransitie Vraagt nu om Nieuwe Veiligheidsbeleid. Available at: https://www.tno.nl/nl/newsroom/2023/03/transport-gevaarlijke-stoffen/

81 Salmon and Banares-Alcantara (2021). Green Ammonia as a Spatial Energy Vector: A Review. Available at: https://pubs.rsc.org/en/content/articlehtml/2021/se/d1se00345c

82 Salmon and Banares-Alcantara (2021). Green Ammonia as a Spatial Energy Vector: A Review. Available at: https://pubs.rsc.org/en/content/articlehtml/2021/se/d1se00345c

83 RVO (2023). Delta Rhine Corridor. Available at: https://www.rvo.nl/onderwerpen/bureau-energieprojecten/lopende-projecten/drc

FIGURE 8: DELTA CORRIDOR

SOURCE: MIEK (2021). MIEK OVERVIEW 2021 MULTIYEAR PROGRAMME INFRASTRUCTURE ENERGY AND CLIMATE. AVAILABLE AT: HTTPS://WWW.RIJKSOVERHEID.NL/DOCUMENTEN/RAPPORTEN/2021/11/26/MEERJARENPROGRAMMA-INFRASTRUCTUUR-ENERGIE-EN-KLIMAAT---OVERZICHT-2021. LAST ACCESSED ON 08.12.2022

Although currently Europe lacks an extensive ammonia pipeline network, it does have a large-scale, high-quality natural gas, crude oil, and oil products pipeline network. Owners of such assets have a strong incentive to repurpose their functionality, to ensure that they remain valuable in the future. Society at large can benefit from such repurposing.

Yet, many of the oil product pipelines in Northwest Europe are owned by NATO. This pipeline system is designed to ensure that NATOs requirements for oil products and their distribution, can be met at all times. As long as NATO needs diesel, petrol and kerosene for its military vehicles, these pipelines will not be available for repurposing.

Repurposing the existing gas pipelines has been intensively discussed in most North-west European countries. The European Hydrogen Backbone is the most noteworthy initiative, which aims to develop extensive hydrogen infrastructure based on existing and new pipelines to accommodate a future low-carbon hydrogen market. In some cases, repurposing gas pipelines for ammonia transportation is also a possibility. This could increase the resilience of our future energy network, as it would add to energy carrier diversity in the system.

In gaseous form, ammonia and natural gas share quite similar physical properties (e.g.: compressibility, viscosity, specific heat and density). Therefore, despite limited research, it appears that no significant retrofit is required.[84] The different chemical makeup of methane does require purging of the pipeline system before it can be used for ammonia transportation.[85] Moreover, the corrosive nature of ammonia remains a potential concern. Most existing pipelines worldwide are made from carbon steel.[86] According to ICEF, carbon steel is generally considered compatible with ammonia and should adequately resist corrosion, but the possibility of minor degeneration still exists.[87] It is worth considering that alternative materials, such as stainless steel, could offer even better corrosion protection.[88]

Furthermore, because of the toxicity of ammonia, there are regulations and limitations which could influence the speed and scale with which repurposing can be executed. In the Netherlands, for instance, the flexibility to change the product transported through a pipeline system is limited, due to regulations that specify pipelines can only be used for specific products.[89] Another potential issue with repurposing natural gas pipelines for ammonia lies in their size; many of the natural gas pipelines in Europe are noticeably larger than the pipelines currently used for ammonia transportation. Consequently, a leakage would result in the release of considerable volumes of ammonia into the atmosphere, potentially posing significant safety haz-

84 Elishav et al., (2021). Chapter 5 – Storage and Distribution of Ammonia. In Techno-Economic Challenges of Green Ammonia as an Energy Vector. Available at: https://www.sciencedirect.com/science/article/abs/pii/B9780128205600000059?via%3Dihub

85 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

86 Sirimanna et al., (2015) 13 – Fiber-reinforced polymer (FRP) repair systems for corroded steel pipelines. Available at: https://www.sciencedirect.com/science/article/abs/pii/B9780857096845000138

87 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

88 Fraunhofer (2022). Conversion of LNG Terminals for Liquid Hydrogen or Ammonia. Available at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2022/Report_Conversion_of_LNG_Terminals_for_Liquid_Hydrogen_or_Ammonia.pdf

89 Internal Discussion CIEP, June 2023

ards.[90] One possible solution could involve installing a smaller pipeline suitable for ammonia within the existing gas pipeline, offering a practical means of repurposing the infrastructure.

4.2 AMMONIA AND THE NECESSITY OF ENERGY STORAGE

As Northwest Europe transitions to a low-carbon energy system, energy storage will become even more crucial than it is today. In dealing with international energy market turmoil, the year 2022 has reminded us of the importance of strategic oil and commercial gas storages for import dependent countries. For national security reasons, the significance of storages increases with the dependence on foreign energy supplies. Therefore, all members of the IEA, except for net oil exporters, are obliged to have strategic petroleum reserves equal to 90 days of their net oil imports in the previous year.[91] Northwest Europe will likely remain an energy short region and a net-importer in a low-carbon future. Consequently, strategic storage of (low-carbon) energy carriers will play a critical role in ensuring energy security in the forthcoming decades. For the coming decades, the storage of fossil fuels remains essential. Even in the distant future, strategic storage of some fossil fuels may be necessary for emergency situations and can be used in combination with CCS technology to decrease carbon emissions. In addition to strategic storages, the importance of commercial storage capacity to match hourly and monthly supply and demand, will increase with the growing share of renewables in our energy system.[92]

With the growing use of low-carbon fuels such as hydrogen in our economy, there will be a greater need for additional storage of those low-carbon fuels. Unfortunately, most low-carbon energy carriers do not seem to match fossil fuels when it comes to volumetric energy density, as can be seen in figure 9. Nevertheless, among the low-carbon alternatives, ammonia is a relatively good carrier for storing energy. As mentioned before, it is often easier and cheaper to store than hydrogen, due to its higher volumetric energy density and higher boiling temperature. However, due to its toxic nature, there are challenges when it comes to safety, environmental risks and public perception when stored on a large scale. Yet, the fertilizer industry has accumulated decades of experience in storing ammonia. Constructing, maintaining and operating ammonia storage facilities is a well-established practice, with

90 Based on conversations with industry expert, September 2023

91 IEA (2023). Oil Stocks of IEA Countries. Available at: https://www.iea.org/data-and-statistics/data-tools/oil-stocks-of-iea-countries

92 IEA, Grid-scale Storage. Available at: https://www.iea.org/fuels-and-technologies/energy-storage Last accessed on: 29-09-2023

numerous certified companies worldwide specialized in these processes.[93] Ammonia can be stored in various ways, both above- and underground.

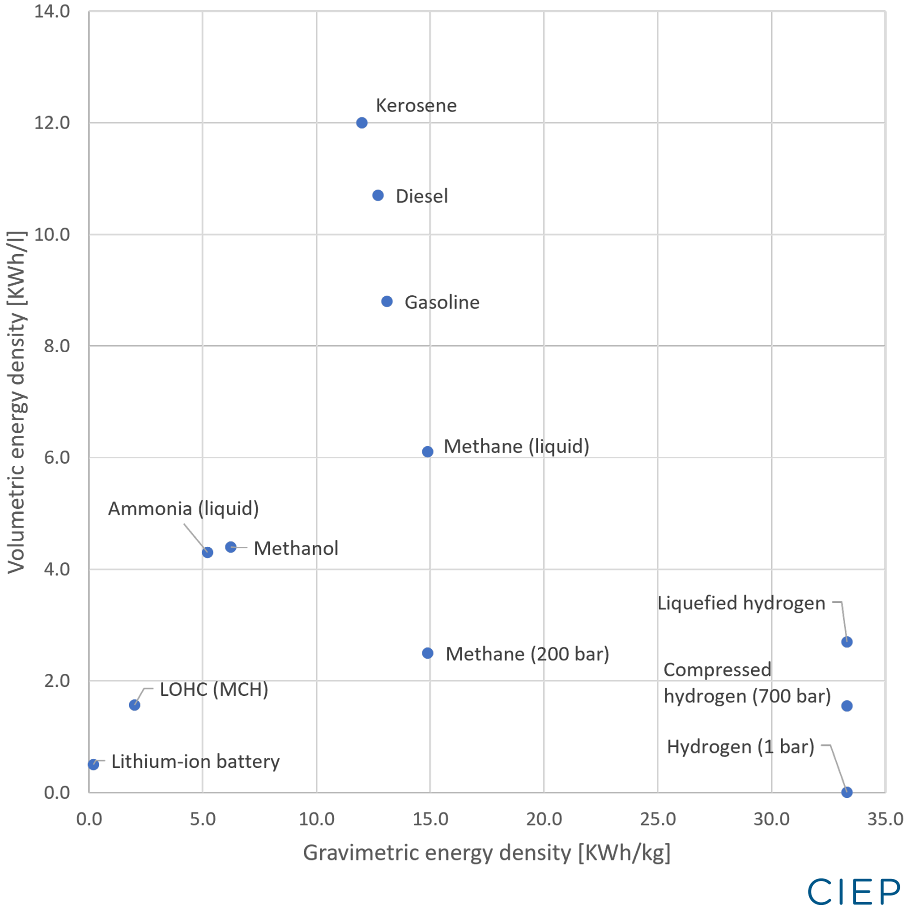

FIGURE 9: VOLUMETRIC AND GRAVIMETRIC ENERGY DENSITY OF VARIOUS FOSSIL AND LOW-CARBON FUELS

COMPILED BY CIEP, DATA SOURCES: ENERGY.GOV. HYDROGEN STORAGE. AVAILABLE AT: HTTPS://WWW.ENERGY.GOV/EERE/FUELCELLS/HYDROGEN-STORAGE. LAST ACCESSED ON 26-10-2023; CHATTERJEE ET AL., (2021). LIMITATIONS OF AMMONIA A HYDROGEN ENERGY CARRIER FOR THE TRANSPORTATION SECTOR. AVAILABLE AT: HTTPS://PUBS.ACS.ORG/DOI/10.1021/ACSENERGYLETT.1C02189; GOFMAN (2023). ENERGY DENSITY OF AVIATION FUEL. AVAILABLE AT: HTTPS://HYPERTEXTBOOK.COM/FACTS/2003/EVELYNGOFMAN.SHTML.

93 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

4.2.1 ABOVEGROUND AMMONIA STORAGE

Ammonia is stored in designated surface tanks, which can broadly be categorized in three types: pressurized (20°C, 10 bar), refrigerated (-33°C, 1 bar) and semi-refrigerated (0°C, 4 bar) tanks. For smaller volumes, ammonia is stored in pressurized and semi-refrigerated spheres with a capacity of up to 5,000 m3 (3,413 tonnes). When larger capacities are needed, refrigerated tanks are used.[94] In 2014, there were more than 50 refrigerated ammonia storage tanks in operation in Europe.[95] These tanks have the capacity to store up to 50,000 tonnes of ammonia, which is approximately equivalent to 260 GWh of energy. To put this in perspective, it equals the energy content of approximately 2.6 million Tesla batteries.[96] As an indication of scale, the Qatar Fertiliser Company has two 50,000 tonnes refrigerated ammonia storage tanks in Mesaieed Qatar, which are approximately 50 meters in diameter and 40.5 meters high. They have a combined footprint of around 160 meters by 90 meters, occupying roughly 1.5 hectares of space.[97,98]

In comparison, tank storage of hydrogen requires significantly more energy for pressurizing or cooling to increase its volumetric energy density, than tank storage of ammonia. Even when liquified, hydrogen's volumetric energy density remains about 50 per cent lower than that of liquid ammonia, making it less practical for storage.[99] Overall, ammonia tank storage is more efficient, uses significantly less energy and is cheaper than hydrogen tank storage.[100]

With over 10,000 storage sites, the United States has the most extensive ammonia storage network in the world (see figure 10). This vast ammonia storage network in the United States demonstrates that it is possible to safely store significant volumes of ammonia. It is important to note that the population density of the United States is noticeably lower than that of Northwest Europe, and that most storage facilities are located in the Mid-West in sparsely populated areas. Iowa is the area where ammonia

94 Londe (2021). Four Ways to Store Large Quantities of Hydrogen. Available at: https://onepetro.org/SPEADIP/proceedings-abstract/21ADIP/2-21ADIP/D022S189R001/473821

95 Fertilizers Europe (2013). Guidance for Inspection of and Leak Detection in Liquid Ammonia Pipelines. Available at: https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Guidance_for_inspection_of_and_leak_detection_in_liquid_ammonia_pipelines_FINAL_01.pdf

96 A Tesla model S battery pack has a capacity of approximately 100 kWh

97 The Royal Society (2020). Ammonia: Zero-carbon Fertiliser, Fuel and Energy Storage. Available at: https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf.

98 McDermott. QAFCO Ammonia Storage Tanks. Available at: https://www.mcdermott.com/What-We-Do/Project-Profiles/QAFCO-Ammonia-Storage-Tanks. Last accessed on: 08-12-2023

99 The volumetric energy density of liquid hydrogen is 8.49 MJ/L, while liquid ammonia has a volumetric energy density of 12.7 MJ/L.

100 Bartels (2008). A Feasibility Study of Implementing an Ammonia Economy. Available at: https://dr.lib.iastate.edu/server/api/core/bitstreams/c0443ee4-2e07-4213-9dbd-ee251dad41ec/content

storage facilities are most abundant, with more than 1,000 facilities and a total storage capacity of about 800,000 tonnes.[101] However, there is also significant ammonia storage capacity in proximity to major cities such as Los Angeles, where the port has a storage capacity of 150,000 tonnes.

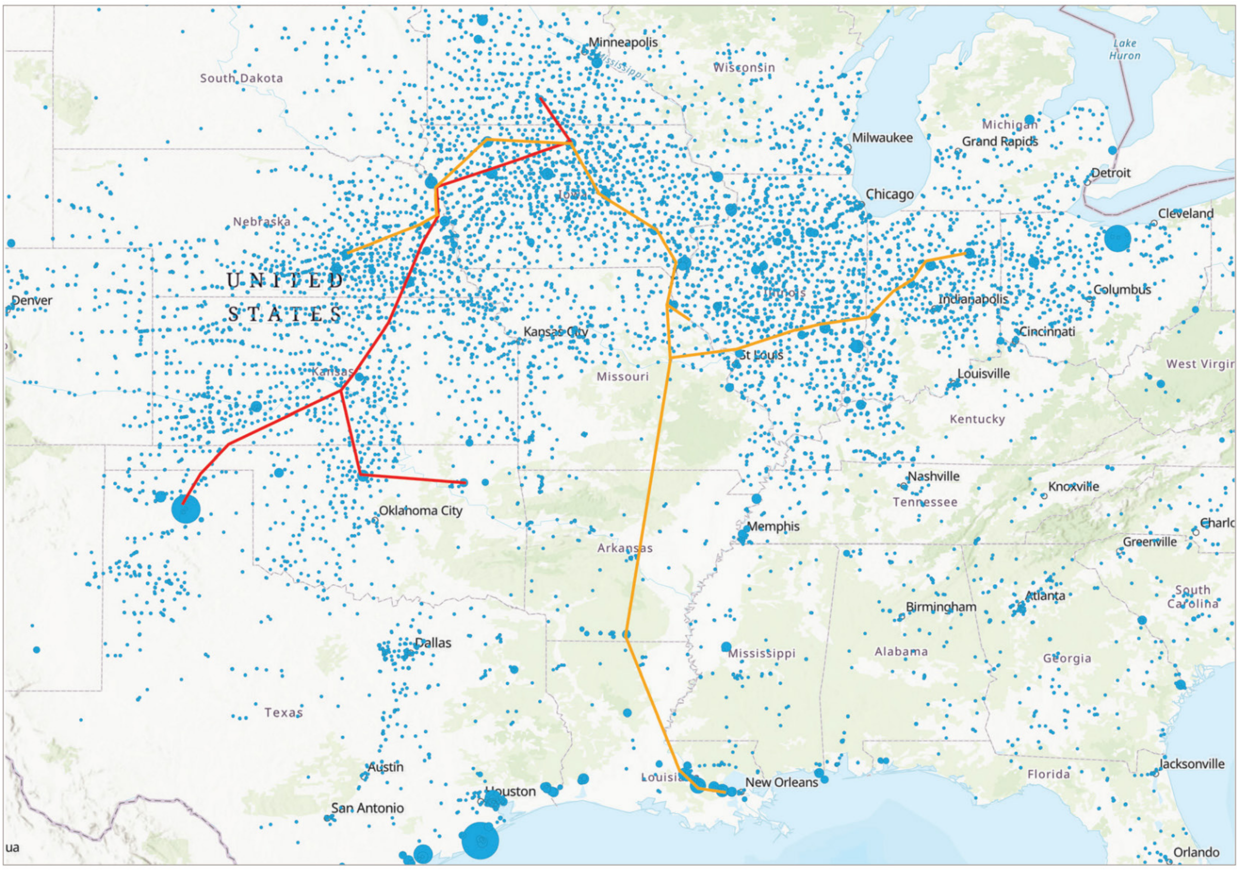

FIGURE 10: AMMONIA STORAGE FACILITIES IN THE UNITED STATES (2020)

SOURCE: THE ROYAL SOCIETY (2020). AMMONIA: ZERO-CARBON FERTILISER, FUEL AND ENERGY STORAGE. AVAILABLE AT: HTTPS://ROYALSOCIETY.ORG/-/MEDIA/POLICY/PROJECTS/GREEN-AMMONIA/GREEN-AMMONIA-POLICY-BRIEFING.PDF. THE DOTS ARE INDICATIVE OF THE STORED AMMONIA TONNAGE. THE LARGEST DOTS CORRESPONDED TO 100,000 TONNE FACILITIES.

101 The Royal Society (2020). Ammonia: Zero-carbon Fertiliser, Fuel and Energy Storage. Available at: https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

4.2.2 UNDERGROUND AMMONIA STORAGE

Subsurface storage possibilities hold great potential for storing large volumes of energy. In Northwest Europe vast amounts of natural gas are currently stored in salt caverns, rock caverns, depleted fields and aquifers. These subsurface natural gas storage facilities are already being studied for storing hydrogen in future, to support the European hydrogen backbone network.[102] This poses some problems, as not all caverns are suitable for storing hydrogen, due to specific geological constraints. For instance, at any pressure, the volumetric energy density of hydrogen gas is about one third of that of methane gas, therefore, the energy storage capacity of existing facilities is drastically reduced when storing hydrogen.[103] On average a salt cavern can store about 6,000 to 9,000 tonnes of hydrogen, which equals 200 to 300 GWh of energy.[104] This is comparable to the energy storage capacity of a large aboveground ammonia tank.[105] However, worldwide, there is a lot of experience with ammonia storage in tanks, contrary to hydrogen storage in salt caverns. To meet the Northwest European energy storage requirements, aboveground ammonia storage tanks could serve as a valuable addition to the underground hydrogen storage facilities. They offer additional capacity and greater geographical flexibility, albeit limited, as they still require connection to the transportation grid.

Furthermore, although research in this area has been limited, it is theoretically feasible to repurpose some of the subsurface storage facilities currently utilized for gas to store ammonia.[106] Underground ammonia storage offers several advantages over storing hydrogen, including increased storage capacity and the absence of the need for extreme pressure or temperature to store substantial quantities. However, a disadvantage is the threat of contaminating the soil and groundwater, which complicates underground ammonia storage.[107]

Ammonia can be stored in rock caverns. Most weathered or fractured rock would be suitable.[108] However, ammonia has a strong affinity for water, its reaction with water

102 European Hydrogen Backbone (2022). A European Hydrogen Infrastructure Vision Covering 28 Countries. Available at: https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf

103 Alternative Fuels Data Center. Energy and the Hydrogen Economy. Available at: https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf. Last accessed on: 29.09.2023

104 Engie (2021). H2 in the Underground: Are Salt Caverns the Future of Hydrogen Storage?. Available at: https://innovation.engie.com/en/news/news/did-you-know-/hydrogen-underground-storage-salt-caverns/25906

105 The storage capacity of a salt cavern is on average about 6,000-9,000 tonnes of hydrogen, which equals 200 – 300 GWh of energy.

106 Londe (2021). Four Ways to Store Large Quantities of Hydrogen. Available at: https://onepetro.org/SPEADIP/proceedings-abstract/21ADIP/2-21ADIP/D022S189R001/473821

107 Internal Discussion CIEP, June 2023

108 Londe (2021). Four Ways to Store Large Quantities of Hydrogen. Available at: https://onepetro.org/SPEADIP/proceedings-abstract/21ADIP/2-21ADIP/D022S189R001/473821

is exothermic, and rather violent and explosive. Therefore, it is not desirable for ammonia to come into contact with water while being stored. In order to ensure the isolation from water, rock caverns should be lined with steel.[109] In Sweden, a lined rock cavern has already successfully been used for storing natural gas, at a pressure greater than 200 bar, for fast cycling purposes, back in 2004.[110] It is expected that there will be no difficulty with ammonia, which would be stored under significantly lower pressure, at roughly 10 bar at ambient temperature.[111] Since 1986, a refrigerated ammonia cavern has been in operation in gneissic granite rock, in Glomfjord, Norway,[112] storing 60,000 m3 of ammonia at a temperature of -33 degrees, which equals about 250 GWh of energy.[113] Lined rock caverns, and other mined cavern techniques, are expected to remain more expensive than salt caverns and porous rock reservoirs. Nevertheless, their greater flexibility in terms of geographical placement, potentially makes them an interesting addition to Europe's energy storage portfolio of the future.

Some researchers argue that salt caverns might be suitable for ammonia storage as well. The Columbia Center for Global Energy Policy (CGEP), states that salt caverns could provide a relatively low cost solution for large scale storage of ammonia.[114] Although no proof of a salt cavern currently used to store ammonia was found, the first patent for storing ammonia in salt caverns originates from 1954.[115] At least one salt cavern to store ammonia has been in operation in the past, which was located in New Jersey.[116] The Oxford Institute for Energy Studies (OIES), argues that salt caverns are often not considered as a viable option for ammonia storage, due to toxicity hazards.[117] More research is necessary to figure out if toxicity hazards are manageable,

109 Londe (2021). Four Ways to Store Large Quantities of Hydrogen. Available at: https://onepetro.org/SPEADIP/proceedings-abstract/21ADIP/2-21ADIP/D022S189R001/473821

110 Glamheden & Curtis (2006). Excavation of a Cavern for High-pressure Storage of Natural Gas. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0886779805000519

111 Londe (2021). Four Ways to Store Large Quantities of Hydrogen. Available at: https://onepetro.org/SPEADIP/proceedings-abstract/21ADIP/2-21ADIP/D022S189R001/473821

112 Broch (1989). Use of the Underground in Norway. Available at: https://tunnel.no/wp-content/uploads/sites/3/2020/04/Publication-9.pdf

113 Ammonia becomes a liquid at -33 degrees at atmospheric pressure, the volumetric energy density of liquid ammonia is 12.7 MJ/L.

114 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

115 United States Patent Office (1954). Underground Storage of Ammonia and its Recovery. Available at: https://patents.google.com/patent/US2901403A/en

116 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

117 OIES (2020). Ammonia as a Storage Solution for Future Decarbonized Energy Systems. Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf

and what adjustments and materials are necessary to make a salt cavern suitable for ammonia storage.

In general, conducting further research is imperative to better understand the safety risks associated with underground ammonia storage, and comprehensively assess the geochemical reactions of ammonia when stored in a reservoir. Currently, this area of study is in its early stages, and therefore, underground ammonia storage is not as immediately apparent a solution as underground hydrogen storage.

5 AMMONIA AS A LOW-CARBON FUEL

For many applications ammonia is not considered to be the fuel of first choice, due to its toxicity, challenging combustion characteristics, technological immaturity, or simply because better alternatives are available. Box 2 provides an overview of the main technical challenges of ammonia combustion. Nevertheless, ammonia is regarded a promising clean bunker fuel option for ships.[118, 119] Moreover, ammonia is recognized as a low-carbon fuel in the power sector, particularly because of its ability to provide flexible, low-carbon electricity.[120,121]

Box 2: Technical challenges of ammonia combustion

The main advantage of ammonia combustion is that it is carbon emission free. However, it comes with relatively difficult combustion characteristics compared to traditional, carbon-based fuels or carbon containing synthetic fuels (e.g., biodiesel, synthetic methane and methanol). Furthermore, owing to its nitrogen element, ammonia combustion also deals with additional challenges compared to hydrogen combustion.[122]

First, the relatively high auto-ignition temperature of ammonia makes it more difficult to ignite than hydrocarbon-based fuels or hydrogen (see table 2). One approach to address this challenge is to start the combustion process with a fuel that has a lower ignition temperature, and then gradually transition to pure ammonia fuel. Alternatively, ammonia can be blended with a more easily ignitable fuel such as hydrogen, gas, or diesel. Another option is to use enriched or multi-stage oxy-

118 IRENA (2021). A Pathway to Decarbonise the Shipping Sector by 2050. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf?rev=b5dfda5f69e741a4970680a5ced1ac1e

119 IEA (2020). Global energy Consumption and CO2 Emissions in International Shipping in the Sustainable Development Scenario, 2019-2070. Available at: https://www.iea.org/data-and-statistics/charts/global-energy-consumption-and-co2-emissions-in-international-shipping-in-the-sustainable-development-scenario-2019-2070. Last accessed on: 02-10-2023

120 IEA (2022). The Role of Low-Carbon Fuels in the Clean Energy Transition of the Power Sector. Available at: https://iea.blob.core.windows.net/assets/01ca16c8-e493-475c-81c4-04ac5d3b9882/Theroleoflow-carbonfuelsinthecleanenergytransitionsofthepowersector.pdf

121 IRENA (2021). A Pathway to Decarbonise the Shipping Sector by 2050. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf

122 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

gen injection during the combustion process.[123] The uniquely high auto-ignition temperature of ammonia makes accidental ignition almost impossible, which can be seen as an advantage over other fuels that typically have a high fire and explosion hazard.[124] Although some modifications of the ignition process are required, the benefit is a fuel that does not explode accidentally.

Second, maintaining flame stability is challenging, due to the narrow flammability range of ammonia in air and low burning velocity (see table 2). Similar to the ignition problem, blending ammonia with a different fuel with more favourable combustion characteristics, or enriching the oxygen content of the combustion air, can improve combustion stability.[125,126] As a result of the combustion characteristics listed above, ammonia engines typically have a lower power output than engines using hydrogen or carbon fuels. Blending with other fuels can also address this issue.[127]

Third, proper emission control is an issue yet to be solved.[128] In theory, when completely combusted, ammonia only emits nitrogen and water.[129] However, in practice, ammonia combustion can lead to three main types of emissions risks: NOx, N_2O and ammonia slip. All three can have negative effects on health, biodiversity, climate and safety.[130] Part of the NOx emissions are ‘thermal’ NOx emissions, which result from any kind of flame, also when you burn hydrogen. Thermal NOx is produced by the oxidation of nitrogen in the combustion air as a result of high temperatures. Besides thermal NOx, fuels containing a nitrogen molecule can also emit ‘fuel’ NOx, which is produced by the oxidation of the nitrogen molecule in the fuel. [131] Similar to NOx, N_2O is also potentially produced as a by-product of am-

123 ICEF (2022). Roadmap Low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

124 Ahlgren (2012). The Dual-Fuel Strategy: An Energy Transition Plan. Available at: http://www.nh3fuel.com/images/documents/IEEE%20-%20Dual%20Fuel%20Strategy.pdf

125 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

126 Kang et al., (2022). A review on Ammonia Blends Combustion for Industrial Applications. Available at: https://www.sciencedirect.com/science/article/abs/pii/S001623612202974X

127 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

128 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

129 Li et al., (2021). A Review on Combustion Characteristics of Ammonia as a Carbon-Free Fuel. Available at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.760356/full

130 Maersk Mc-Kinney Moller Center (2023). Managing Emissions from Ammonia-Fueled Vessels. Available at: https://cms.zerocarbonshipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf

131 Li et al., (2021). A Review on Combustion Characteristics of Ammonia as a Carbon-Free Fuel. Available at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.760356/full

monia combustion, and thus has a global warming potential, which is about 300 times higher than that of CO_2.[132] Furthermore, in some instances, due to the difficulty of maintaining stable combustion, ammonia is not fully combusted, causing uncombusted ammonia molecules to end up in the exhaust gas as well, which is known as ammonia slip.

Although challenging, the emission risks discussed above are avoidable and are solvable engineering problems, unlike the thermodynamic inevitability of CO_2 emissions from fossil fuel combustion. According to Lee et al. (2010), both NOx and N_2O emissions can be significantly reduced under fuel rich conditions and high pressure.[133] In order to further prevent this problem, ammonia oxidation catalyst and catalytic reduction can be applied.[134] Even though significant progress has already been made, additional research on ammonia combustion and exhaust chemistry is necessary to further optimize the ammonia combustion process.

	Ammonia	Hydrogen	Methane
Autoignition temperature [˚C]	657	537	586
Flammability limit range	0.83	8.71	1.21
Laminar burning velocity [cm/s]	7	350	35
Adiabatic flame temperature [˚C]	1577	2055	1950

CIEP

TABLE 2: COMBUSTION CHARACTERISTICS OF AMMONIA, HYDROGEN AND METHANE

ADJUSTED BY CIEP, DATA SOURCE: ALKHATEEB (2020). STABILITY LIMITS AND NO EMISSIONS OF TECHNICALLY-PREMIXED AMMONIA-HYDROGEN-NITROGEN-AIR SWIRL FLAMES. INTERNATIONAL JOURNAL OF HYDROGEN ENERGY. AVAILABLE AT: HTTPS://WWW.RESEARCHGATE.NET/PUBLICATION/342757202_STABILITY_LIMITS_AND_NO_EMISSIONS_OF_TECHNICALLY-PREMIXED_AMMONIA-HYDROGEN-NITROGEN-AIR_SWIRL_FLAMES

132 Chrobak (2021). The World's Forgotten Greenhouse Gas. Available at: https://www.bbc.com/future/article/20210603-nitrous-oxide-the-worlds-forgotten-greenhouse-gas#:~:text=Yet%20molecule%20for%20molecule%2C%20N2O,also%20depletes%20the%20ozone%20layer.

133 Lee et al., (2010). Studies on Properties of Laminar Premixed Hydrogen-added Ammonia/Air Flames for Hydrogen Production. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360319909018412

134 Erdemir & Dincer (2020) A perspective on the Use of Ammonia as a Clean Fuel: Challenges and Solutions. Available at: https://onlinelibrary.wiley.com/doi/full/10.1002/er.6232#:~:text=As%20given%20in%20Table%201,spark%20ignition%20and%20compression%20engines

5.1 MARITIME BUNKERING SECTOR

At present, most of the maritime bunkering sector's final energy demand is met by Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), and very low-sulphur fuel oil (VLSFO). More recently, Liquefied Natural Gas (LNG) has also been used on a smaller scale in this sector.[135] Backcasting studies conducted by the IEA, IRENA and BP, which are based on a (near) carbon-neutral shipping scenario in 2050, envision a variety of new low-carbon fuels to emerge and play a role in the maritime bunkering sector.[136,137,138] However, the capital-intensive nature of the shipping sector, price disparity between conventional fossil fuels and low-carbon alternatives, and technical obstacles related to low-carbon fuels, present hurdles to the adoption of low-carbon fuels.[139] Therefore, major shifts in fuel use are not anticipated before 2030. Estimates regarding the maritime fuel mix after 2030 vary, due to the wide range of uncertainties, but ammonia is widely seen as one of the most promising fuels in reducing carbon emissions in this sector.[140,141,142,143]

5.1.1 AMMONIA AS A MARITIME BUNKER FUEL

Ammonia is regarded as a promising shipping fuel for several reasons. First, being a carbon-free molecule, no carbon emissions occur during combustion. This gives ammonia an advantage over carbon-based fuels like LNG, which would require an on-board carbon capture and storage system in order to reduce combustion emissions. [144] Second, ammonia's relatively high energy density makes it a suitable fuel for

135 IEA. International Shipping. Available at: https://www.iea.org/energy-system/transport/international-shipping. Last accessed on 02-10-2023

136 IEA (2023). Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach. Available at: https://iea.blob.core.windows.net/assets/d0ba63c5-9d93-4457-be03-da0f1405a5dd/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf

137 IRENA (2021). A Pathway to Decarbonise the Shipping Sector by 2050. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf?rev=b5dfda5f69e741a4970680a5ced1ac1e

138 BP (2023). BP Energy Outlook 2023. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023.pdf

139 HCCS & CE Delft (2023). Decarbonising Maritime Bunkering in the Netherlands and the Embargo on Russian oil. Available at: https://hcss.nl/wp-content/uploads/2023/02/Decarbonising-Maritime-Bunkering-Netherlands-and-Embargo-Russian-Oil-HCSS-2023.pdf

140 IEA (2023). Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach. Available at: https://iea.blob.core.windows.net/assets/d0ba63c5-9d93-4457-be03-da0f1405a5dd/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf

141 ICEF (2022). Roadmap low-Carbon Ammonia. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

142 IRENA (2021). A Pathway to Decarbonise the Shipping Sector by 2050. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf?rev=b5dfda5f69e741a4970680a5ced1ac1e

143 BP (2023). BP Energy Outlook 2023. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023.pdf

144 Ash (2019). Sailing on Solar- Could Green Ammonia Decarbonise International Shipping? Available at: https://www.researchgate.net/publication/332845713_Sailing_on_Solar_-_Could_green_ammonia_decarbonise_international_shipping

long-distance sea transportation, and unlike hydrogen there is no need for cryogenic storage. According to Kim et al. (2020), ships powered by ammonia would require approximately 1.6 to 2.3 times the volume of fuel compared to conventional HFO ships.[145] Third, it does not require complicated onboard processing and can be used in internal combustion engines and future fuel cells.[146] Last, the existing infrastructure and experience of the global shipping industry in handling ammonia as a cargo, provide a solid foundation for its potential role as a fuel in the maritime sector.

Currently, low flammability and high NOx production during combustion (discussed in box 2), present the main challenges for ammonia-fuelled maritime engines. Nevertheless, marine engine developers are confident that they can produce engines that will perform up to industry standards, fall within regulatory NOx emission limits and are safe for the onboard crew.[147]

The first commercially available ammonia-powered two-stroke and four-stroke ships are expected to be operational at sea by 2024 or 2025.[148] One of those ships is being developed by Wärtsilä and Grieg Ede: a tanker vessel that will transport and run on ammonia. The ammonia needed for the project is to be sourced from an upcoming low-carbon ammonia plant located in Berlevåg, Norway. Norway offers an interesting environment to test and start using ammonia fuelled vessels, given its considerable fleet of ships powered by LNG or alternative fuels and high volume of renewable energy.[149]

An increasing number of new vessels are being designed to be 'ammonia-ready'. In an ammonia-ready ship, the main engine, fuel tank, generator and boiler are constructed with the flexibility to be retrofitted for ammonia fuel use in future. Whether an actual retrofit will be profitable in future is uncertain, in any case it provides valuable optionality.[150]

145 Kim et al. (2020). A preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Available at: https://www.mdpi.com/2077-1312/8/3/183

146 Ash (2019). Sailing on Solar- Could Green Ammonia Decarbonise International Shipping? Available at: https://www.researchgate.net/publication/332845713_Sailing_on_Solar_-_Could_green_ammonia_decarbonise_international_shipping

147 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

148 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

149 Wärtsilä Corporation (2020). Wärtsilä and Grieg to Build Groundbreaking Green Ammonia Tanker. Available at: https://www.wartsila.com/media/news/18-12-2020-wartsila-and-grieg-to-build-groundbreaking-green-ammonia-tanker-2836740#:~:text=The%20technology%20group%20W%C3%A4rtsil%C3%A4%20and,greenhouse%20gas%20emissions%20by%202024.

150 ICEF (2022). Low-Carbon Ammonia Roadmap. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

Furthermore, ships equipped with a dual fuel engine are gaining in popularity. These ships can operate on a mixture of two different fuels, currently often diesel and LNG and in future possibly diesel and ammonia. These engines have the capability to switch between the two fuels, providing flexibility and the ability to use one if the other becomes temporarily unavailable. This protects these ships from potential issues with the availability of low-carbon fuels, which is currently considered as one of the main investment risks.[151]

Not all market participants are embracing ammonia-fuelled ships, notable companies like Cargill and Maersk are currently focusing on methanol as a fuel instead.[152,153] According to some, methanol seems to offer more short-term advantages as it is closer to market, while ammonia might be a more favourable long-term option as it eliminates the need for a carbon source.[154]

Presently, ammonia is not approved as a fuel by the International Maritime Organization (IMO).[155] Consequently, each ship seeking to use ammonia as a fuel, must obtain individual approval from its flag state. This is the country where the ship is registered and under which it operates, ensuring compliance with safety and environmental regulations specific to ammonia-based propulsion systems. As flag states, countries in Northwest Europe can contribute to the overall acceleration of ammonia-fuelled ships, by supporting and streamlining the regulatory approval process of ammonia-fuelled ships that demonstrate safe operation. However, in order to further facilitate the widespread adoption of ammonia as a maritime fuel, adjustments to the regulatory framework of the IMO will be necessary, and ammonia will eventually need to be approved as a fuel.[156]

5.1.2 AMMONIA BUNKERING IN THE PORT OF ROTTERDAM: PROSPECTS AND COMPETITION

While marine fuels can be found at nearly every port involved in ocean trade, the bulk of sales are concentrated in a select number of strategic ports worldwide. These

151 ICEF (2022). Low-Carbon Ammonia Roadmap. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

152 Maersk (2023). Equinor and Maersk Partner up to Ensure Continued Green Methanol Supply for the World's First Methanol-Enabled Container Vessel. Available at: https://www.maersk.com/news/articles/2023/09/08/equinor-and-maersk-partner-to-supply-first-methanol-enabled-container-vessel

153 Cargill (2023). Cargill and Lauritzen Order Another Pioneering Methanol-Fueled Bulker. Available at: https://maritime-executive.com/article/cargill-and-lauritzen-order-another-pioneering-methanol-fueled-bulker

154 Maritime Executive (2022). The Decarbonization Tradeoffs for Ammonia, Methanol and H2. Available at: https://maritime-executive.com/editorials/the-decarbonization-tradeoffs-for-ammonia-methanol-and-h2

155 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

156 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

bunkering ports are often strategically positioned along major trade routes and are distinguished by their high ship traffic and trade activities. This makes these hubs convenient refuelling points for ships, minimizing the deviation from their scheduled voyages. Bunkering hubs often develop around ports with large energy clusters, situated near major industrial centres with a high demand for oil products. Energy clusters consist of facilities such as oil refineries, natural gas terminals and major storage sites, handling large volumes of oil and oil products. This concentration of activities allows for efficient bunkering services and competitive fuel prices in the region.[157]

The Port of Rotterdam is the largest bunkering port in Northwest Europe. In 2021, the ARA region, home to the Port of Rotterdam, ranked as the world's second biggest bunkering region, following behind Singapore (see figure 11).[158] The bunkering market in the Port of Rotterdam had to adapt when the import of cheap Russian fuel oil ceased.[159] As a result of the European sanctions on Russian crude oil and oil products, Rotterdam's standing in the global bunker market may undergo further changes over the coming years.

Major bunkering ports are strategically positioning themselves to capitalize on the emerging bunkering market for low-carbon fuels.[160] Numerous ports around the world have agreed to work together to build out bunker infrastructure for alternative fuels, to accommodate low- and zero-carbon vessels.[161] The emergence of low-carbon fuels has the potential to reshape the position and market share of bunkering ports worldwide.

In the Port of Rotterdam, various stakeholders collaborate to facilitate the storage and bunkering of a diverse range of alternative fuels, enabling shipping companies to adopt their preferred low-carbon fuel in future.[162] As a result, it was the first port

157 Livebunkers. A Deep Insight Into Bunkering Business. Available at: https://livebunkers.com/deep-insight-bunkering-business. Last accessed on 05-10-2023

158 CE Delft (2021). The Impacts of The ETD Proposals on Shipping and Bunkering. Available at: https://cedelft.eu/wp-content/uploads/sites/2/2022/03/CE_Delft_210349_The_impacts_of_the_ETD _proposals_on_shipping_and_bunkering_def.pdf. Refering to Repsol data

159 Clingendael International Energy Programme (2022). From Just-in-Time to Just-in-Case or Just to Late? The impact of the EU oil sanctions on crude oil and oil product markets in the Netherlands and its relevant markets. Available at: https://www.clingendaelenergy.com/publications/publication/the-impact-of-eu-oil-sanctions-on-crude-oil-and-oil-product-markets-in-the-netherlands-and-its-relevant-markets.html

160 S&P Global (2023). Regulators Push for Low-Carbon Bunker Transition for net-zero 2050. Available at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/shipping/082423-regulators-push-for-low-carbon-bunker-transition-for-net-zero-2050

161 Hellenic Shipping News (2023). Major Ports Agree to Accelerate Alternative Fuels Uptake. Available at: https://www.hellenicshippingnews.com/major-ports-agree-to-accelerate-alternative-fuels-uptake/

162 Port of Rotterdam. Bunkering in Rotterdam Europe's Largest Bunkering Port. Available at: https://www.portofrotterdam.com/en/sea-shipping/bunkering-in-rotterdam. Last accessed on 05-10-2023

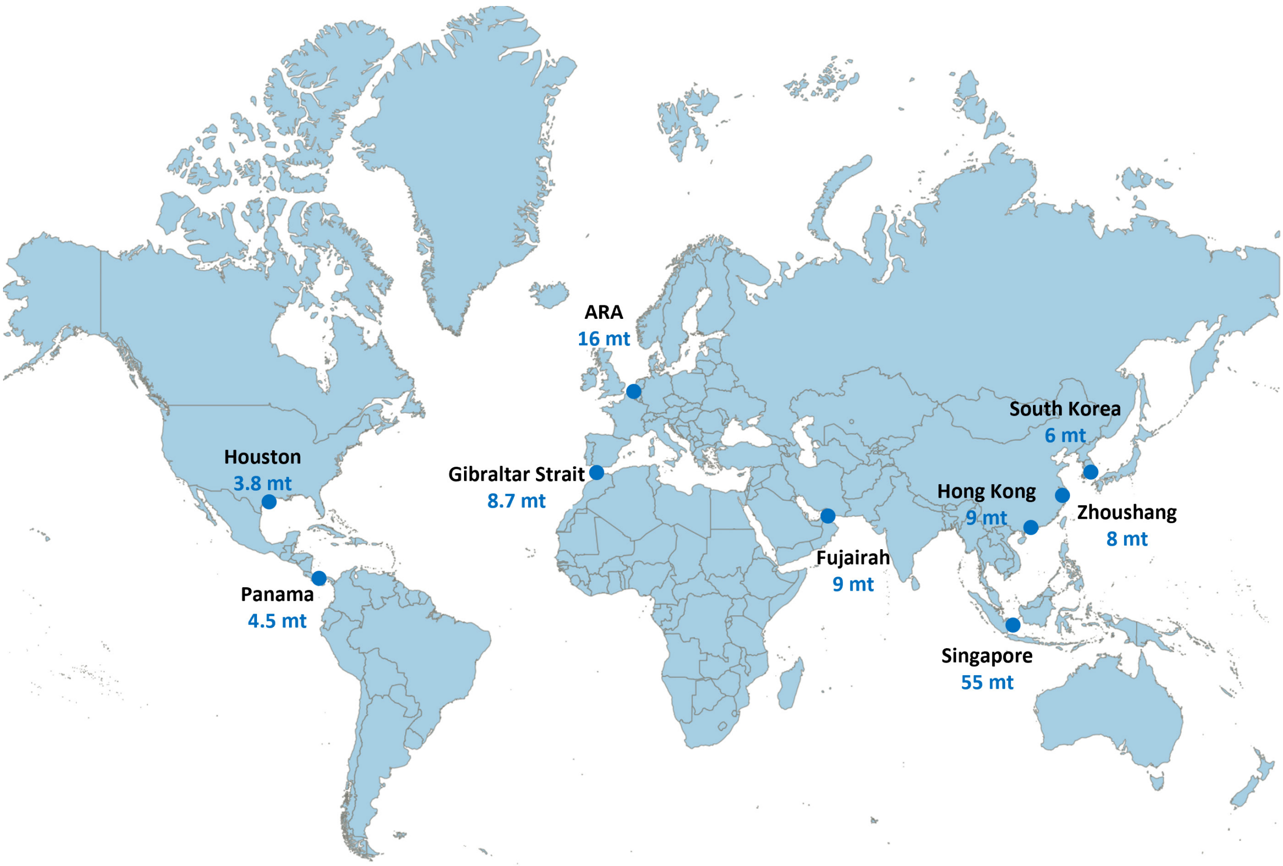

FIGURE 11: CURRENT GLOBAL BUNKERING MARKET

DATA SOURCE: CE DELFT (2021). THE IMPACTS OF THE ETD PROPOSALS ON SHIPPING AND BUNKERING. AVAILABLE AT: HTTPS://CEDELFT.EU/WP-CONTENT/UPLOADS/SITES/2/2022/03/CE_DELFT_210349_THE_IMPACTS_OF_THE_ ETD _PROPOSALS_ON_SHIPPING_AND_BUNKERING_DEF.PDF. REFERING TO REPSOL DATA

in the EU to offer LNG bunkering possibilities and it was the first in the world to introduce a barge-to-ship bunkering service for methanol.[163,164] Moreover, preparations are currently underway to conduct a first pilot project for ammonia bunkering in 2024.[165]

163 Port of Rotterdam. Bunkering in Rotterdam Europe's Largest Bunkering Port. Available at: https://www.portofrotterdam.com/en/sea-shipping/bunkering-in-rotterdam. Last accessed on 05-10-2023

164 Port of Rotterdam (2021). Waterfront Shipping takes Leadership Role in Demonstrating Simplicity of Methanol Bunkering to Marine Industry. Available at: https://www.portofrotterdam.com/en/news-and-press-releases/waterfront-shipping-takes-leadership-role-demonstrating-simplicity-methanol

165 Port of Rotterdam (2022). Lancering van Joint Study Framework en MoU Veilig Bunkeren Ammoniak. Available at: https://www.portofrotterdam.com/nl/nieuws-en-persberichten/lancering-van-joint-study-framework-en-mou-veilig-bunkeren-ammoniak

Rotterdam is well-positioned for a role in the global ammonia bunker market. Its strategic location within the global trading network, substantial oil cluster and nearby demand centres, which have granted it a leading position in the contemporary bunker market, are expected to be valuable for the ammonia bunker market as well.

Part of the extensive energy infrastructure in the Port of Rotterdam can be adapted for ammonia bunkering purposes. Moreover, the Port already has an established ammonia infrastructure, including a terminal and storage facilities, which are currently utilized for the fertilizer industry. These existing facilities can be repurposed to facilitate ammonia bunkering. As mentioned in chapter 3, OCI, the owner of the ammonia import terminal in the Port of Rotterdam, has recently announced a final investment decision to expand the terminal. With this expansion, the terminal could serve as a hub for hydrogen imported in the form of ammonia, but also to provide ammonia bunkering services.[166]

In addition to these infrastructural advantages, the Port of Rotterdam provides access to substantial ammonia demand centres. These demand centres include the chemical industry in Rotterdam and other industrial clusters in the ARA region and Germany, where ammonia serves as a crucial feedstock.[167]

Furthermore, the port's significant bunkering market share, positions it as an attractive hub for bunkering services for new low-carbon fuels. However, it is still unclear how changes in global oil flows due to the EU's sanctions on Russian crude oil and oil products will impact Rotterdam's position in the global bunkering market in the coming years.

Despite the advantages of the Port of Rotterdam, it is worth noting that many of its biggest competitors share similar features. In addition to a strategic location, energy cluster, existing ammonia infrastructure and local demand centres, however, some of these bunkering ports are also blessed with exceptionally high renewable energy potential, or abundant natural gas resources. This potentially grants them a cost advantage in producing low-carbon ammonia in the future.[168]

166 Port of Rotterdam (2022). OCI Expands Import Terminal for (green) Ammonia. Available at: https://www.portofrotterdam.com/en/news-and-press-releases/oci-expands-import-terminal-for-green-ammonia

167 HCCS & CE Delft (2023). Decarbonising Maritime Bunkering in the Netherlands and the Embargo on Russian oil. Available at: https://hcss.nl/wp-content/uploads/2023/02/Decarbonising-Maritime-Bunkering-Netherlands-and-Embargo-Russian-Oil-HCSS-2023.pdf

168 HCCS & CE Delft (2023). Decarbonising Maritime Bunkering in the Netherlands and the Embargo on Russian oil. Available at: https://hcss.nl/wp-content/uploads/2023/02/Decarbonising-Maritime-Bunkering-Netherlands-and-Embargo-Russian-Oil-HCSS-2023.pdf

On the other hand, ammonia's volumetric energy density is significantly lower than that of conventional bunker fuels. Consequently, it is likely that ships will need to re-fuel more frequently, somewhat reducing the significance of fuel prices for bunkering in comparison to the strategic location of ports. It remains to be seen how the Port of Rotterdam and ports in Northwest Europe in general, will compare with bunkering ports with access to cheap renewables.

5.2 POWER SECTOR

Low-carbon fuels, such as ammonia or hydrogen, currently remain expensive options for electricity generation and are in most cases not ideal for providing baseload power. However, as the price of electricity increases during times of scarcity, they offer an interesting solution for facilitating flexible low-carbon power generation. Nevertheless, there are significant doubts as to whether the entire upstream low-carbon ammonia infrastructure will be developed solely for limited hours of usage in the power sector each year. On the other hand, if a low-carbon ammonia supply chain is established to serve various sectors and applications, such as the fertilizer industry, shipping sector and overseas hydrogen transportation, the power sector could potentially leverage this existing infrastructure.

Low-carbon flexible power generation becomes essential to match supply and demand in an energy system dominated by intermittent renewable energy sources. The applicability and potential value of low-carbon fuels for flexible power supply, differ from country to country, depending upon factors such as the seasonal mismatch, energy system characteristics, the existing power fleet and regional considerations.

For example, Norway is gifted with enormous hydropower potential. It currently generates 92 per cent of their electricity from hydropower (see figure 12). A hydropower plant can start or shutdown on short notice, making them ideal for providing flexible low-carbon electricity. Hydropower provides a cost-effective source of flexible power, and therefore (more expensive) low-carbon fuels are not the most obvious solution to balance supply and demand in Norway. Nevertheless, the Norwegian government has started a project to retrofit an old coal-fired powerplant to run on ammonia in Longyearbyen on the Island of Svalbard to showcase the potential of ammonia as a low-carbon fuel.[169]

The rest of Northwest Europe does not have clean flexible supply readily available at a large enough scale, and will encounter serious balancing challenges as their share

169 Wärtsilä (2021). Full Speed Ahead For Onshore Green Ammonia Production in Norway. Available at: https://www.wartsila.com/insights/article/full-speed-ahead-for-onshore-green-ammonia-production-in-norway

of variable renewable energy grows. It will need to deal with various balancing issues, including a seasonal energy mismatch. To match yearly supply and demand, countries will need some sort of seasonal storage and most likely synthetic fuels. Currently a significant amount of their energy is provided by (flexible) coal and gas-fired powerplants (figure 12). These assets will eventually have to be decommissioned or modified, to adhere to the carbon reduction targets. Some of these powerplants could potentially be retrofitted to (co-)fire low-carbon ammonia or hydrogen, offering the flexibility necessary to successfully integrate variable renewable energy on a large scale.

While ammonia has combustion properties suitable for power generation, it cannot act as a direct replacement. Due to its particular combustion characteristics, discussed in box 2, some modifications to existing coal and gas powerplants are necessary to combust ammonia effectively. Nevertheless, repurposing existing plants can be more cost-effective and easier to realize than building completely new ones. A substantial number of the coal and gas-fired power plants in Northwest Europe is still rather young and they are potentially good candidates to be retrofitted to (co-)fire low-carbon ammonia or hydrogen.

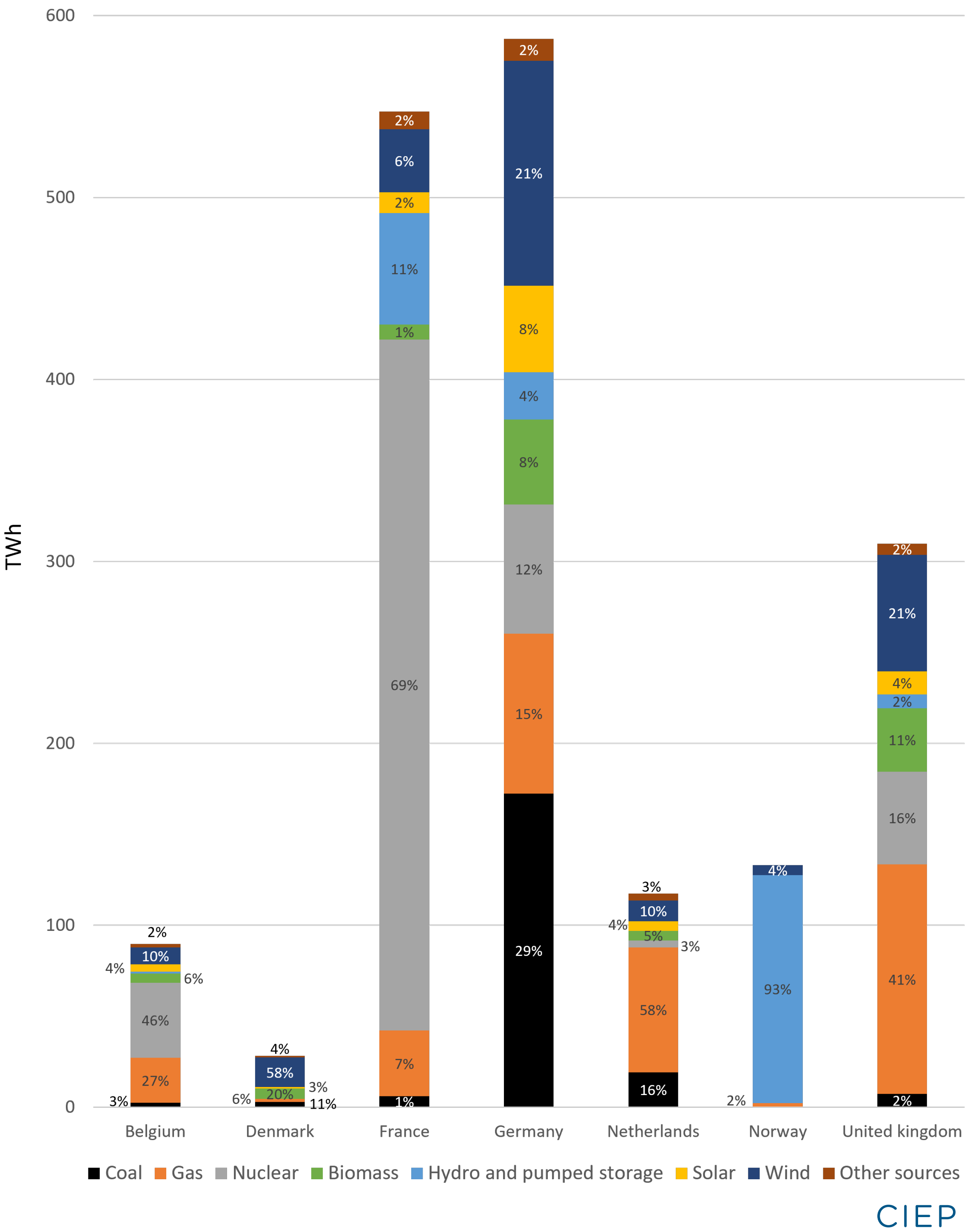

FIGURE 12: ELECTRICITY MIX NORTHWEST EUROPEAN COUNTRIES (2019)

COMPILED BY CIEP, DATA SOURCE: IEA (2020). MONTHLY OECD ELECTRICITY STATISTICS. AVAILABLE AT: HTTPS://IEA.BLOB.CORE.WINDOWS.NET/ASSETS/4979DA92-959D-41B7-9BB5-948FF5CC0224/MES.PDF

5.2.1 (CO-)FIRING AMMONIA IN COAL-FIRED POWERPLANTS

Globally, coal-fired power plants have an average operational lifespan of 46 years, with some exceeding 60 years.[170] As depicted in Figure 13, a significant portion of Northwest Europe's coal-fired capacity, over 20 per cent, has not yet reached its 20th year of operation. Consequently, it is worth exploring the possibility of retrofitting some of these plants to accommodate low-carbon fuel usage.

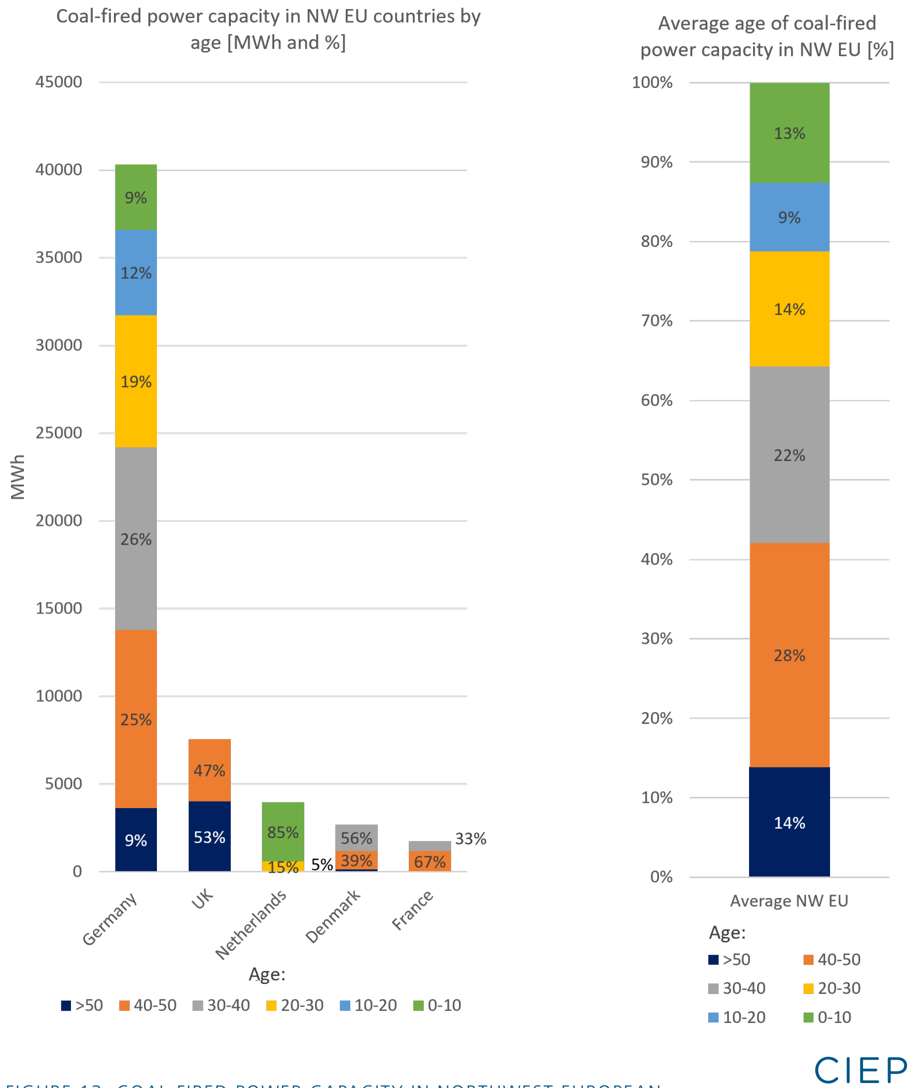

FIGURE 13: COAL-FIRED POWER CAPACITY IN NORTHWEST EUROPEAN COUNTRIES BY AGE

COMPILED BY CIEP, DATA SOURCES: ETSOE (2023), BUNDESNETZEGENTUR (2023), GOV.UK (2023) AND WIKIPEDIA (2023).

170 Cui et al. (2019). Quantifying Operational Lifetimes for Coal Power Plants Under the Paris Goals. Available at: https://www.nature.com/articles/s41467-019-12618-3#:~:text=Lifetime%20limits%20for%20coal%20power,years%20or%20longer32%20(Fig.

A co-firing ratio of up to 20 per cent ammonia (energy value) has been successfully tested in multiple coal-fired prototypes, with only minor adjustments to the power plant.[171] This was achieved without a reduction in power output and no ammonia slip, while meeting NOx emission limits.[172] JERA, a Japanese company, targets a 50-60 per cent ammonia co-firing ratio in a coal-fired powerplant on an industrial scale by 2030, and aims to have a 100 per cent ammonia fuelled plant operating by 2040.[173] The higher the co-firing ratio, the more difficulties have to be overcome regarding combustion, power output and emission management. To deal with these challenges further research into burners is necessary and bigger reconfigurations to existing plant might be needed.

If co-fired with 50 per cent ammonia (energy value), the carbon intensity of coal-fired powerplants can be reduced to the level of gas-fired powerplants.[174] In case a country has both gas-and coal-fired powerplants, it might make more sense to keep the gas-fired plants, and close the coal-fired plants, instead of repurposing them. Besides, while co-firing of low-carbon fuels in coal-fired powerplants can potentially lead to serious carbon reduction, co-firing in gas powerplants is far superior on an energy per carbon basis.

5.2.2 (CO-)FIRING AMMONIA IN GAS-FIRED POWERPLANTS

An average gas-fired power plant typically has a technical life expectancy of around 30 years, but this can be significantly extended through regular maintenance and timely repairs.[175] In Northwest Europe, more than 50 per cent of the gas-fired power capacity is younger than 20 years, of which 10 per cent has not yet entered its 10th year of operation (see figure 14). In Germany, 18 per cent (5.5 GW) of the country's gas-fired power capacity is less than 10 years old. In France, despite having a modest gas-fired power capacity, totalling about 2 GW, almost the entire fleet (97 per cent) has been in operation for less than 10 years.

171 IHI Corporation (2019). New Technology of the Ammonia Co-firing with Pulverized Coal to Reduce the NOx Emission. Available at: https://www.ammoniaenergy.org/wp-content/uploads/2019/08/20191112.1517-AIChE2019_IHI_final.pdf

172 ICEF (2022). Low-Carbon Ammonia Roadmap. Available at: https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

173 Reuters (2023). Japan's JERA Signs Ammonia Supply MOUs With Yara, CF Industries. Available at: https://www.reuters.com/markets/deals/japans-jera-signs-ammonia-supply-mous-with-yara-cf-industries-2023-01-17/

174 IEA (2022). The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector. Available at: https://iea.blob.core.windows.net/assets/01ca16c8-e493-475c-81c4-04ac5d3b9882/Theroleoflow-carbonfuelsinthecleanenergytransitionsofthepowersector.pdf

175 IEA (2022). The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector. Available at: https://iea.blob.core.windows.net/assets/01ca16c8-e493-475c-81c4-04ac5d3b9882/Theroleoflow-carbonfuelsinthecleanenergytransitionsofthepowersector.pdf

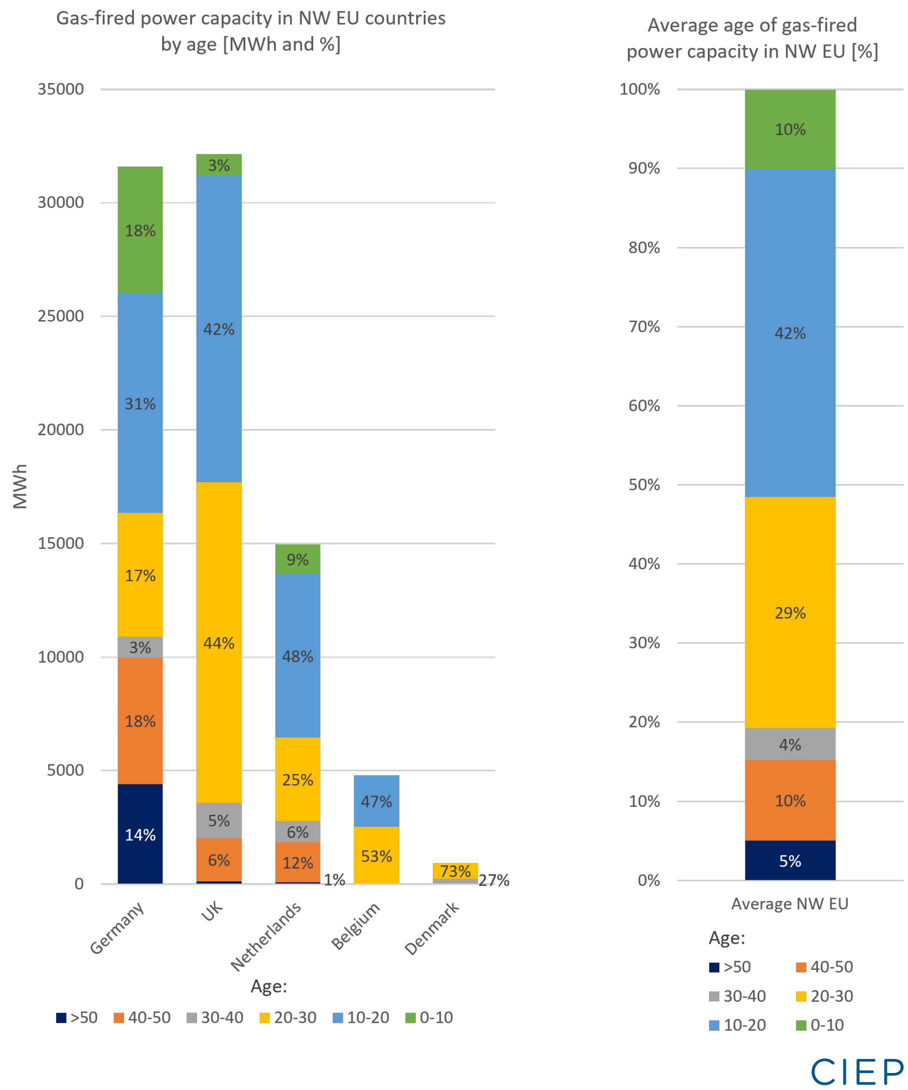

FIGURE 14: GAS-FIRED POWER CAPACITY IN NORTHWEST EUROPEAN COUNTRIES BY AGE

COMPILED BY CIEP, DATA SOURCES: ETSOE (2023), BUNDESNETZAGENTUR (2023), GOV.UK (2023) AND WIKIPEDIA (2023).

Gas turbines could either (co-)fire ammonia, hydrogen or a blend of ammonia and hydrogen. Currently, ammonia (co-)firing in gas turbines has a lower technological readiness than hydrogen (co-)firing. Nevertheless, various turbine manufacturers, predominantly from Asia, have announced plans to develop (industrial-scale) ammonia-fired gas turbines before 2025.

IHI corporation has already demonstrated co-firing of 70 per cent ammonia in an existing 2 MW gas turbine. This was achieved with a relatively low concentration of harmful substances in the exhaust gas, as ammonia slip and N_2O emissions remained below the regulatory limits in Japan. [176] When the ammonia ratio was higher than 70 per cent, N_2O formation became an issue. IHI is currently optimizing its burner design to achieve stable ammonia combustion at higher co-firing ratios, while simultaneously further reducing emissions. The company's goal is to construct a practical application of a gas turbine fully operating on ammonia by 2025.[177] Besides IHI, Mitsubishi Heavy Industries have also announced the development of a commercial 40 MW gas turbine fully running on ammonia, and which will be operational by 2025.[178]

Although it is yet to be tested on a large scale, theoretically, current gas-fired powerplants in Northwest Europe could be retrofitted to co-fire ammonia and natural gas, with relatively simple adjustments. The powerplants would need to be equipped with an ammonia supply system, while the gas turbine itself would only need a new combustor, which is compatible with the combustion characteristics of ammonia (see figure 15).[179] Both coal-fired powerplants and most modern gas-fired powerplants already use ammonia to decrease NOx emissions via Selective Catalytic Reduction (SCR) of exhaust gases. Therefore, some of the necessary infrastructure and expertise for handling ammonia already exist within the industry.[180]

176 IHI (2020). IHI Becomes World's First to Attain 70% Liquid Ammonia Co-Firing Ratio on 2,000-Kilowatt-Class Gas Turbine. Available at: https://www.ihi.co.jp/en/all_news/2020/resources_energy_environment/1197060_2032.html

177 Power (2023). Ammonia Gas Turbine Combustion Has Economic Potential, GE-IHI Study Suggests. Available at: https://www.powermag.com/ammonia-gas-turbine-combustion-has-economic-potential-ge-ihi-study-suggests/

178 Mitsubishi Power (2021). Mitsubishi Power Commences Development of World's First Ammonia-fired 40 MW Class Gas Turbine System – Targets to Expand Lineup of Carbon-free Power Generation Options, with Commercialization Around 20250--. Available at: https://power.mhi.com/news/20210301.html

179 Takeishi & Krewinkel (2023). Advanced Gas Turbine Cooling for the Carbon-Neutral Era. Available at: https://www.mdpi.com/2504-186X/8/3/19

180 IEA (2022). The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector. Available at: https://iea.blob.core.windows.net/assets/01ca16c8-e493-475c-81c4-04ac5d3b9882/Theroleoflow-carbonfuelsinthecleanenergytransitionsofthepowersector.pdf

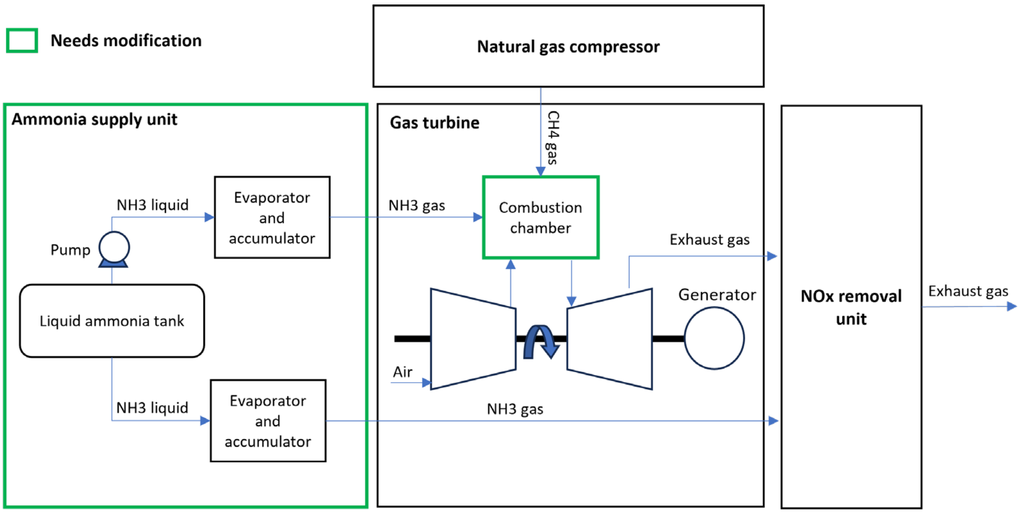

FIGURE 15: SCHEMATIC OVERVIEW OF GAS-FIRED POWERPLANT RETROFITTED FOR AMMONIA CO-FIRING

ADJUSTED BY CIEP, DATA SOURCE: ITO ET AL., (2019). EMISSION CHARACTERISTICS OF A LEAN-PREMIXED AMMONIA/NATURAL-GAS GAS-TURBINE COMBUSTOR AND EFFECT OF SECONDARY AMMONIA INJECTION. AVAILABLE AT: HTTPS://LINK.SPRINGER. COM/CHAPTER/10.1007/978-981-19-4767-4_35#CITEAS

Co-firing a low-carbon fuel such as ammonia, offers a possibility for a step-by-step increase in the use of the fuel over time.[181] Powerplants that are interested in using a low-carbon alternative are not instantly dependent on large volumes, as they can gradually increase the co-firing ratio. Co-firing could decrease the barrier to retrofit existing facilities and start using low-carbon fuels, because there would still be the option to use the conventional fuel, which reduces the otherwise strict necessity for supply security for the new fuel. Powerplants in Northwest Europe near international harbours with ammonia terminals or existing ammonia transportation infrastructure would be good candidates for first retrofits, as only short and therefore inexpensive pipeline connections would be necessary.

Currently, the majority of proposed power plant retrofits in Europe intend to burn hydrogen. Using hydrogen as a fuel makes sense when the hydrogen used is produced within Europe. However, if hydrogen is imported in the form of ammonia, it may be more sensible to burn ammonia directly. The Dutch government, for example,

181 IEA (2022). The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector. Available at: https://iea.blob.core.windows.net/assets/01ca16c8-e493-475c-81c4-04ac5d3b9882/Theroleoflow-carbonfuelsinthecleanenergytransitionsofthepowersector.pdf

intends to prioritize direct electrification over hydrogen production, which may lead to an increased need of ammonia import to fulfil the country's hydrogen demand (see box 3).

Box 3: A potential dilemma between direct electrification or hydrogen production in the Netherlands

On 1 December 2023, the Dutch government published the Nationaal Plan Energiesysteem (NPE; National Plan Energy system).[182] This policy document outlines the government's strategy to guide the country towards achieving a net-zero energy system by 2050. The government anticipates the supply of low-carbon electricity and the required electricity infrastructure to remain limited until 2035. This situation may create a potential conflict between the objective of reaching 8 GW electrolysis capacity by 2032 and the desired expansion of direct electrification for end-users.

The Dutch government has made it clear that during periods of scarcity, priority will be given to direct electrification. Despite the ambitions on domestic hydrogen production, the uncertain availability of low-carbon electricity may limit the expansion of hydrogen production and synthetic fuels in the coming decade. In this scenario, demand for ammonia import in the Netherlands might increase to fill the gap of domestic hydrogen production.

The current emphasis in the EU on (co-)firing hydrogen, rather than (co-)firing ammonia, is partly attributed to the stringent regulations governing the handling and utilization of ammonia, stemming from its toxicity. The EU's Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) regulation governs and oversees the storage, transport and utilization of ammonia. This piece of legislation places responsibility on manufacturers, importers and downstream users of ammonia to identify and manage the risks associated with the substance. Companies must provide evidence that they can manage all potential risks and need special authorization from the EU authorities to use a substance like ammonia. Using ammonia in the power sector entails a significant level of compliance complexity. The stringent approach in REACH regulation, forms a barrier to large scale ammonia use, such as ammonia storage, transportation and power generation in the European Union.[183]

182 Ministry of Economic Affairs and Climate (2023). Nationaal Plan Energiesysteem. Available at: https://www.tweedekamer.nl/kamerstukken/detail?id=2023Z19589&did=2023D47696

183 Erasmus Commodity & Trade Centre (2023). CommodipHy The Commodification of Ammonia and the Role of Rotterdam as a Global Pricing Centre. Available at: https://www.eur.nl/en/erasmusctc/media/2023-03-commodiphy-research-report-march-2023

If the European Union decides that ammonia should play a more significant role in the energy sector, beyond its potential application as a hydrogen carrier for overseas energy transportation, it is essential for regulations to become more lenient and accommodating towards energy-related uses of ammonia. Striking a good balance between promoting chemical safety, environmental protection and the potential benefits of using ammonia as a clean energy carrier, would be fundamental.

6 CHANGING MARKET DYNAMICS

As the world population increases, developing countries use more synthetic fertilizer to grow crops, and ammonia demand for the energy sector starts to take shape, ammonia is likely to play an increasingly important role in the world. According to IRENA, in their 1.5 degrees scenario[184], global ammonia demand could almost increase by a factor four, from 183 Mt in 2020 to 688 Mt in 2050.[185] S&P Global Commodity Insights foresees a threefold expansion of the global ammonia market in the forthcoming decades.[186] In 2050, more than half of the demand is expected to be in non-fertiliser applications, including shipping, hydrogen transportation, power generation and other existing use cases. At the same time the nitrogen fertilizer industry is actively working to reinvent its production process to reduce carbon emissions. The changes in global production and demand are bound to reshape the dynamics of the ammonia market in Northwest Europe.

6.1 SHIFTING BUSINESS LANDSCAPE AND A CHANGING SUPPLY CHAIN

Established fertilizer producers such as Yara, BASF and OCI, which currently dominate the ammonia market in Northwest Europe, are facing a shifting business landscape. Some of the fertilizer producers are well positioned to adapt to the changing market. Yara for example, is currently one of the largest traders and shippers of ammonia globally. Its fleet of ammonia tankers and strategically located production facilities near ports, position them as a potential enabler for ammonia's role as an overseas energy carrier.[187] Moreover, several fertilizer producers are working on bringing ammonia to the market as a marine fuel, collaborating across the value chain with ports and shipping companies. These efforts include the development of ammonia combustion engines and the establishment of a logistical network. Furthermore, it is worth noting that fertilizer producers that require carbon dioxide for the production

184 IRENA's 1.5 degrees scenario presents a pathway to achieve the 1.5 degrees target by 2050, as set in the Paris Agreement.
185 IRENA (2022). Innovation Outlook Renewable Ammonia. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf
186 S&P Global (2023). Ammonia Market to Triple by 2050 with Nearly All Growth Coming from Low-Carbon Supply. Available at: https://press.spglobal.com/2023-07-11-Ammonia-Market-to-Triple-by-2050-with-Nearly-All-Growth-Coming-from-Low-Carbon-Supply
187 Yara (2022). Yara International and Azane Fuel Solutions to Launch World's First Carbon-Free Bunkering Network; Delivering Green Ammonia Fuel to the Shipping Industry. Available at: https://www.yara.com/news-and-media/news/archive/news-2022/yara-international-and-azane-fuel-solutions-to-launch-worlds-first-carbon-free-bunkering-network-delivering-green-ammonia-fuel-to-the-shipping-industry/

process, currently employ carbon capture techniques within their ammonia production processes. This expertise can potentially be leveraged for future carbon capture and storage technology in other uses. Lastly, producing hydrogen from electrolysis is not a new endeavour for the fertilizer industry. Until 1991, for instance, Yara operated a 155 MW electrolyser for hydrogen production in Glomfjord, Norway. This prior experience has equipped some of the players in the industry with valuable knowledge and expertise regarding electrolysis.[188,189] In terms of production, certain producers opt to diversify their feedstock options (see box 4).

Box 4: Yara Sluiskil is diversifying its feedstock source.

Yara Sluiskil in the Netherlands is committed to diversify its feedstock sources to increase the resilience of their business and reduce future risks. They intend to invest in CCS to produce low-carbon ammonia at their current ammonia plant. Additionally, they have import terminals in place for the direct import of ammonia, and aim to establish a large-scale connection to the hydrogen backbone.

The CCS project ensures that enough low-carbon hydrogen can be produced, even if the hydrogen backbone is unable to provide the necessary volumes. This diversified feedstock approach enables Yara Sluiskil to act as a buffer and a flexible consumer with regard to the hydrogen backbone. [190]

In the coming decade, ammonia producers may face increasing competition from new entrants joining the market, despite their pole position. Various new low-carbon ammonia plants are being announced worldwide, developed by consortia including energy firms and industrial gas companies. Energy companies such as Shell, Saudi Aramco and others, intend to leverage their capabilities to produce the required energy for the production of low-carbon ammonia. Likewise, industrial gas and liquid fuel companies, such as Air Products, Air Liquide and Linde, with their expertise in hydrogen production, purification, and compression, are well-positioned to adapt their

188 Yara (2022). Yara International and Azane Fuel Solutions to Launch World's First Carbon-Free Bunkering Network; Delivering Green Ammonia Fuel to the Shipping Industry. Available at: https://www.yara.com/news-and-media/news/archive/news-2022/yara-international-and-azane-fuel-solutions-to-launch-worlds-first-carbon-free-bunkering-network-delivering-green-ammonia-fuel-to-the-shipping-industry/

189 Yara is used as an example several times, because they have extensive, publicly available documentation of their position and strategy in the shifting business landscape

190 Yara (2023). Yara Wil in 2030 1,5 Megaton Minder CO_2 Uitstoten. Available at: https://www.yara.nl/nieuws-en-evenementen/nieuws/2023/yara-wil-in-2030-15-megaton-minder-co2-uitstoten/

operations and diversify into the emerging low-carbon ammonia market. Storage companies like Vopak, Vitol and Koole, intend to construct new facilities or expand on their existing ammonia infrastructure to serve the energy sector by providing storage solutions for ammonia, facilitating bunkering services and potentially enabling the conversion of ammonia into hydrogen.

Newly announced low-carbon ammonia projects are concentrated in renewable energy abundant regions like the Middle East, Australia, various parts of Africa and the Americas, with the aim of exporting ammonia to demand centres around the world. The current ammonia market is predominantly characterized by captive use, meaning that ammonia is utilized on-site for the production of fertilizers or other products. However, the multitude of newly announced ammonia export and import projects suggests a potential shift towards more globally traded markets in the coming decade. S&P Global Commodity Insights even anticipates a tenfold increase in global ammonia trade, driven by new demand for low-carbon ammonia within shipping and power sectors.[191]

Given the elevated gas prices and the growing interest in renewable energy-based ammonia production, it is likely that Northwest Europe will progressively transition from domestic ammonia production, used to manufacture fertilizers, to an increased reliance on ammonia imports to satisfy fertilizer and energy demand. This development challenges the Northwest European nitrogen fertilizer producers, who will have to reinvent their business model to stay competitive. The specific impact on producers in Northwest Europe depends on the particular attributes of their operations and their location.

Coastal nitrogen fertilizer producers that have access to terminals which connect them to the global ammonia market, can potentially increase their import capacity and shift their focus to the production of fertilizer from imported ammonia. Conversely, producers that are landlocked and do not have access to an ammonia import terminal, might struggle to compete with those that do as long as no ammonia pipeline connection is available for inland fertilizer plants. Whether inland producers are protected from coastal competition in this situation, largely depends on the price disparity between imported ammonia and domestically produced ammonia, in comparison to the additional transportation costs of fertilizers transported from coastal

191 S&P Global (2023). Ammonia Market to Triple by 2050 with Nearly All Growth Coming from Low-Carbon Supply. Available at: https://press.spglobal.com/2023-07-11-Ammonia-Market-to-Triple-by-2050-with-Nearly-All-Growth-Coming-from-Low-Carbon-Supply

producers to the inland markets.[192] This development has similarities with the inland coal and steel industries a few decades ago, when Japan gained a competitive edge with its coastal plants. Only plants with captive inland supply and demand, where the transportation costs or lack of infrastructure protected them from the new competition, survived. Refineries have experienced a similar development.[193]

Worldwide, the carbon used in fertilizer production is currently exclusively derived from the ammonia production process. If new ammonia production shifts largely to third countries, the organization of the fertilizer supply chain in Northwest Europe will be impacted. For instance, urea containing fertilizers, which are the most common types of fertilizer, rely on the synthesis of ammonia and carbon dioxide.[194] The same applies to AdBlue, which is essentially a mixture of water and urea used to reduce NOx emissions in diesel engines. [195] Typically, the carbon dioxide necessary for both products is a by-product from the ammonia production process. When ammonia is no longer domestically produced, or produced via electrolysis, either a new carbon source must be found, or these products can no longer be manufactured at those facilities. This also applies to the supply of carbon dioxide from the fertiliser industry to the food and medical industry and horticulture, encompassing applications including the production of carbonated beverages, beer, dry ice for laboratories, and various other uses. Although carbon-free fertilizers can replace a portion of the carbon containing fertilizers, for some (wet) crops the use of urea fertilizers remains agronomically necessary.[196] The growth of low carbon ammonia imports replacing domestic production, should therefore go hand in hand with the ability to tap into a carbon infrastructure carrying captured carbon dioxide from other facilities, or sustainable carbon sources. It is plausible that producing carbon-based fertilizers in Northwest Europe may not be financially viable if the carbon source is no longer freely available from the ammonia production process. European fertilizer producers might focus on ammonium nitrate and its derivatives instead (see figure 16).[197]

192 Based on conversations with industry expert, September 2023

193 Clingendael International Energy Programme (2017). The European Refining Sector: A Diversity of Markets. Available at: https://www.clingendaelenergy.com/inc/upload/files/CIEP_paper_2017-02_web.pdf

194 IEA (2021). Ammonia Technology Roadmap. Available at: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

195 Palamatic. 6 Things to Know About Adblue. Available at: https://www.palamaticprocess.com/blog/six-things-to-know-about-adblue-def-aus32- arla32#:~:text=AdBlue%20is%20composed%20of%2032.5%25%20urea%20and%2067.5%25%20demineralized%20water. last accessed on 11-10-2023

196 Yara (2023). Yara Wil in 2030 1,5 Megaton Minder CO2 Uitstoten. Available at: https://www.yara.nl/nieuws-en-evenementen/nieuws/2023/yara-wil-in-2030-15-megaton-minder-co2-uitstoten/

197 Based on conversations with industry expert, September 2023

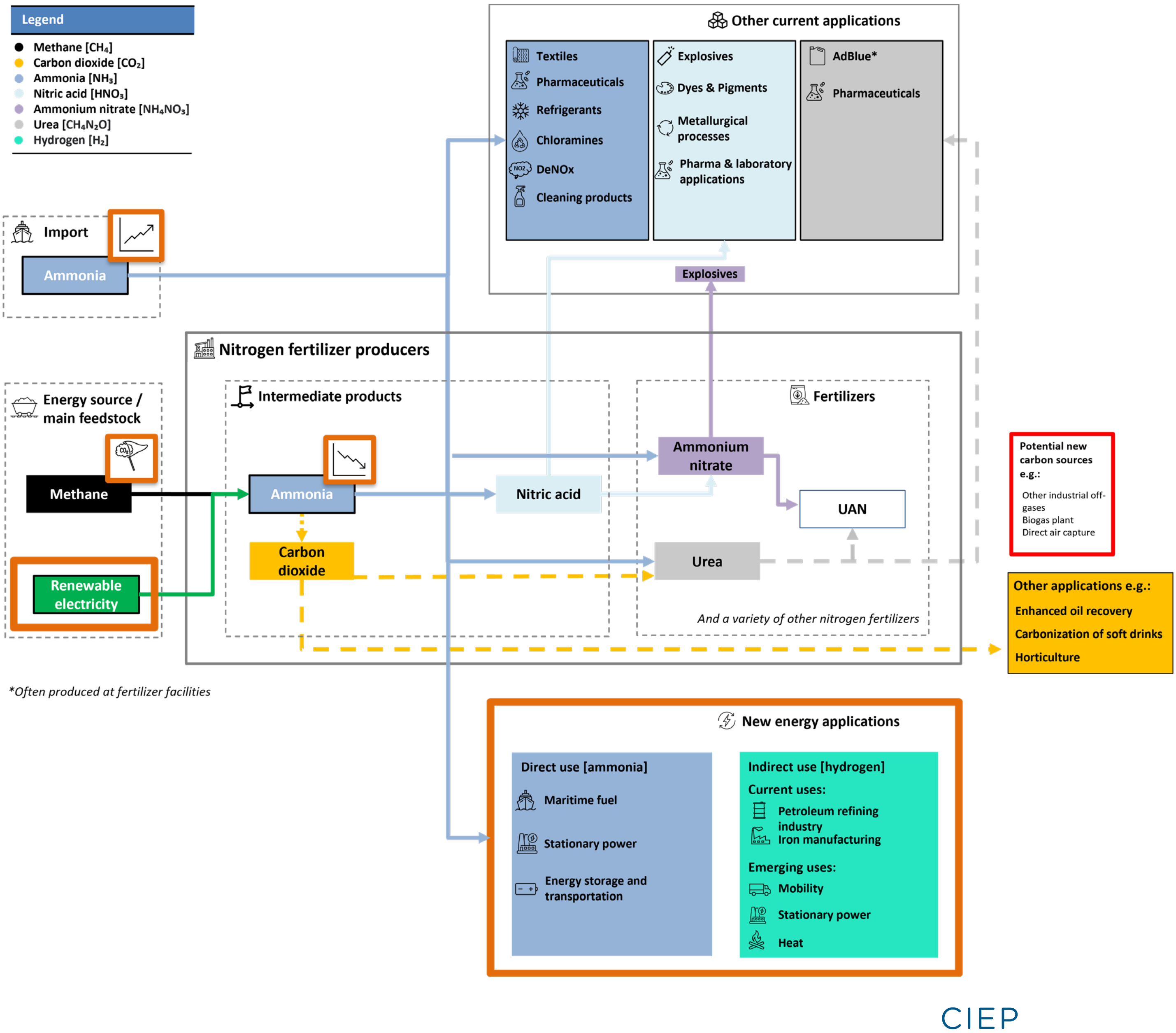

FIGURE 16: POTENTIAL FUTURE AMMONIA SUPPLY CHAIN IN NORTHWEST EUROPE

Figure 16 illustrates potential changes in the ammonia supply chain in Northwest Europe (denoted by the orange boxes and dashed arrows). Anticipated changes on the supply side include an increase in imports, potentially leading to a decrease in conventional domestic production. Some producers may adopt carbon capture and storage (CCS) technology or shift to renewable electricity-based production to align with carbon reduction targets. A decline in conventional domestic production implies a reduced availability of carbon dioxide (as indicated by the dashed arrows). This shift necessitates finding alternative sources of carbon for fertilizers and other applications that currently utilize carbon dioxide waste gases from the ammonia production process (red box). Alternatively, production may relocate to other regions. On the demand side, new applications may emerge in the energy sector, either directly in the form of ammonia or indirectly as hydrogen. These developments may reshape the business landscape.

Apart from a shift in ammonia production and the emphasis on using imported ammonia to produce fertilizer, it is conceivable that a growing portion of fertilizer production may relocate, to be in proximity to the new ammonia production sites in third countries. Since most of the value is added during the hydrogen and ammonia production phases, expanding the manufacturing process to also encompass the remaining production steps, becomes a relatively small undertaking, as the most significant obstacle has already been overcome.

Depending on their location, nitrogen fertilizer producers in Northwest Europe generally primarily serve their domestic markets and benefit from import tariffs, which offer a certain degree of protection from third country competition. This enables them to capitalize on their close proximity to their clients. To address fertilizer shortages, the European Union temporarily suspended the import tariffs on urea and ammonia from all origins, with the exception of imports from Russia and Belarus, between December 2022 and June 2023.[198] As of 17 June 2023, these tariffs have been reinstated at their original rates of 5.5 per cent for ammonia imports and 6.5 per cent for urea imports.[199] In contrast to producers catering for domestic markets, producers that focus on international markets, lack this protective trade policy and may have to adjust to the new circumstances. The coastal facilities and pipeline connected facilities may either redirect their products deeper into the European market, or focus on expanding their trade platform and cater increasingly for the energy sector, or pursue both. The ultimate restructuring and survival of the sector will largely hinge on the geographic location of the production facilities and the availability of adequate infrastructure, but also on the regulatory framework.

The RED III regulation of the EU requires each member state to ensure that 42 per cent of total hydrogen use for final energy and non-energy purposes in the industry, is from Renewable Fuels from Non-Biological Origin (RFNBO) by 2030. This responsibility will largely rest on the shoulders of the EU fertilizer sector, being the largest hydrogen consumer in the region. Meeting this target will be manageable for countries with limited hydrogen usage, while it may prove challenging for member states with the highest consumption of hydrogen, such as Germany and the Netherlands. Furthermore, each country is free to choose how they translate the requirements into their legislation. Some member states may choose a more business-friendly approach, potentially offering advantages to certain companies, while others may adopt stricter

198 CZAPP (2023). EU Suspends Fertiliser Import Tariffs For 6 Months. Available at: https://www.czapp.com/analyst-insights/eu-suspends-fertiliser-import-tariffs-for-6-months/

199 Argus (2023). EU Import Duties Take Effect Again on Ammonia, Urea. Available at: https://www.argusmedia.com/en/news/2460827-eu-import-duties-take-effect-again-on-ammonia-urea

measures, potentially resulting in disadvantages for companies operating in their country. Lastly, having access to hydrogen generated through electrolysis is crucial, as hydrogen produced from natural gas with CCS is not considered an RFNBO and does not contribute to meeting the target. However, it is highly uncertain whether the necessary volumes will be available in the European Union in 2030. If not, more ammonia will need to be imported. Yet, by 2030, the availability of sufficient volumes of hydrogen produced via electrolysis in other regions also remains uncertain. In the absence of such availability, it will not be possible to achieve the RFNBO targets and fertilizer production will shift to other regions. See figure 16 for a depiction of the changing supply chain.

6.2 INCREASED INTERCONNECTEDNESS OF FOOD AND ENERGY MARKETS

The growth of the ammonia market and the further internationalization could have multiple advantages. First, a bigger market gives companies more possibilities to reap benefits from economies of scale, which could lead to overall cost reductions. Second, an expansion of the ammonia commodity market is likely to stimulate innovation, as it incentivizes investment in research and development to setup more efficient production processes, improve existing products and develop new applications for ammonia. Third, a larger ammonia market enables sectors with relatively little demand, who probably otherwise could not afford to set-up a supply chain, to piggyback on the expanded ammonia supply chain. An example could be the power sector, which is looking into the use of ammonia for flexible power generation.

At the same time, new applications of ammonia in the energy sector could further intensify the already existing interdependence between world food and energy markets. Much like the adoption of first-generation biobased fuels constituted a problem for food security, the expansion of ammonia trade into the energy sector could be a complicating factor for food security, as it competes head-on with the agricultural sector. As Northwest Europe and other high-income regions start to use ammonia in the energy sector, it is important to give some serious thought to the potential effects on global ammonia markets in relation to food security.

Most of the ammonia produced today is 'captive' ammonia, produced on-site, where it is used as a feedstock for nitrogen fertilizer. Only about 10 per cent of global production is traded. Current global ammonia trade is dominated by a few large suppliers. Their considerable market share enables them to exert a certain level of influence over the global price of ammonia through their production decisions and pricing strategies. Because of market concentration, economies of scale and capital requirements, the barriers to enter this market are relatively high.

In the vast majority of cases, current ammonia trade takes place by means of long-term contracts (about 97 per cent of total trade).[200] These contracts can provide price and supply stability, but they can also limit the ability of smaller buyers to negotiate favourable prices. Individually, smaller buyers do not have significant impact on market demand, and therefore have limited bargaining power. Furthermore, due to a lack of resources, smaller buyers often have limited access to information about the market and suppliers. This makes it more difficult for them to make informed decisions and negotiate favourable prices.

The increasing use of ammonia in the energy sector has the potential to considerably impact the organization of the international ammonia market, changing the structure, pricing and bargaining power of the various groups of buyers and sellers. New suppliers may enter the market to take advantage of the growing demand. This could increase competition and potentially reduce some of the market power of existing suppliers. The new buyers from the energy sector might be larger and more financially powerful compared to the existing buyers from the fertilizer sector. These firms may be able to negotiate more favourable terms and prices with ammonia suppliers, particularly if they are able to commit to large, long-term purchases, which are needed for the investment decision in new projects. In the more distant future, smaller fertilizer buyers may be pushed out of the high-volume, long-term ammonia trade business and redirected to trade with mid-streamers or to local commodity markets as they emerge. If the ammonia production based on solar and wind takes off, it will shake up the current, more localised fertilizer sector in many countries, including that in Northwest Europe.

Historically, ammonia has been a strategic asset for food production. In future, ammonia may also become a strategic asset in the energy sector. Under pressure from ambitious government targets and policies, the introduction and expansion phase of ammonia for the energy sector may create a period of uncertainty and instability for the current mature fertilizer business, shaking up business models, changing the distance to the market and challenging the uneven ability of countries worldwide to adapt to these new market dynamics. The pull from energy markets can become very strong and leave less agile market players unable to cope in this new market structure. At the same time, captive markets may be left largely untouched in the early stages of development, either due to a lack of infrastructure to import the new flows, or trade policies protecting domestic producers for the time being. What is

200 Erasmus Commodity & Trade Centre (2023). CommodipHy The Commodification of Ammonia and the Role of Rotterdam as a Global Pricing Centre. Available at: https://www.eur.nl/en/erasmusctc/media/2023-03-commodiphy-research-report-march-2023

clear, is that the ammonia sector in many countries is confronted with large impending changes. They can learn from earlier vast changes in the market structure of other sectors and prepare for this new development.

The position of the Northwest European fertilizer industry will potentially become more vulnerable. In the past, the lion's share of the Northwest European fertilizer demand was serviced by domestically produced products. In 2022, a considerable portion of this production was curtailed because of high natural gas prices, and as a result, import of ammonia and ammonia-based fertilizers drastically increased. Perhaps this was a first sign of the larger changes still in store for the industry, and of the need to adapt to the new market circumstances and prepare for a structural adjustment in international flows of ammonia.

CONCLUSION

For more than a century ammonia has been valued for its nitrogen element, serving as an essential feedstock for nitrogen fertilizer production. Recently, due to the energy transition, ammonia is also gaining recognition for its hydrogen element, emerging as a promising energy carrier suitable for overseas transportation or direct utilization as a fuel. While using ammonia in the energy sector presents serious challenges due to its toxicity, decades of experience have taught us how to safely produce, transport, store and utilize it.

This paper explored the evolving role of ammonia in Northwest Europe and how the existing ammonia infrastructure, knowledge and expertise, can be harnessed to facilitate ammonia's integration as an energy carrier and low-carbon fuel in the region.

Ammonia is seen as a promising candidate carrier for low-carbon energy import, to contribute to Northwest Europe's future energy needs. The European Union is currently the biggest ammonia importer in the world, and therefore it already has considerable ammonia import capacity in place. Nevertheless, the capacity will need to increase significantly for ammonia to play an important role in overseas energy import in Northwest Europe. Expanding existing infrastructure where possible is a good starting point for a relatively easy, quick and cost-effective increase of capacity. Projects constructing entirely new terminals will have to find ways to deal with complex permitting processes, safety issues, public acceptance and the already existing space constraints in key ports in Northwest Europe.

In the Northwest European energy conversation, there is a common assumption that ammonia should primarily serve as a hydrogen carrier for overseas energy transportation, with conversion occurring near the receiving port. Nevertheless, there are compelling reasons why conversion further in the supply chain, or skipping conversion altogether, should be considered. These encompass supply security for hinterland countries, port space limitations, ammonia's more favourable energy density, and energy savings that come with bypassing conversion.

In case ammonia is used further on in the supply chain, pipelines are considered the safest and most cost-effective candidate for inland transportation. While current European ammonia pipelines are typically short, covering distances of only 1-12 km, there is extensive global experience with approximately 8,000 km of operational ammonia pipelines. The construction of ammonia pipelines, either by repurposing old gas infrastructure or building completely new pipelines, could increase the resilience of the future energy system in the region, by adding diversity to the energy carriers.

Ammonia could play an important role in meeting the future energy storage needs in Northwest Europe. Ammonia can be stored both aboveground and underground. Underground storage of ammonia has rarely been done and requires further research to fully grasp the related challenges and risks. On the other hand, aboveground ammonia storage is a widely adopted practice around the world. Refrigerated aboveground ammonia storage tanks store energy in the same order of magnitude as hydrogen-filled salt caverns, and they benefit from a substantially greater wealth of accumulated experience. Therefore, ammonia storage tanks present a promising supplementary solution to the more frequently discussed hydrogen salt caverns.

While ammonia is not the primary fuel of choice for most applications, it is considered a promising low-carbon bunker fuel for ships and a fuel source for power plants to supply flexible electricity. The Amsterdam-Rotterdam-Antwerp (ARA) region is well-positioned for a role in the global ammonia bunker market, due to its strategic location within the global trading network, substantial oil cluster, existing ammonia infrastructure and nearby demand centres. Nonetheless, it is uncertain how ports in Northwest Europe will measure up in the future ammonia bunkering market, when compared to bunkering ports with access to cheap renewable energy. Many coal and gas-fired power plants in Northwest Europe are relatively young and potentially suitable for retrofitting to (co-)fire low-carbon ammonia or hydrogen. While most retrofit projects in Europe are currently focused on hydrogen, if hydrogen is imported as ammonia, rather than being produced domestically, burning ammonia directly might be more efficient.

At present, strict regulations in the European Union pose a barrier to widespread ammonia use in the energy sector. Balancing regulatory measures to ensure chemical safety and environmental protection, while still being able to harness the advantages of using the molecule, is crucial for ammonia to play a substantial role in the energy sector.

The changes in global ammonia production processes, propelled by the efforts to reduce carbon emissions and new demand for ammonia from the energy sector, can potentially reshape the Northwest European ammonia market. Driven by elevated gas prices and the growing interest in ammonia made from renewable energy, Northwest

Europe is expected to gradually shift from domestic ammonia production to increasingly rely on ammonia imports. This transformation places considerable pressure on fertilizer producers in Northwest Europe to reinvent themselves to stay competitive. The industry's evolution and its ability to endure will predominantly depend on the geographical location of production facilities, the accessibility of essential infrastructure, and the regulatory environment.

As ammonia starts to be used in the energy sector, the interconnection between global food and energy markets will become more pronounced. Demand for ammonia in the energy sector could compete directly with the agricultural sector's need for it. With Northwest Europe and other high-income regions adopting ammonia for their energy needs, it is important to carefully assess its potential effect on both worldwide ammonia markets and food security.

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