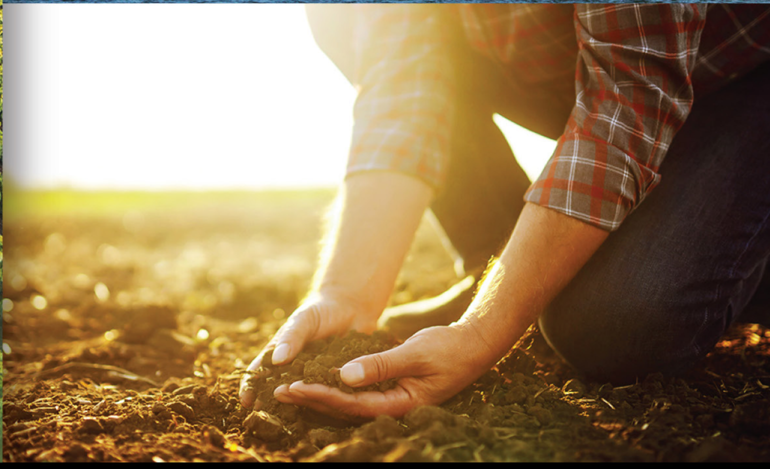
Low-Carbon Ammonia Roadmap

ICEF

Innovation for Cool Earth Forum



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CONTENTS

PREFACE

Modern society depends on ammonia (NH_3). The chemical compound plays a central role in modern agriculture, delivering nitrogen essential for soil fertility. Ammonia is also a key feedstock in plastics, rubber and other products.

Current methods of producing ammonia result in significant carbon dioxide (CO_2) emissions—almost 2% of the global total. Low-carbon production methods can dramatically reduce these emissions. Low-carbon production of ammonia also creates a fuel with very low life-cycle greenhouse emissions and the potential to help decarbonize a range of sectors.

This roadmap explores a number of topics related to low-carbon ammonia. The roadmap examines the global ammonia industry today, low-carbon production options, infrastructure needs, potential uses for low-carbon ammonia, safety and local environmental issues, R&D needs and policy options. The roadmap finds that low-carbon ammonia could produce significant greenhouse gas reductions in key sectors this decade and deep reductions in some sectors by 2050.

This roadmap builds on the body of literature produced annually in connection with the ICEF conference. Previous roadmaps have addressed:

- Carbon Mineralization (2021)
- Biomass Carbon Removal and Storage (BiCRS) (2020)
- Industrial Heat Decarbonization (2019)
- Direct Air Capture (2018)
- Carbon Dioxide Utilization (2017 and 2016)
- Energy Storage (2017)
- Zero Energy Buildings (2016)
- Solar and Storage (2015)

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The ICEF Innovation Roadmap Project aims to contribute to the global dialogue about solutions to the challenge of climate change. We welcome your thoughts, reactions and suggestions.

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EXECUTIVE SUMMARY

Chapter 1: Introduction

Ammonia (NH_3) is one of the building blocks of modern society—a feedstock for fertilizers, plastics, rubber, fibers, explosives and other products. Ammonia is a gas at room temperature and liquid with modest pressure or refrigeration, which makes it easy to use and store.

Almost 2% of global carbon dioxide (CO_2) emissions come from the production of ammonia. Most of these emissions come from separating hydrogen from natural gas or coal. These emissions could be reduced or eliminated with low-carbon production methods. The leading options are (1) capturing the CO_2 emitted in these processes and storing it underground or in long-lived products and (2) separating hydrogen from water using electricity made from zero-carbon processes.

In this roadmap, we use the term "low-carbon ammonia" to refer to ammonia made with low-carbon production methods. Low-carbon ammonia can contribute to decarbonization in two ways. First, low-carbon production methods can reduce the CO_2 emissions that currently come from ammonia production. Second, low-carbon ammonia can be used as a replacement for carbon-intensive fuels in shipping, heavy industry, power generation and other sectors.

Many countries, including Chile, Saudi Arabia and Australia, are investing in low-carbon production methods for ammonia. This has implications for agriculture, fuels, the natural environment and geopolitics.

Chapter 2: The Ammonia Industry: Past and Present

The development of a method to synthesize ammonia by German chemists Fritz Haber and Carl Bosch was one of the most important technological advances of the 20th century. By one estimate, half of the current global population could not be fed without synthetic ammonia.

Last year, almost 180 million tons (Mt) of ammonia were produced globally (72% from natural gas and 26% from coal). The largest ammonia producer is China (approximately 30% of global production), followed by Russia, the European Union, the United States, India and the Middle East. Approximately 10% of global ammonia is traded internationally, with more than 100 ports and nearly 200 ships currently capable of handling bulk ammonia. Ammonia is also transported by pipeline (primarily in the United States and Russia/Ukraine), rail and truck.

The International Energy Agency's Sustainable Development Scenario (SDS) envisions that ammonia demand in 2050 will total 230 Mt for fertilizer and 125 Mt for novel uses—primarily in marine fuel and power generation.

Chapter 3: Production of Low-Carbon Ammonia

Today, almost all ammonia is made with hydrogen from fossil fuels (72% from natural gas and 26% from coal). Hydrogen production is responsible for roughly 90% of the CO_2 emissions from the current ammonia synthesis industry.

Blue ammonia adds carbon capture to conventional hydrogen production from fossil fuels. Adding carbon capture to steam methane reforming (SMR) is relatively inexpensive for approximately two-thirds of the total CO_2 emissions (which are already separated during production) but is significantly more expensive for the remaining CO_2 emissions. Modern SMR systems with a smaller primary reformer or oxygen-blown autothermal reformers (ATRs) may bring these costs down substantially. Any upstream fugitive methane emissions increase total life-cycle emissions for these systems, and access to CO_2 transportation and storage is a key barrier.

Green ammonia uses electrolysis—electric current flowing through water—to produce hydrogen. The carbon intensity depends primarily on the electricity source. Zero-carbon electricity sources can help produce very low-carbon ammonia, but high-carbon electricity sources can increase total life-cycle CO_2 emissions as compared to conventional SMR-based hydrogen production. Limited global manufacturing capacity for electrolyzers is a key barrier.

Ammonia can also be produced from bio-hydrogen (hydrogen produced from biomass). Biomass feedstocks include agricultural waste, forestry waste, black liquor from paper production, municipal solid waste, dedicated energy crops, and micro- and macro-algae.

Chapter 4: Ammonia Infrastructure

Ammonia requires special purpose infrastructure, including pipelines, tanks and facilities for maritime bunkering. At present, nearly 8000 kilometers of ammonia pipeline run worldwide, along with 38 export and 88 receiving terminals. These facilities provide an excellent basis for understanding the likely costs and performance of additional ammonia infrastructure, which will be critically needed as the ammonia industry grows. The need for innovation is limited; additional ammonia infrastructure principally depends on finance, economics and policy.

Pipeline transport of liquid ammonia is a safe, low risk and cost-effective mode of transporting ammonia between locations. Almost all ammonia is stored in tanks. There are three main types—pressurized, low-temperature and semi-refrigerated.

Port facilities will serve essential functions for the scale-up of low-carbon ammonia. For maritime fuel application, bunkering is a key prerequisite for deployment. Liquified natural gas (LNG) infrastructure—in particular LNG receiving terminals and storage facilities—can be converted to use for ammonia.

Human capital, permitting and environmental justice concerns are important in new ammonia infrastructure. Without significant new infrastructure, ammonia cannot reach its full potential in contributing to deep decarbonization.

Chapter 5: Uses

Low carbon ammonia can be used in many sectors to reduce carbon emissions. The first, most important use is as a drop-in replacement for conventional ammonia in existing applications, including agricultural fertilizer and chemical feedstocks. Ammonia can also be used for marine shipping, power generation, heavy industry, road transport, aviation fuel and refrigeration. The potential market for low-carbon ammonia in 2050 is several times current global ammonia production.

For ammonia to be more widely used in power engines and turbines, a better understanding of ammonia's combustion characteristics is required. In the short-term, co-combustion of ammonia mixed with other fuels (e.g., coal/natural gas) is the most technically mature with least risk. More advances are required for high-blending ratios or pure ammonia combustion applications.

Low-carbon ammonia faces competition with other decarbonization strategies. The most promising new uses for low-carbon ammonia are in marine shipping fuel and power generation. Developing novel uses for low-carbon ammonia will require investment in R&D.

Chapter 6: Local Environmental and Safety Risks

The widespread use of ammonia has led to a mature understanding of the safe handling of ammonia transportation and distribution and to appropriate risk management methods within the existing application areas. Supplying low-carbon ammonia for existing applications will not substantially alter the human health and environmental risks. If low-carbon ammonia is adopted into new application areas, such as power generation and maritime fuels, new risks will require careful attention and management.

The primary health and environmental concerns associated with ammonia are its flammability, acute toxicity to humans at high concentrations, contribution to the formation of fine-particle pollution in the atmosphere, and negative impacts on aquatic ecosystems.

Because ammonia has a low odor-detection threshold, a slow leak will easily be detected before dangerous concentrations are reached. However, a large uncontrolled release poses serious human health risks, and safety measures must be in place to minimize the likelihood of such events.

Slow ammonia leaks and other limited releases are less of a concern for worker safety, but released ammonia can react with other pollutants to form harmful particles in the atmosphere. Ammonia can also deposit in water bodies and contribute to eutrophication, causing harmful algal blooms that consume dissolved oxygen, leading to fish kills. The fate and transport of ammonia in the environment is complex and requires further research to develop an improved understanding.

Chapter 7: Research and Development (R&D)

The research and development (R&D) needs for safely and sustainably scaling up low-carbon ammonia are focused in four major areas:

1. Developing deep integration schemes with renewable energy, particularly solar, wind and biomass, which tend to occur in areas far from ammonia markets.
2. Increasing life-cycle energy efficiency and reducing capital intensity.
3. Ensuring that we understand and can manage any safety and environmental risks.
4. Ensuring that energy and climate impacts of ammonia use are well understood.

Chapter 8: Policy

Policy support will be essential to substantially increase production and use of low-carbon ammonia. Key policies for consideration include demand-side policies (such as carbon pricing, low-carbon fuel standards and power plant emissions standards), supply-side policies (such as investment in R&D and government loan guarantees), regulatory controls (such as health and safety regulations) and enabling policies (such as accelerated permitting and public-private partnerships).

One simple step governments could take is to highlight low-carbon ammonia more centrally in their national hydrogen strategies. Guidelines on life-cycle assessments of greenhouse gas emissions from ammonia fuels are also important. (The International Maritime Organization—where work is already underway—is an important venue for developing such guidelines.) In many governments, inter-ministerial coordination will help with policy development.

Governments should promote the optimal use of low-carbon ammonia within a broad portfolio of decarbonization strategies—not simply strive for the maximum use of low-carbon ammonia everywhere.

Chapter 9: Findings and Recommendations

FINDINGS

Finding 1: Low-carbon ammonia can produce significant greenhouse gas reductions in key sectors this decade and deep reductions in some sectors by 2050.

Finding 2: There are no technical barriers to producing low-carbon ammonia in large volume before 2030.

Finding 3: Cost is the chief barrier to deployment.

Finding 4: Safety and environmental risks from ammonia scale-up will require attention and management.

Finding 5: Global low-carbon ammonia trade will require infrastructure investment and more ships.

Finding 6: Before low-carbon ammonia can deliver substantial abatement of greenhouse gas emissions, more work on applications is a priority.

Finding 7: Very few countries have policies that support low-carbon ammonia today.

Finding 8: Low-carbon ammonia trade could have geopolitical implications.

RECOMMENDATIONS

Recommendation 1: *Governments should support investment in new low-carbon ammonia supplies.*

Recommendation 2: *Governments should launch a set of public-private partnerships to plan, develop and finance key infrastructure for low-carbon ammonia production, transportation and use.*

Recommendation 3: *Governments and industries should invest heavily in innovations for use of low-carbon ammonia.*

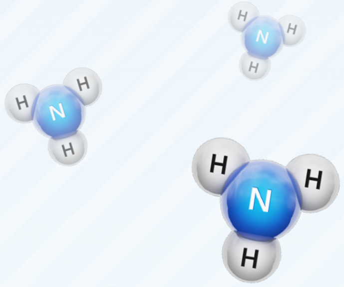
Recommendation 4: *Government regulators should take steps to prevent safety and environmental problems in the ammonia trade.*

Recommendation 5: *Key governments should institute supporting policies to drive wider use of ammonia as a fuel and feedstock.*

Recommendation 6: *Policy incentives for low-carbon ammonia should be based on carbon intensity rather than ammonia "color" (such as green or blue).*

Recommendation 7: *Business and governments should support local, national and international data-gathering and data-sharing.*

Recommendation 8: *Business, governments and training institutions should focus on human capital development.*



Chapter 1

INTRODUCTION

Ammonia (NH_3) is one of the building blocks of modern society—an essential feedstock for fertilizers on which modern agriculture depends. (By one estimate, only half of the current global population could be fed without ammonia.) Ammonia is also used in manufacturing plastics, rubber, fibers and explosives.

Almost 2% of global carbon dioxide (CO_2) emissions come from the production of ammonia. Most of these emissions come from separating hydrogen from natural gas or coal. These emissions could be reduced or eliminated with low-carbon production methods. The leading options are (1) capturing the CO_2 emitted in these processes and storing it underground or in long-lived products and (2) separating hydrogen from water using electricity made from zero-carbon processes.

In this roadmap, we use the term "low-carbon ammonia" to refer to ammonia made with low-carbon production methods. Low-carbon ammonia can contribute to decarbonization in two ways. First, low-carbon production methods can reduce the CO_2 emissions that currently come from ammonia production. Second, low-carbon ammonia can be used as a replacement for carbon-intensive fuels in shipping, heavy industry, power generation and other sectors.

Much of the interest in ammonia as a clean-fuel solution is based on ammonia's physical and chemical properties, as well as the potential for manufacturing it with a low-carbon footprint.

- Ammonia is a gas at room temperature and a liquid with modest pressure or refrigeration. This makes it easy to store and widely usable in many applications.
- Ammonia is one of the few synthetic fuels that does not contain carbon. Use of ammonia, either through combustion or conversion, releases no greenhouse gases.
- Ammonia has a higher energy density than liquid hydrogen. This makes it attractive as a carbon-free fuel for transportation, heating, power generation and industrial applications.
- Ammonia made from low-carbon hydrogen—including blue hydrogen, green hydrogen and bio-hydrogen—can have a near-zero carbon footprint and (if waste biomass and carbon capture technology is used) potentially net-negative life-cycle emissions.
- As a low-carbon fuel, ammonia can substitute for dirtier and more carbon-intensive fuels, including coal, oil and natural gas. This substitution can either be complete or as a blend with other fuels to reduce their total environmental impacts, including in coal boilers, gas turbines, combined heat-power systems, steel mills and internal combustion engines.

Ammonia is produced today at large scale—roughly 200 million tons per year (Mt/y) from roughly 35 Mt of hydrogen—mostly for use in fertilizers. This means that some infrastructure already exists and that many companies already make, ship and use ammonia. This also means that ammonia ships (and ports) already exist, although more will be needed to achieve key national and international goals. Similarly, ammonia is already traded and shipped around the world as a feedstock, making future global trade of ammonia as a fuel easy to understand and imagine in terms of cost, risk and logistics.

Three compelling issues drive decision making around the mix of low-carbon fuels, including ammonia: climate change, geopolitics and human health impacts of dirty fuels.

Climate crisis needs are unambiguous—low-carbon clean fuels are essential to reduce the risk of climate change and maintain economic activity and growth. The most recent Intergovernmental Panel on Climate Change (IPCC) Working Group III Assessment Report[1] delivers a strong scientific consensus, requiring deep, rapid and profound decarbonization in all sectors by 2060–2100. To reach these goals, estimates indicate that the use of low-carbon fuels must increase by 50–100% before 2030 and 200–700% before 2050, depending on the scenarios.[2]

Geopolitical risk is a related concern and potential advantage for clean fuels. Heavy reliance on conventional fossil fuel supplies has always posed geopolitical risks, but these risks have gained prominence and urgency following the Russian invasion of Ukraine and the associated global political, economic and energy crisis. One consequence of this invasion is that the European Union has placed immediate emphasis on domestic production of green hydrogen[3] and has accelerated imports of liquified natural gas (LNG) and other fuels (including low-carbon ammonia) in some instances through new bilateral agreements (e.g., Renewables Now, 2022[4]).

Although the human health and environmental consequences of fossil-fuel use have long been known, growth of fossil-fuel use in developing countries has made the costs more apparent.[5] In addition, recent studies reveal that the health effects of even small exposure to soot, volatile organic compounds (VOC) and sulfur emissions are more profound and long-lived than previously thought.[6] As such, the economic benefit of reduced fossil-fuel use, including through displacement by clean fuels, is equally profound—and indeed could yield net savings (negative carbon prices) through health benefits.[7,8]

Capturing the benefits of clean-fuel use, including ammonia, will require production, distribution and use at an enormous scale. Because of ammonia production's dependence on hydrogen, their commercial growth is closely connected. The International Energy Agency (IEA) estimates that more than 540 Mt/y of low-carbon hydrogen will be needed by 2050 to limit warming to 2 °C (3.6 °F) over pre-industrial levels, and 730 Mt/y of low-carbon hydrogen will be needed by 2050 to limit warming to an increase of 1.5 °C (2.7 °F) over pre-industrial levels. This represents a 6x increase compared to current production of conventional hydrogen (90 Mt/y) to achieve a 2 °C (3.6 °F) stabilization by 2050 and an increase of over 400x in clean hydrogen production.[9] In particular, this growth in demand will be necessary to decarbonize "harder to abate" sectors, such as heavy-duty transportation and heavy industry. Recent studies by the Energy Transition Commission[10] and IEA[11] point to the role of hydrogen in providing low-carbon fuels or feedstocks for steel, cement, chemicals, sustainable aviation, long-haul trucking, maritime operations and shipping, as well as some applications in the power sector for nations with limited renewable resources (e.g., Korea and Japan).

Markets have recognized the potential benefits of hydrogen in tackling climate change, and new projects, companies and investments are appearing rapidly. The EU Green Deal (2021),[12] EU FitFor55 plan (2022),[13] US Infrastructure Investment and Jobs Act (2021)[14] and US Inflation Reduction Act (2022)[15] feature policies to encourage growth in both production and use of low-carbon hydrogen. As of 2021, more than 520 new clean-hydrogen projects have been announced.[16] According to the IEA,[11] 16–24 Mt/y of new hydrogen production projects would come online by 2030—roughly 60% from electric water splitting and 40% from carbon capture and storage (CCS) of emissions from fossil fuels used in production. Nonetheless, the likely total costs could prove substantial. The investments required to produce low-carbon clean fuels at that scale are likely to be enormous, potentially exceeding $16 trillion over the next 28 years.[2,17,18]

Hydrogen also faces real challenges in deployment. The two most important challenges are hydrogen's low energy density and the difficulty in transporting it. Hydrogen's low energy density is a function of its very low gravimetric density. Even when compressed to 300 atm pressure in tanks and pipelines, hydrogen has roughly 30% the energy density of natural gas and 10% that of gasoline. As for transportability, hydrogen molecules are very small and prone to leaking, thus presenting challenges for conventional infrastructure.[11] To move hydrogen by ship is much more challenging than moving LNG: hydrogen only liquifies at extremely low temperatures (-253 °C) and very high pressures (> 350 atmospheres), which both require very large energy inputs to achieve. As such, the costs of transporting and shipping hydrogen are commonly more than 30% of the total costs of delivering hydrogen to market[19] and in some cases may exceed the costs of production.[17,20]

The physics and chemistry of ammonia overcome many of the challenges of hydrogen, especially ammonia's higher energy density, ease of storage and transport, and potential use directly as a fuel.[21] Ammonia also appears to be the current and future lowest-cost synthetic fuel; the IEA predicts[11] that ammonia costs will drop faster and to substantially lower levels than methanol or kerosene.

None of this suggests that ammonia is without environmental or health concerns—quite the contrary. Ammonia is a gas at ambient temperatures, leading to real concerns about vapor leakage (sometimes called "slip"). It can also enter the environment through spills. Like other fuels, ammonia is toxic. If inhaled, it causes respiratory problems and can have lingering health effects. Global growth and profound scale-up of ammonia production and use would likely create some new environmental risks and could add environmental burdens. Since ammonia is often produced in areas with heavy industrial footprints, these burdens could disproportionally affect disadvantaged and frontline communities.

Since hydrogen can be produced in many geographies, the same is true of ammonia. Countries investing in ammonia production include the following.

- **Chile:** Chile is positioned to become a major clean ammonia exporter given its domestic renewable energy resources. Because Chile has extremely high-quality wind, solar and hydroelectric resources, its government has created a basket of policies to support production of hydrogen and ammonia. In its National Green Hydrogen Strategy,[22] Chile aims to be a major producer and exporter of liquid hydrogen, green ammonia and clean fuels to global markets by 2030. From 2025 to 2050, Chile estimates that its exports of green ammonia could scale from a total market size of $0.4 billion per year in 2025 to $24 billion per year by 2050+. The country also plans to use ammonia domestically for end-use applications, such as maritime shipping and oil refineries. A major project has already been announced by Total Eren (a subsidiary of TotalEnergies) that is scheduled to produce 4.4 million tonnes of renewable ammonia per year at full capacity.[23]
- **Saudi Arabia:** Saudi Arabia hosts one of the world's largest green ammonia projects, the Neom development. At $7 billion total estimated cost, the project will generate 5 GW of green electricity to make hydrogen, all of which will become ammonia for global sale.[24] In addition, Saudi Arabia is already producing "blue" ammonia and shipping it to Japanese markets.[25] They have already announced an 11 Mt/y blue ammonia project[26] and are expected to announce large additional ammonia projects later in 2022.
- **Australia:** The largest announced project is the Asian Renewable Energy Hub (AREH) in northwest Australia. Although originally posed as a green electricity project for sale in Southeast Asia, it has since changed focus to green ammonia production and export.[27] The $40 billion project would yield 26 GW of electricity to produce 10 Mt/y of green ammonia.[28] Also, like Saudi Arabia, Australia is home to large blue ammonia projects, including the Latrobe Valley project—a joint venture with Kawasaki.
- **Other geographies:** New ammonia projects are emerging in geographies with high-quality renewable resources or low-cost natural gas. These include, but are not limited to, Namibia, Iceland, Spain, Uruguay, Morocco, Indonesia, the United Arab Emirates, Qatar, the United States and Canada.

The growth in both supply and demand for low-carbon ammonia reveals an avenue for global wealth creation. It may also represent a geopolitical shift—with more fuel producers, the role of petrostates in determining national policies may change profoundly. The growth in ammonia supply and use, especially in developing nations, could present additional environmental concerns, ranging from local health effects of ammonia slip to global consequences of hydrogen and ammonia leakage on climate. This last point is particularly noteworthy—recent studies suggest that, by extending the life of non-CO_2 greenhouse gases in the atmosphere and thus increasing their effective radiative forcing, large-scale hydrogen production for ammonia and other uses could significantly contribute to global warming if leakage rates are high.[29,30]

These issues prompt us to consider many features, aspects and points of concern in our roadmap for low-carbon ammonia.

- **Chapter 2** discusses the history and current state of the ammonia market globally.
- **Chapter 3** discusses methods for producing low-carbon ammonia.
- **Chapter 4** discusses ammonia infrastructure, including for pipeline transportation, shipping cargo, shipping fuel and energy storage.
- **Chapter 5** discusses how ammonia may be used in different sectors, including fertilizer manufacturing, heavy industry, transportation and the power sector.
- **Chapter 6** discusses the local environmental and safety risks related to ammonia production and use.
- **Chapter 7** presents research and development priorities for low-carbon ammonia.
- **Chapter 8** presents current and potential policy actions for scaling up of low-carbon ammonia production and use.
- **Chapter 9** presents findings and recommendations.

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Chapter 2

THE AMMONIA INDUSTRY: PAST AND PRESENT

Ammonia is one of the four basic industrial chemicals that provide the foundation for all other chemicals and plastics production. Approximately 179 million tons (Mt) of ammonia were produced globally in 2020, a 40% increase over 2001.[1] The largest ammonia producer is China (approximately 30% of global production), followed by Russia, the European Union, the United States, India and the Middle East (see Figure 2-1). Existing global ammonia production capacity has a utilization rate of roughly 80%, with the installed global annual production capacity exceeding 230 Mt in 2020.[2,3] The total global market size is estimated to be over $100 billion.[4] As an energy-intensive process, the production of synthetic (manufactured) ammonia consumes 8.6 EJ per year, or approximately 2% of total final energy consumption globally.[3,5] It is responsible for 450 Mt of direct CO_2 emissions, as well as an additional 170 Mt of CO_2e emissions due to the electricity consumed by the ammonia production process and release of nitrous oxide that occurs when ammonia-derived fertilizers are applied to agricultural land.[6]

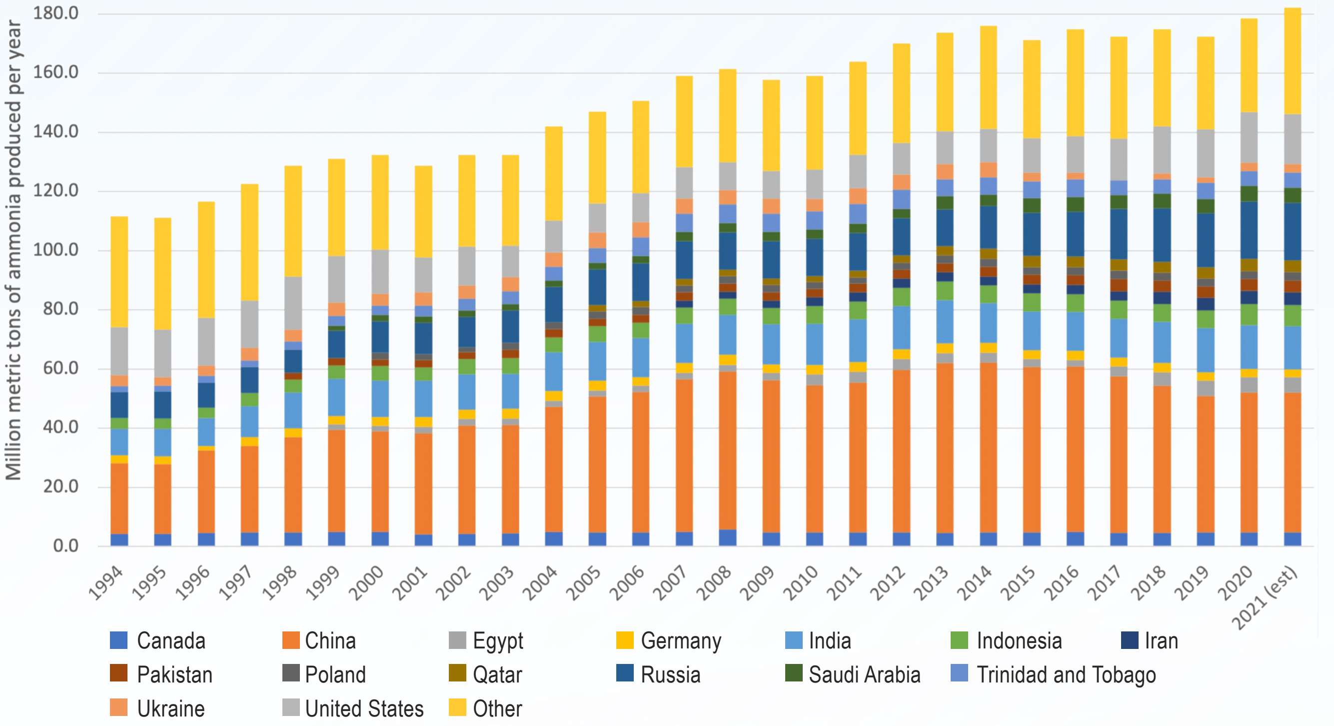

Figure 2-1. *Global ammonia production by country and total (million metric tons/year). Data: USGS. Note that USGS data are reported as tons of fixed nitrogen, which we adjust here to tons of ammonia.*

Unlike the other three basic industrial chemicals (methanol, ethylene and propylene), ammonia is primarily used to produce nitrogen-based fertilizers, which include urea, ammonium nitrate and ammonium sulfate (see Figure 2-2). Ammonia is also used directly as a fertilizer in North America. Ammonia-derived fertilizers are vital for supporting global food production; by one estimate, only half of the current global population could be fed without synthetic ammonia (see Figure 2-3).[7] The remainder of ammonia produced is used for a range of applications, including manufacturing plastics, rubber, fibers (via acrylonitrile) and explosives (via ammonium

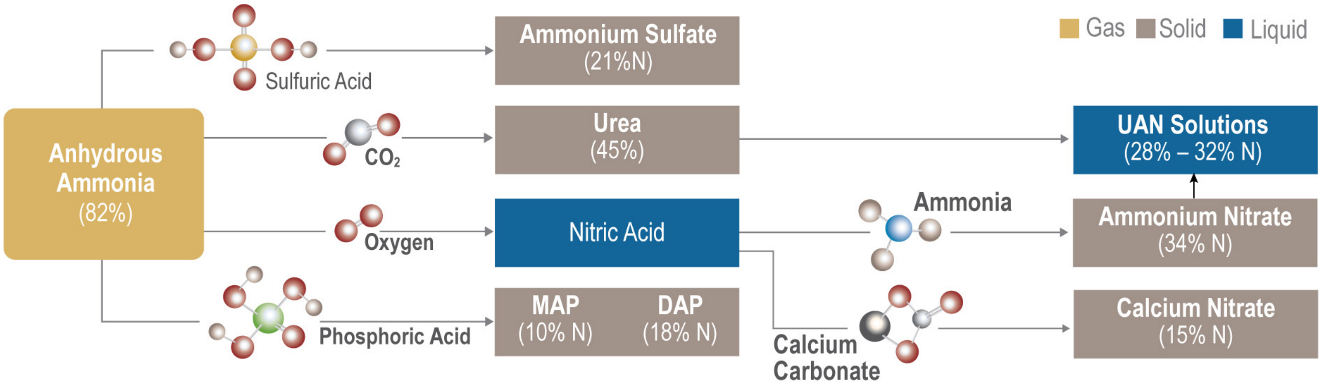

Figure 2-2. *Ammonia is converted into multiple types of fertilizer using different chemical routes illustrated here.*

nitrate), and directly as an air pollution control agent, refrigerant and cleaning agent. Development of a method to chemically synthesize ammonia was one of the most important scientific and technological advances of the 20th century.[7,8] The value of nitrogen-based fertilizers for agriculture has been understood for centuries, and the use of various forms of natural nitrogen fertilizers has a long history. Beginning in the 19th century, several nations began to recognize the value of seabird guano as fertilizer, originating from island deposits in South America. Following Peru's independence from Spain in 1824, exports of guano from Peru grew rapidly, rising to hundreds of thousands of tons annually by the 1840s. This fueled the "Guano Boom" that dramatically increased crop yields and enabled high population growth in many countries.[9]

Unfortunately, over-exploitation of the Peruvian guano resource led to a crash in supply by the late 19th century. Exports shifted to nitrates from mined ore (*caliche* deposits), but the scientific community began to grow concerned that insufficient supplies of nitrogen fertilizer could lead to global starvation.[10] Motivated by this concern and an interest in developing synthetic explosives to replace natural saltpeter deposits, chemists Fritz Haber and Carl Bosch developed a high-pressure ammonia chemical synthesis method now known as the Haber-Bosch process.[11]

The Haber-Bosch process was the first industrial pressurized catalytic process and required several independent technological innovations to become practical. One of the most important of these was to develop a reactor that could withstand pressures of 200 bar, which was unprecedented. This required lining a pressure-bearing steel

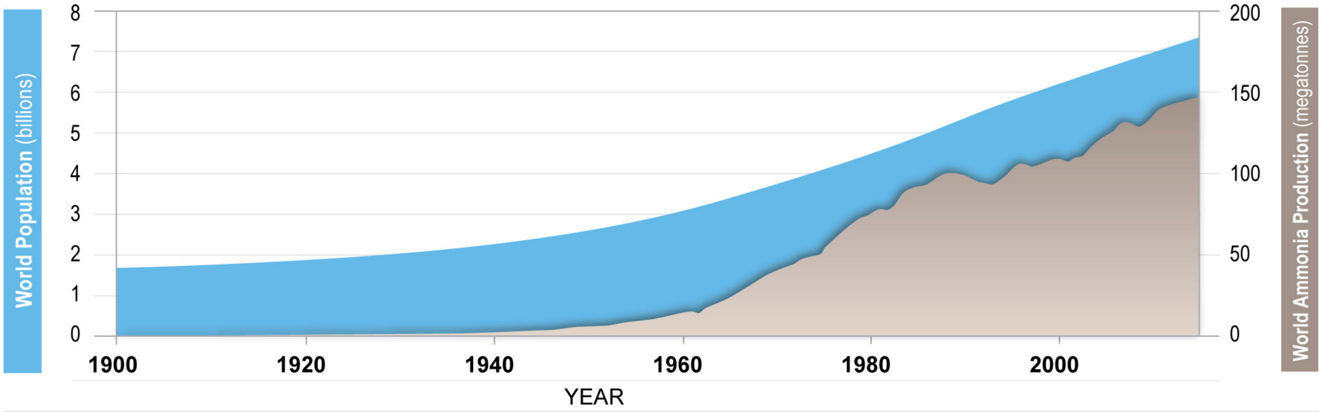

Figure 2-3. *The growth of global population has been partly enabled by a corresponding growth in the production of synthetic ammonia for fertilizers to support food production. From DOE, 2016.*[15]

exterior tube with soft iron and providing a means to release hydrogen that diffused through this liner so that it would not embrittle and destroy the steel. A second key innovation was to find an economical alternative to the original osmium and uranium catalyst used by Haber in early experiments. Bosch and his colleague Alwin Mittasch tested thousands of alternatives, eventually identifying an iron-based catalyst with a small addition of aluminum, which is still in broad use today.[4,12,13]

Bosch and Mittasch conducted their work as employees of German chemical company BASF, which built the first industrial Haber-Bosch plant in Oppau, Germany in 1913. The plant had a capacity of 10,000 tons of ammonia per year; it used coal and air to produce nitrogen, and hot coke (derived from coal) and water to produce hydrogen. The nitrogen and hydrogen were then reacted at high pressure and temperature over the iron catalyst to produce ammonia.[14] A key feature of the plant, and all subsequent Haber-Bosch plants, is the relatively low fraction of reactants converted to ammonia in a single pass through the reactor. To address this, the unreacted components are repeatedly recycled with the addition of fresh nitrogen and hydrogen, increasing the overall amount converted to ammonia.[15] Germany continued to be the only producer of synthetic ammonia using the Haber-Bosch process through 1920, with BASF unwilling to offer licenses.[16] However, many governments understood its importance and sought to develop or otherwise acquire it. The United States appropriated funds in 1916 to develop nitrogen-fixation technology for both military and agricultural purposes, and the resulting military Fixed Nitrogen Research Laboratory (FNRL) was transitioned from the War Department to the Department of Agriculture in 1921.[17] The United Kingdom began developing a nitrogen-fixation plant during World War I, which was later converted to fertilizer production using the Haber-Bosch process and started producing ammonia in 1924.[18] Several alternative processes for synthetic ammonia production were developed throughout the 1920s and 1930s, in Italy (Casale, Fauser processes), France (Claude, Mont Cenis processes), the United States (General Chemical/Allied, Nitrogen Engineering processes) and Japan (Showa Fertilizer process).[16,19] In general, these were variants of the Haber-Bosch process and were mostly available for licensing, leading to large-scale adoption in many countries by the end of the 1920s.

By 1934, the United States, Germany and Japan were the largest producers of synthetic ammonia. During the 1930s, coal remained the primary energy source for ammonia production, but up to 30% of ammonia produced globally was made with hydrogen derived from hydro-powered electrolysis.[16] While fossil-based ammonia production gained market share after this, electrolysis-based ammonia plants continued to be constructed until at least 1960.

An important development in the transition to the modern ammonia industry came during World War II, when the United States constructed ten large-scale nitrogen fixation plants, seven of which used hydrogen derived from the steam reforming of methane (natural gas).[20] This was a novel departure from the standard use of coal and coke and provided several benefits, including much lower sulfur content, which reduced feedstock pre-treatment requirements and allowed the use of advanced catalysts for carbon monoxide (CO) conversion. Reforming-based ammonia synthesis became increasingly standard during the 1960s due to its favorable economics. Other important innovations introduced around this time included replacing reciprocating compressors with centrifugal ones (allowing much greater unit capacities), introducing single stream reactors, and increasing the use of shaped catalysts to improve activity while maintaining pressure drop.[18]

The tremendous importance of the Haber-Bosch process for fertilizer production continued to be recognized as these innovations were introduced. The technology's success may have played a role in China's decision to open to the West in 1972, as its agricultural production was under enormous strain from population growth. Following President Nixon's famous visit, US companies built at least eight large ammonia plants in China, helping to significantly increase synthetic fertilizer production there.[21,22] China became the world's largest ammonia producer in 1991.

Further innovations continued through the 1990s, leading to ever-larger plant capacities and corresponding improvements to energy efficiency. Because of the need to provide high pressure and temperature, Haber-Bosch plants display strong economies of scale, with a cost-scaling exponent of roughly 0.65.[23] Average plant capacities grew from 500 tons per day (tpd) in the 1960s to over 3000 tpd today (two orders of magnitude larger than the original Oppau plant). At the same time, specific energy consumption has fallen from nearly 100 GJ/t ammonia for early coal-based plants to 28 GJ/t today for new plants using natural gas as feedstock, approaching the theoretical minimum specific energy of 18 GJ/t.[24] Modern coal-based plants have specific energy consumption of 42 GJ/t.[18]

Modern Haber-Bosch plants are highly integrated and include additional innovations, such as lower-pressure synthesis loops and radial and horizontal catalyst beds. Approximately three quarters of global production is based on natural gas feedstock; most of the remainder, which is almost entirely in China, is based on coal. The front end of conventional natural gas–based plants consists of a methane desulfurization stage, followed by two reformers. The first of these, called a steam methane reformer (SMR), is heated by external natural gas combustion (the dominant energy consumption of the entire process) and operates at 850–900 °C. (This first reformer is the reason these plants are often referred to as “SMR” ammonia plants.) The second, called an autothermal reformer (ATR), is heated to 900–1000 °C by injection of compressed air and partial oxidation of the reagents. This injection of air also provides nitrogen for the Haber-Bosch reaction downstream. The resulting syngas and nitrogen are passed through a water-gas shift (WGS) reactor to maximize the recovery of hydrogen, and heat from the ATR and WGS reactors is used to raise steam for compression elsewhere in the plant. Following the WGS, CO_2 is removed (usually using the Rectisol, Selexol or Benfield process) and vented, and the remaining CO is converted to methane to avoid poisoning the Haber-Bosch catalyst. The resulting feed—containing hydrogen, nitrogen, and residual argon and methane (which accumulate as inerts)—is fed to the Haber-Bosch reactor. Because of a tradeoff between reaction speed and equilibrium, most reactors achieve a conversion to ammonia of only 10–15% per pass (increasing to 20% for very recent plants). Following a cooling step in which ammonia is liquefied and removed, the remaining hydrogen and nitrogen are recycled into the reactor to achieve overall conversion rates that approach 100%. Today, a small number of vendors dominate the market for design and construction of new ammonia plants and continue to pursue technology innovations for competitive advantage; as a result, both average plant capacity and energy efficiency are likely to continue to increase.[4,24,25] (See Chapter 3 – Production of Low-Carbon Ammonia.)

Modern plants can produce ammonia at costs as low as $160/t due to economies of scale.[23] However, this cost is heavily dependent on the price of feedstock natural gas, which contributes more than half of the levelized cost of ammonia production.[26] As a result of sharp increases in natural gas prices, world ammonia prices have increased dramatically since 2021, from $200–300/t to over $1000/t in Europe, the Middle East and the United States.[27] Idled capacity appears to be restarting in response to these price rises, but the market remains extremely dynamic.[28]

Approximately 10% of global ammonia production is traded internationally, with more than 100 ports and nearly 200 ships currently capable of handling bulk ammonia.[29] Ammonia is also transported by pipeline (primarily in the United States and Russia/Ukraine), rail and truck. (See Chapter 4 – Ammonia Infrastructure.) Accidents have occurred with both production and transportation of ammonia and have been the subject of significant analysis, which has led to improved safety, leak detection and accident mitigation procedures.[30-33] (See Chapter 6 – Safety and Local Environmental Impacts of Ammonia.)

Currently, the global ammonia market is undergoing significant changes. Concerns about climate change have sparked increasing interest in low-carbon ammonia as a replacement for carbon-intensive fuels, fertilizers and other products. A wide array of low-carbon ammonia production projects has been announced, including both “blue” ammonia, which adds carbon capture and storage (CCS) to conventional, natural gas- or coal-based production, and “green” ammonia, which produces hydrogen through electrolysis powered by low-carbon electricity. This includes many of the world's largest fertilizer companies, such as Nutrien,[34] Wesfarmers,[35] CF Industries[36] and Yara International.[37] Several shipments of blue ammonia have already been demonstrated, including production by Saudi Aramco and Saudi Basic Industries Corporation (SABIC),[38] as well as Abu Dhabi National Oil Company (ADNOC) and Fertiglobe.[39] (See Chapter 3 – Production of Low-Carbon Ammonia). Similarly, many technology development and demonstration projects have been announced that focus on the use of low-carbon ammonia in novel applications, particularly in power generation and marine fuels. (See Chapter 5 – Uses of Low-Carbon Ammonia.)

The International Energy Agency's Sustainable Development Scenario (SDS) envisions that ammonia demand for fertilizer in 2050 will total 230 Mt, an increase over current demand that reflects population growth and dietary changes (increased consumption), as well as fertilizer application efficiency and a shift from urea toward nitrate-based fertilizers (decreased consumption). The SDS also envisions 125 Mt of ammonia demand for novel applications by 2050, primarily in marine fuel and power generation.[5] While the latter category (energy carriers) will be overwhelmingly low-carbon ammonia, the adoption rate of low-carbon ammonia into existing uses (primarily fertilizers) is unclear. Other analysts have projected up to 150 Mt of ammonia demand for marine fuel alone[40] and up to 200 Mt of ammonia demand for the power sector alone,[41] both of which would presumably be dominated by low-carbon ammonia. As a result, forecasting the future demand for low-carbon ammonia depends on a complex mix of factors but may be several times current global ammonia production.

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Chapter 3

PRODUCTION OF LOW-CARBON AMMONIA

Conventional ammonia production is an emissions-intensive, fossil fuel–based business. Of the 179 million tons (Mt) of ammonia produced in 2020, 72% relied on natural gas–based steam methane reforming (SMR), 26% on coal gasification, 1% on oil products and finally a fraction of a percentage point on electrolysis.[1,2] In terms of geographic concentration, China is the largest ammonia producer, at 30% of global production capacity, of which 85% relies on China's coal reserves.[2] The Middle East, United States, Russia, European Union and India each account for 8–10%, with low-cost natural gas in the Middle East, United States and Russia fueling production there.[2]

Ammonia production begins with the production of hydrogen, which is then combined with nitrogen in the Haber-Bosch process to produce ammonia.[3] To achieve a sufficient reaction pace, modern Haber-Bosch plants operate at high temperatures and pressures.[4] These high capital costs result in significant economies of scale, leading to ever-larger-scale ammonia production.[5] The typical capacities for new-build plants have grown over time, reaching 2000 t/day in the 2000s and increasing to 3300 t/day today.[6]

High capital costs combined with plant lifetimes of 50 years builds inertia into the ammonia production system.[2] The capital investment (including engineering, procurement and construction costs) for an SMR plant runs around $1.675 billion.[2] A carbon capture and storage (CCS) retrofit would require capital investments of around $335 million, or about 20% of the initial investment cost.[2] Regional differences in plant age and local resource

Figure 3-1. *BASF Ammonia Plant in Ludwigshafen, Germany. The first industrial scale ammonia synthesis plant was built by BASF near Ludwigshafen (BASF).*[7]

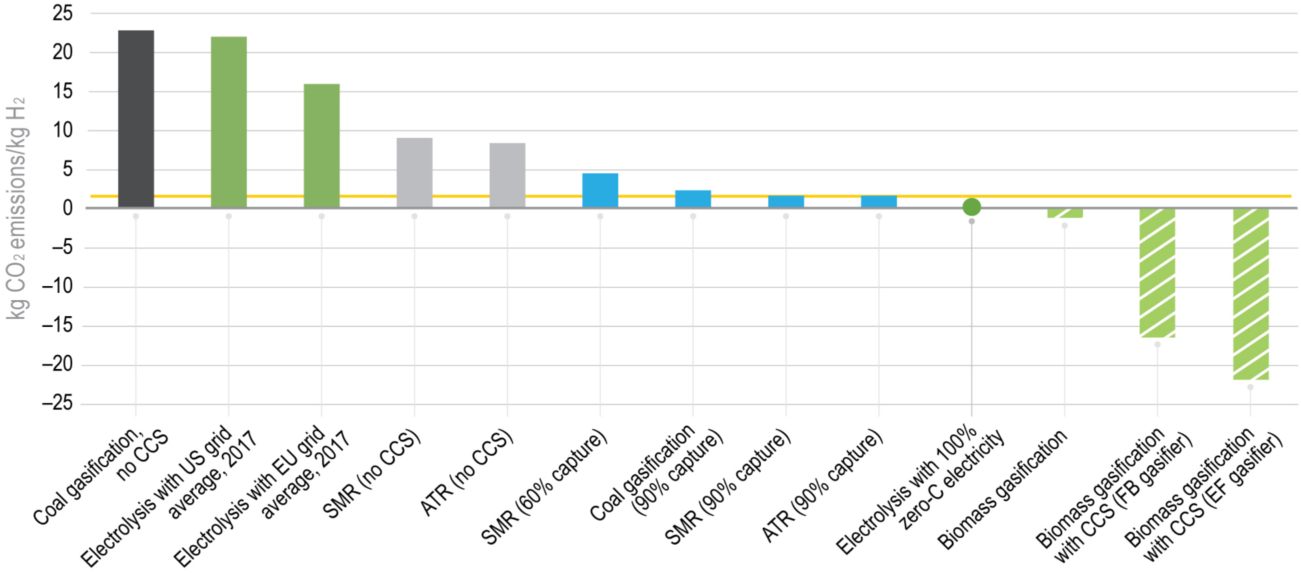
availability mean that the most cost-effective path toward low-carbon ammonia will vary. CCS retrofits have an outsized role to play in China, where an average plant age of 12 years means assets still have long remaining lifetimes compared to Europe, where an average plant age of 40 years means assets are nearing the ends of their lifetimes.[2] As of October 2021, existing and announced low-carbon ammonia projects in the range of 8 Mt were planned to come online by 2030.[2]

The carbon footprint of ammonia production varies by plant age and fuel type. With the inefficiencies of today's aging fleet and the continued reliance on coal for some ammonia production, the average ton of ammonia produced results in 2.4 tons of direct CO_2. Thus, ammonia has a direct CO_2 emissions profile that is twice as intensive as crude steel and four times as intensive as cement on a mass basis.[2] As newbuild ammonia plants have achieved higher efficiencies with scale-up and technology optimization, a ton of ammonia produced with the best available technology for SMR results in 1.8 tons of direct CO_2 emissions, with the possibility of reducing the emissions to 0.1 tons using CCS retrofits.[2,6] Efforts to decarbonize ammonia concentrate on emissions from hydrogen production because it is the most carbon-intensive part of the production process. Specifically, hydrogen production accounts for 90% of the carbon emissions in the synthesis of ammonia, assuming minimal emissions from natural gas production and transport (see below).[8]

The major pathways to decarbonizing ammonia production are often described in terms of colors. Gray ammonia refers to conventional, fossil fuel–based ammonia production methods. Blue ammonia is based on these same conventional production methods, with the addition of carbon capture equipment to achieve a lower carbon footprint. Green ammonia refers to ammonia produced using electrolysis powered by clean electricity. Despite these qualitative descriptors, there is no widely accepted quantitative measure of how small the emissions footprint of ammonia must be to qualify as "blue" or "green," allowing for substantial variation in emissions within these categories. As a result, the label "blue" or "green" ammonia alone does not provide sufficient information to determine whether a given batch of ammonia has low life-cycle emissions.

This chapter examines three pathways to low-carbon ammonia production:

1. Reducing CO_2 emissions from existing ammonia production facilities with carbon capture or electrification.
2. Using electrolysis running on clean electricity.
3. Creating hydrogen from biomass with carbon capture (ammonia from bio-hydrogen).



Source: Fan et al., 2021; Global CCS Institute, 2021

Figure 3-2. *Emissions intensity of hydrogen production methods vary widely. Sources: Minervini et al., 2021[23] and Fan et al.,2021[57]*

Each of these pathways and the numerous design variations within them involve trade-offs between the achievable greenhouse gas emissions reductions, speed and scale of implementation, and the cost of production and transportation. The most advantageous low-carbon ammonia pathway will vary by geography due to the importance of local resources and infrastructure, as well as over time as some of the most promising pathways under R&D have yet to reach the market.

Natural gas–based ammonia originally became widespread due to its low cost, with a levelized cost of ammonia as low as \$160/t due to economies of scale.[9] However, the economic competitiveness of blue versus green ammonia will depend partly on the relative differences in their primary production cost drivers—the price of natural gas versus the price of clean electricity. The volatility of both natural gas and clean electricity prices creates an uncertain future production landscape. For example, from 2000 to 2020, market prices for ammonia ranged between \$100/t to \$600/t, but natural gas shortages starting in 2021 drove prices above \$1000/t in all regions.[10] (See Chapter 2 – The Ammonia Industry: Past and Present.) As a result, green ammonia imports to Europe became cheaper than fossil fuel–based gray ammonia in 2022.[11] This variation in energy prices over time and geography, in combination with the age and status of existing conventional ammonia production plants, leads to a complex scenario in which both blue and green ammonia facilities are being developed in different locations globally. While many analyses attempt to forecast the future balance between blue and green ammonia production, both need to be scaled to meet projections for growing future demand for low-carbon ammonia.

Another important factor in price variation is the potential for different levels of centralization for blue and green ammonia production. Given that gray ammonia production is centralized, blue ammonia will likely be similar, resulting in additional costs for ammonia transportation and distribution of ammonia. This is estimated at \$52/t via pipeline, \$100/t via truck or \$140/t via railway for 1600 km.[12] The modularity of green ammonia production means there is less economic advantage from large-scale production facilities, creating greater opportunities for distributed production with lower transportation costs to end users.

Each type of low-carbon ammonia production faces a number of barriers. The primary obstacle for blue ammonia production is the enabling infrastructure to identify and then transport captured CO_2 to storage sites. Furthermore, while the concentrated process stream from reforming natural gas for blue ammonia is easily captured, capturing the dilute CO_2 from combustion is more difficult and expensive. For green ammonia, the likely bottleneck for scale is the limited existing capacity to manufacture new electrolyzers, leading to a discrepancy between announced projects and the likely ability to deliver on them. Green ammonia also struggles with the intermittency of renewable energy sources, potentially requiring the use of some higher-emissions grid-supplied power. Finally, all forms of low-carbon ammonia face the barrier of a market reluctant to pay a green premium for a lower carbon footprint, meaning they depend on policy to drive an uptake in demand and for subsidies to close the cost and corresponding price gap with gray ammonia (for further details, see Chapter 8: Policy).

Blue Ammonia

The existing fleet of coal- and natural gas–based ammonia production, as well as new builds using the same technology, can become low carbon through the introduction of CCS technology. Without CCS, ammonia's carbon footprint is primarily determined by the emissions profile of the hydrogen production method. Ammonia produced from coal has the largest carbon footprint, with a direct CO_2 intensity of 3.2 tCO_2/t, followed by natural gas with SMR at 1.8 tCO_2/t (see Table 3-1). This section will focus primarily on cutting emissions for natural gas–based SMR, given its dominance at 72% of global ammonia production.[2]

The multistep SMR process is based on the reaction of desulfurized natural gas with steam at high pressure and temperature, followed by further steps to purify the gas streams, including CO_2 removal through absorption in an amine solution.[2,13] (See Chapter 2- The Ammonia Industry: Past and Present.) This produces a mixture of hydrogen

Table 3-1. *Energy needs to produce one tonne of ammonia for each route using BAT.*

Production route	Energy intensity (GJ/ton)						Direct CO_2 intensity (ton CO_2/ton)
	Feedstock	Fuel	Electricity	Steam	Gross	Net	
Natural gas SMR	21.0	11.1	0.3	-4.8	32.4	27.6	**1.8**
Natural gas ATR	25.8	2.1	1.0	0.0	28.9	28.9	**1.6**
Coal gasification	18.6	15.1	3.7	-1.3	37.4	36.1	**3.2**
SMR with CCS	21.0	11.1	1.0	-3.1	33.1	30.0	**0.1**
ATR with CCS	25.8	2.1	1.5	0.0	29.4	29.4	**0.1**
Coal with CCS	18.6	15.1	4.9	2.6	38.6	41.2	**0.2**

Notes: SMR= steam methane reforming; ATR=auto-thermal reforming; CCS=carbon capture and storage. All energy intensities presented for the production of 1 tonne of ammonia. The arrangements considered here include capture of both concentrated and dilute CO_2 streams. Negative values represent net steam generation, which is available for use by other process units or for export. Methane pyrolysis produces solid carbon as a by-product, the energy content of which is not reflected in the values shown. Methane pyrolysis is at an early stage of technology development and the estimates provided direct CO_2 emissions from the energy system, following IEA emissions accounting conventions. Source: Data gathered and reviewed in collaboration with the IA and its members.
IEA Ammonia Roadmap[2]. pg. 33

and nitrogen (which are subsequently reacted to produce ammonia) and a separate stream of pure CO_2 (see Figure 3-4).

Natural gas–based SMR ammonia production is well-suited for carbon capture because CO_2 is already separated from the process gas and removed to avoid poisoning the iron-based Haber-Bosch catalyst. Conventionally, this pure stream of CO_2 is simply vented, but it can be dewatered and compressed for storage or utilization at low cost, roughly \$34/tCO_2 (NETL[14]; costs adjusted to 2022 using CPI). Transport and storage add approximately \$25–50/tCO_2 (see discussion below) for a total of approximately \$60–85/tCO_2. This reduces the overall process emissions by approximately two-thirds.[15] Getting to 90% or greater total emissions reductions is more difficult because it requires also capturing CO_2 from the more dilute flue gas stream that is emitted when natural gas is combusted to produce heat for the primary reformer.[15] Capturing these additional emissions in order to achieve this lower carbon footprint requires installing and operating additional carbon capture equipment and incurring similar transport and storage costs and is thus significantly more expensive, approximately \$100–150/tCO_2.[10] Additionally, decarbonization of the full life-cycle of SMR-based ammonia is limited by the upstream greenhouse gas emissions resulting from the extraction, treatment and transport of natural gas, which can be substantial in some cases.[8]

Figure 3-3. *CO_2 pipeline infrastructure will be decisive for enabling carbon capture for blue ammonia production.*

Some modern SMR plants have begun to adopt a design based on reducing the size and reforming capacity of the primary, externally heated reformer (the SMR) while increasing the reforming in the secondary, air-blown reformer called the autothermal reformer (ATR).[16,17] When combined with a cryogenic nitrogen wash to adjust the hydrogen:nitrogen ratio of process gas entering the synthesis loop, this configuration can potentially achieve over 80% reduction of CO_2 emissions just by dewatering and compressing the CO_2 already separated from the process gas. Achieving higher capture rates involves either capturing CO_2 from the dilute flue gas or designing the plant to produce excess syngas and combusting it (after CO_2 has been removed). Notably, the former approach may allow new build plants to achieve relatively high levels of CO_2 reduction (potentially over 80%) while deferring

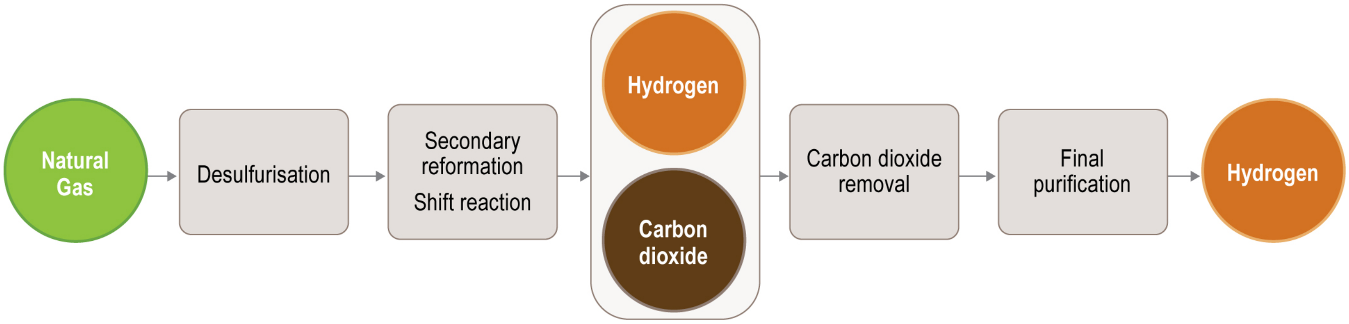


Figure 3-4. *Steam Methane Reformation (SMR) Schematic (Royal Society 2020,[8] pg. 13) shows that carbon dioxide (CO_2) removal is already embedded in the production of hydrogen from natural gas using SMR.*

the additional expense of adding carbon capture equipment for even higher capture fractions—in response to changing standards of required capture fraction— to a later date. (See Chapter 8 – Policy.)

Another approach for future blue ammonia production is a design that largely or entirely eliminates the primary reformer (SMR) and instead relies on an oxygen-blown ATR in a (mostly) stand-alone configuration.[18-20] The use of separate oxygen and corresponding nitrogen injections allows tuning of the hydrogen:nitrogen ratio and minimizes the need to combust feed gas to provide external heat, hence increasing the fraction of overall CO_2 that is separated from the process gas and allowing high capture rates (above 90%) without capture from dilute flue gas. However, the electric load from the air separation unit (ASU) required to produce oxygen and nitrogen can be considerable and may lead to additional emissions (Scope 2) depending on the electric generation supply. Estimated costs for capture of the pure CO_2 stream are in the range of \$40–80/tCO_2, including similar transport and storage costs to the SMR case.[2,10] While this approach is currently in use for methanol synthesis, it has not yet been applied to ammonia production.

The relative advantages of these multiple approaches for blue ammonia optimization (including others not described here and future innovations) remain to be seen, and a variety of market and other factors will determine their rates of adoption.

It is important to note that transporting CO_2 over long distances can also increase the total cost of CCS. For example, Lee et al., 2022[21] found that increasing the CO_2 transport distance from 100 miles to 1000 miles increases costs by \$60/tCO_2.[21] CCS projects are therefore enabled through appropriately sized geological storage locations within a reasonable distance from the ammonia plant. Existing oil and gas fields are especially attractive options, given the depth of the data already available on them.[22] Governments can support the development of CCS by identifying suitable storage locations, which early analysis suggests can be identified in nearly every industrialized region of the world.[23] Given the sizeable impact of transport on the cost of CCS, the growth of CCS will likely depend on clustering CCS hubs in industrial regions.[22]

While blue ammonia is often discussed in terms of carbon capture technology, electrifying conventional SMR would also lower emissions. Using combustion of natural gas to heat the reforming reaction produces the flue gas stream, whose dilute carbon emissions are difficult and expensive to capture. One approach currently under development to eliminate these emissions involves electrically heating the reaction through an integrated catalytic coating, which enables temperatures above those of conventional SMR reactors, thus producing higher methane conversion rates and pushing start-up times down to minutes.[24] With 17–41% of emissions in conventional SMR produced from hydrocarbon combustion, electrification with renewables could produce substantial climate benefits.[24] In regions with abundant renewables, preliminary estimates suggest costs would be similar to traditional SMR production.[24]

Figure 3-5. *Green Ammonia production depends upon the continued build-out of renewable energy production capacity.*
(credit: Ann-Kathrin Merz)

Green Ammonia

The green ammonia produced today only meets a fraction of a percent of the world's ammonia demand, but to reach a net-zero world this share is expected to grow.[2] Green ammonia differs from blue ammonia primarily in the hydrogen production method. Specifically, with green ammonia, hydrogen is produced via electrolysis, in which an electric current flows through water to separate the hydrogen and oxygen atoms composing water molecules.[25] Pure hydrogen is then combined with nitrogen separated from the air to run the Haber-Bosch process, creating ammonia. Producing hydrogen via electrolysis as opposed to SMR results in minor differences in the Haber-Bosch process. For instance, in an electrolysis-based Haber-Bosch plant, the ammonia synthesis loop has lower energy losses because hydrogen can be produced at high pressure, there is no need to purge inert gases after synthesis, and compressors powered by electric motors can achieve greater efficiencies.[26]

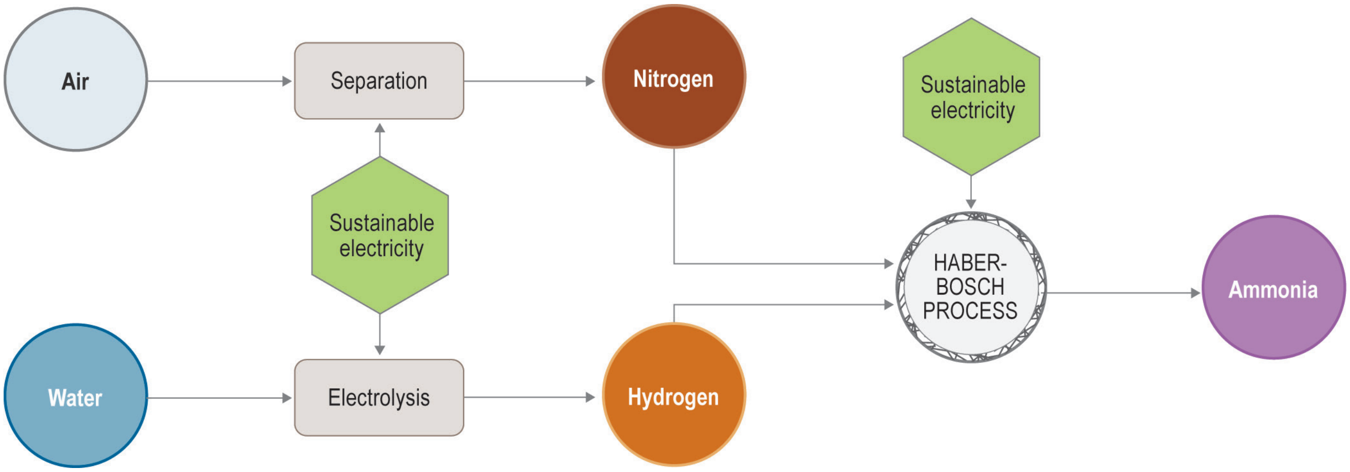
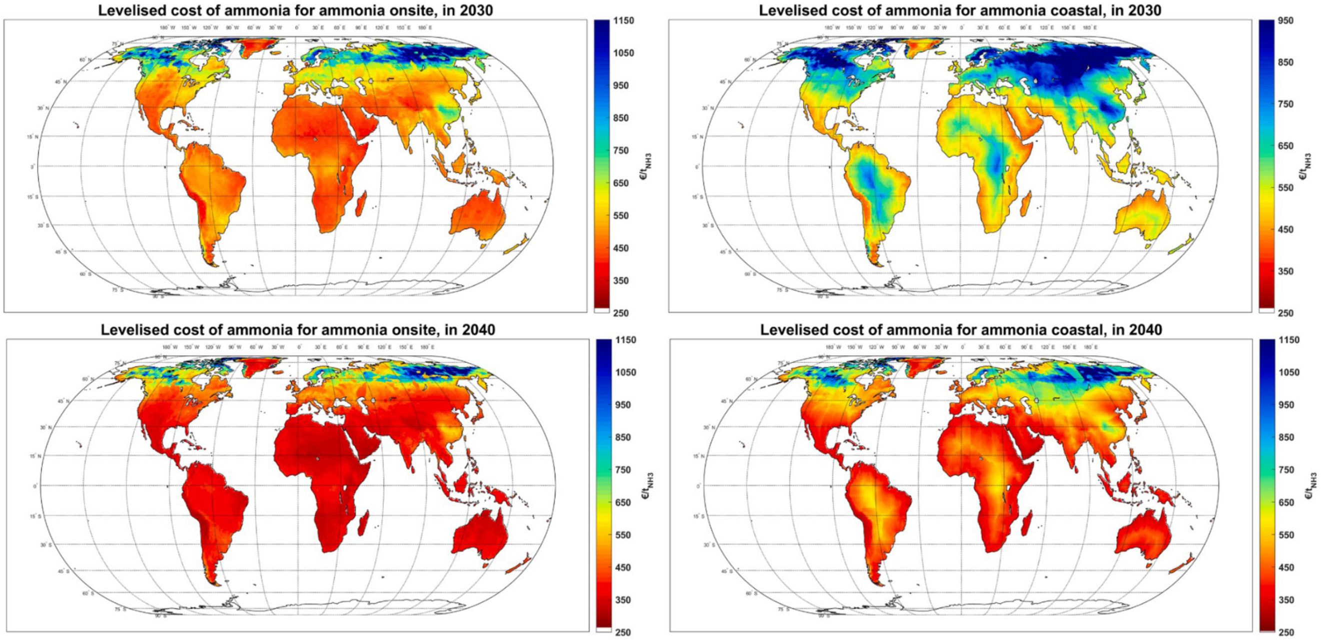


Figure 3-6. *Green ammonia can be produced using water, air and clean electricity. The carbon footprint will depend primarily on the carbon footprint of the electricity used. The Royal Society,[8] pg. 15.*



Source: Fasihi et al., 2021,[31] pg. 6

Figure 3-7. *The levelized cost of ammonia (LCOA) for ammonia production using alkaline electrolyzers powered by hybrid PV-wind power plants and some balancing technologies is modeled. The Onsite Scenario (left graphs) represents the potential for local consumption, while the Coastal Scenario (right graphs) represents the potential for export.*

Because green ammonia production is powered by electricity, its carbon footprint depends on the emissions intensity of the electricity source used. For example, hydrogen from electrolysis powered by approximately one-third zero-carbon power and two-thirds power from natural-gas combined-cycle generation will have a higher carbon intensity than conventional hydrogen from natural gas via SMR.[27] The capacity of a green ammonia plant to produce carbon-free ammonia will therefore be determined by a location's energy profile, including how long and at what times low-carbon electricity sources are available. With capacity factors of 25% for solar, 35% for wind, 50% for hydropower (albeit ranging widely between 25% and 80%), 70% for geothermal and 90% for nuclear, the hourly availability of clean electricity will vary dramatically with resource availability in each geography.[28,29] Early adoption of green ammonia will therefore likely begin in geographies with exceptionally generous renewable energy profiles, such as a cost-effective location in Tasmania's grid in Australia, which runs 80% on hydropower.[30] Locations with multiple complementary clean energy sources will also be attractive.

The primary obstacle for the deployment of green ammonia is its high cost. When assuming an electricity price of 7 cents per kWh, the baseline levelized cost for green ammonia is roughly $1000/t using renewable energy and $900/t using nuclear energy.[21] The primary cost driver of green ammonia is the cost of green hydrogen, which is dependent on the price of electricity. In places where optimal renewable conditions produce low electricity prices, green ammonia may already be cost competitive, such as at prices of 4.5, 3.2 and 2.3 cents/kWh for utility solar in Morocco, Chile and Saudi Arabia.[8] Furthermore, massive investments by government and industry are expected to drive down capital costs. In fact, the cumulative capacity for projects under development is already projected to reduce capital expenses by almost 60% by 2030.[15]

Government investment to cut the cost of green hydrogen will further improve green ammonia economics. Figure 3-8 shows the cost of avoided CO_2, calculated as the increase in the levelized cost of ammonia production (compared to conventional production) divided by the decrease in greenhouse gas emissions (also compared to conventional production).[21] At green hydrogen costs of $4/kg, the cost per ton of avoided CO_2 for green ammonia production is above $250/t$CO_2$.[21] Yet if the cost of clean hydrogen were to fall to $1/kg in line with the target set

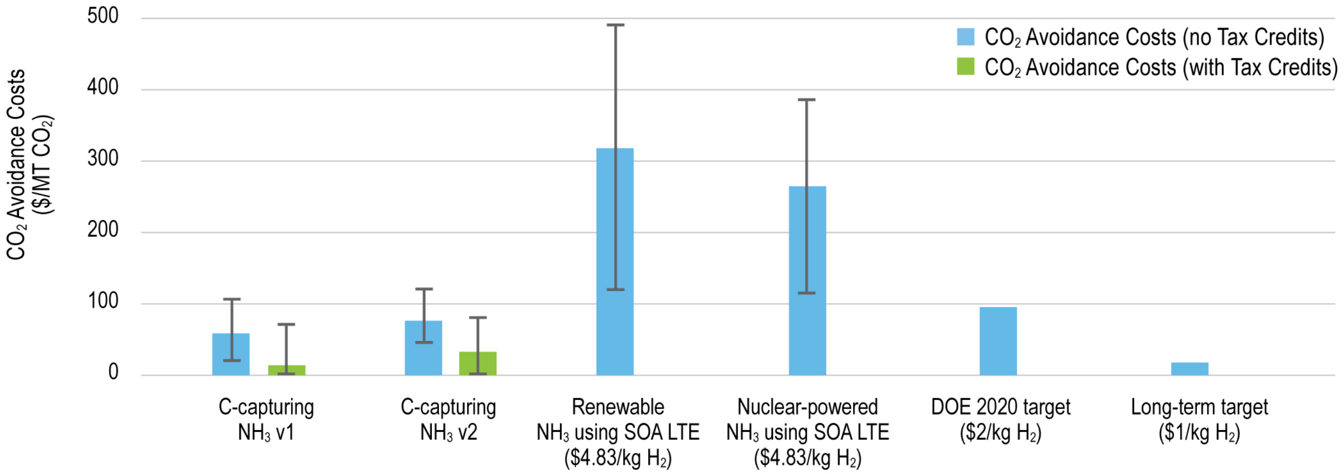


Figure 3-8. *The US Department of Energy's target to bring costs of hydrogen down to \$1/kg dramatically cuts the cost of avoided CO_2 (Lee et al., 2022[21], pg. 12)*

by the US Department of Energy in June 2021, this would bring the cost of avoided CO_2 down to \$16/tCO_2.[21,32] This low cost of avoided CO_2 would be well below the average global CO_2 price of around \$30/tCO_2 at the start of 2022.[33]

Given the novelty of electrolyzer technology and the changing dynamics of the energy system, there is no current consensus on the most effective electrolyzer type and configuration for ammonia production in the long-term. In the short-term, limited electrolyzer manufacturing capacity is one of the likely obstacles for the rapid growth of green hydrogen or ammonia production. Unfortunately, industry analysis estimates that the worldwide electrolyzer supply by 2030 will likely fall in the 30–40 GW range, compared to 54 GW of announced projects and 94 GW of "pledged" projects.[34] This suggests that existing electrolyzer capacity, as well as the capacity to manufacture additional electrolyzers, will be essential.

A potential bottleneck in electrolyzer supply gives the incumbent—the alkaline electrolyzer—increased importance. Alkaline electrolyzers made up 61% of installed capacity in 2020 and currently have the lowest capital cost among all electrolyzer technologies.[15,35,36] Given the technology's long commercial history—400 alkaline electrolyzers were already running by 1902, many for ammonia production[37]—some industry voices have doubted the possibility of further cost reductions or substantial innovations, such as increasing their ability to rapidly ramp capacity in response to fluctuating renewable electricity. However, recent efforts have shown progress in achieving ramping times on the order of seconds, and other innovations, such as zero-gap technology to reduce specific energy consumption and cost-efficient coatings to drive down costs while enhancing cell efficiencies, are being pursued.[38,39]

Proton exchange membrane (PEM) electrolyzers represent 31% of current installed capacity, and have the advantage of delivering hydrogen at high pressure, reducing compression costs.[12,15,26] Furthermore, their wide operating range (0–160% of design capacity) and extremely fast ramping rate give them a flexibility well-suited for integration with renewables.[36,40] First commercially introduced in the late 1980s, PEM electrolyzer technology is still improving.[41] Efficiencies for PEM electrolyzers are reported between 60% and 75% lower heating value, with some commercially available PEM electrolyzers self-reporting efficiencies as high as 84%.[42,43] Industry experts likewise expect substantial future cost reductions.[44]

Finally, solid oxide electrolyzers (SOEC) may be well-suited for green ammonia production due to their high-temperature, high-efficiency operation. First, the typical SOEC operates at 600–850 °C.[45] Because the typical Haber-Bosch process runs at lower temperatures of 425–450 °C, this enables additional efficiencies from heat integration. Furthermore, SOECs outperform alkaline and PEM electrolyzers on efficiency. The IEA estimates

Table 3-2. *Techno-economic characteristics of different electrolyzer technologies.*

Source: IEA 2019, "The Future of Hydrogen"[36]	Alkaline electrolyzer			PEM electrolyzer			SOEC electrolyzer		
	Today	2030	Long term	Today	2030	Long term	Today	2030	Long term
Electrical efficiency (%, LHV)	63-70	65-71	70-80	56-60	63-68	67-74	**74-81**	**77-84**	**77-90**
CAPEEX (USD/kW$_e$)	500 –1400	400 – 850	200 – 700	1100 – 1800	650 – 1500	200 – 900	2800 – 5600	800 – 2800	500 – 100
Stack lifetime (operating hours)	60000 – 90000	90000 – 10000	10000 – 150000	30000 – 90000	60000 – 90000	100000 – 150000	10000 – 30000	40000 – 60000	75000 – 100000
Load range (%,relative to nominal load)	10-110			0-160			**20-100**		
Operating temperature (ºC)	60-80			50-80			**650- 1000**		
Operating pressure (bar)	1-30			30-80			**1**		

Notes: LHV = lower heating value; m^2/kW$_e$ = square metre per kilowatt electrical. No projections made for future operating pressure and temperature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

Sources: Buttler and Spliethoff (2018), "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review"; Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), *The Future Cost of Electricity-Based Synthetic Fuels; NOW (2018), Studie IndWEDe Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr,Strom und Warme;* Schmidt et al. (2017), "Future cost and performance of water electrolysis: An expert elicitation study"; FCH JU (2014), *Development of Water Electrolysis in the European Union, Final Report;* Element Energy (2018), "Hydrogen supply chain evidence base".

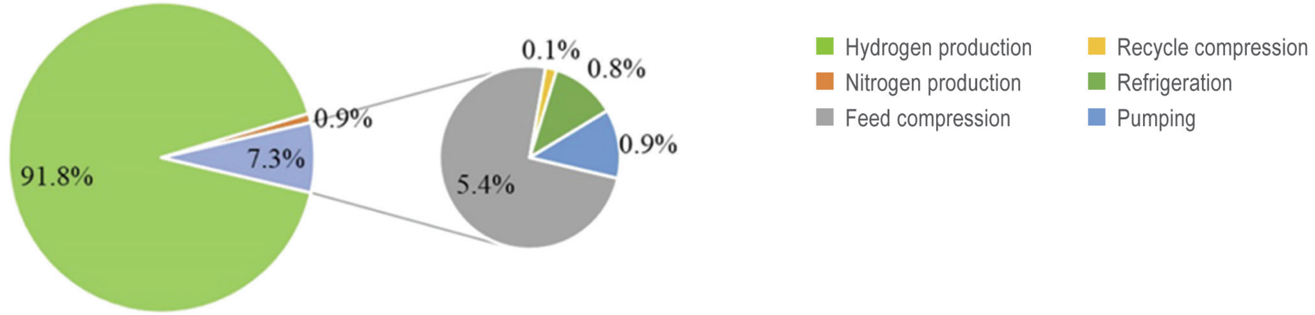
efficiencies of 74–81%, while commercially available SOECs self-report efficiencies as high as 84%.[36,46] In the long-term, if electricity costs continue to constitute the majority of green ammonia production costs (estimated at 85% today),[8] then efficiency levels will be an important factor in choosing an electrolyzer technology, likely favoring SOEC. While much remains unknown at the pre-commercial stage, some industry experts expect substantial cost reductions will make the SOEC technology disruptive to the industry.[44]

Gray ammonia production was optimized through large-scale production and centralization, and these features will likely apply to blue ammonia as well. However, the geographical spread and diversity of clean energy sources for green ammonia production may give rise to small-scale, distributed production. Interest in improving the economics of small-scale, distributed green ammonia motivates research into redesigning the Haber-Bosch process for operation at milder conditions. This research explores both catalyst development and alternative methods to separate out produced ammonia. A typical ammonia synthesis reactor uses a fused-iron catalyst combined with other promoter materials, which is heated to 400 °C at around 150 bar.[26] This produces a single-pass conversion rate below 20%, requiring produced ammonia to be separated out with condensation, meaning it is cooled to -25 to -33 °C at 140 bar before being compressed back to reaction conditions to repeat the cycle.[26] Studies on catalyst development explore strategies for achieving higher catalytic activity at milder conditions, such as by employing alternative metals, using cocatalysts, increasing tolerance to poisons and improving catalyst regeneration.[4,5,47] Likewise, separating newly generated ammonia with absorption technology enables conversion rates of around 80% at pressures as low as 25 bar.[48] Using absorption as opposed to condensation may also provide cost savings, as it reduced manufacturing costs 10% in a 55t/day renewable ammonia pilot plant.[49]

Bio-Hydrogen

Ammonia can also be produced from bio-hydrogen, which refers to hydrogen produced from biomass. Biomass feedstocks include agricultural waste, forestry waste, black liquor from paper production, municipal solid waste, dedicated energy crops, and micro- and macro-algae.[50] Many biomass feedstocks have a high hydrogen-to-carbon ratio, meaning they serve as hydrogen-rich fuel sources.[51] Hydrogen is produced through the thermal decomposition of biomass or through biological processing by living organisms like bacteria.[50]

(a) Total energy consumption in RXN-CON: 9.70 kWh/kg NH_3



(b) Total energy consumption in RXN-ABS: 9.36 kWh/kg NH_3

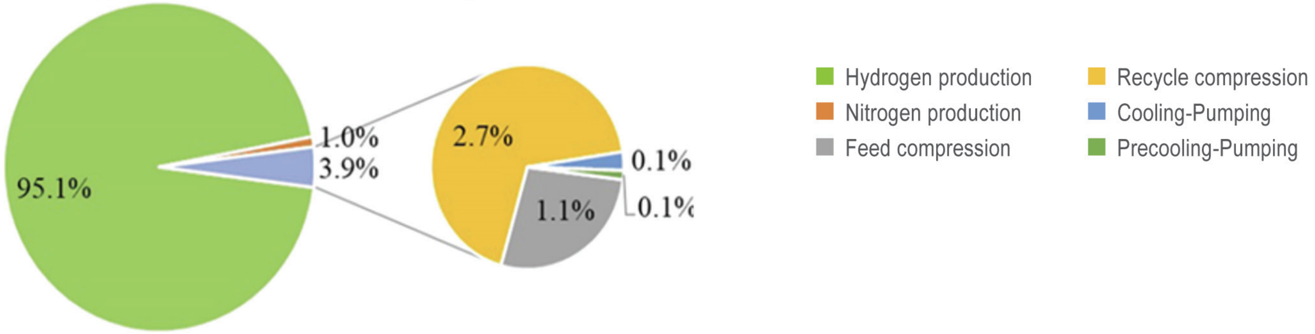


Figure 3-9. *Energy consumption in (a) RXN-CON (150 bar) and (b) RXN-ABS (20 bar). The bigger pie represents energy consumption of the whole plant consisting of hydrogen/nitrogen production and the ammonia synthesis loop. The smaller pie illustrates the energy consumption of unit operations in the ammonia synthesis loop. (Lin et al. 2020,[49] pg. 15525).*

The use of biomass to produce hydrogen can sometimes lead to land-use change (LUC), particularly if economic incentives for producing particular types of biomass are large. This can significantly increase the carbon footprint from bio-hydrogen, such as in the case of converting forest to farmland, which releases stored CO_2 from the soil and vegetation. By contrast, growing perennial grass on depleted land increases the soil's ability to hold CO_2, avoiding major LUC-based emissions.[52] In general, creating carbon sinks on degraded or abandoned land through crops such as switchgrass is preferable and also avoids a competition with land for food or fiber production.[50]

The use of agricultural, forestry or municipal residues and wastes as feedstocks also has a low emissions footprint and eliminates harmful methane emissions released by waste during decomposition, as well as the air pollution released from burning.[50] For instance, roughly 80% of forest residue is burned to prevent forest fires, resulting in additional emissions.[53] Therefore, harvesting wastes and residuals for bio-hydrogen production is typically considered carbon neutral feedstock. Furthermore, ammonia from waste biomass can achieve a negative emissions balance under some circumstances, meaning more greenhouse gases are absorbed throughout the production process than are released to the atmosphere. When biomass feedstocks are (close to) carbon neutral and CCS is used to capture and store this biogenic CO_2 during production,[54] bio-hydrogen is CO_2 net-negative. In a life-cycle analysis of ammonia produced using wood as the biomass feedstock, which is carbon positive due to

Figure 3-10. *The benefits of hydrogen from biomass depend on implementation. Using waste feedstocks is one avenue to maximize benefits.*

LUC and emission during production, employing CCS resulted in negative emissions of-1.7 $kgCO_2/kgNH_3$, meaning the production of ammonia from wood biomass with CCS sequestered more emissions than it released on a life-cycle basis. Although the production pathways and feedstocks for bio-hydrogen vary dramatically, net negative emissions can be achieved in almost all scenarios when CCS is deployed. Conversely, directly using biomass as fuel does result in re-release of carbon stored within the biomass, but in some cases—notably manufacturing ethanol and ammonia—carbon is released as a high purity CO_2 stream that is relatively easy to capture and store.[50]

Biomass has additional features that make it particularly amenable to being used with carbon capture to achieve a negative carbon footprint. Biomass resources are often co-located with places ideal for geological storage of carbon emissions, reducing transportation costs for biomass and/or CO_2.[50] With biomass' low bulk density, transport over large distances could consume more fuel than is stored in the biomass; a 100-km limit is recommended for transport distance.[55]

Depending on the balance between feedstock and electricity prices, ammonia from bio-hydrogen may have a cost advantage over other low-carbon ammonia production methods. In a case study of low-carbon ammonia production routes in the United States, using hardwood as a fuel was 8% more profitable than natural gas in Texas and 32% more profitable than natural gas in California.[56] Wind and solar were not competitive with either, given that the low efficiency of water electrolysis resulted in high electricity consumption and costs.[56] The case study speaks to the importance of local prices, conditions and feedstock availability in determining bio-hydrogen's cost effectiveness.

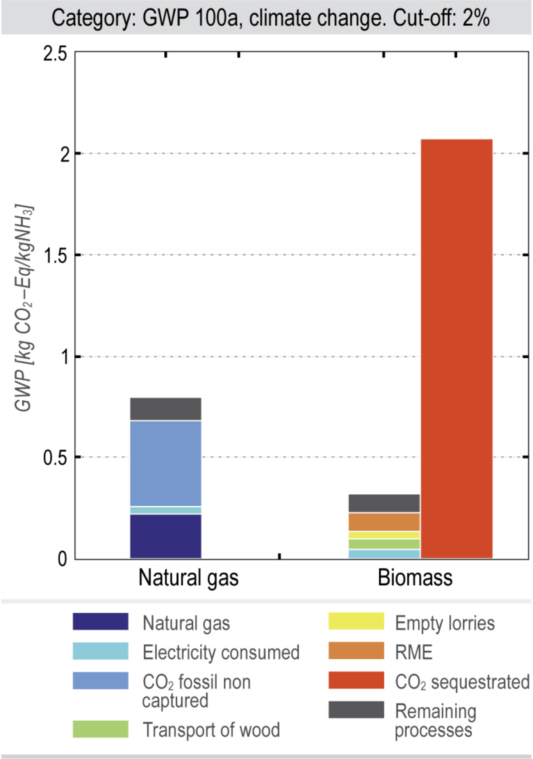


Figure 3-11. *Environmental performance: IPCC07 method GWP 100 years. (Source: Tock et al, 2015,[54] pg. 360).*

Just as biomass has the potential to do tremendous good through effective implementation, it can also cause tremendous harm when done poorly. Biomass cultivation for carbon removal could damage diverse ecosystems (such as through destructive monocultures), have an adverse impact on food security by competing with arable farmland, result in net increases in CO_2 from a poor understanding of emissions in the biomass life-cycle, and risk eco-colonialism should wealthy countries negatively exploit resources in developing countries to mitigate climate change.[50] Responsible sourcing and implementation are central to ensuring biomass is employed to produce ammonia using methods that maximize societal benefit.

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Chapter 4

AMMONIA INFRASTRUCTURE

Using ammonia as a fuel, feedstock or commodity requires special purpose infrastructure dedicated to trade, transportation and fueling. This infrastructure is independent of infrastructure for ammonia production (such as transmission power lines for green hydrogen production) or use (such as local fueling infrastructure). The special purpose infrastructure includes pipelines for transportation, tanks for storage and facilities for maritime bunkering. The type of infrastructure needed is in general a function of the distance ammonia is being transported, with rail and maritime shipping commonly used for transporting ammonia long distances (Figure 4-1).[1]

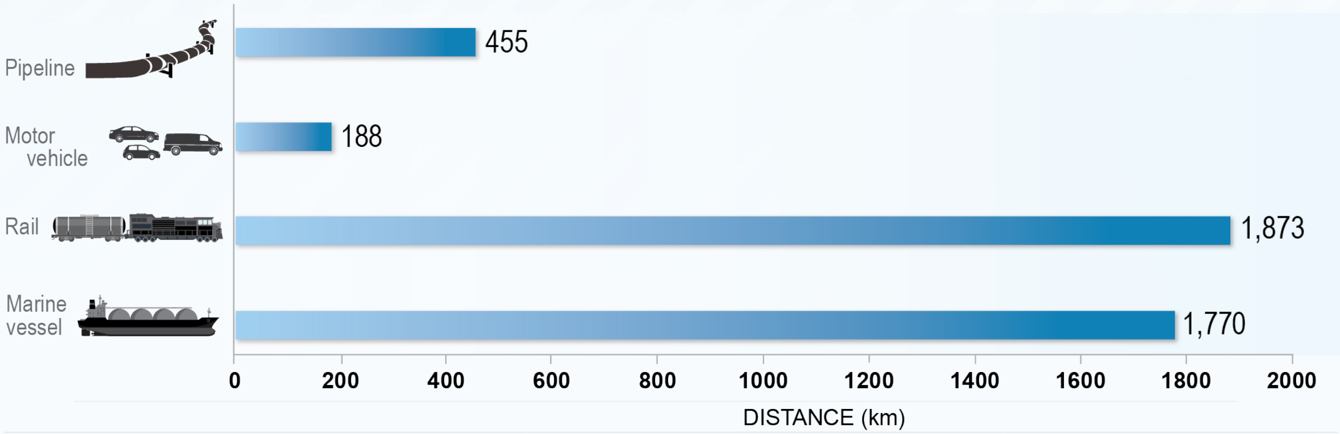


Figure 4-1. *Average distance per shipment by pipelines, motor vehicles, rail and marine vessels in 2017. Source: Elishav et al., 2021.*[1]

At present, the limited extent of this infrastructure constrains the production, trade, shipment, monetization and use of ammonia. Inevitable chokepoints will slow ammonia deployment without substantial investment in permitting, siting and building. The high capital costs and immature markets of today would benefit from new approaches to building and financing dedicated ammonia infrastructure.

Existing Infrastructure and Associated Standards

Ammonia infrastructure, although limited compared to projected demand, exists today with specifications described in standards and executed by regulatory bodies. For example, nearly 8000 kilometers of ammonia pipeline run worldwide today, along with 38 export and 88 receiving terminals (Figure 4-2).[2,3] The US alone has 5000 kilometers of ammonia pipeline and more than 10,000 ammonia storage tanks (Figure 4-3).[3,] These facilities provide an excellent basis for understanding likely costs, performance and scale of ammonia as a future fuel and feedstock. As such, the need for innovation is limited, and the roadmap for deployment is essentially about finance, economics and policy.

These assets and infrastructure elements are built and operated according to standards and regulations in host nations. They generally reflect the core physics and chemistry of ammonia and are well-aligned world-wide. For example, the US Occupational Safety and Hazard Authority (OSHA) publishes their anhydrous ammonia storage tank standard 1910.111,[5] which is similar to the Minnesota pipeline requirements[6] (and built upon the American Society of Mechanical Engineers (ASME) standard B31.4[7]). The standards include requirements for operating pressure, metallurgy, corrosion resistance and labeling.

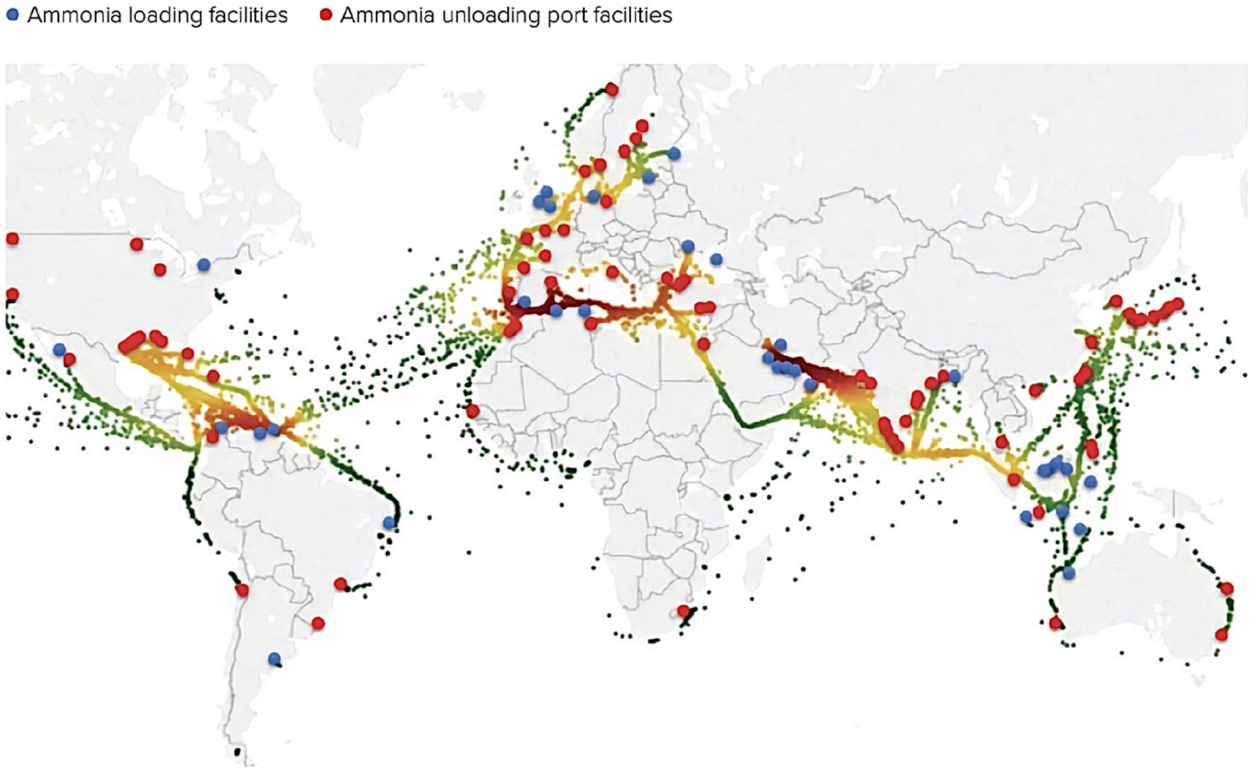


Figure 4-2. *Map of global ammonia facilities, including a heat map of liquid ammonia carriers and existing ammonia port facilities. Source: Royal Society, 2020.*[3]

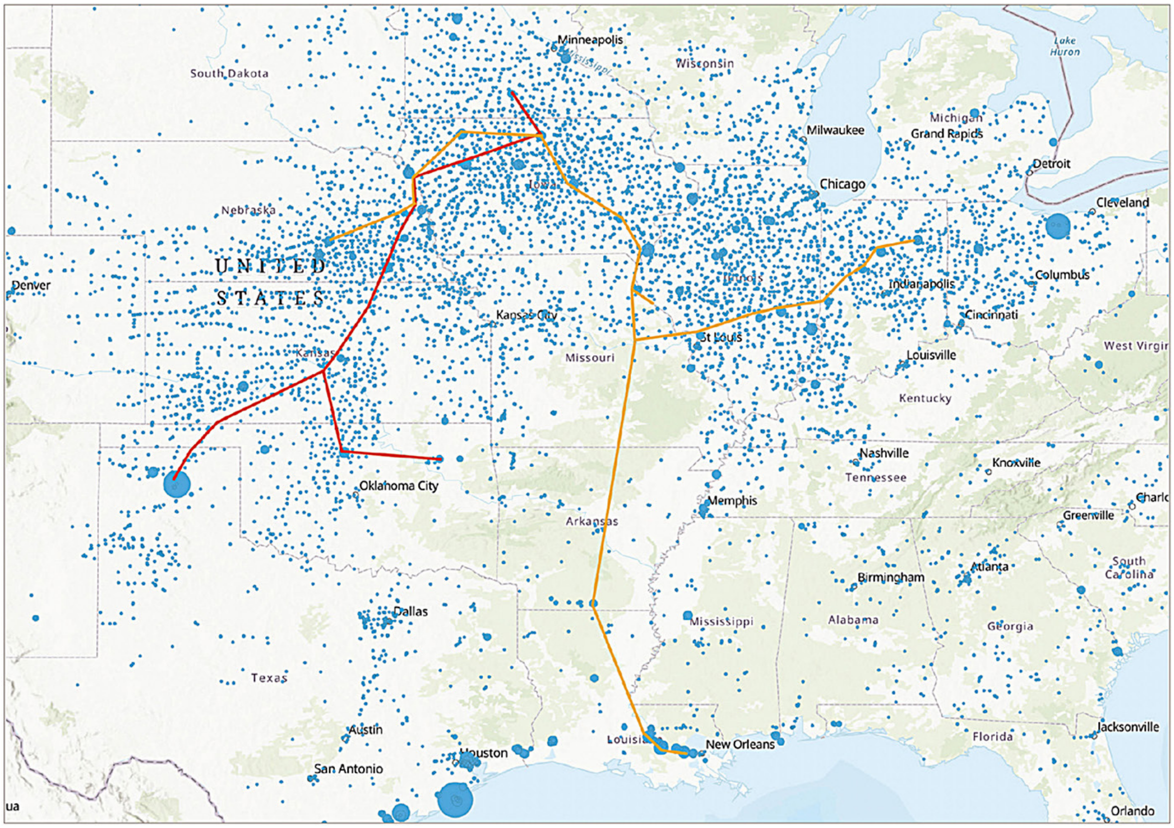


Figure 4-3. *Map of central US storage facilities and pipelines. Orange line is the Kaneb Pipeline; red is the Magellan pipeline. Circles are storage facilities, with largest circle representing 100,000-ton storage capacity. Source: Royal Society, 2020.*[3] *Data, EPA, 2017.*[4]

Ports and Bunkering Facilities

Port facilities will serve essential functions for low-carbon ammonia scale up. Chiefly, they will serve as hubs of trade, where large volumes of ammonia are stored and shipped as cargo. They will necessarily serve as bunkering (fueling) facilities for maritime fuel use. In addition, they will host some production facilities and ammonia conversion and use facilities. To accommodate these roles, existing facilities will be upgraded, existing ports will be expanded, and new ports and facilities will be added to the global portfolio.

PORTS

The majority of ammonia ports today (120 ports out of 195 total) are receiving terminals linked to fertilizer production. A smaller number (35) are cargo export terminals.[8] Projected increases from announced projects would grow 50% by 2030 and 100% by 2040.[8] Many of these will serve southeast Asia, for maritime fueling and logistics support as well as local consumption and use.

Table 4-1. *Liquid hydrogen terminals and ammonia terminals – a comparison.*

Export terminal parameters	Unit	LH_2 carrier	HN_3
Tank capacity	m^3	192,000	104,000
CAPEX	M$	1161	209
Electricity consumption	kWh/kg	0.2	0.001
Duration one loading	days	1.5	1.5
Time between loadings	days	15	15

Import terminal parameters	Unit	LH_2 carrier	HN_3
Tank capacity	m^3	192,000	104,000
CAPEX	M$	1161	209
Electricity consumption	kWh/kg	0.2	0.001
Boil-off rate	%	0.1	0.1
Duration one loading	days	1.5	1.5
Time between loadings	days	15	15

Cost assumption based on data from the Institute of Applied Energy (Japan) report: "Economical Evaluation and Characteristic Analyses for Energy Carrier Systems (FY 2014–FY 2015) Final Report". Link: www.nedo.go.jp/library/selka/shosai_201610/20160000000760.html

^^(IEA, 2021,[9] pg. 109)

Port of Rotterdam Facility

The Port of Rotterdam is Europe's largest port and industrial hub, including serving current fuel and feedstock imports (i.e., liquefied petroleum gas (LPG) and liquefied natural gas (LNG)) that supply refineries, chemical manufacturers, and steel and cement production. To meet EU climate obligations (specifically the "FitFor55" plan"), national obligations (e.g., the Netherlands Paris commitments), and the proposed carbon border adjustment mechanism, as well as reducing reliance on important natural gas, the Port has set a target of supplying northern Europe with 4.6 Mt/y of clean hydrogen by 2030,[10] largely supplied by green and blue ammonia.

Three projects have been announced to date—all in 2022:

- OCI will expand its current ammonia facility from 400,000 t/y to 1.2 Mt/y—a 3x expansion. This project has already received final investment decision and should be operational by 2023. This first phase of the project will cost less than $20 million.[11] In the second phase, a new ammonia tank will be built to allow throughput to increase beyond 3 million t/y.[11]

Figure 4-4. *Gasunie's planned hydrogen distribution infrastructure for northern Europe.*

- Gasunie, HES International and Vopak will develop a new import terminal (the ACE terminal) for ammonia adjacent to Gasunie's existing ammonia storage complex. The project will expand existing tank storage, add a new deep-sea quay and include a cracking facility that ties to existing hydrogen pipelines and repurposed natural-gas pipelines. The project should be operational in 2026. While data on the cost of the ACE terminal are not publicly available, it will likely fall in the range of the GATE LNG terminal nearby, with costs of $1.1 billion in 2011.[12]

Air Products and Gunvor Petroleum are modifying an existing refinery to serve as a green-ammonia receiving terminal. The new facility should be operational in 2026.

Ports for loading and unloading ammonia cargo require docks, quays, berths and storage tanks. The tanks are pressurized isothermal tanks connected to special pipe and valve systems that discharge and receive ammonia cargo and are placed on special pressurized, refrigerated ships (similar to LPG tankers). For a substantial facility, costs can exceed $1 billion for this infrastructure, as shown by a detailed US Army Corps of Engineers analysis of a new port in Galveston, TX.[13,14]

BUNKERING

For maritime fuel application, bunkering is a key prerequisite for deployment and requires separate consideration from fuel supply or cargo storage infrastructure. In many ports, physical space for these new elements (fueling storage and bunkering facilities) is a limiting constraint. In others, fuel supply is the limiting constraint. For example, the storage tanks at bunkering facilities are commonly 25–50% greater capacity than the ships they serve.[1]

Investment is urgently needed to assess the challenges of bunkering and develop potential solutions. Many groups have begun work to develop alternatives and solutions:

- **Analysis:** Japan, Singapore, France and other nations have created a joint study framework[15] that will include assessments of challenges and solutions for both bunkering and maritime architecture for ammonia fueling.
- **Investment:** Several governments, including Japan,[16] have dedicated funds to building ammonia bunkering infrastructure, in partnership with domestic[17] and international companies. Similarly, the Singapore-based Global

Centre for Maritime Decarbonisation has approved funding for pilots[18] of both truck-to-ship and ship-to-ship bunkering with an eye toward knowledge-building for regulation and safety practice.

- **Floating bunkering:** To avoid space constraints, bunkering facilities can be added offshore. One company, Azane Fuels, has developed floating, movable bunker[19] equipment, specifically to help facilitate the transition to ammonia as a maritime fuel. Yara, a Norwegian fertilizer producer, has pre-ordered[20] the first 15 [21] of these facilities for Scandinavian green ammonia supplies. Singapore has commissioned a ship-to-ship bunkering assessment[22] with the goal of creating the first green ammonia bunkering hub.

As part of a transition roadmap to low-carbon ammonia use, analysis on the costs and trade-offs of bunkering infrastructure would greatly reduce risk and cost while speeding deployment. Importantly, companies and nations should share information from such analysis to avoid waste or delay in deployment. Such information sharing could begin easily under existing bilateral agreements and be further facilitated by the International Maritime Organization (IMO) or groups like the Ammonia Energy Association or the Clean Fuel Ammonia Association.

Ammonia Storage

Ammonia must be stored before transport and shipping. Although there is a rich set of ideas and potential novel approaches to ammonia storage (a search revealed over 270 US patents for ammonia storage technology), almost all ammonia is stored in tanks. There are three main types of storage system: pressurized, low-temperature and semi-refrigerated.[1] The majority of tanks are the low-temperature variety (Figure 4-5), of which there are five main designs (Figure 4-6[1,23]) that can hold large volumes of ammonia (up to 50,000 tons). Tanks are built and operated to commercial standards (e.g., the API 620 R or EN 14620 standards), and tank construction and operation are straightforward, with many companies providing these services.

Costs are relatively well known and can represent a substantial cost to project developers. For a proposed Mt/y facility in Galveston, TX, the two storage tanks required have a combined estimated cost of $500 million.

Salt caverns could provide a storage option for large ammonia volumes at low cost. Salt domes occur on every continent, and some are used today to store other fuels and feedstock (e.g., crude oil, natural gas and hydrogen). Salt caverns are made through dissolution mining and can store large amounts of energy indefinitely at low cost (~$1/kwH up-front cost). Room and pillar mining is also an option in the right geologies. Salt-cavern storage can be difficult to permit depending on local circumstances.

Despite being an old idea (patents stretch back to 1954[24]), there appear to be no subsurface ammonia facilities operating today (although at least one US facility stored ammonia underground in salt, unexpectedly, in New Jersey[25]). It is believed that conventional salt domes can serve as large, localized storage hubs, like those used to store crude oil and hydrogen today. It is unclear what is needed to convert a salt storage facility to ammonia with respect to metallurgy, other special materials and permitting.

Ammonia Pipelines

Large volumes of ammonia move across continents by pipeline. Most pipelines are short; for example, although Europe has 25 pipelines, most are less than 10 km in length and only two are 25 km or greater.[1] However, the US does have several major trunk lines totaling nearly 5000 km, and Russia has built a 2400 km pipeline. The US pipelines move over 2 million tons of ammonia per year (Mt/y) and were built with an estimated cost of ~$250 million in 2019 dollars.[26,27]

Pipeline transport of liquid ammonia is a safe, low risk and, once installed, cost-effective mode of transporting ammonia between locations.[28] Overall, ammonia pipelines appear to have an excellent safety record—roughly 2 times better than other pipelines and 7–8 times better than other forms of bulk transportation (NuStar, 2021[29] based on 2019 Bureau of Labor Statistics studies).

__Figure 4-5.__ Refrigerated ammonia storage tanks.

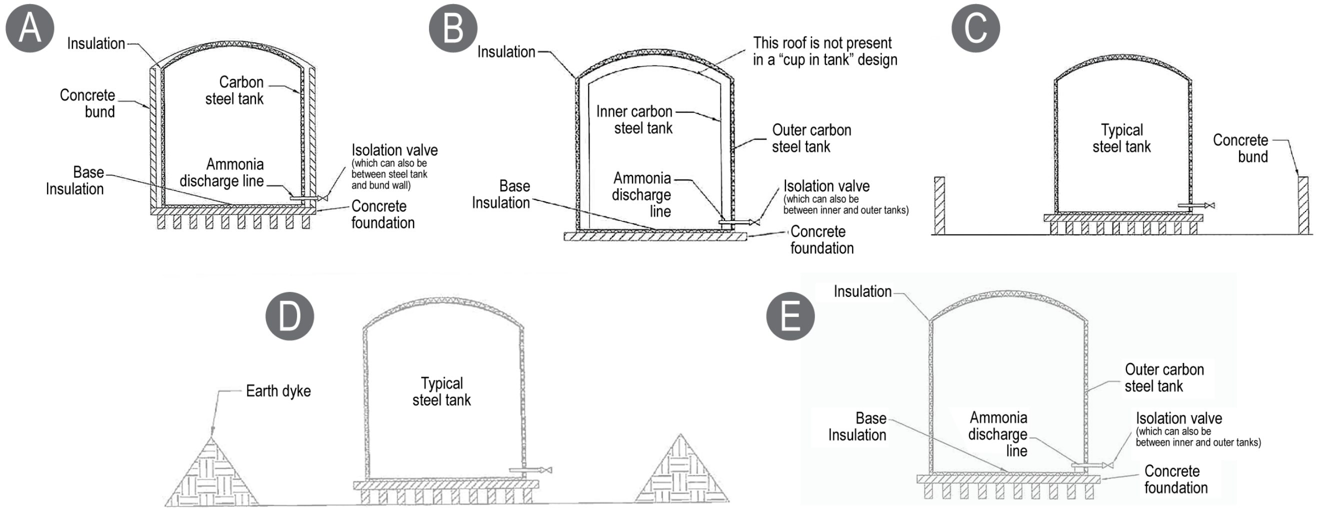


__Figure 4-6.__ Low-temperature ammonia storage tank types: (A) steel tank enclosed by a concrete wall, (B) tank with outer and inner steel walls, (C) tank with distant partial height concrete bund, (D) tank with earth dike, and (E) single wall tank. Source: Elishav et al., 2021.[1] Original image courtesy of Fertilizers Europe; 2014[23].

NEW PIPELINES

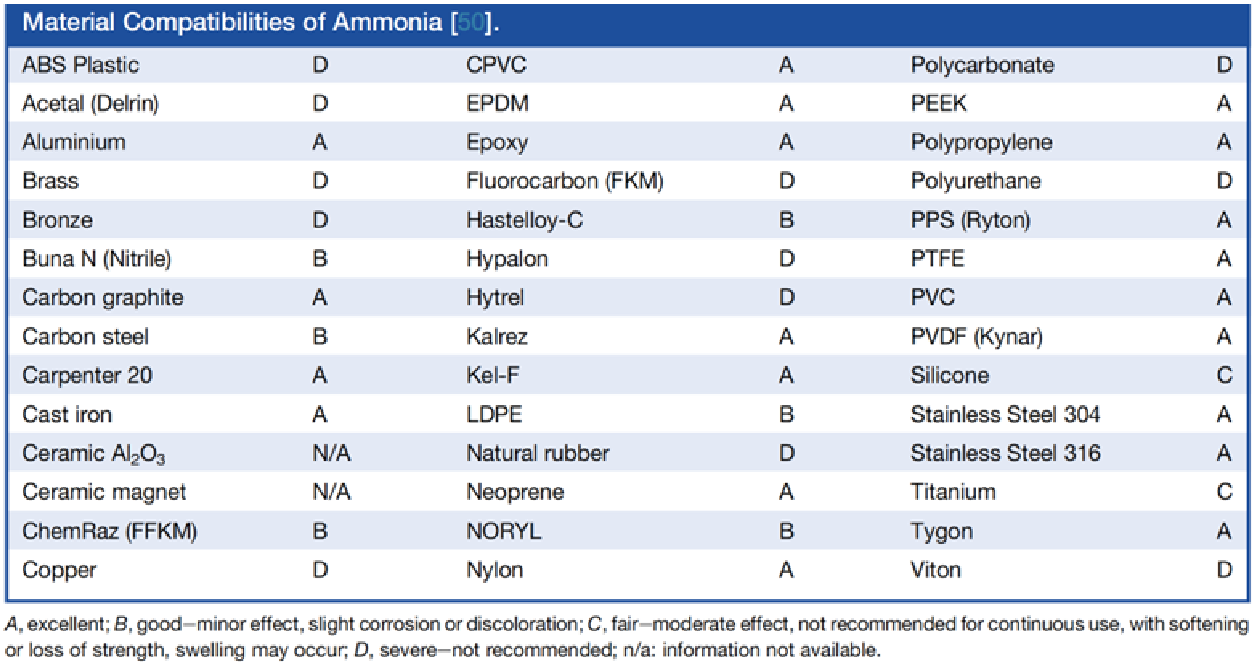
New pipeline costs vary as a function of flow-rate, length, diameter, geography and temperature. Long-distance costs do not require compressors but do require pumps (usually centrifugal pumps). Costs are reasonably well understood—CAPEX costs are roughly \$500/km/year and OPEX per booster station is ~\$400,000/y.[28]

Such costs are ultimately low. Salmon et al., 2021[28] estimates that, for 1000-km pipelines that are 1 Mt/y or larger, the costs are \$2–4/t of ammonia, or less than 1% of the market delivery price. Al-Breiki & Bicer, 2020[30] found similar estimates at ~\$1/GJ.

In general, ammonia moves through pipelines as a liquid, not a gas. As such, the footprint is reasonably small—commonly 6–10-inch (20–26-cm) diameter and as large as 16 inches (~50 cm). Carbon steel is sufficient to transport ammonia, so no special alloys are required, although low water content is also required. Because of the relatively low pressures involved, most refrigeration operating costs are similar to those of LPG pipelines—roughly 50% less than pressurized natural gas distribution lines and 75% less than dedicated new hydrogen pipelines.[30]

Many different pipeline materials (and storage materials) are compatible with ammonia (Table 4-2.[31]). In particular, plastic compounds (nylon, neoprene, PVC) appear effective. The most commonly used material for ammonia tanks

Table 4-2. *Material Compatibilities of Ammonia. A = excellent; B = good (minor effect, slight corrosion); C = fair (moderate effect, not recommended for continuous use); D = severe (not recommended). Source: Crolius et al., 2021,[31] data from Cole-Parmer.*



Material Compatibilities of Ammonia [50].

ABS Plastic	D	CPVC	A	Polycarbonate	D
Acetal (Delrin)	D	EPDM	A	PEEK	A
Aluminium	A	Epoxy	A	Polypropylene	A
Brass	D	Fluorocarbon (FKM)	D	Polyurethane	D
Bronze	D	Hastelloy-C	B	PPS (Ryton)	A
Buna N (Nitrile)	B	Hypalon	D	PTFE	A
Carbon graphite	A	Hytrel	D	PVC	A
Carbon steel	B	Kalrez	A	PVDF (Kynar)	A
Carpenter 20	A	Kel-F	A	Silicone	C
Cast iron	A	LDPE	B	Stainless Steel 304	A
Ceramic Al_2O_3	N/A	Natural rubber	D	Stainless Steel 316	A
Ceramic magnet	N/A	Neoprene	A	Titanium	C
ChemRaz (FFKM)	B	NORYL	B	Tygon	A
Copper	D	Nylon	A	Viton	D

A, excellent; *B*, good—minor effect, slight corrosion or discoloration; *C*, fair—moderate effect, not recommended for continuous use, with softening or loss of strength, swelling may occur; *D*, severe—not recommended; n/a: information not available.

is carbon steel, which has proven effective overall. However, steel and some steel alloys, suffer stress corrosion cracking, which present a valid risk to operations.[1,31] Although corrosion can be prevented or limited by simple low-cost approaches (e.g., adding small amounts of water or hydrazine), care must be taken in building and operating pipelines, and regular surveys and checks are recommended. In addition, on a performance and exergy basis, circulating loops can help reduce corrosion from volumetric differences in transfer points.[32]

An innovation agenda focused on novel, low-cost solutions to ammonia-related stress corrosion cracking (both prevention and mitigation) would likely serve companies and the communities involved. To quote Elishav et al., 2021,[1] "additional research on suitable corrosion-resistant steels is vital to reduce construction metal capital costs in ammonia combustion services."

RETROFIT/REPURPOSED PIPELINES

In anticipation of ammonia infrastructure build out, recent research has focused on repurposing existing natural gas lines for ammonia transport. At ambient conditions (i.e., in gaseous form), the physical properties of ammonia and methane (such as density, specific heat, compressibility, viscosity) are quite similar. In addition, ammonia lines have benefited historically from joint construction of LPG and refined product pipelines in terms of materials, rights of way and construction costs.[26]

Based on limited study,[1] it appears that no special metallurgy or retrofit is required. However, to avoid substantial pressure changes, it appears that pipelines of diameter >0.75 m show the most promise for repurposing. Also, since many natural-gas pipeline networks have multiple diameters and compositions along any given length, detailed survey and testing is required. Finally, the different chemistry of natural gas requires purging, decommissioning and recommissioning prior to use for ammonia transport. Permitting bottlenecks and lack of human capital may limit the speed and scale to which natural gas systems could be converted for ammonia transport.

Generally speaking, repurposing of existing infrastructure (natural gas, LPG, etc.) for ammonia transport is under-investigated. This area represents another potential focus for R&D and analysis as part of a low-carbon ammonia transition roadmap.

Hybrid LNG-Ammonia Infrastructure

It appears straightforward to convert LNG infrastructure—in particular LNG receiving terminals and storage facilities—to ammonia.[33] This has important implications, specifically around avoiding or mitigating fossil fuel infrastructure lock in.

Two key infrastructure elements for both import and bunkering are the regasification and storage systems (Figure 4-7). Some important components of the systems, such as the compressor systems, pumps, and sensors or control systems, would require substantial modification or replacement.[33] However, the full capital cost of these modifications represents a small fraction (11–20%) of the total capital cost of the original system. For a facility that cost roughly $1 billion to build, repurposing costs would range from roughly $100–200 million per facility—a substantial cost but within the realm of both public and private financing.

For storage systems, the materials and metallurgy for LNG and ammonia storage are compatible.[33] Stress corrosion cracking (described above) would remain an issue for those tank systems built of carbon steel and nickel steel. Owners and operators must adhere to the design codes for storage tanks to avoid additional safety and cost risks. Since the storage temperatures for ammonia are much higher than for LNG, repurposed tanks would already reach the boil-of-gas thresholds for operation.

Conversion from LNG to ammonia would require decommissioning and recommissioning. Again, this could present both time and cost for adoption based on the ability of permitting agencies to grant permits—which itself is a function of local laws and regulations—and human capital.

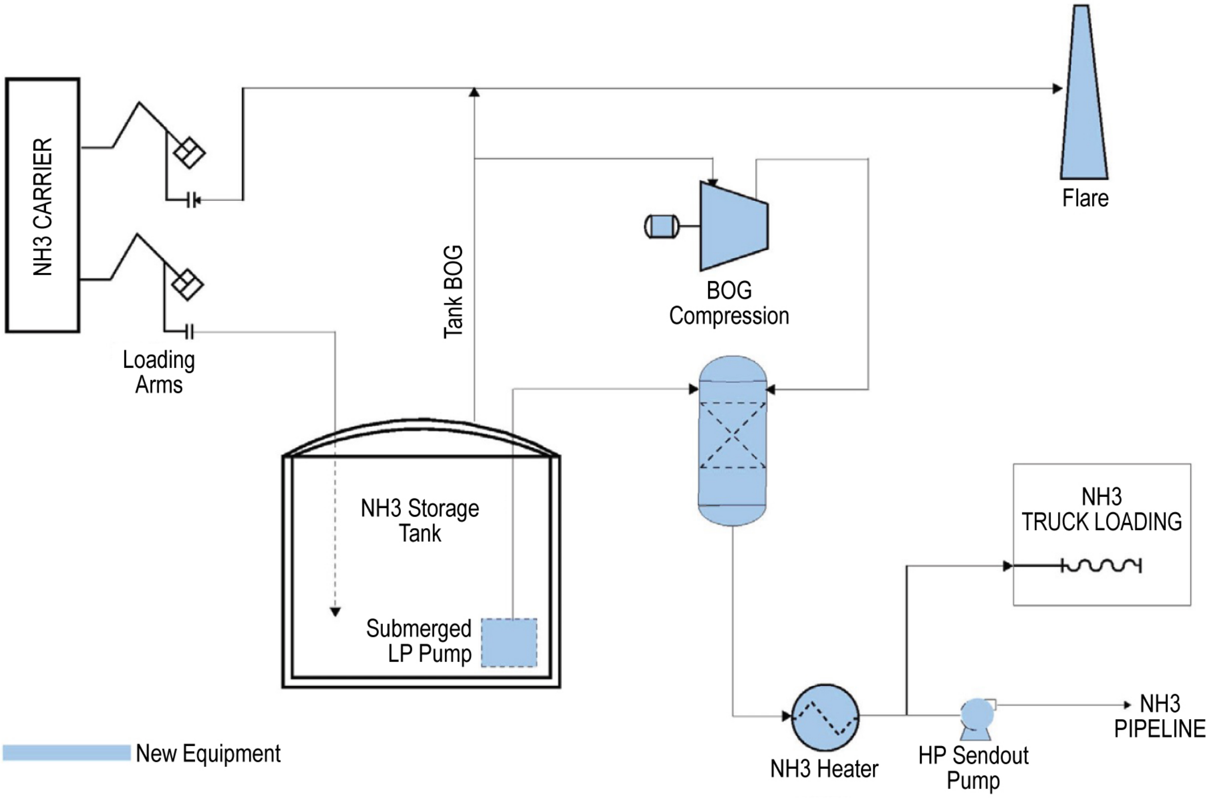


Figure 4-7. *Schematic diagram of an LNG import and storage facility that has been converted to ammonia. The blue shading indicates equipment and material that require substantial modification or replacement for ammonia import and storage. Ghasemi, 2020.*[33]

Table 4-3. *Estimated capital expense required to convert an existing LNG export terminal into an ammonia terminal. Ghasemi, 2020*[33]

Impacted Systems	LNG Import CAPEX (%)	Modification cost impact (%)	Total CAPEX impact (%)	Remarks
Storage Tank	40-50	3	1.0-1.5	Full containment, 63% capacity
Boil-off gas (BOG) system	10-15	5-8	5.0-8.0	A new compressor package is required (total CAPEX impact), based on 2x50% compressors.
LP/HP pump	3-5	1-3	1.0-3.0	New pumps as old pumps are replaced
Piping	5-10	40	2.0-4.0	Includes flare support & new flare-stack piping
Instrument & Control System	3-5	70	2.0-3.5	Includes control valves, fire & gas sensors, inline devices, etc.
Total			**11.0-20.0**	

In considering LNG-ammonia hybrid-design or retrofit, forward analysis would help investors and policy makers understand the range of potential opportunities, costs and barriers. Such analysis could provide insights to roadmaps and better frame policy options for public financing, incentives and public-private partnerships associated with both new facilities (fixed or floating) and retrofits for existing facilities. Such policies would affect timelines for deployment and, potentially, affect national commitments to clean energy transition.

Additional concerns

Overall, design and construction of ammonia infrastructure for transportation, bunkering and storage is well understood and relatively straightforward. However, rapid deployment as part of the energy transition is likely to face challenges from limits that lie outside technical or financial concerns. The most critical limits include limits in human capital, rate of permitting and concerns around equity and justice.

HUMAN CAPITAL

Three kinds of human capital are required to deploy ammonia bunkering and storage infrastructure. The first is experts in ammonia-specific construction, including specialty welders, builders, electricians and maritime (surface and subsea) workers. The second is designers and architects, both maritime and onshore, familiar with the construction of ammonia pipelines, tanks and port facilities. The third is experts in regulation and approval, including inspectors, regulators and safety authorities.

All three are in short supply. In general, skilled workers are in short supply and demand competitive wages (e.g., Boreham, 2022[34]), which can increase labor and project costs. Similarly, the number of years of experience in ammonia handling (e.g., refrigeration) has decreased due to labor shortage; quoting Evapco, 2017,[35] which states "the number of available ammonia… jobs dwarfs the number of qualified operator/technicians available. Utilizing… ammonia systems does not eliminate the need for operator training." In addition, training and regulatory bodies (e.g., the US OSHA) have rigorous training requirements and educational standards.[36] The same is true for designers, architects, inspectors and regulators—there is a global shortfall of trained experts with experience.

This problem could be resolved through focused and committed training programs. Programs could be expanded within existing industrial and commercial companies and supported through a combination of public-private partnerships. Trade schools and community colleges could play outsized roles (e.g., apprenticeship programs), and minority-serving institutions could receive additional support to expand programs and, with them, opportunities.

Governments could expand certification training programs and pay for short courses, both online and in the field, to expand the worker pool. Absent such measures, it is likely that projects and roadmaps will experience delays in implementation due to worker shortages and face increased risk due to lack of training and expertise in the field.

PERMITTING

Timely approval of permits for ammonia infrastructure faces challenges beyond human capital shortages. Because of the popularity of anhydrous ammonia as a fertilizer and the risks associated with transportation and storage, many nations have specific regulations for ammonia handling and infrastructure.[37] Approval for permits to build and operate ammonia infrastructure can be time consuming, specifically because the health and environmental risks are substantial.

The tendency of many government officials and regulators in such circumstances will be to take additional time or add requirements to projects, especially large projects of regional or national importance. This is not limited to ammonia. Hydrogen pipelines have already suffered these delays (e.g., in the EU), which will directly limit ammonia opportunities. The approval process has also languished for natural gas pipelines,[38] offshore wind projects[39] and power transmission lines.[40-42] Regional regulators with limited or no experience permitting analogous systems will reasonably wish to take extra care in approval. In addition, permitting guidelines are changing, often to reflect new desires for both better local environmental outcomes and environmental justice.[43]

Absent direct focus on accelerating approval processes without compromising safety, it is reasonable to expect the permitting and approval process to be a chokepoint. Legislators and regulators should work with experts in safety, environment and health to understand what the most salient concerns and risks are and how to respect those risks while approving projects.

ENVIRONMENTAL JUSTICE AND EQUITY CONCERNS

Ammonia storage, bunkering and pipeline facilities raise concerns about equitable application of existing laws. Some portion of these facilities—potentially a large portion—will seek permits to build and operate in areas with underserved and disadvantaged populations. Although the substantive health, safety and environmental hazards can be managed effectively and well, communities near proposed facilities may have reasonable concerns about potential risks, ranging from property values to disease and childhood mortality.

Recent focus on questions of equity and justice around energy development, notably in the US, have prompted questions about how best to balance the needs of disadvantaged communities with the needed rapid response to climate change. At present, there are few clear pathways to both respect and resolve concerns. The Biden Administration has created special offices, in both the White House[44] and the Department of Energy,[45,46] to better serve community needs while also supporting valid projects of import. As ammonia projects grow in local and national importance, these offices will generate new findings and processes that hopefully can serve all stakeholders well.

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Chapter 5

USES OF LOW-CARBON AMMONIA

Low-carbon ammonia could help cut greenhouse gas emissions across many sectors. This chapter explores that potential, examining possible uses of low-carbon ammonia, their technical feasibility and the extent to which using low-carbon ammonia could contribute to net-zero emissions.

Ammonia is already in widespread use globally, as a fertilizer and for other purposes. (See Chapter 2 – The Ammonia Industry: Past and Present.) The most straightforward way for low-carbon ammonia to contribute to achieving net-zero emissions is by replacing conventional ammonia in existing applications. This could cut global CO_2 emissions by roughly 1.3% (the percent of global emissions currently attributable to ammonia production).[1] Beyond that, low-carbon ammonia could substitute for fossil fuels in transportation, the power sector and heavy industry. This appears to be a promising decarbonization strategy in some sectors and sub-sectors, though less promising in others. In all cases, low-carbon ammonia will need to compete against other decarbonization strategies as the world transitions to net-zero emissions.

Low-carbon fertilizer

Ammonia is most widely used today as nitrogen fertilizer for agriculture. Around 70% of ammonia production globally is used to make fertilizers, with the rest used as a feedstock in making explosives, plastics and other products.[1]

Emissions of ammonia for fertilizer production amount to 434 million tons of CO_2 per year ($MtCO_2/y$). This includes 315 $MtCO_2/y$ from direct emissions from the ammonia production process (Scope 1), as well as 119 $MtCO_2/y$ emissions from external power and steam consumption (Scope 2) and fertilizer synthesis, such as urea or ammonium nitrate (Scope 3), combined.[1] The International Energy Agency (IEA) projects that ammonia demand for agriculture will grow roughly 40% by 2050 as a result of population growth and economic development, if governments' current policies remain roughly the same. Emissions from ammonia production will grow proportionally unless changes are made to current production processes.

The climate impact of low-carbon ammonia for fertilizer is a function of the replacement ratio (i.e., how much conventional ammonia is replaced by low-carbon ammonia) and the carbon footprint of the low-carbon ammonia itself. Because the use of ammonia-based fertilizer is a technically mature application, ***no innovation is required to transition to low-carbon ammonia in agriculture from an application perspective;*** it is effectively a "drop-in" replacement for conventional ammonia. The agriculture sector can therefore immediately adopt low-carbon ammonia within the existing infrastructure for ammonia transport and distribution and directly apply it (or derivatives, such as urea and ammonium nitrate) to crops. However, this is likely to increase costs compared to conventional ammonia.

Substituting low-carbon ammonia for conventional ammonia will not change the greenhouse gas emissions caused by applying ammonia fertilizer to fields. This process releases the greenhouse gas nitrous oxide (N_2O) to the atmosphere no matter how the ammonia is made, although different ammonia-derived fertilizers have very different N_2O emissions levels after application (see Figure 5-1).[2] Sosulski et al., 2020[3] analyzed the relationship of soil N_2O emission level with the fertilizer application, showing that excessive surface-soil fertilizer application will lead to unnecessary high-level N_2O emission, which can be greatly abated by precise deep-soil application. Low-carbon ammonia substitution, however, only contributes to climate-change mitigation by eliminating production-phase N_2O emissions, which are already insignificant. Strategies for reducing N_2O emissions from

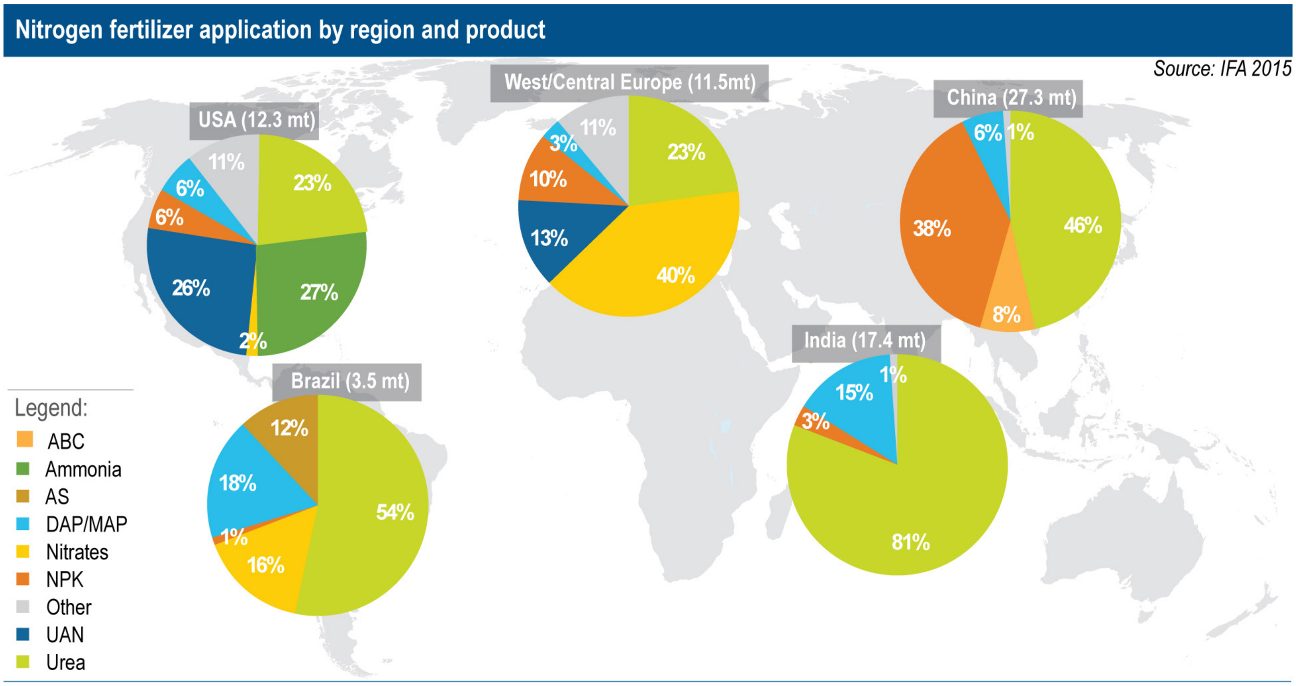

Figure 5-1. *Nitrogen fertilizer application by region and product. (Source: IFA[4])*

agricultural application of ammonia fertilizer is a separate research topic. It is worth noting that any ammonia that leaks during production and transport may lead to additional N_2O emissions, depending on its fate. (See Chapter 6 – Safety and Local Environmental Impacts of Ammonia.)

Hydrogen carrier

While ammonia is used as a fertilizer because of its nitrogen carrier capability, it is now widely investigated for its hydrogen carrier capability. This is because ammonia is much easier to store and transport at large scale than hydrogen due to its much stabler and more moderate physical and chemical properties. The International Renewable Energy Agency (IRENA) estimates that 127 Mt/y of ammonia (18% of total global production and ~37% of globally transported ammonia) will be converted back to hydrogen before being used in 2050.[5]

Ammonia conversion to nitrogen and hydrogen (also known as ammonia decomposition, cracking or dehydrogenation) is a thermo-catalytic process under relatively high temperature, roughly 200–400 °C depending on the types of catalysts.[6] Typically, after ammonia decomposition, the hydrogen stream will be harvested and used for further applications, and the nitrogen stream will be directly vented to the atmosphere. This process requires energy input and results in inevitable energy loss, typically 0.28–0.30 MWh/ton-ammonia.[7] For high-purity hydrogen applications, 15% hydrogen loss is considered the current best practice scenario because only 85% of the input hydrogen can be recovered due to the purification process. The combination of energy and hydrogen loss leads to a total ammonia cracking efficiency of 76%.[7] Additional losses will occur if there is a need for additional compression and transportation/delivery of the resulting hydrogen.

The decomposition reactions can also be applied as part of a two-step indirect ammonia fuel-cell system: (1) ammonia decomposition to N_2 and H_2 and (2) using hydrogen for power generation in a standard hydrogen fuel cell. The indirect ammonia fuel-cell system can maximize the technology benefit from the hydrogen fuel-cell system, which leads to potential cost saving and technical maturity, representing an opportunity available in the short-term. (Direct ammonia fuel cells that avoid decomposition to hydrogen have a much lower technology readiness level, see "Power generation section.")

Ammonia combustion

Many of the proposed novel applications of low-carbon ammonia are based on combustion. Compared to carbon-containing synthetic fuels (e.g., methanol, bio-diesel, synthetic methane), ammonia combustion is carbon-free with no direct greenhouse gas effect from CO_2. Ammonia is also relatively easy to store and transport, providing an option for international trading and long-term storage to balance seasonal demand. However, these novel ammonia combustion applications all face similar challenges because of the drawbacks of combusting ammonia compared to well-established carbon-based fuels.[8-10] Similarly, due to its nitrogen element, ammonia combustion also has drawbacks compared to pure hydrogen combustion, which is also a strong candidate currently under development.

First, ammonia is harder to ignite than hydrogen and hydrocarbon fuels because of its relatively high auto-ignition temperature (650 °C compared to methane at 630 °C and hydrogen at 520 °C) and lower flame temperature, meaning it is hard to ignite while the heat release rate is generally lower. Additionally, ammonia oxidation during flame combustion is very different from the ignition phase: the ignition phase lacks O/H radicals but is dominated by N_2H_i radicals, which are far less important during flame combustion. In many cases, this can be addressed by initiating combustion with a more easily ignited fuel and then transitioning to pure ammonia fuel.[11] Another approach is to use an ammonia blend with hydrogen or similar fuel for spark ignition engines, or an ammonia-diesel or-dimethyl ether (DME) blend for compression ignition engines. Ammonia combustion in furnaces is currently being tested with coal co-firing in Japan. Industrial processes with furnaces typically use enriched oxygen (O_2) or multi-stage air injection to address the ignition and combustion challenges. In all cases, this adds complexity to the engine/furnace design and potentially to fuel management.

Second, once ammonia or an ammonia-blend fuel has been ignited, maintaining flame stability is difficult because of the narrow flammability range in air. The very slow laminar flame speed of ammonia also makes it challenging to enable good flame propagation and stability. As noted above, the heat release rate and flame temperature of ammonia/air combustion are also lower than methane/air combustion, which creates additional challenges for maintaining a stable flame. These characteristics lead to a narrow stable operation range of ammonia combustion compared to carbon-based fuels. As with ignition, blending ammonia with hydrogen or other fuels can partially compensate for these drawbacks at the cost of some increased complexity in engine design and fuel management.[12] An alternative approach is to enrich the oxygen content of combustion air, which can improve flame stability, although it introduces additional costs for oxygen production. The logical extrapolation of this approach is pure ammonia-oxygen combustion, which has also received significant research attention but implies even higher costs for oxygen supply.

Third, exhaust management of ammonia combustion is problematic because of the increased potential for ammonia slip and the formation of N_2O and NO_x.[13] Ammonia slip results from the difficulty of maintaining stable combustion, which can result in uncombusted ammonia being directly emitted with exhaust gas. The formation of N_2O and NO_x results from complex combustion chemistry. Unfortunately, these two engine design challenges are in tension with each other because a higher combustion temperature usually leads to a more complete combustion that consumes all fuels to avoid slip, but it can also lead to more NO_x formation and emission for ammonia combustion. The understanding of foundational combustion chemistry and applied engine design of ammonia fuel (either pure or blended) remains incomplete and is an important area for further research.

Generally, ammonia-fueled engines have lower power output compared to hydrogen engines or carbon-based fuel engines due to drawbacks listed above, which can be partially mitigated by fuel blending. While the understanding of both pure and blended ammonia combustion has improved, important gaps remain in the ability to fully model its physical and chemical properties in technologically relevant engines, turbines and other systems. Further progress is needed on fundamental science and high-fidelity simulations to help guide the engineering design of these devices.

Marine fuel

The global shipping industry is responsible for emissions of slightly more than 1 Gt CO_2 per year, with approximately three-quarters of that due to international shipping.[14] Recent International Maritime Organization (IMO) regulations have significantly limited the amount of sulfur that is allowable in marine fuel,[15] and the industry has committed to a 50% reduction in greenhouse gas emissions by 2050 compared to a 2008 baseline.[16] These changes have prompted a re-examination of the options for marine fuel, which today is primarily heavy fuel oil (HFO) and marine gas oil (MGO). Low-carbon ammonia is one of the leading candidates for adoption as a decarbonized fuel for shipping and is receiving considerable attention.

The global shipping industry already has extensive experience handling ammonia as a cargo. (See Chapter 4 – Ammonia Infrastructure.) Ammonia is a globally traded commodity—in 2019, international trading approached 20 Mt/y, about 10% of total global production.[1] There are 120 terminals that import/export ammonia globally, covering all major economic zones, some of which are close to existing ammonia plants and equipped with storage/handling facilities.[17] (See Chapter 4 – Ammonia Infrastructure).

Low-carbon ammonia is appealing as a marine fuel for several reasons. First, as a carbon-free molecule, all CO_2 emissions will occur upstream during production, not during use (see Figure 5-2[18]). This eliminates the need to consider on-board carbon capture and storage (CCS) systems for ships, which face considerable economic, logistical and technological hurdles,[19] and are thus a problematic consideration for carbon-based fuel, such as liquified natural gas (LNG).

Second, despite the different characteristics of ammonia combustion, dual-fuel (ammonia/diesel) two-stroke marine engines for large vessels are under rapid development and are expected to be commercially available starting in 2024, with retrofits available shortly thereafter.[20-26] "Ammonia-ready" ships that can be easily converted from other fuels (such as LPG) to ammonia in the future are also under rapid development.[27,28] Although early development is focusing on two-stroke combustion engines, four-stroke engines and ammonia fuel cells are also under active development.[29]

Future advancement of ammonia-hydrogen co-combustion and ammonia fuel-cell systems can further improve the carbon footprint without worrying about ammonia-diesel co-combustion lock-in. In fact, Imhoff et al., 2021[30]

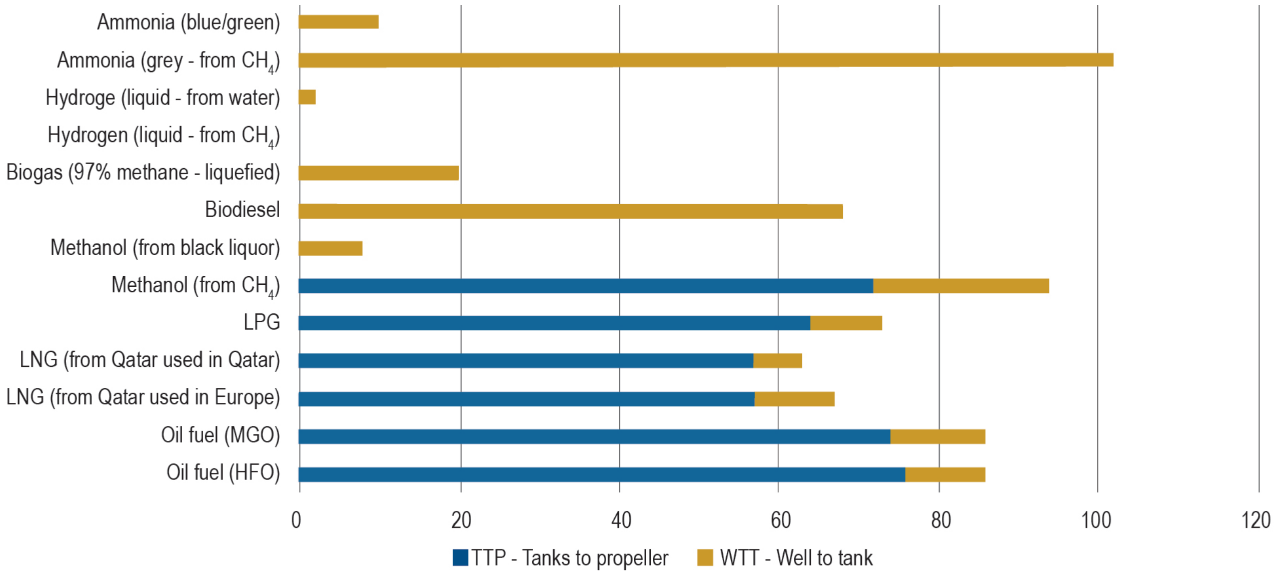

Figure 5-2. *Shipping fuel carbon intensity (g-CO_2/MJ) by fuel types. (Sources: DNV[18])*

found that a mixture of 28% hydrogen and 72% ammonia by volume yields combustion characteristics that are comparable to methane combustion in air. Furthermore, fuel-cell systems could potentially serve as the long-term permanent solution for using ammonia fuel due to the higher maximum efficiency potential.[29,31]

By 2050, ammonia might contribute to more than one-third of total shipping fuel consumptions, much larger than any other alternatives.[32] According to the long-term business as usual (BAU) scenario by IEA and IMO,[33,34] 1.5 Gt/y total emissions will come from the shipping sector by 2050. Ammonia as an alternative shipping fuel therefore has the potential to reduce greenhouse gas emissions by 500 Mt/y assuming one-third fuel replacement with carbon-neutral ammonia (see Figure 5-3[32]). For ammonia dual-fuel engines, the blending ratio (typically 40–60%) limits the maximum decarbonization potential using ammonia, assuming that the low-carbon ammonia is carbon neutral itself.[35] Further increasing the total decarbonization potential would require either a higher blending ratio (which necessitates more technical advancement) or a pure ammonia-powered system.

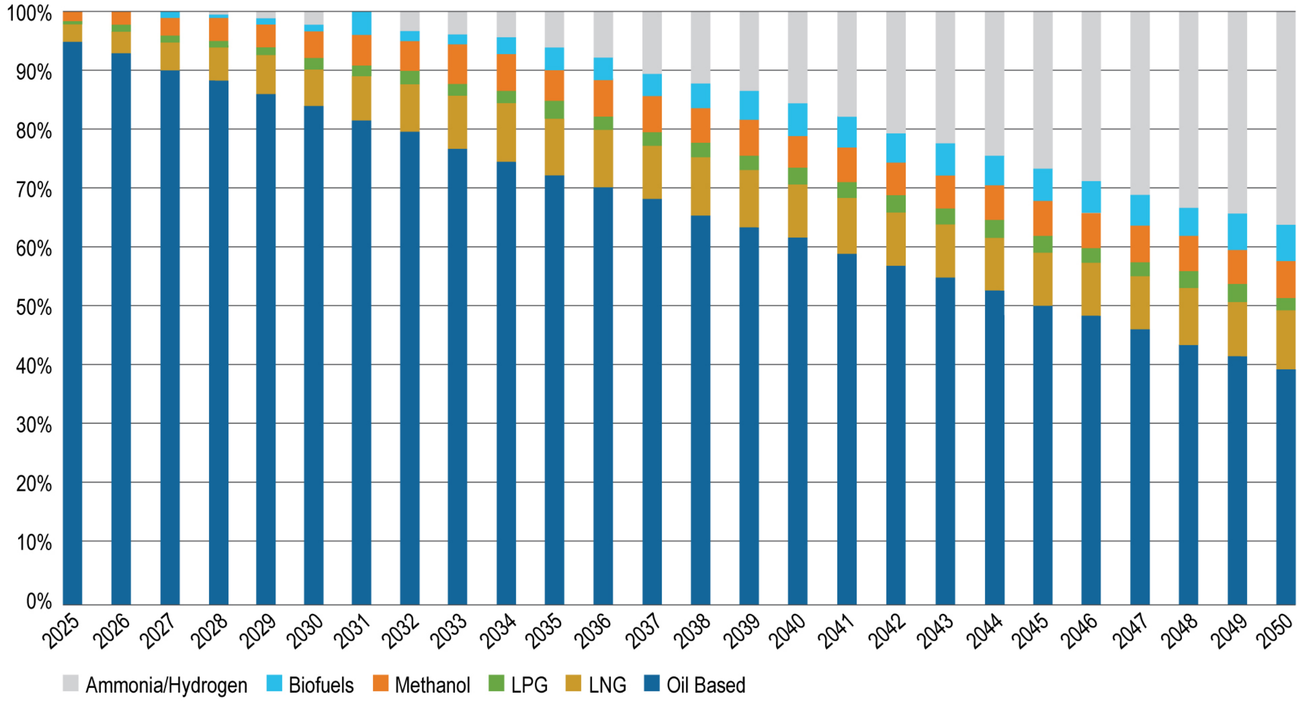

Figure 5-3. *Ammonia as alternative shipping fuel will gradually increase its market share in the following decades. (Source: ABS, 2019*[32]*)*

Economic feasibility remains a major challenge for ammonia used as shipping fuel. Fuel is the largest cost component of shipping operations, making up more than 30% of the total cost for bulk cargo ships and more than 50% for container ships.[36,37] To illustrate this, if green hydrogen were to fall in cost to \$2/kg-H_2 by 2030, resulting in green ammonia costs of \$600–700/t, the per-unit energy cost of this low-carbon ammonia would be approximately 2–5 times that of current HFO.[38]

Another major challenge comes from the high capital cost of ships and shipping engine systems. International shipping fleets have very long lifetimes (about 30 years) and turn-over rate (about every 10 years), meaning the existing fleet will serve for a long time and lock in the fuel consumption for the duration of service.[39] One approach to resolving the uncertainty of low-carbon fuel is to develop dual-fuel engines to minimize the fueling cost and supply risk of a single low-carbon fuel.[40] In an attempt to future-proof new builds beginning construction today, a growing number of ships are designed to be "Ammonia-Ready," meaning that the main engine, fuel tank, generator and boiler are designed to allow a retrofit to ammonia fuel.[41] Whether the high cost of conversion will be economical remains to be seen. Nonetheless, strategies to accommodate multiple fuel types in ships are becoming increasingly valuable, as this approach protects ship owners against potential issues with future availability of low-carbon fuels, which they view as one of the top risks for investment in low-carbon ships today.[40]

Ammonia used for marine fuel for dual-fuel engines is one of the most technically mature applications of novel uses for ammonia with great emissions-abatement potential. Future use of higher ammonia blending ratios, pure ammonia combustion, and ammonia fuel-cell systems remain to be explored and developed.

Power generation

The global power sector currently relies primarily on fossil fuels (coal, natural gas and oil) to generate electricity—roughly 63%. Electricity and heat production are responsible for ~14 Gt-CO_2/y, the largest of all sectors, making it imperative to find methods for reducing its emissions.[42] Power generation using low-carbon ammonia (or generally low-carbon alternative fuels) is of special interest when other decarbonization pathways are not available or are limited due to a shortage of renewable resources and CO_2 storage.

One strategy for decarbonizing power generation is to substitute low-carbon fuels for fossil fuels in the existing power systems, such as gas-fired turbines and coal-fired boilers. This includes adoption of ammonia as a fuel, either in a co-firing configuration (i.e., blended with fossil fuels) or as a complete fuel replacement. Ammonia could also be converted (cracked) to hydrogen and used through co-firing or in fuel cells for power generation. Such low-carbon fuel power generation strategies are of special interest for some nations (e.g., Japan, South Korea) with limited renewable resources (wind, solar, hydro) that are projected to continue importing energy but intend to transition from fossil fuels to chemicals such as hydrogen and ammonia.

While ammonia has appropriate energy density and combustion physical properties to be used for power generation, it is not a direct drop-in replacement, meaning that significant modifications to current coal/natural gas power generation equipment are required.[35] These modifications are due to the typical challenges of ammonia combustion discussed above and apply to all ammonia power generation.

Some of these limitations can be overcome with co-firing. An initial approach for adopting ammonia in power generation is co-firing it with coal. The Japanese Chugoku Electric Power Corporation successfully tested a 1% share of ammonia co-firing system for a commercial coal power station (120 MW) in 2017. Higher blending—up to 20% ammonia (percentage of energy)—is theoretically feasible with minor reconfiguration and has

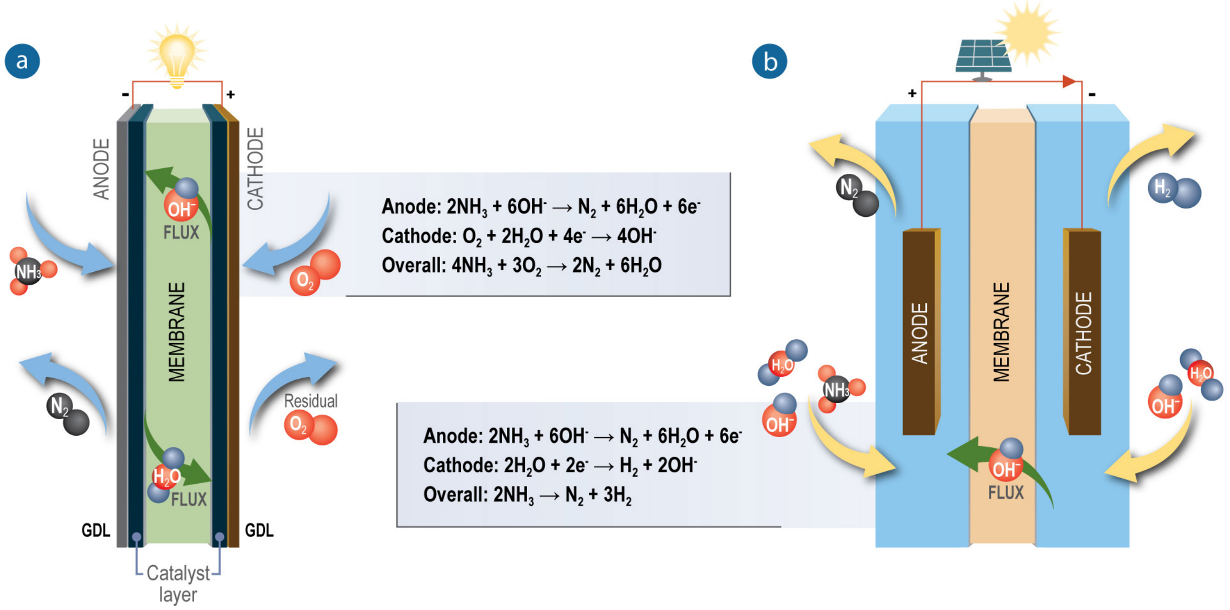

Figure 5-4. *Direct ammonia fuel cell (left) and indirect ammonia fuel cell with ammonia decomposition (right).*

been successfully tested with smaller prototypes.[43] Such technology can be achieved without sacrificing the designed maximum power output and can still meet the NO_x emission limits without ammonia slipping into exhaust gas, through the use of a more advanced combustion system and exhaust post-treatment similar to automobiles.[44,45]Ammonia can also be used in gas-fired power plants, both boiler and turbine configurations, with similar combustion to natural gas. The life-cycle assessment (LCA) shows that ammonia replacing natural gas in the gas turbine can reduce its greenhouse gas emission level by 60% based on the current demonstrated blending limit of ammonia with methane, but it can be as high as 100% if blended with hydrogen.[8,46] From the LCA perspective, the main greenhouse gas emissions of ammonia firing for power generation remain the production emissions of ammonia itself. The remaining greenhouse gas emission contributions come from residual fossil fuel combustion and potential excessive non-CO_2 greenhouse gas emission, such as N_2O.[47,48] Research and development (R&D) is currently underway to establish fundamental understanding of ammonia-combustion physics for ammonia power generation, including controlling N_2O and NO_x formation, preventing ammonia slip, and achieving a stable flame.[49,50]

Direct ammonia fuel-cell power generation represents a long-term opportunity with higher power-generation efficiency. These direct ammonia fuel-cell technologies have various subtypes according to the electrolyte materials and are mostly still at the R&D level.[51] Direct ammonia solid-oxide fuel cells (SOFCs), whose operation temperature ranges from 500-1000 °C, are typically regarded as the most efficient method for power generation with ammonia and are also the most widely studied so far. One potential concern is the formation of NO_x, although some subtypes of SOFCs appear to be able to significantly reduce this. Compared to SOFCs, alkaline-, molten alkaline– and alkaline membrane–based ammonia fuel-cells are far more developed for practical systems, operating at temperatures ranging from 200–450 °C. Unlike SOFCs, alkaline-based fuel cells can decompose ammonia at the very initial stage without forming NO and produce electricity directly. They are conceptually easier to operate but have lower potential than SOFCs for achieving maximum overall efficiency by combining waste-heat recycling management. Microbial-based direct ammonia fuel cells may be able to combine wastewater treatment capability with power generation. All of the above pure-ammonia fuel-cell systems are not yet mature for commercial applications and are still limited to lab-scale development.[51]

Heavy industry – feedstocks and energy source

Ammonia has a long history of being used for industrial feedstocks to form other chemicals: nitric acid, fibers and plastics, explosives, cyanides, etc. Similar to fertilizers, low-carbon ammonia can be used directly as a drop-in replacement for conventional (fossil-derived) industrial feedstock for these applications, making it an immediate opportunity for decarbonization. This portion of non-agricultural ammonia demand represents about 30% of global total demand (54 Mt/y ammonia) and an emissions reduction potential of 136 $MtCO_2$/y.[1]

Another important and potentially far-reaching application of ammonia within heavy industry is providing primary energy, most importantly for high-temperature, high-quality heat. Most industrial heat is provided through combustion of fossil fuel, making it the biggest source of industrial emissions—contributing about 10% of global greenhouse gas emissions.[52] High-quality heat is particularly important in blast furnace operation (steel making), kiln operation (cement making) and reactor operation (e.g., methanol, ethylene and even ammonia production). Combusting ammonia could potentially replace this usage of fossil fuels, leading to deep decarbonization. However, similar to the power case (above), it would not be a drop-in replacement, requiring substantial modification of operating systems or brand-new system design.

Studies on ammonia used for industrial heat applications remain at an initial stage. Lots of recent studies address the details of ammonia combustion characteristics, which differ significantly from conventional hydrocarbon fossil fuels. Honzawa et al., 2020[53] uses numerical simulations to study the ammonia/city gas (hydrogen and methane) mixture used for industrial heating fuels and the effectiveness of moderate or intense low-oxygen dilution (MILD) combustion to reduce the potential NO emissions. MILD combustion is also called flameless combustion for the diluted fuel and slow reaction rate (long reaction time to consume unstable NO formation), which is suitable for some stable high-temperature industrial furnace reactions. Such studies aim to resolve the barriers to ammonia combustion for high-temperature industrial applications, such as very low burning velocity, low flammability, higher ignition temperature and lower burning temperature. Efforts are also being made to resolve the general application of ammonia furnace development. Murai et al., 2019[54] investigated the fundamentals of direct ammonia combustion in industrial furnaces. Typical drawbacks of ammonia combustion can be mitigated by standard strategies, such as adjustment of oxygen concentration, air-fuel ratio, etc.

Compared with ammonia's application for power generation, ammonia uses for industrial energy purposes are much less well understood. Since more complicated chemical reactions are typically involved for industrial production, introducing ammonia fuel combustion internally (such as in blast furnaces, cement kilns and autothermal reforming units) creates different oxidation kinetics in the overall reaction and introduces more uncertainties for product quality control, a topic that has received only minimal investigation so far.[8] Using ammonia combustion to provide heat externally will be technically more straightforward as it can be done without altering existing chemical reactions. The application of ammonia for industrial energy use, especially high-temperature heat, therefore, needs significant research before it can be adopted at scale. In particular, R&D studies are needed that focus on fundamental characteristics to fully investigate the feasibility of ammonia for industrial energy.

Heavy-duty road/surface transport

The fundamental technical details of ammonia used for heavy-duty road transport are very similar to those discussed in previous sections. For example, ammonia used for diesel internal combustion engines shares characteristics with ammonia used for 2-stroke diesel engines for shipping. Ammonia fuel-cell systems used to power road transport vehicles share the same design as ammonia fuel-cell systems used for stationary electric power generation.

Despite concern regarding health and safety risks of handling ammonia as a fuel, as well as potential NO_x emissions, ammonia fuel for city transport is overall more environmentally friendly than diesel and gasoline, based on a combined emission metric that includes particulate matter, soot, NO_x, SO_x and other pollutants.[11] From the global warming potential (GWP) perspective, ammonia fuel can reduce 40–60% of total greenhouse gas emissions through dual-fuel blending, provided that the ammonia itself is carbon neutral. Similar to shipping and other applications that use ammonia as an energy source, the vast majority of greenhouse gas emissions from ammonia come from upstream production rather than onsite combustion. Ammonia fuel combustion has overall lower pollutant emissions than high-sulfur diesel and bunker fuel combustion, therefore potentially abating rain acidification and ozone depletion, especially in jurisdictions where trucks and trains use high-sulfur diesel without NO_x controls. Low-carbon ammonia was found to greatly reduce the overall environmental impact of city transport of human health.[55]

Successful testing has already been performed for ammonia-fueled road transport. Gitlin (2022)[56] reported that the world's first ammonia-powered tractor started testing in June 2022. China's first ammonia diesel engine for heavy vehicles was ignited for testing in April 2022, jointly developed by Dongfeng Commercial Vehicle and Tsinghua University.[57] Recent studies have also investigated ammonia-hydrogen dual-fuel combustion for heavy-duty engines.[58] These very recent developments demonstrate that ammonia is a potential fuel option for some road-transport applications.

Compared to other alternative fuels (e.g., methanol, alcohol, bio-diesel) used for internal-combustion engines, ammonia is not ideal for compact road/surface transportation. Experimental results suggest that ammonia slipping (unburnt ammonia directly emitted to the atmosphere) is problematic for small internal-combustion engines.[59] Due to space and operation limitations, high-temperature ammonia fuel cells such as SOFCs are not suitable for road transport. Some fuel-cell systems like proton-exchange membrane (PEM), direct ammonia-alkaline membrane fuel cells, and on-board ammonia cracking hydrogen fuel cells[60] can operate at room temperature but are not technically mature today.

Compared to ammonia used for stationary electric power generation and shipping fuels, ammonia faces stronger economic, infrastructure and performance competition from other fuels in the road transport sector and may prove a minor player. As battery and hydrogen fuel-cell vehicles are more technically mature and likely to be cheaper, major adoption of ammonia-powered vehicles is likely to be limited to heavy-duty diesel vehicles, such as long-haul trucks and trains.

Refrigerant/coolant

Ammonia is currently widely used as a refrigerant in some industrial systems, such as food refrigeration, distribution warehousing and process cooling. There has also been discussion about ammonia use for residential/commercial air conditioning, but this has not yet been widely adopted because of safety concerns.

Ammonia can be considered a potential refrigeration alternative to conventional hydrofluorocarbons (HFCs). The advantages of ammonia used for refrigeration are well understood and are chiefly functions of its chemical and physical properties:

1. High latent heat, providing more refrigeration effect per unit mass flow compared to any other commercial refrigerant with vapor compression systems.
2. Low gas density, providing increased compressor swept volume.
3. High critical temperature, suitable for air-cooled equipment in high ambient temperatures.
4. High acoustic velocity, resulting in small liquid pipe size and a more compact system.

Combining these advantages, ammonia refrigeration has a very high coefficient of performance (CoP, a ratio of useful thermal energy transferred per unit of electrical energy consumed by heat pumps), making it a strong and efficient choice.

However, before ammonia can replace traditional refrigerants, it must be proven safe (from both a human health and an environmental perspective), simple, cheap and, most importantly, technically mature. The safety considerations are the biggest barrier for ammonia refrigeration. The toxic effect of ammonia depends on concentration (see Chapter 6 – Safety and Local Environmental Impacts of Ammonia), making ammonia unsuitable for use in residential refrigerators or air-conditioners because it is not compatible with the materials commonly used in these systems, particularly copper.[61] The biggest potential for ammonia refrigerants is for industrial applications, such as air-to-air industrial-sized heat pumps, water chilling equipment[62] and marine vessels.[63] The size of the market and the impact on greenhouse gas emission reduction are unclear and remain prominent research and analysis topics. Adopting low-carbon ammonia to replace conventional fossil ammonia for refrigeration/cooling systems does not provide additional benefit and advantages other than the production emission itself. The potential for further

Figure 5-5. *Industrial ammonia refrigeration system*[65]

adoption of ammonia refrigeration/cooling is estimated to be low, as there is already effort toward developing new refrigerants with low GWP that are both safe and cost competitive.[64]

Aviation fuel

Ammonia can potentially be used as a low-carbon aviation fuel.[59,66,67] Compared to other potential aviation-fuel alternatives, such as hydrogen, ammonia has advantages due to its moderate physical and chemical properties: it is very stable, which is safer for aviation applications, and it can be easily transported and stored under moderate pressure and temperature. The fundamental principles of aviation engines are similar to the gas turbines discussed in the power generation section, so there is no theoretical application barrier in using ammonia for aviation. Recent progress has been made toward the first ammonia-powered jet flight, which is expected to occur in 2023 with a small nine-seat passenger jet[68] with at least one of the jet engines powered by ammonia. Active research for ammonia jet-engine development by multiple research groups is underway.[69] Research has found that blending ammonia in jet engines can greatly reduce greenhouse gas emissions by at least 60% with 70% mass blending ratio,[70] but may significantly increase NO_x emissions.[71]

From energy density (energy per volume) and specific energy (energy per mass) perspectives, ammonia is not an ideal aviation fuel alternative. For economic considerations, the aviation industry has very high requirements for fuels' energy density and specific energy, especially on long-haul flights, due to limited space and strict mass control. Additionally, commercial jets have very strict safety regulations that limit development of new aviation fuels that are yet unproven. All non-drop-in fuels for aviation, such as methanol and hydrogen, are facing adoption challenges similar to ammonia and, as a result, drop-in fuels (e.g., bio-fuels, e-fuels derived from hydrogen and CO_2) or even fossil fuel offsets[72] are widely considered to be preferable.

Summary discussion

Ammonia, as a hydrogen-based fuel, is of high interest and potential for various energy applications. Both the IEA and IRENA forecast that there will be hundreds of millions of tons of ammonia used for energy purposes by 2050, mostly in the transportation and power-generation sectors.[1,5] IEA's projection[1] under the 2050 net-zero target shows about 266 Mt/y ammonia (57 Mt/y hydrogen feedstock conversion) for power generation and transportation, satisfying 45% of global shipping energy demand and a small portion of power generation. IRENA's projection[5] shows that, in 2050 under the 1.5 °C scenario, 354 Mt/y of ammonia (about half of total annual demand) will be for energy applications; specifically, 127 Mt/y of ammonia will be produced as a hydrogen carrier (and then converted back to hydrogen for final energy application) and the rest will be used for shipping and power generation (Japan only). The future potential demand for ammonia for energy applications is larger than the total demand for ammonia today, marking a significant market opportunity.

A few common characteristics are observed across different ammonia applications:

1. Low-carbon ammonia's high production cost (see Chapter 3 – Low-Carbon Production of Ammonia) is a major barrier for low-carbon ammonia's adoption. High cost of low-carbon ammonia compared to conventional ammonia and baseline fossil fuels makes it financially unattractive, greatly limiting potential technological advancement and low-carbon ammonia adoption. Production cost reduction and market strategy aiming to close the cost gap is critical to low-carbon ammonia's widespread deployment, and government support will be essential to accomplish this (see Chapter 8 – Policy).
2. Current technologies are not commercially mature enough to support large-scale ammonia energy applications, and the technical barriers are similar across different types of ammonia applications. Even for the most technologically mature sectors, such as ammonia shipping fuel and ammonia-fueled power generation, system-level integration is not yet mature enough to support a high blending ratio. Other potential ammonia applications, such as industrial energy uses and ammonia fuel-cells, are still at very early stages of development. R&D and demonstration projects are critical for achieving technological maturity

and expanding the application potential for ammonia applications that share typical barriers and thus have potentially similar solutions. Common research topics include ammonia combustion physics (pure ammonia combustion or co-firing with other fuels), NO_x emission control and system optimization.

3. Despite the widely available ammonia infrastructure existing today, a new global ammonia infrastructure suitable for non-agricultural applications using hundreds of Mt/y is required (see Chapter 4 – Ammonia Infrastructure). Both IEA and IRENA project that around half of global ammonia production by 2050 will be globally traded, demanding a significant increase in ammonia transportation and storage. Each of ammonia's specific energy applications will also demand specific infrastructure for ammonia delivery and storage. Key infrastructure support is essential for global ammonia trading and applications in countries that cannot produce ammonia locally (e.g., Japan).

Overall, there are significant challenges in extending the use of ammonia to new sectors. The most promising new uses are concentrated in shipping fuels and power generation. In both these sectors, significant growth in the use of ammonia is possible by 2030. In other sectors, new uses of ammonia are limited by technical challenges and competition from other low-carbon pathways, including electrification.

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Chapter 6

SAFETY AND LOCAL ENVIRONMENTAL IMPACTS OF AMMONIA

Ammonia is widely used today in a variety of applications, primarily as a fertilizer and chemical feedstock but also as a refrigerant, cleaning agent and air pollution control agent (see Chapter 2 – The Ammonia Industry). This widespread use has led to a mature understanding of the safe handling of ammonia transportation and distribution and to appropriate risk management methods within these application areas. It has also led to an understanding of the environmental impacts of ammonia in these use cases. To the extent that low-carbon ammonia will displace conventional ammonia in existing applications, there will be no qualitative changes to the associated human health and environmental risks, and no substantially new or modified risk management strategies will need to be adopted.

However, if low-carbon ammonia is adopted into new application areas, such as power generation and maritime fuels, new potential risks to human health and the environment may arise. These risks will require careful attention and management. Additionally, if the total quantity of ammonia that is transported and handled globally increases significantly, existing impacts may increase correspondingly. This chapter outlines the state of knowledge regarding ammonia's impact on human health and safety and on air and water quality and the ways in which those risks may change with new applications. Ammonia does not contribute directly to ozone depletion or climate forcing; instead, ammonia's human health and environmental risks are primarily due to (1) flammability, (2) acute toxicity to humans at high concentrations, (3) chronic toxicity to humans at low concentrations (due to ammonia's role in the formation of fine particles in the atmosphere) and (4) negative impacts on aquatic ecosystems.

Flammability and Acute Toxicity

FLAMMABILITY

Like other fuels, ammonia can burn in air. This poses risks when ammonia is transported and/or stored in enclosed environments, such as industrial buildings. Pure anhydrous ammonia must reach concentrations of at least 15% in air (lower flammability limit, see Table 6-1) for combustion to occur, which is much higher than methane (4.4%). As a result, the risk of unintended fires or explosions associated with ammonia leaks is lower than with methane and most other hydrocarbon fuels (e.g., propane) because building up this higher concentration from leaks or accidental releases is less likely. However, at ammonia concentrations of 16–25% there is a risk of fire or explosion, and the US Environmental Protection Agency (EPA) cautions that this range may be expanded when ammonia is contaminated with lubricating oil.[1] In fact, a prior study indicated that lubricating oil contamination can reduce the lower flammability limit to 8%, depending on the composition and quantity of oil present.[2] Particularly in cases where contamination or intentional blending of ammonia with other substances will take place, safety standards should be updated accordingly based on the behavior of these mixtures.

In terms of managing releases, diluting leaks quickly is the key approach for preventing unintended combustion. In situations where ammonia could build up in enclosed environments, venting to the atmosphere via pressure relief valves is generally effective at avoiding dangerously high concentrations and thus mitigating flammability risk.[3] Although ammonia has several advantages over natural gas in terms of its flammability risks, concerns remain regarding its use as a refrigerant in non-industrial settings (e.g., residential heat pumps) because of both its flammability and human toxicity (see below).[3] However, as none of the proposed large-scale novel applications of low-carbon ammonia would be in non-industrial settings, it is reasonable to assume that appropriate safety measures (such as venting) will be in place at any location where large quantities of ammonia are stored or used.

Table 6-1. *Ammonia concentrations in parts per million (volume) and corresponding impacts on air quality and human health.*

Concentration (volume-based)	Impacts
0.0011–0.010 ppm	Typical outdoor concentrations, no noticeable effects
0.008–0.061 ppm	Typical indoor concentrations, no noticeable effects
1–5 ppm	Odor detection threshold
25 ppm	8-hour exposure limit[13]
30–35 ppm	Short-term exposure limit[13]
100–200 ppm	Immediate eye irritation occurs
400 ppm	Immediate throat irritation occurs
700 ppm	Coughing and severe eye irritation occur, possible loss of sight[14]
1700 ppm	Can cause serious lung damage, death if not treated[14]
2400 ppm	Life threatening after 30 minutes of exposure
5000 ppm	Life threatening after several minutes of exposure[13]
150,000 ppm	Lower flammability limit

ACUTE HUMAN HEALTH EFFECTS FROM AMMONIA EXPOSURE

The most common health effect from ammonia inhalation is chemesthesis (irritation of the skin and mucous membranes).[4] As shown in Table 6-1, relatively low concentrations (100–200 parts per million (ppm)) will cause eye irritation, concentrations of 400 ppm will cause throat irritation, 700 ppm will cause coughing and severe eye irritation with possible loss of sight, 1700 ppm causes serious lung damage, and 2400 ppm results in death after 30 minutes of exposure. A key advantage of ammonia is that humans can smell it at concentrations even lower than the threshold for irritation; odor detection thresholds are around 1.5 to 5 ppm.[5,6] Further, the intensity of ammonia's odor increases with its concentration, which is not the case with all airborne compounds (e.g., hydrogen sulfide). These odor properties mean that ammonia is "self-alarming," and any leaks occurring near humans are likely to be detected and repaired quickly.[3]

In the presence of a slow leak, people will easily detect increased concentrations of ammonia in air long before they rise to levels that pose major health hazards, allowing them to take action to leave the area, dilute with fresh air and/or address the source of the leak. Similarly, the threshold for combustion (15% or 150,000 ppm) far surpasses the level detectable by people, so concentrations would be unlikely to reach this level in areas where people are nearby unless there is a rapid and catastrophic release. Ammonia's narrow flammability range has been cited as evidence that it can be stored safely on board ships.[7] A recent quantitative risk assessment for ship-to-ship bunkering of ammonia noted that the risks associated with toxicity exceeded those associated with its flammability, highlighting the need to avoid uncontrolled releases near people.[8]

In rare industrial accidents, ammonia has been released at sufficiently high rates that it cannot be diluted before workers or other populations are exposed to unsafe concentrations. The US Chemical Safety Board reviewed a 2010 incident in which approximately 15 metric tons of anhydrous ammonia were released at Millard Refrigerated Services Inc. in Alabama (United States) as a result of a catastrophic pipe failure, ultimately exposing 150 nearby workers and resulting in hospitalization of approximately 30 people.[9,10] Proper training for workers, adequate safety protocols and periodic hazard analysis at industrial facilities are necessary to prevent future unintended releases.[10,11] Storing ammonia at atmospheric pressure, for example, and avoiding large swings in temperature and pressure wherever possible can reduce the risk and severity of unintended releases. Ammonia is also corrosive, so selecting appropriate materials for storage and operation is critical to avoiding uncontrolled releases. While there are valid concerns about the potential for catastrophic releases in freight transport applications, particularly with regard to worker safety, the transport of large volumes of ammonia is not entirely new. Ammonia is already transported in maritime shipping as a refrigerant and as liquefied cargo.[12]

Role of Ammonia in Particle Formation and Chronic Human Health Impacts

At concentrations far below the odor detection threshold, ammonia emissions contribute to the formation of fine particles that remain in the atmosphere for days. At ground level, these particles can be inhaled by humans. At higher altitudes, they can impact cloud formation (with highly uncertain impacts on climate forcing). Commonly used integrated assessment models (e.g., APEEP, EASIUR) predict that increasing ammonia emissions will cause substantial human health damages, particularly when the emissions occur near sources of other common air pollutants (sulfur oxides (SO_x) and nitrogen oxides (NO_x)). This raises potential concern about how a dramatic increase in ammonia production and use may impact air quality and human health.

At concentrations commonly found both indoors and outdoors, ammonia participates in reactions that form $PM_{2.5}$ (particulate matter with a diameter < 2.5 µm) in the atmosphere.[15]-$PM_{2.5}$ is the primary driver of air quality–related human health damages, including cardiovascular disease, intracellular oxidative stress, mutagenicity/genotoxicity and inflammatory responses.[16]-As summarized in the review by Nazaroff & Weschler,[17] ambient indoor ammonia concentrations can range from 8 to 61 parts per billion (ppb), with human skin and breath serving as the main source of emissions (ammonia is emitted naturally when microbes break down proteins).[18] Ambient outdoor ammonia concentrations in those same locations tend to be an order of magnitude lower than indoor concentrations (1.1 to 10 ppb). However, even at these low concentrations, the reactions that form $PM_{2.5}$ will occur. In the outdoor environment, ammonia drives the formation of $PM_{2.5}$ by reacting with sulfuric acid (H_2SO_4) and nitric acid (HNO_3) to form sulfate and nitrate salts: ammonium sulfate ($(NH_4)_2SO_4$) and ammonium nitrate (NH_4NO_3) (see Figure 6-1). H_2SO_4 and HNO_3 are produced in the atmosphere when SO_x and NO_x emissions react with water and oxygen (this is also what causes acid rain). NO_x and SO_x are products of combustion, with sources ranging from cars and trucks to power plants and iron and steel mills. Thus, ammonia is likely to have the greatest impact on formation of PM when it is released near large sources of NO_x and SO_x.

Predicting the marginal impact of ammonia emissions on $PM_{2.5}$ formation is difficult because it varies widely on a location and even hour-by-hour basis. For example, a study in Pittsburgh, Pennsylvania (United States) tracked a nucleation event in which ammonium as a fraction of total mass of aerosols in the atmosphere increased from near-zero to approximately 20% in a matter of hours.[19] In particular, temperature plays a role in governing the formation and residence time of sulfate and nitrate salts in the atmosphere. Furthermore, the degree to which ammonia forms these salts can also be impacted by the presence of other pollutants; ammonia has been shown

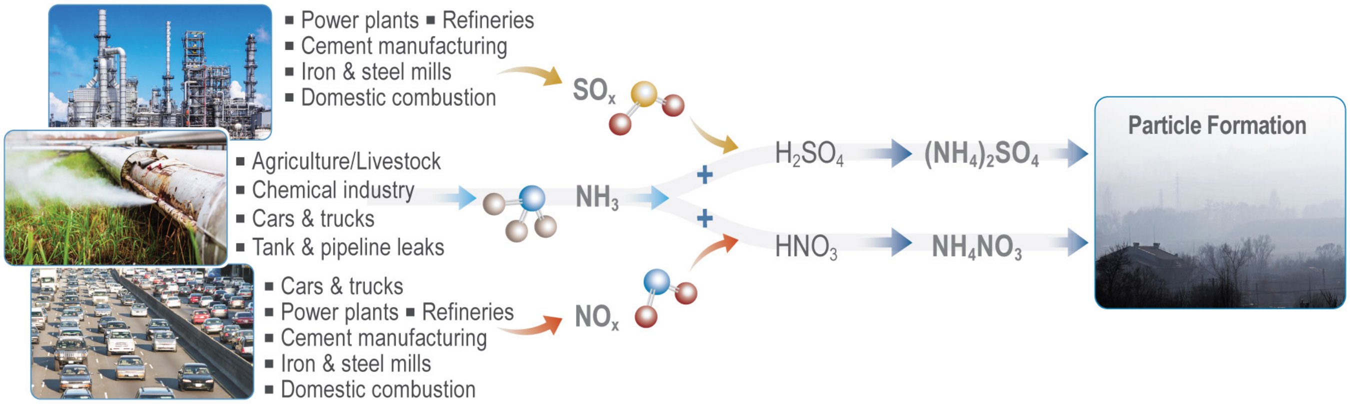

Figure 6-1. *Primary mechanisms for secondary particle formation involving ammonia (adapted from Ehrnsperger and Klemm, 2021[21])*

to react with other organic particles in the atmosphere, thus reducing its availability to form ammonium sulfate and ammonium nitrate salts.[20]

There are efforts to improve basic scientific knowledge of particle formation, although some of the most high-profile studies have focused on particle formation at higher altitudes and the resulting impacts on cloud formation (and possible climate forcing effects), rather than on ground-level concentrations that affect human health. Since it began in 2009, the Cosmics Leaving Outdoor Droplets (CLOUD) experiment at CERN (the European Organization for Nuclear Research) has yielded new insights into how ammonia reacts with ammonium sulfate and ammonium nitrate to form particles that act as cloud condensation nuclei—seeding clouds in the lower atmosphere. Kirby et al., 2011[22] used the CLOUD experiment to explore the dependence of nucleation rates ($PM_{2.5}$ formation) on ammonia concentration when it reacts with H_2SO_4. They found that ammonia concentrations of 100 parts per trillion (ppt) increased the nucleation rate of particles (e.g., NH_4HSO_4) by more than 100–1000-fold.

More recent research has highlighted how much is still not known about the fate and transport of ammonia and revealed higher-than-anticipated ammonia concentrations in the upper troposphere where particles can act as cloud-condensation nuclei. For example, ammonia was previously believed to be short-lived in the atmosphere because of its solubility in water and reactivity with acids. Then a 2022 study using the CERN CLOUD chamber found concentrations of 30 ppt averaged over 3 months and up to 1.4 ppb in hotspots within the upper troposphere over the Asian monsoon region.[23] Notably, in the upper troposphere, nitric acid produced by lightning is more readily available to react with ammonia.[24] While these particles are too far above ground level to directly impact human health, their effect on cloud formation can substantially impact global radiative forcing (whether the impact is positive or negative is highly uncertain and dependent on optical properties of the resulting clouds).[23] In short, ammonia emissions in the Asian monsoon region may impact climate forcing, but the magnitude and direction of those impacts remains uncertain.

Even at ground level, there is still much to be learned about how local meteorology, background concentrations of other pollutants and net changes in ammonia emissions will impact $PM_{2.5}$ concentrations. However, there is broad consensus that the marginal impact of increasing (or decreasing) ammonia emissions depends on (1) background emission rates of NO_x and SO_x and (2) how much ammonia is already present in the air (from other sources). This second point addresses whether the local atmospheric chemistry is and will continue to be ammonia-limited. An ammonia-limited environment refers to local atmospheric conditions in which ammonia is the limiting reactant, meaning that if more ammonia is added to the atmosphere, other pollutants are available at sufficient concentrations to form more $PM_{2.5}$. An agricultural area with high concentrations of ammonia and relatively low NO_x and SO_x emissions is unlikely to be ammonia-limited. Conversely, an urban or heavy industrial area, including ports, with very little agricultural activity is far more likely to be ammonia-limited. Some studies have attempted to quantify these ammonia concentration thresholds, but large gaps in scientific knowledge remain.

In an effort to capture the cost-benefit tradeoffs of mitigating nitrogen emissions (both NO_x and ammonia), Gu et al., 2021[25] estimated the global average relationship between ammonia emissions and $PM_{2.5}$ formation using a combination of atmospheric chemistry transport models (EMEP-WRF, TM5-FASST and GEOS-Chem). The authors converted the resulting changes in $PM_{2.5}$ concentration to monetized human health damages based on mortality. They calculated a marginal global average health damage cost of 5.7 (range of 3.1 to 9.0) $/kg ammonia. Wu et al. (2016)[26] similarly indicated that in China many regions are not ammonia-limited and $PM_{2.5}$ concentrations are more strongly related to changes in ammonia emissions than to shifts in NO_x and SO_x emissions. Results in the United States have been more mixed. Baker and Scheff (2007)[27] studied one urban and nine rural locations across the central and eastern United States and found that these locations were nitric acid–limited (not ammonia-limited). A study comparing different organic waste–management strategies in California (United States) used two different US-specific integrated assessment models (EASIUR and APEEP) and found that human health damages from ammonia dominated their total social cost results, with damage factors varying widely by specific location within the study area and model type ($44/kg ammonia to more than $300/kg).[28]

Air Emissions from Ammonia Combustion

As noted in Chapter 5, NO_x is an air pollutant that contributes to the formation of smog—namely ozone and secondary $PM_{2.5}$—in the atmosphere. Ammonia, if unintentionally released during production, storage, transport and/or use, can react with nitric acid in the atmosphere (a product of reactions between emitted NO_x, water and air). The combustion of ammonia can itself serve as a source of NO_x, raising the question of whether simultaneous increases in ammonia leakage and NO_x emissions could have a synergistic effect, driving the formation of additional $PM_{2.5}$ in the atmosphere.

Ammonia is used as a reducing agent in selective catalytic reduction (SCR) to convert NO_x emissions from power plants and vehicles to N_2. However, ammonia can also be oxidized to NO_x during combustion. The degree to which this occurs and the net impacts on NO_x emissions relative to alternative fuels depend on the engine type, combustion conditions, and whether ammonia is combusted as a neat fuel (which has disadvantages as discussed in Chapter 5) or co-fired with methane, hydrogen or other fuels.[13] Because of the nonlinear effects that co-firing ammonia with a variety of fuels has on NO_x emissions, it is difficult to say with certainty whether the possibility of elevated NO_x emissions can be easily addressed. However, given the potential for synergistic effects between ammonia and NO_x emissions in terms of secondary particle formation, the net effects of ammonia combustion on NO_x emissions must be further studied and regulated.

Ammonia Impacts on Aquatic Ecosystems

Direct releases of ammonia into bodies of water, such as a spill of liquid ammonia, can kill aquatic life, including fish. Many existing emissions sources contribute to acute aquatic toxicity from ammonia, including release of untreated municipal wastewater, agricultural and urban runoff, manure management, and the release of leachate from landfills. In water, ammonia takes both its un-ionized form (NH_3) and ionized form (NH_4^+), the balance of which depends on the local water body's pH and temperature. Un-ionized ammonia is very toxic to fish and other aquatic animals, while ionized ammonia is less toxic.[29,30]

If ammonia is released into the atmosphere, it may react with other molecules or it may be directly deposited on surfaces or in water bodies (known as dry and wet deposition, respectively). Salts formed when ammonia reacts with acids in the atmosphere can also be deposited in water bodies. Excess nitrogen present in water bodies, known as eutrophication, causes harmful algae blooms, which consume dissolved oxygen and lead to fish kills.[31,32] The impacts will vary depending on which nutrient is limiting (nitrogen or phosphorus). Current life-cycle assessment models used to characterize eutrophication impacts make the simplifying assumption that freshwater ecosystems are phosphorus-limited while marine ecosystems are nitrogen-limited.[33] Following this logic, ammonia releases will cause more eutrophication impacts if they occur along the coast or from offshore sources. Ammonia emissions would then have less of an impact on freshwater ecosystems (e.g., lakes and rivers). However, Morelli et al., 2018[33] point out that this simplified assumption does not always hold true, and the conditions of local water bodies should be taken into account.

Historically, fertilizer use and the resulting runoff from agricultural activities has been the primary driver of eutrophication impacts.[31,34] The degree to which an expanded ammonia industry may drive additional eutrophication will depend on the magnitude of releases and the ultimate fate of those emissions, as discussed further below. Monitoring nutrient levels in water bodies near key ammonia production and storage operations will be critical, and further research is required to better understand the fate of ammonia releases from industrial activities.

Leak Detection and Mitigation Measures

Avoiding undue burdens on workers, nearby communities and ecosystems requires leak detection and mitigation measures. The appropriate mitigation measures for ammonia leaks depend on the specific conditions in which the release is occurring. Enclosed spaces where ammonia is stored or pumped should be continuously vented and monitored with ammonia detectors because workers, who would otherwise detect leaks based on odor, may not be present in all of these spaces. This monitor-and-vent strategy prevents accumulation to hazardous levels. When ammonia is released (intentionally or unintentionally) in open spaces, water may be sprayed to dissolve released ammonia until concentrations are below hazardous levels. Finally, in cases of over-pressurization of tanks, rapid release using pressure-release valves and flaring may be necessary.[35] Regular monitoring of ammonia concentrations downwind of storage sites and other large infrastructure can also be an effective strategy to ensure that emissions do not exceed allowable levels. Multiple technologies are available for measuring the concentration of ammonia in air,[36] and these measurements can be used to estimate emission rates from individual sources.

Current and Potential Future Sources of Ammonia Emissions

Ammonia is emitted from a wide variety of anthropogenic and natural sources. Livestock, fertilizer application, forest fires and biomass burning, soils, concrete treated with urea-based antifreeze, selective catalytic reduction systems in vehicles, industrial processes, domestic activities such as cooking and cleaning, and even humans themselves are all sources of ammonia.[17] According to US EPA reports, flux measurements from natural vegetation and agricultural lands have suggested that soil and vegetation can be a source or sink for ammonia.[37] However, the combined impact of agricultural activities, including livestock, fertilizer volatilization, emissions from soils and biomass burning, are estimated to contribute more than 80–90% of global ammonia emissions currently.[38-40]

Global ammonia emissions in 2012 were estimated to be 58,671 Gg (58.671 million tonnes).[41] This includes emissions from the microbial decomposition of nitrogen-rich material and the application of nitrogenous fertilizer (neither of which are considered leakage). Of that total ammonia emissions value, only 6.346 million tonnes were estimated to come from non-agricultural sources,[41] which includes ammonia slip from SCR systems on motor vehicles, biomass burning, industrial processes, refrigerant leakage, human waste and natural emissions from soils.[42] This raises the question: how significant of an impact would novel ammonia applications have on global ammonia emissions and how might this impact the global nitrogen cycle?

If ammonia emissions from novel uses are driven by leakage, one potentially useful point of reference is methane leakage in the oil and gas industry. Alvarez et al., 2018[43] estimated a US-wide methane leakage rate of 2.3% as a fraction of total production. It is reasonable to expect that novel uses of ammonia would result in leakage at or below this level given that ammonia is more easily detected and mitigated due to the "self-alarming" characteristic described above, namely its distinctive odor and low detection threshold. Also, while methane is transported into homes for use in cooking, heating, etc., ammonia storage and use is expected to be more centralized. Based on an International Energy Agency (IEA) scenario in which 125 million tonnes of ammonia are introduced for novel uses (power and marine fuels),[44] a hypothetical 2.3% ammonia leakage/release rate would translate to 2.9 million tonnes of additional ammonia released to the atmosphere. Compared to the 58.671 million tonnes emitted in 2012, the result would be a 5% increase in emissions.

Based on these ammonia emissions calculations, the potential increase in ammonia emissions through leakage is likely to be small relative to existing (and future) agricultural ammonia emissions. However, the magnitude of global ammonia releases from novel uses ultimately depends on both the leakage rate and total annual consumption. If either or both of those values greatly exceeds the figures discussed here, ammonia leakage could become a more significant environmental concern.[45]

Another issue raised by Wolfram et al., 2022[45] is the potential for ammonia emissions to drive an increase in N_2O emissions (a potent greenhouse gas) from the microbial process known as denitrification. Based on the 2.3% leakage rate discussed above and a 1.5% conversion of nitrogen in ammonia to N_2O in the environment, the emissions would be an order of magnitude lower than the level estimated to negate low-carbon ammonia's climate benefits.

There is still much to be learned about the environmental impacts of increased ammonia use, but the mechanisms for tracking and limiting these impacts are known. The key to minimizing the impact of increased ammonia use on air quality, water quality, and human health and safety will be leak detection, regular measurement and monitoring, and more reliable guidance for where emissions must be limited or avoided altogether based on local atmospheric and aquatic ecosystem conditions.

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Chapter 7

RESEARCH AND DEVELOPMENT

The research and development (R&D) needs for safely and sustainably scaling up low-carbon ammonia are focused in four major areas:

1. Developing deep integration schemes with renewable energy, particularly solar, wind and biomass, which tend to occur in areas far from ammonia markets.

Production of low-carbon ammonia could be an integral part of a low-carbon economy, but today ammonia production is not well integrated with non-fossil sources of electricity and heat. While the use of dispatchable low-carbon energy sources—such as hydro, nuclear and geothermal—is relatively straightforward, utilizing solar and wind power for ammonia production will require R&D to develop intermittent operation schemes. The appropriate balance among strategies that enhance the operational flexibility of ammonia production, strategies that buffer variable power production through energy storage, and strategies that store produced hydrogen remains unclear and likely depends strongly on local grid conditions, the cost of energy and hydrogen storage, and ammonia demand.

The potential for using biomass as a hydrogen source through biomass carbon removal and storage (BiCRS) methods, as outlined in the 2021 ICEF Roadmap, is an important option for ammonia production. Biomass-based systems can also provide required heat and power. Developing integrated biomass-based ammonia production, with efficient heat integration and tolerance of heterogeneous biomass feedstocks, requires significant R&D and process engineering.

The availability of large amounts of variable renewable power and biomass is often largest in regions that are far from centers of ammonia demand. This implies that green ammonia production will be accompanied by long-distance bulk transportation from these resource-rich regions to key markets. (In some cases, smaller-scale, distributed low-carbon ammonia production may be preferable given these constraints.) While a large amount of planned low-carbon ammonia production is located in developing countries, projects are also being pursued in countries such as Sweden, Spain and Chile. For blue ammonia, the availability of pore space for CO_2 storage may similarly be far from ammonia demand centers. Because of these factors, R&D is needed to improve understanding of the optimal global-level logistics of production, transportation and distribution of low-carbon ammonia, which may differ significantly from conventional ammonia infrastructure.

Finally, these large-scale integrated efforts need careful evaluation of the carbon intensity of all parts of the supply chain to ensure that integrated efforts are in fact more carbon- and energy-efficient than separated processes. This need for full life-cycle analysis exists throughout the various futures for ammonia (as fertilizer, fuel or hydrogen source) and most effectively will include direct comparison to the *alternative* ways of making, transporting and using ammonia in a clean energy economy. These global-scale evaluations need to consider the local advantages that can accrue from heat integration or use of novel resources, such as biomass.

2. Increasing life-cycle energy efficiency and reducing capital intensity.

Conventional ammonia synthesis plants are highly optimized, with well-engineered approaches to heat integration and energy efficiency. Low-carbon ammonia production will require renewed attention to these issues and new approaches to efficiently reuse produced heat. For example, the Haber-Bosch synthesis loop itself is exothermic, which could potentially enable heat integration with green hydrogen production using solid oxide electrolysis cells (SOECs), which operate at high temperature. In the case of blue ammonia, carbon capture systems require heat for sorbent regeneration, which could also benefit from heat integration. R&D activities in this area include full system analysis of heat integration opportunities across a variety of low-carbon ammonia plant configurations and corresponding process design.

Improved catalysts could also provide improved energy efficiency, although current catalysts are highly optimized and will be economically difficult to replace. However, some promising concepts have emerged, such as more efficient use of expensive ruthenium and cobalt catalysts and the use of cocatalysts to weaken the nitrogen triple bond. Increasing catalyst resistance to poisoning will also improve overall efficiency. R&D is needed to improve catalyst design; improved catalysts could increase per-pass ammonia conversion efficiency, thus improving the capital efficiency of the reactor.

Reducing the operating temperature for ammonia synthesis is a high-profile target for R&D. Along with catalyst improvement, process changes such as removing ammonia continuously from the reactor could improve efficiency and reduce required operating temperature.

Direct electrolytic production of ammonia has not been utilized to date because of its poor selectivity for ammonia over hydrogen evolution at the cathode, in addition to energy loss due to the evolution of oxygen at the anode. However, recent progress in areas such as lithium-mediated electrochemical ammonia synthesis is encouraging, and this general area should continue to be a focus of R&D.[1,2]

One of the most direct ways to improve ammonia production is to reduce the cost and carbon footprint of hydrogen electrochemical production. R&D opportunities in this space have been outlined in a number of publications, including NREL,[3] IRENA,[4] US DOE[5] and IEA.[6] Key areas for innovation include increasing the lifetime of catalysts and systems for hydrogen evolution and reducing manufacturing and material costs.

3. Ensuring that we understand and can manage any safety and environmental risks.

Ammonia has clear safety hazards that are well understood by industry and appear manageable in most industrial settings. However, consideration of the additional issues presented by transportation and large-scale use as a stationary fuel is needed. While crop and livestock production remain the dominant sources of ammonia in air and water, novel uses of ammonia can exacerbate these environmental impacts. The degree to which increased ammonia production and use impacts air and water quality is a function of the overall scale, leakage rate, and local air and water chemistry. Local environments may experience increased atmospheric $PM_{2.5}$ concentrations as a result of ammonia leakage. The impact of additional ammonia emissions, especially to the aquatic environment, needs evaluation, both as a function of local environmental impacts and as an overall examination of likely leak rates. Although there are no red flags at this time, with possible large-scale increases in global ammonia production, transportation and use, it is important to confirm that global climate effects will truly be limited.

Ammonia can interact with other pollutants, including NO_x, to form harmful fine particulates in the air. Given the potential for synergistic effects between ammonia and NO_x emissions in terms of secondary particle formation, the net effects of ammonia combustion on NO_x emissions must be further studied, monitored and controlled.

This synergistic effect between NO_x and ammonia is particularly concerning in areas with poor air quality, given the potential for even greater damage to human health. However, R&D is needed to identify areas where increasing the level of ambient ammonia might trigger significant additional $PM_{2.5}$ formation. Many agricultural areas already have more ammonia than NO_x, implying that increased ambient ammonia would not lead to increased $PM_{2.5}$ formation. This issue is extremely important and should be resolved before large-scale ammonia infrastructure is expanded, especially in seaports, which tend to have low ammonia levels, and where $PM_{2.5}$ levels could increase with ammonia leakage. R&D should focus on improving understanding of where new ammonia use is likely to result in significant increases in $PM_{2.5}$ formation, including the role of NO_x and SO_x. A closely related R&D topic is determining whether there are classes of areas where ammonia usage should be avoided because of a high potential for significantly increasing air pollution.

R&D should also evaluate the levels of overall ammonia leakage that are likely to result from increased ammonia use, with both modeling and measurement of existing facilities. The devices and systems required to make these measurements must be developed and demonstrated to have appropriate sensitivity levels. In general, ammonia does not tend to persist in indoor air (especially in facilities with well-managed ventilation systems), but the mechanisms by which it is removed from outdoor air need to be reexamined with global impacts in mind. Aquatic impacts are of particular interest and may require new levels of sensitivity.

These ecological (as opposed to climate) impacts are one of the most concerning for large-scale utilization of ammonia as an energy carrier. Immediate attention to realistic leakage rates and the impacts of these emissions, coupled with an ability to measure and eliminate leaks on an active basis, must be given to a variety of environments and regions. Ammonia leakage impacts may be quite different in different places, depending on leak rate and local environment: these differences could range from small to significant. Substantial R&D is warranted.

The second major possible impact of ammonia use as an energy carrier is NO_x production from burning it as a fuel. While our roadmap makes it clear that fuel-cell use is much more efficient, there is current interest in using ammonia as a combustion fuel. Rates of NO_x production need to be evaluated, and effective engines and pollution-control equipment must be developed to ensure that levels of NO_x emissions are extremely low. For ocean applications, NO_x may have ecological impacts on plankton blooms and other aquatic life. This is another high priority area of research but may not be as localized as the ammonia leakage impacts. Closely linked to the ecological aspects are the possibility that marine exhaust could change cloud formation and albedo, thus affecting climate.

Research on the combustion characteristics of ammonia, either as neat fuel or as an additive, should be conducted under a variety of conditions. Particularly since ammonia affects flame speed, the details of individual uses need to be carefully examined. Engines using ammonia require attention for both overall efficiency and fundamental pollution control.

Hazards to human health and safety are well understood because of existing industrial and agricultural uses of ammonia, but R&D for design of safe, large-volume transportation options is warranted. Safety systems on board ships carrying large amounts of ammonia deserve special attention. A study indicating that lubricating oil contamination can reduce the lower flammability limit to 8% suggests that, in cases where contamination or intentional blending of ammonia with other substances will take place, safety standards should be updated accordingly based on the behavior of these mixtures.[7] R&D should therefore include a broad-ranging assessment of the interaction of ammonia, both neat and mixed, with combustion and engine systems.

4. Ensuring that energy and climate impacts of ammonia use are well understood.

Hydrogen production, ammonia combustion and increased emissions from ships over the open ocean all have second-order climate effects that need to be evaluated. In many cases, these are tradeoffs (e.g., methanol vs. ammonia) whose climate impacts should be more carefully quantified than has been done to date. These are not so much questions of the direct impacts of ammonia usage as outlined in the previous R&D descriptions but rather assessments of the overall system impact and comparisons to the alternative means by which services could be obtained. These are questions principally of analysis, and not research, but they are pressing and important.

When considering the round-trip efficiency of ammonia used as a transport fuel or used in ammonia-fired turbines for power generation, R&D is necessary to understand how energy is converted along the supply chain and how leakage could contribute for the full cycle of production and use. The same context is required to evaluate the environmental impacts of global schemes for use of ammonia as an energy transport method. Immediate R&D should be conducted on the benefits of ammonia versus hydrogen or other energy carriers like methanol. A full life-cycle and environmental-impact assessment needs to be done to consider these questions and questions we do not even know we should be asking today. For example, it remains unclear at what point in an energy system it would make sense to crack ammonia to hydrogen for use as a fuel. Further, unless this and related issues are analyzed at the system level, local decisions could be made that lock in undesirable outcomes.

As ammonia gains attention for use as maritime fuel and consideration as a fuel for stationary power, there are significant system questions to be asked about energy uses that may be quite different from the existing agricultural transport and use of ammonia. These questions include evaluation of the critical infrastructure needs for low-carbon ammonia, such as pipelines or reforming stations to turn ammonia back into hydrogen (cracking). The most efficient places in the transport chain should be evaluated. Are centralized or local facilities better for energy and the environment? And do those answers vary by region? Evaluating current ammonia-handling facilities and their cost and environmental impact may give insight into that problem. Tracking existing shipping can point out places to examine environmental impacts. Pipeline transport and storage of ammonia should be evaluated in terms of the energy value and issues of safety and environment. A related question is whether it is possible to convert existing LNG facilities to handle ammonia. Life-cycle assessment approaches that are uniform and, to the extent possible, technology neutral, need to be developed to make these evaluations.

Demand for ammonia is currently predicted to grow 40% for just conventional usage by 2050, and required energy use would increase significantly. Realistic and publicly available assessments of ammonia demand should be developed at a regional scale to help governments plan for ammonia use and regulation.

Technology to enable ammonia use in energy systems will need significant R&D if it is to be added to existing systems. This includes ammonia combustion needs and challenges, spark versus compression engines, and other engine design issues. How would NO_x controls be added to stationary power sources fueled by ammonia? What are the most efficient ammonia-cracking methods, and can they be integrated with other activities to be more energy efficient?

Finally, what application areas are likely to adopt low-carbon ammonia the earliest? Immediate R&D on the commercial and policy drivers that will increase ammonia use in energy systems should be done to inform regulators, policy makers and researchers working on the questions listed above. Questions such as the possible amount of fuel-switching in existing facilities are currently hard to evaluate and deserve immediate attention.

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Chapter 8

POLICY

Policy support will be essential to substantially increase production and use of low-carbon ammonia.

At present, barriers to the growth of low-carbon ammonia are significant.

- Production costs are high.
- Infrastructure for distributing low-carbon ammonia is inadequate.
- Financing barriers limit the private capital available for project development.
- Markets rarely value low-carbon attributes in fuels or other products.

Government policies can play a central role in overcoming these and other barriers. Indeed government policies have played a central role in recent years in the growth of several clean energy technologies, including solar power, wind power and electric vehicles. Policies broadly similar to those that have accelerated the deployment of these technologies could (with some differences and adjustments) do the same for low-carbon ammonia.

In the past several years, national hydrogen strategies have proliferated, recognizing the central role hydrogen can play in decarbonization.[1] Many of these hydrogen strategies contain policies directly relevant to low-carbon ammonia, including research and development funding, budget support for infrastructure development, public partnerships and more. Some of these hydrogen strategies already address low-carbon ammonia (such as the Japanese government's target of 3 million tons (Mt) of low-carbon ammonia demand by 2030), but that is not universal.[2]

One simple step governments could take is to highlight low-carbon ammonia more centrally in their national hydrogen strategies. Ammonia will often be the best hydrogen carrier and, as a result, should always be considered as governments develop these strategies. National hydrogen strategies can highlight the potential for businesses in a number of sectors to use low-carbon ammonia.

Inter-ministerial coordination will also be important. Policies on low-carbon ammonia may involve energy ministries, environment ministries, agriculture ministries, labor ministries, transport ministries, finance ministries and others. Some governments have well-developed tools for coordinating among these different departments; other governments have less well-developed tools. Engaging stakeholders with a broad range of interests and expertise in the most efficient manner will lead to better policy making.

One central point: governments should promote the optimal use of low-carbon ammonia within a broad portfolio of decarbonization strategies—not simply strive for the maximum use of low-carbon ammonia everywhere. Low-carbon ammonia will provide a compelling decarbonization strategy in some sectors but not in others. In agriculture and shipping, for example, the potential for low-carbon ammonia to contribute to emissions reductions is already clear. (See Chapter 5 – Uses of Low-Carbon Ammonia.) In other sectors, the potential is less clear. The sectors and sub-sectors that will benefit the most from low-carbon ammonia will emerge with time, as technologies and markets develop in the years ahead. Governments should help low-carbon ammonia overcome market barriers and provide the enabling environment for it to scale, while always proceeding based upon analysis with respect to optimum decarbonization strategies.

Policymakers have sometimes focused support on a particular “color” of ammonia over others. While this is based on a desire to accelerate decarbonization, reliance on color-based descriptors of ammonia (such as green or blue) as a basis for policy support risks sub-optimal or even counterproductive results. Life-cycle carbon emissions within each color category can vary significantly, and there is no guarantee that ammonia labeled green, blue or other is actually contributing significantly to decarbonization. Policy support for accelerating low-carbon ammonia should be based on a technology-neutral approach that measures life-cycle carbon intensity.

A number of policies could help low-carbon ammonia reach its full potential. We consider those policies in four categories below.

A. DEMAND-SIDE POLICIES

Government policies can play a central role in building demand for low-carbon ammonia.

1. **Carbon pricing.** Historically, manufacturers of conventional ammonia have been able to externalize the climate change costs of their product, venting carbon dioxide (CO_2) into the atmosphere for free. Carbon pricing corrects this market imperfection by charging emitters (including manufacturers of conventional ammonia) for their CO_2 emissions. This allows low-carbon ammonia to compete in the marketplace on a more level playing field against conventional ammonia.

   Carbon pricing programs come in two broad categories—carbon taxes and emissions-trading programs. Under carbon tax regimes, emitters are charged for every ton of CO_2 emitted. Under emissions trading programs, the right to emit CO_2 requires a permit. Governments give or sell these permits to emitters, who may then trade the permits among themselves. Under many emissions trading programs, governments gradually reduce the number of permits (often called emissions allowances), thereby reducing total pollution.

   Roughly 36 jurisdictions around the world have carbon tax programs. Emissions trading programs for CO_2 are now in place in the European Union, China, California, the northeast United States and Canada, among other places. In general, prices under these programs have been too low to motivate significant increases in demand for low-carbon products.[3,4]

2. **Low-carbon fuel standards.** A low-carbon fuel standard requires fuel sellers to reduce the life-cycle carbon intensity of their fuels over time. California has the world’s leading low-carbon fuel standard.[5]

   Low-carbon fuel standards could help significantly to bring low-carbon ammonia to market. Ammonia produces no greenhouse gases when burned, and low-carbon ammonia—by definition—produces very little heat-trapping gasses during the manufacturing process. Low-carbon ammonia can be an important compliance option for a range of industries facing low-carbon fuel standards.

3. **Power plant CO_2 emissions standards.** Emissions standards can require power plants to reduce their CO_2 emissions over time. Compliance strategies can include fuel shifting and/or co-firing with a clean fuel such as low-carbon ammonia. Japanese power plants are increasingly using low-carbon ammonia to help achieve emissions targets.[6]
4. **International Maritime Organization (IMO) guidelines.** The IMO is a specialized agency of the United Nations responsible for improving the safety of international shipping and preventing pollution from ships. In 2018, the IMO’s Marine Environment Protection Committee (MEPC) adopted a resolution setting forth an Initial Strategy for reducing greenhouse gas emissions from ships. The Initial Strategy calls for peaking

greenhouse gas emissions from ships as soon as possible, steadily reducing greenhouse gas emissions intensity of shipping in the years ahead and cutting total annual greenhouse gas emissions from shipping by 50% by 2050.[7]

Ammonia has significant potential to help the shipping industry achieve these goals (see Chapter 5 – Uses of Low-Carbon Ammonia), but that will require the IMO to develop guidelines on several topics.

Guidelines on the safe handling of ammonia on ships are essential. Risks to personnel and marine life in the event of release should be addressed. Work on this topic is already underway by an IMO subcommittee, with a target completion date of 2023 for the first stage.[8] These guidelines will need to be continually developed and elaborated in the years ahead.

Guidelines on life-cycle assessments of greenhouse gas emissions from ammonia fuels will also be essential. Initial work on this topic is underway by an IMO subcommittee as well.[9]

5. **Government procurement.** In many countries, government procurement makes up more than 10% of GDP.[10] This spending provides an important opportunity to jumpstart markets for new products with public benefits, such as low-carbon ammonia. First, government purchase contracts can provide manufacturers with an assured market, which can be especially important in securing debt capital. Second, government purchases can help establish standard technical specifications for new products, which can help catalyze efficient supply chains.

   Governments are major purchasers of bunker fuels and other products in which low-carbon ammonia could play a role. Coast Guards around the world provide a perfect opportunity to begin scaling up the use of low-carbon ammonia, in part because Coast Guard vessels often return for refueling to the same port where they launched. As a result, the operators of most Coast Guard vessels powered by ammonia would not be constrained by the lack of low-carbon ammonia infrastructure at remote locations.[11,12] Establishing strong preferences for low-carbon ammonia in government procurement could help jumpstart markets and promote low-carbon ammonia as a climate solution.

B. SUPPLY-SIDE POLICIES

1. **Government Support for R&D.** National governments spend at least $30 billion annually on R&D for clean energy technologies. These programs have played important roles in developing countless technologies in recent decades.[13]

   As set forth in Chapter 7, R&D on a range of topics are important for low-carbon ammonia to reach its full potential. Priority topics include the following:

   - Electrochemical reduction of nitrogen to ammonia
   - Integration of ammonia production with renewable energy sources
   - Better catalysts for ammonia production to reduce temperatures required for operation
   - Reducing CO_2 emissions from blue hydrogen production
   - Climate change impacts of ammonia leakage

   Much of this research involves fundamental science or pre-commercial topics that private companies have little incentive to fund. As a result, government funding for research on these topics will be essential. National governments, including those in the United States, Japan, the European Union, Russia and China, have historically provided most of the support for fundamental science and pre-commercial research.

In June 2021, ministers from more than 20 countries announced Mission Innovation 2.0, pledging "a decade of innovation to catalyze increased investment in clean energy research, development and demonstrations to deliver affordable clean energy solutions by 2030."[14] Member governments include Japan, the United States, China, the United Kingdom, Germany and Saudi Arabia. The resulting increase in government R&D budgets in these countries in the years ahead offers an opportunity to increase R&D funding for low-carbon ammonia.

2. **Loan guarantees.** Cutting the cost of debt capital can help make a project financially viable. Government loan-guarantee programs seek to do this by reducing risk to lenders, resulting in lower borrowing costs. The US Department of Energy's loan-guarantee programs helped launch the utility-scale solar industry in the United States, among other successes. Loan guarantees for the capital expenditures required for manufacture of low-carbon ammonia could significantly speed deployment.

C. ENABLING POLICIES

1. **Accelerated permitting processes.** For low-carbon ammonia to play a significant role in decarbonization, significant new infrastructure will be needed. New and expanded ports and pipeline networks will be essential. Although requirements vary significantly from jurisdiction to jurisdiction, such infrastructure typically requires regulatory approvals and permitting. Policies that give priority to low-carbon projects and recognize the public interest in expeditious review processes would help facilitate scale-up of necessary facilities.

   In many jurisdictions, environmental and occupational safety permits may be required for operation of ammonia facilities. These permitting procedures may often be important for public health and safety. They may also help minimize the risk of accidents that could tarnish the industry's reputation and slow its growth. Clear and uniform environmental and occupational standards, applied in a transparent and expeditious manner, can help support growth of the low-carbon ammonia industry.

2. **Public-private partnerships.** Public-private partnerships play an important role in the development of ports in many countries. One standard model is for a public sector agency to own the port land and be responsible for developing the port, with private entities responsible for port operations.[15] National legal frameworks that facilitate establishment of such public-private partnerships for ports designed to handle low-carbon ammonia could help accelerate the development of critical infrastructure.

   Related to this, some government programs provide grant or debt financing to port developers. In the United States, for example, the federal government's Port Infrastructure Development Program provides planning grants, as well as operational and capital financing, to assist with port development.[16] Such programs can de-risk and accelerate development of critical infrastructure for low-carbon ammonia.

3. **Life-cycle emissions methodologies.** Widely accepted methodologies for evaluating the life-cycle greenhouse gas emissions of low-carbon ammonia can play an important role in growing the industry. Buyers will want assurances with respect to the low-carbon attributes of their ammonia, and government agencies will need to establish eligibility criteria to determine whether ammonia supplies qualify for favorable treatment under low-carbon incentive programs. This issue will arise soon in the context of the European Union's Carbon Border Adjustment Mechanism, which will cover imports of ammonia to the European Union.[17] Reliable, transparent methodologies for evaluating life-cycle emissions for ammonia can also help reduce confusion and mislabeling associated with the current *ad hoc* system of colors (e.g. blue, green, etc.) that do not truly capture the full emissions impacts of different ammonia production methods.

A growing body of research explores this topic globally.[18-20] Government funding is essential to support this work. Governments can also help by convening key stakeholders in expert dialogue and by recognizing consensus results in regulatory programs.

D. REGULATORY ISSUES

1. **Water and air quality regulations.** Governments around the world regulate ammonia to protect water and air quality.[21,22] Some of these regulations focus directly on ammonia; others focus more broadly on nitrogen pollution (for which ammonia is often the principal source).

   Low-carbon ammonia is identical to the conventional ammonia for which these regulations were developed. (The difference is in the production method, not the final product.) As a result, regulations developed for conventional ammonia should be mostly applicable to low-carbon ammonia. However, novel uses of ammonia may create new risks. Regulators should be attentive to these as the industry develops

2. **Worker health and safety regulations.** Governments around the world regulate ammonia to protect worker health and safety. A 2016 study identified dozens of worker health and safety regulations related to ammonia globally.[23] These regulations are designed to address two principal types of hazards: those related to loss of containment and those related to rapid phase change.

   As noted just above, low-carbon ammonia is identical to the conventional ammonia for which these regulations were developed. However, many of the use cases for low-carbon ammonia may be quite different than those for conventional ammonia. (Conventional ammonia is rarely used as a bunker fuel, for example, or to co-fire coal in power plants.) As new use cases for ammonia are developed in the years ahead, attention to worker health and safety considerations will be essential. In the shipping sector and elsewhere, this may require new analyses as ammonia begins to be used at a large scale in new ways.

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Chapter 9

FINDINGS AND RECOMMENDATIONS

FINDINGS

FINDING 1: Low-carbon ammonia could produce significant greenhouse gas reductions in key sectors this decade and deep reductions in some sectors by 2050. Low-carbon ammonia could have applications in agriculture, transportation and power. Two key sectors stand out: fertilizers and maritime shipping. Current supply chains for ammonia production and transport are large and able to grow. The substantial existing market for conventional ammonia provides experience, standards and immediate market opportunities for low-carbon ammonia (notably in fertilizer production). The potential to replace fossil fuels with low-carbon ammonia at scale is not limited globally by natural resources or critical minerals (although local limits can be substantial).

FINDING 2: There are no technical barriers to producing low-carbon ammonia in large volume before 2030. Low-carbon ammonia can be produced from low-carbon hydrogen production (e.g., blue, green, bio-hydrogen) and Haber-Bosch process synthesis. Green hydrogen production faces manufacturing limits (for electrolyzers) and siting constraints (for transmission and generation of zero-carbon electricity) that must be addressed to scale rapidly. Blue hydrogen supply is chiefly limited by CO_2 transport and storage access and can be accelerated by adding carbon capture to existing ammonia production units and new projects. Local factors—such as the availability and price of low-carbon electricity, natural gas prices and proximity to CO_2 storage—will determine the relative cost of blue and green ammonia in different locations.

FINDING 3: Cost is the chief barrier to deployment. The use of low-carbon ammonia for fertilizer production would raise the cost of food and fiber production. When used as a fuel, low-carbon ammonia would cost substantially more than natural gas, coal, diesel or even hydrogen on an energy-density basis. It would also require additional capital expense to retrofit existing assets, such as engines and turbines. To achieve widespread deployment, production costs must be substantially reduced. This can be achieved through a combination of cost reductions and demand-support policies, such as incentives and mandates.

FINDING 4: Safety and environmental risks from ammonia scale-up will require attention and management. The large global ammonia industry today has deep experience in managing the safety risks of ammonia, as well as many of the key environmental risks. Preventing large uncontrolled releases will continue to be essential, requiring robust safety measures and worker training. In general, more gradual releases are relatively easily detected because ammonia has a strong aroma at low levels, allowing operators and communities to identify leaks before they pose a significant human health or flammability concern. (Unpopulated locations require automated sensors.) Ammonia emissions can impact air quality and human health by contributing to the formation of fine particulate matter ($PM_{2.5}$) in some regions, particularly in urban and industrial areas without other background ammonia emissions sources. Novel uses are likely to cause a small increase in global ammonia emissions. More research is needed to understand the impact of ammonia emissions on air quality.

FINDING 5: Global low-carbon ammonia trade will require infrastructure investment and more ships. Although there are a substantial number of ammonia terminals and long-haul ships today, more infrastructure will be necessary for use of low-carbon ammonia to grow. This need is particularly acute in regions of new supply (e.g., Chile, North Africa, northwest Australia) and new demand (e.g., Singapore, North Sea). While no technical barriers prevent scale-up, there will likely be issues with siting, permitting and construction of new docks, storage and pipelines. Building such infrastructure often involves long lead times.

FINDING 6: Before low-carbon ammonia can deliver substantial abatement of greenhouse gas emissions, more work on applications is a priority. Ammonia use is the least mature component of low-carbon ammonia value chains and therefore the area that would most benefit from investment in innovation. Potential applications span all major emitting sectors.

- Fertilizer provides the most immediate and one of the largest applications for low-carbon ammonia. Use of low-carbon ammonia requires little or no operational changes.
- Shipping is a very high-impact application with high decarbonization potential. Some use can begin today by blending in existing ships and engines (with some modification of maritime architecture). High levels of blending and fuel substitution require additional innovation to scale.
- Power-sector applications require advances in blending and feed systems, combustion science, ammonia fuel cells, environmental hazard management and improved efficiency of use.
- Heavy-industry applications require the same advances as power sector applications, with special focus on ammonia as a low-carbon fuel for producing steel, cement, glass and chemicals/refining. In some cases, it may prove easier to use hydrogen reconstituted from ammonia rather than to use ammonia directly.
- Low-carbon ammonia for transport applications, such as trucks, trains and aircraft, could become useful but face a wider set of competing technology options and may prove less important.

A long-lived, substantial innovation program focused on ammonia use in many sectors with many technology pathways could help identify the most promising early pathways and most profound opportunities for decarbonization. Even then, analysis, practical experience and input costs may determine that low-carbon ammonia is not cost competitive for many applications.

FINDING 7: Very few countries have policies that support low-carbon ammonia today. While roughly 35 nations have low-carbon hydrogen policies (mostly production and use), very few have policies tailored to the potential or the specific requirements of ammonia. This includes a lack of policies focused on ammonia infrastructure, innovation, supply creation or specific economic applications (e.g., in agriculture, shipping or power). Few countries today have supporting policies of sufficient scale and durability to overcome the economic hurdles. (Japan provides an important exception, supporting industrial transition to ammonia fuels, infrastructure support, international policy for low-carbon production and a green-premium for low-carbon ammonia supply.) Because the low-carbon attributes provide the key rationale for low-carbon ammonia, life-cycle accounting and standards will underlie market structures and investments. Without policies that close the cost gap or value the low-carbon attributes (such as those in Japan), the market will remain small and stagnate.

FINDING 8: Low-carbon ammonia trade could have geopolitical implications. Because low-carbon ammonia can be produced in many geographies and help decarbonize many sectors, its trade may create new bilateral energy and investment relationships. Like liquified natural gas (LNG), low-carbon ammonia requires special infrastructure and could be traded with bilateral agreements and investments. Nations may increase their production and import of low-carbon ammonia as part of their broader climate strategies. Since many potential suppliers lie in the Global South and are not traditional petrostates, there is an opportunity for new global energy players to emerge, counterbalancing traditional energy suppliers. Developed countries may choose to redress some North-South inequities through development investment in low-carbon ammonia in these countries.

RECOMMENDATIONS

RECOMMENDATION 1:

Governments should support investment in new low-carbon ammonia supplies. Governments should consider fast-track permitting for early demonstration projects for low-carbon ammonia production as a means of accelerating learning and greenhouse gas reductions. Nations and provinces without the appropriate mix of natural resources for primary production should pursue investments in regions hosting the appropriate resources and governance structures for speed, scale and cost, possibly as bilateral agreements. Analysis may reveal specific recommendations for investment that also achieve important national and regional geopolitical goals and provide a vector for sustainable development, energy access and wealth-creation in developing regions. Quantitative life-cycle emissions accounting—rather than qualitative green/blue designations—is essential to ensure production is truly low-carbon. Further, life-cycle emissions accounting must eventually be codified in standards and regulations.

RECOMMENDATION 2:

Governments should launch a set of public-private partnerships to plan, develop and finance key infrastructure for low-carbon ammonia production, transportation and use. The economies of scale in ammonia drive very large projects with large capital requirements. Dedicated policies to stimulate low-carbon ammonia infrastructure investments must feature prominently in policy design and legislative process since dedicated infrastructure is needed for ammonia production, transportation, use and health/risk management. Public-private partnerships would reduce risk and crowd in private capital for key infrastructure projects, including electric transmission lines, CO_2 transportation and storage, ammonia fueling and storage systems, and pipeline upgrades. In particular, ports for import, export and bunkering—especially industrial ports—represent chokepoints for trade and deployment and should receive immediate focus for retrofit, new construction and permitting.

RECOMMENDATION 3:

Governments and industries should invest heavily in innovations for use of low-carbon ammonia. New innovation programs should include a mixture of foundational science (e.g., combustion chemistry), applied science (e.g., fuel mixing) and pilot demonstrations across power, industrial, transportation and chemical sectors. A combination of material science, simulation, engineering and system analysis could provide the crucial insights to enable commercially viable use. Absent these investments, there will be no market for ammonia as a fuel, limiting ammonia-based decarbonization to the fertilizer market.

RECOMMENDATION 4:

Government regulators should take steps to prevent safety and environmental problems in the ammonia trade. The most immediate action should be to launch monitoring programs for hydrogen and ammonia production, use and transport, with a focus on fueling systems. Monitoring should serve as the basis for amending and upgrading regulations regarding leakage tolerances. Facilities should manage “unacceptable risks” associated with ammonia production, transportation and trade. Analysis should assess potential local risks, including increased air and water pollution, and health effects on communities. As low-carbon hydrogen and ammonia production increases, operators and regulators should work together to ensure minimal leakage—ideally less than 0.5% of production—beginning with active monitoring of pilots and new developments.

RECOMMENDATION 5:

Key governments should institute supporting policies to drive ammonia into wider use as a fuel and feedstock. Firm policies supporting production and use and valuing low-carbon attributes will prove essential to growing supply, transportation and use, including a mixture of incentives, procurements and regulations. Initial projects and policies should focus on overcoming cost barriers. Market pull mechanisms, such as incentives, grants and procurement (e.g., "buy clean" initiatives), should be based on quantitative assessments of life-cycle carbon footprint for goods and services where ammonia is currently used and could serve as a low-carbon feedstock or fuel. Due to the long-lived nature of commercial ammonia-related assets, long-term commitments (i.e., offtakes, financial terms) may be needed to achieve deployment breakthroughs.

RECOMMENDATION 6:

Policy incentives for low-carbon ammonia should be based on carbon intensity rather than ammonia "color" (such as green or blue). Carbon emissions from ammonia production methods labeled as "green" or "blue" can vary dramatically. Ammonia labeled green can have higher carbon emissions than ammonia labeled blue or even, in some cases, conventional fossil-based ammonia. While the color system can be a useful qualitative descriptor, it should not be used as a proxy for carbon intensity. Policy incentives for low-carbon ammonia should be based on the full life-cycle carbon intensity of a batch of ammonia (including upstream emissions from fugitive methane, grid power emissions and land-use change), not on the type of production method.

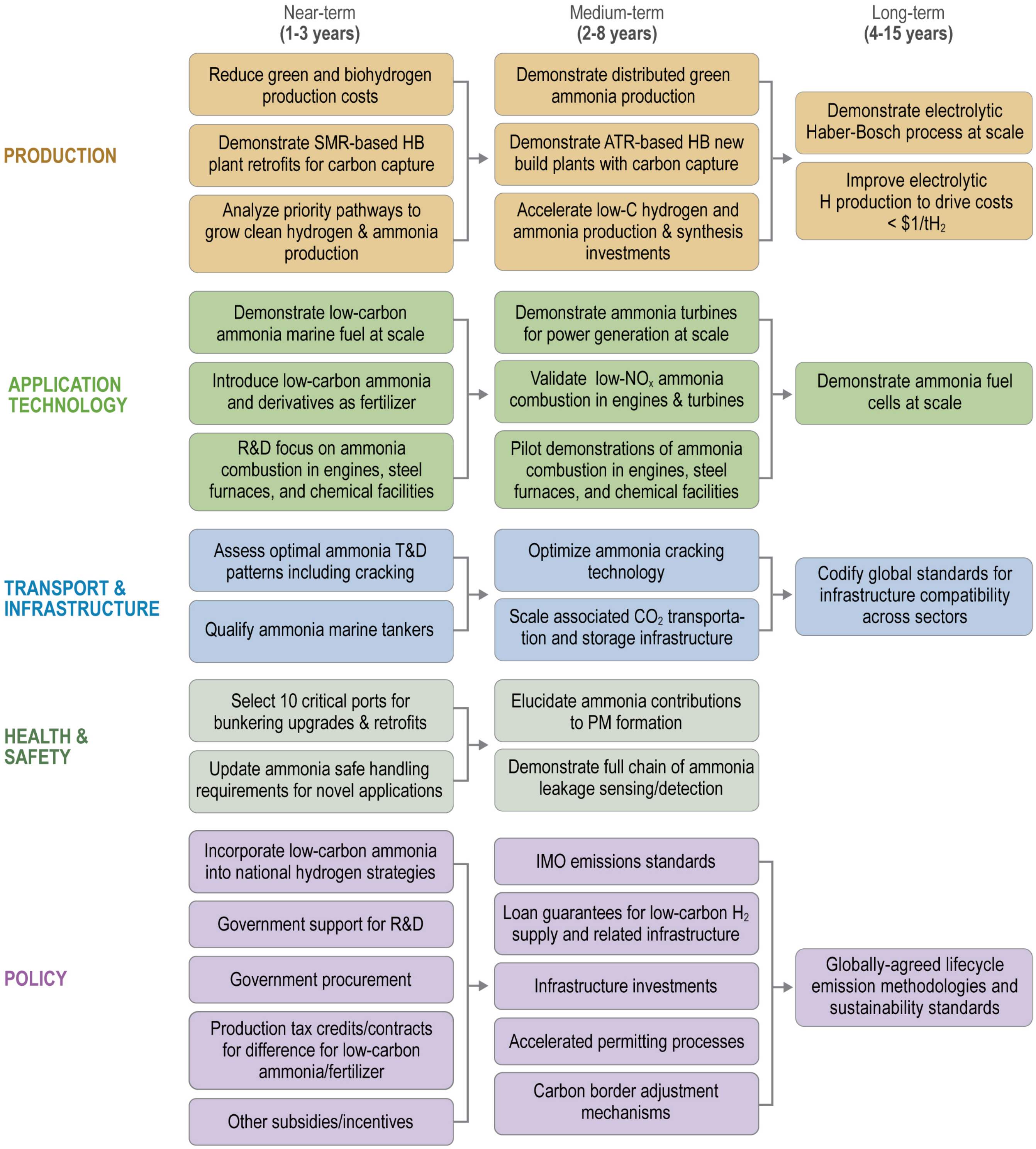
RECOMMENDATION 7:

Business and governments should support local, national and international data-gathering and data-sharing. Since the low-carbon ammonia enterprise is in its earliest stages and since many commercial applications have not yet commenced, there is an opportunity to avoid potential failure, risks and capital misallocation through data gathering and sharing. Business should expect to monitor emissions from the production and use of ammonia—especially for projects that receive public sector grants and subsidies. This should apply to production, transportation, conversion, and use cases and projects. Governments may choose to compel such data gathering and sharing from business. They may also wish to construct and manage federated data sites that host information for future scholars and practitioners.

RECOMMENDATION 8:

Business, governments and training institutions should focus on human capital development. The scarcity of human resources will greatly limit the speed and scale of low-carbon ammonia deployment. Expertise is needed in the trades (welders, pipefitters, builders, subsea workers), designers (architects), high technology (engineering, sensors, novel electrolyzers), regulation (permitting, inspection, oversight) and governance (finance, law, international affairs). Skills can be built through apprentice programs, certification processes, short courses, executive education and dedicated curricula. Sectors should begin at once and should simultaneously explore possible collaborations to speed and strengthen human capital development.

Low-Carbon Ammonia Roadmap



	Near-term (1-3 years)	Medium-term (2-8 years)	Long-term (4-15 years)
PRODUCTION	Reduce green and biohydrogen production costs Demonstrate SMR-based HB plant retrofits for carbon capture Analyze priority pathways to grow clean hydrogen & ammonia production	Demonstrate distributed green ammonia production Demonstrate ATR-based HB new build plants with carbon capture Accelerate low-C hydrogen and ammonia production & synthesis investments	Demonstrate electrolytic Haber-Bosch process at scale Improve electrolytic H production to drive costs < $1/tH_2$
APPLICATION TECHNOLOGY	Demonstrate low-carbon ammonia marine fuel at scale Introduce low-carbon ammonia and derivatives as fertilizer R&D focus on ammonia combustion in engines, steel furnaces, and chemical facilities	Demonstrate ammonia turbines for power generation at scale Validate low-NO_x ammonia combustion in engines & turbines Pilot demonstrations of ammonia combustion in engines, steel furnaces, and chemical facilities	Demonstrate ammonia fuel cells at scale
TRANSPORT & INFRASTRUCTURE	Assess optimal ammonia T&D patterns including cracking Qualify ammonia marine tankers	Optimize ammonia cracking technology Scale associated CO_2 transportation and storage infrastructure	Codify global standards for infrastructure compatibility across sectors
HEALTH & SAFETY	Select 10 critical ports for bunkering upgrades & retrofits Update ammonia safe handling requirements for novel applications	Elucidate ammonia contributions to PM formation Demonstrate full chain of ammonia leakage sensing/detection	
POLICY	Incorporate low-carbon ammonia into national hydrogen strategies Government support for R&D Government procurement Production tax credits/contracts for difference for low-carbon ammonia/fertilizer Other subsidies/incentives	IMO emissions standards Loan guarantees for low-carbon H_2 supply and related infrastructure Infrastructure investments Accelerated permitting processes Carbon border adjustment mechanisms	Globally-agreed lifecycle emission methodologies and sustainability standards

DISCLAIMER

Roger Aines and Corinne Scown contributed to the technical evaluations but not the policy recommendations in this document.

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