Carbon Direct



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Clean Ammonia: Prospects for Decarbonization

Major Findings

01. Ammonia is a commonly produced and globally-traded industrial commodity that is used in many applications, the largest (85 percent) being nitrogen fertilizer production.

02. Conventional ammonia synthesis relies heavily on fossil fuels both as a direct energy source and as a feedstock - most critically for hydrogen production and also heat for ammonia synthesis. Hydrogen production (typically through steam methane reforming with or without carbon capture) is the first step for producing ammonia.

03. Estimates suggest a current commercial-scale global ammonia production capacity of 183 million metric tonnes per year at a total annual market value of roughly $60 billion. The exact market size is surprisingly uncertain in the literature.

04. The price of ammonia is highly sensitive to the price of natural gas and electricity. The carbon footprint is sensitive to the upstream emissions from gas and electricity production.

05. Global demand for ammonia could grow by a factor of 3-4 times current levels to an estimated 688 million metric tonnes per year by 2050 in a 1.5°C scenario. By midcentury, the two largest use cases for ammonia are anticipated to be for fertilizer production and as a fuel for maritime shipping (and to a lesser extent as a hydrogen carrier and for power generation).

06. Conventional production pathways for ammonia are emissions-intensive - roughly 1.9-2.4 metric tonnes of CO_2 for every metric tonne of ammonia produced (in terms of emissions intensity, ammonia production is quadruple cement and twice steel). Ammonia production is responsible for around 500 $MtCO_2$ per year - roughly 15-25 percent of the total CO_2 emissions from the chemical industry and 1-2 percent of global CO_2 emissions.

07. Options for reducing emissions from the ammonia value chain include using clean hydrogen which can be achieved through methods such as steam methane reforming with CCS and electrolysis with clean electricity; fuel-switching to biomass; improvements in technology performance; and demand destruction for fertilizers or use of fertilizer alternatives.

08. Future production and consumption of ammonia will be geographically distributed. Market trends suggest a co-location of future ammonia production projects in areas with relatively cheap renewable energy resources such as Australia, Chile, and MENA (including Saudi Arabia, Oman, United Arab Emirates, Egypt, and Morocco).

09. The ultimate success of clean ammonia as a commodity is predicated on the production of clean hydrogen and ability to use ammonia as a fuel (e.g., in fuel cells, direct combustion in turbines and boilers, or through ammonia cracking).

10. Although the ammonia industry already has established infrastructure, the buildout of a clean ammonia market at scale will require major investments in new physical infrastructure and supply chains along with policy and regulatory support.

Executive Summary

Ammonia is a commonly produced and globally-traded industrial commodity used in a wide array of industrial applications, notably fertilizer and chemical production. Due to its current market size and versatility of end-use applications, the ammonia industry is poised to play an important role in decarbonization efforts across multiple sectors, featuring a new role as a fuel for shipping, heavy industry, and power generation. In this report, we explore the most promising mitigation strategies for decarbonizing ammonia production. We also look at the future market potential of ammonia for newer applications, including maritime transport and power generation, and key geographies and markets for potential production and use.

Overview

Ammonia (NH_3) is a commonly produced and globally-traded industrial commodity that is used in a variety of applications, and is the second most produced chemical (by mass) after sulphuric acid. The largest end-use sector for ammonia globally is fertilizer production (estimates suggest 85 percent of ammonia is used to produce nitrogen fertilizer),[1] while other applications include (but are not limited to) chemical production and as an agent in household cleaning solutions. Proposed applications involve many sectors and markets, including fuel for power generation (e.g., natural gas turbines, portable generators that promote fuel-switching from diesel to ammonia), internal combustion engines (e.g., on-farm tractors), maritime vessels and oceanic shipping (particularly long-distance routes), working fluid in refrigeration systems, long-duration energy storage, district heating systems, industrial furnaces, and serving as an energy carrier for hydrogen (Figure 1).[2,3,4,5,6,7,8]

The synthesis of ammonia via conventional production methods relies heavily on the use of fossil fuels both as a direct energy source and as a feedstock for production, and ultimately combines nitrogen and hydrogen through the Haber-Bosch process.[9] Hydrogen production (typically through steam methane reforming [SMR]) is usually the first step for producing ammonia, but it can also be produced through methods such as water electrolysis. Similar to hydrogen, the production of ammonia can fall into several categories including gray ammonia (SMR to produce hydrogen), blue ammonia (same as gray ammonia but with carbon capture and storage or CCS), and green ammonia (water electrolysis with clean electricity from renewable or nuclear energy). Clean hydrogen must ultimately be the primary mechanism for decarbonizing ammonia production.

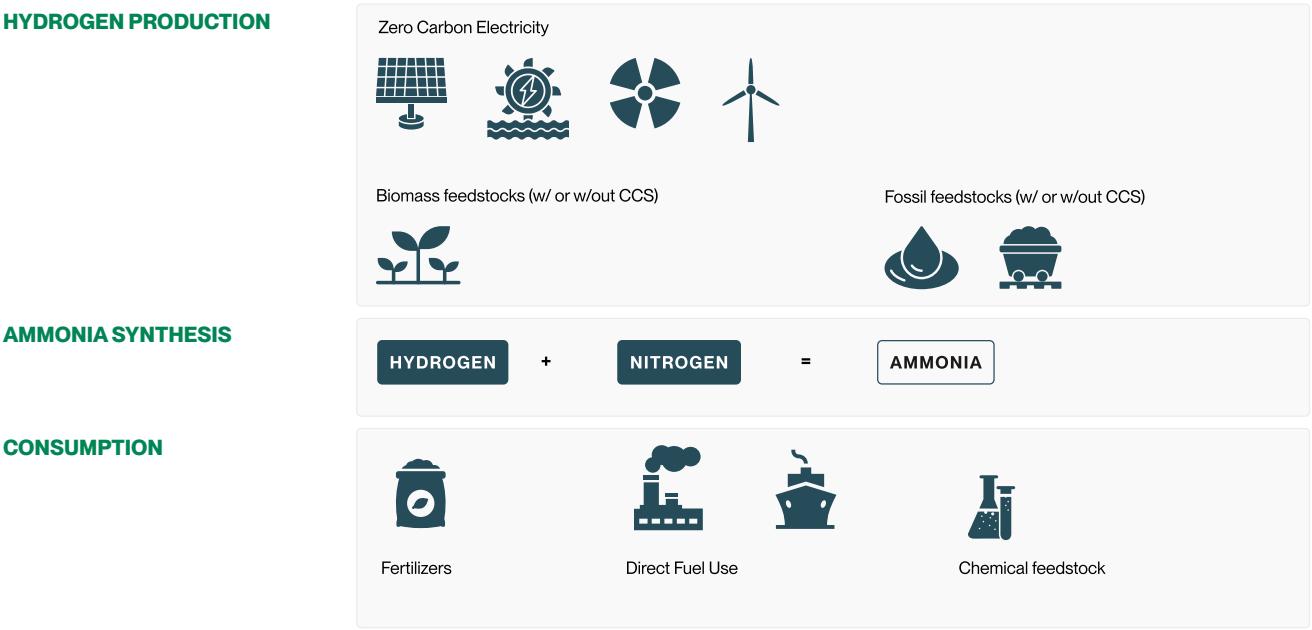


Figure 1 Ammonia Production Pathways and Major End Uses. Source: Carbon Direct Inc. 2023. Images from Noun Project

Benefits of ammonia as a fuel include being cheaper and safer to transport than hydrogen (not typically explosive), easier to liquefy (condenses from gas to liquid at higher temperature than hydrogen), and allows for ease of detection if leakage occurs.

State of the Market

Current estimates suggest a commercial-scale global ammonia production capacity of 183 million metric tonnes per year[18] that has consistently risen over the last couple decades (approximately 10 percent of which is traded),[19] with the potential for rapid market growth by midcentury.[20,21,22,23] The production scale amounts to a total annual market value of roughly $60 billion at present.[24] Ammonia production currently accounts for approximately 45 percent of hydrogen consumption,[25] five percent of natural gas consumption, and two percent of total final energy consumption globally.[27]

Ammonia fertilizers have historically sold for around $750 per metric tonne, using historical feedstock ammonia prices ranging from $200-600 per tonne over the time period 2017-2021[28] (largely based on natural gas prices of $3-4 per MMBtu).[29] Modern day spot prices for ammonia have been estimated at more than $1,000 per metric tonne (prior to price disruptions in natural gas and other energy and commodity markets during the geopolitical energy crisis of the Russia-Ukraine war in 2022) and now commonly exceed $1,200 per metric tonne according to some indices.[30,31] Given the energy-intensive nature of ammonia production, the process is highly sensitive to the cost of natural gas and electricity inputs.[32]

MAJOR USE CASES

There are numerous potential uses for ammonia as mentioned above. By midcentury, the two largest use cases for ammonia are anticipated to be for use in fertilizer production (similar to current consumption patterns) and as a fuel for maritime shipping (Figure 2):

Fertilizer

Global fertilizer production currently contributes around 400-450 $MtCO_2$ per year (direct emissions) and is expected to increase to 550 $MtCO_2$ per year by midcentury to satisfy food production requirements for a growing population.[33,34] SMR for hydrogen production is the most emissions-intensive process of fertilizer manufacturing, accounting for roughly 90 percent of CO_2 emissions throughout the production process.[35] Despite its benefits for global food production, the use of nitrogen fertilizers can have adverse environmental consequences aside from greenhouse gas (GHG) emissions such as disruption of the nitrogen cycle and toxic algae blooms.[36] Precision agriculture that attempts to reduce fertilizer usage could result in lower demand for ammonia production,[37] although success to date is limited.

Maritime Shipping

Although there are no purpose-built ammonia-fueled maritime ships to date, existing ships can co-fire ammonia as a fuel blend or be retrofitted with ammonia fuel cells. For example, several companies such as Equinor are exploring production options for ammonia fuel cells that are scheduled to become operational by 2024 (for which ammonia would satisfy 60-70 percent of the fueling needs and be balanced by liquefied natural gas [LNG] and battery usage).[38] In a survey of shipowners and operators, roughly 60 percent of respondents indicated that hydrogen and ammonia were the most viable long-term fuel options for maritime transport,[39] which currently emits more GHGs than the aviation sector.[40] The current market size for the international maritime shipping of ammonia as a commodity is estimated at 18-20 million metric tonnes per year.[41]

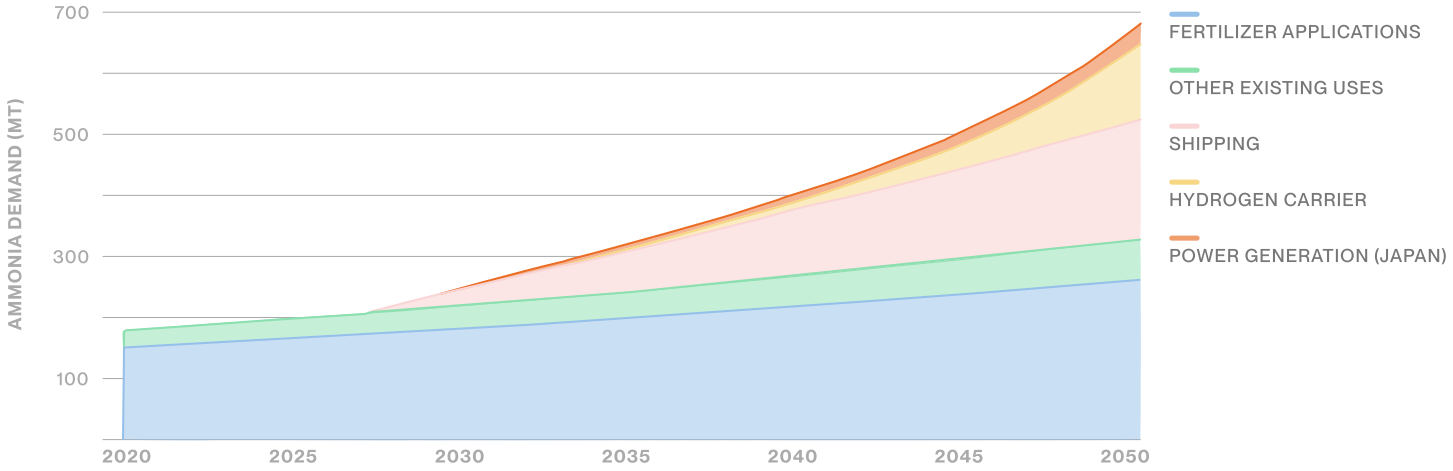


Figure 2. Projected Demand for Ammonia to 2050 (1.5 °C Scenario) by Use Case

Source IRENA and AEA (2022), Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn. Available at: https://irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia

Key Geographies for Production and Consumption

The production and consumption of ammonia (current and forecasted) is geographically distributed (Figure 3).[42] However, market trends suggest a co-location of future ammonia production projects in areas with relatively cheap renewable energy resources such as Australia, Chile, and MENA (including Morocco, Oman, United Arab Emirates, Egypt, and Saudi Arabia).[43] In 2020, the global ammonia trade was estimated at $6.5 billion, with major exporters that included Russia and Saudi Arabia and major importers that included India and South Korea.[44]

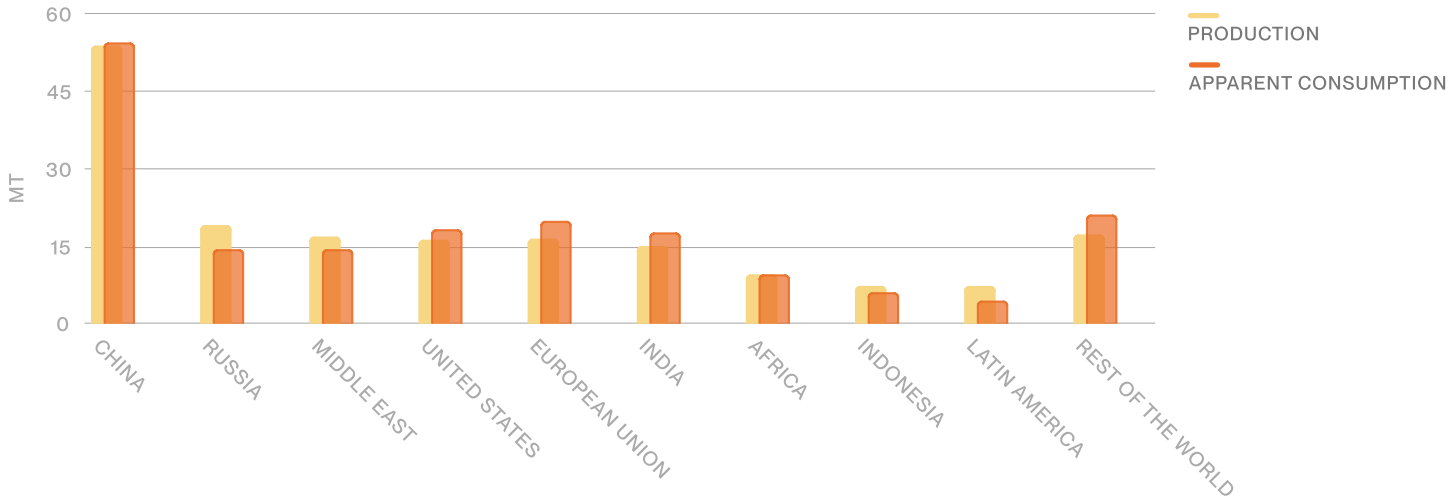


Figure 3. Major Demand and Production Centers for Ammonia, 2019

Source (adapted) IEA (2021), Ammonia Technology Roadmap, IEA, Paris https://www.iea.org/reports/ammonia-technology-roadmap

Projections from the International Renewable Energy Agency (IRENA) suggest that around 25 percent of total hydrogen supply could be traded globally under a 1.5°C scenario (as opposed to domestic production and consumption), for which 45 percent of that supply would be transported by ocean in the form of ammonia (and mostly consumed directly as ammonia without reconversion to hydrogen).[45] Projected major players in the ammonia market by 2050 are shown in Figure 4.[46]

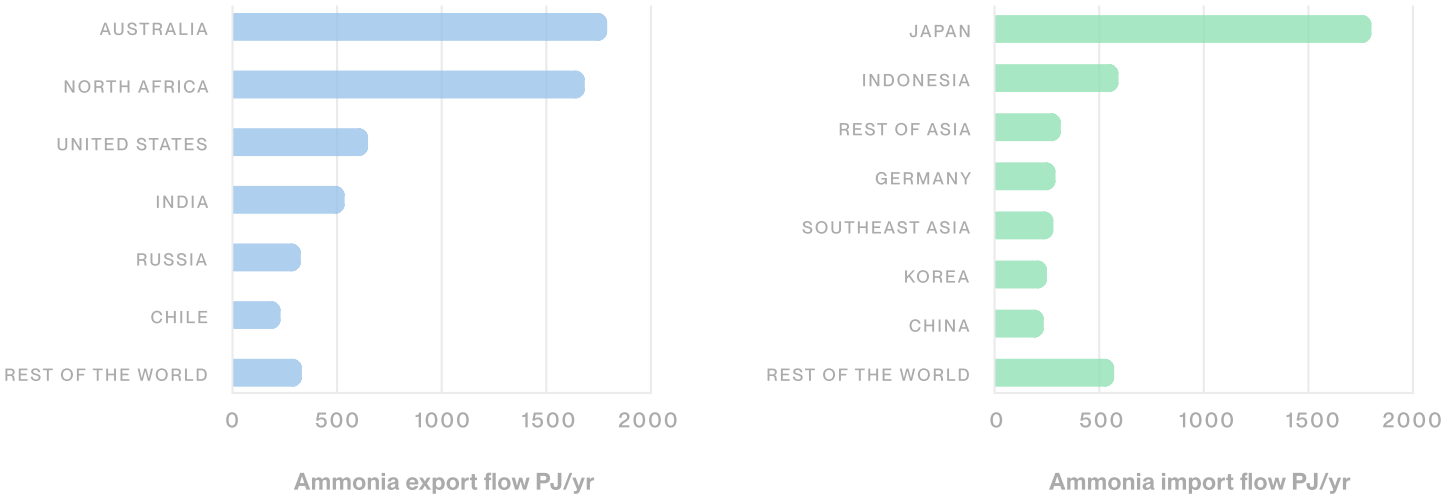


Figure 4. Projected major Players of Future Global Ammonia Market

Major exporters are shown on the left and major importers are shown on the right. Countries and regions anticipated to be largely 'self-sufficient' include Brazil, Canada, China, and Latin America. Source: IRENA (2022), Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward, International Renewable Energy Agency, Abu Dhabi. Available at: https://irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook

Several notable geographic areas for production and consumption:

Australia

Australia could become a major global player in ammonia production and export (due in part to its extensive network of trading partners and proximity to Asian markets),[47] with politicians promoting ammonia as a source of jobs and tax revenue creation involving both production and export (through the construction of dedicated terminals).[48] Western Australia in particular has been identified as an ideal geographic location for the production of clean ammonia at scale given its abundant renewable energy resources, with plans by Yara and ENGIE to develop a plant (backed by funding from the Australian government) that will produce hydrogen and ammonia.[49]

Chile

Chile is positioned to become a major clean ammonia exporter given its domestic renewable energy resources. In its National Green Hydrogen Strategy, Chile aims to be a major producer and exporter of liquid hydrogen, green ammonia, and clean fuels to global markets by 2030. 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.[50] A major project has already been announced by Total Eren (subsidiary of TotalEnergies) that is scheduled to produce 4.4 million tonnes of renewable ammonia per year at full capacity.

China

China is currently the largest producer of ammonia at around 25-30 percent of total supply, while other major producers (each accounting for roughly 8-10 percent of global production) include the U.S., EU, India, Russia, and Middle East.[52,53] Estimates suggest that China could see production rates nearly double by midcentury.[54] Importantly, none of this ammonia is produced cleanly as it relates to hydrogen production or ammonia synthesis. Without low-carbon hydrogen production (blue or green), growth in Chinese ammonia production would result in increased emissions.

Japan

Japan has developed a roadmap for the use of ammonia in its Green Growth Strategy, with the intent to export ammonia to other countries in Asia over the coming decades.[55] Defined use cases for ammonia in Japan include power generation through ammonia-fired gas turbines and maritime transport.[56] Estimates suggest that Japan could import around 3 million metric tonnes of ammonia per year by 2030 and 30 million metric tonnes by 2050.[57] Japan is reportedly considering co-firing coal with ammonia in its coal-fired power plants as a means to reduce the emissions intensity of the fleet (up to a 20 percent ammonia blend by 2030 and 100 percent ammonia by 2050). Pilot projects

have already demonstrated the feasibility of co-firing at a 20 percent ammonia blend, with further trials set to take place by JERA (power generation company) to co-fire at a 50 percent ammonia blend.[58,59,60]

Other notable geographic locations

- Countries with national-level plans to produce clean ammonia include Japan, Australia, UK, Chile, and the Netherlands.[61,62]
- India and Africa are expected to experience considerable increases in the production of ammonia by midcentury.[63]
- South Korea has stated its intention to increase the use of ammonia for power generation to help reduce its reliance on coal and LNG. A research and demonstration phase is expected to occur through 2027, with widespread commercial deployment by 2030.[64]
- In the United States, synergies could exist between wind resource potential in the Midwest for green ammonia production.[65] Blue ammonia projects have already been announced such as the $4.5 billion project in Louisiana by Air Products.[66]

Mitigation Strategies for Ammonia Production

Ammonia is a carbon-free molecule (NH_3) that is approximately 18 percent hydrogen by weight.[67] Although ammonia does not release CO_2 upon combustion or conversion to hydrogen, its combustion does result in the release of nitrous oxide (potent GHG) and toxic air pollutants through nitrogen oxide gases[68,69] which must be managed through aggressive operational controls and regulations. Conventional production pathways for ammonia are emissions-intensive and equate to roughly 1.9-2.4 metric tonnes of CO_2 for every metric tonne of ammonia produced (four times more emissions intensive than cement and two times more emissions intensive than steel).[70,71] Ammonia production is responsible for around 500 $MtCO_2$ per year, which amounts to roughly 15-25 percent of the total CO_2 emissions from the chemical industry[72,73] and 1-2 percent of global CO_2 emissions.[74,75] Under the International Energy Agency's (IEA) Stated Policies Scenario, ammonia production increases 40 percent by midcentury, while CO_2 emissions increase three percent by 2030 but then decline to an emissions level that is 10 percent below current levels.[76]

Although clean ammonia has been produced at commercial scale since the 1920s using hydropower, natural gas became the dominant fuel for ammonia production beginning in the 1940s. Roughly 70 percent of ammonia production is currently done through SMR, while coal gasification (particularly in China) accounts for most of the remaining production (naphtha and heavy fuel oil also contribute to a minor extent).[77,78,79] Industry projections suggest that clean ammonia production plants will dominate capacity additions starting around 2025 (only 20,000 metric tonnes of renewable ammonia was produced in 2021).[80,81] There are numerous options for reducing emissions from the ammonia value chain (Figure 5) that include (but are not limited to) the use of clean hydrogen which can be achieved through methods such as SMR with CCS and electrolysis with clean electricity, fuel-switching to biomass, improvements in technology performance (e.g., electrolyzer efficiency), demand destruction for fertilizer consumption, and the use of alternatives to urea-based fertilizers (e.g., cyanobacteria or nitrate-based fertilizers).[82]

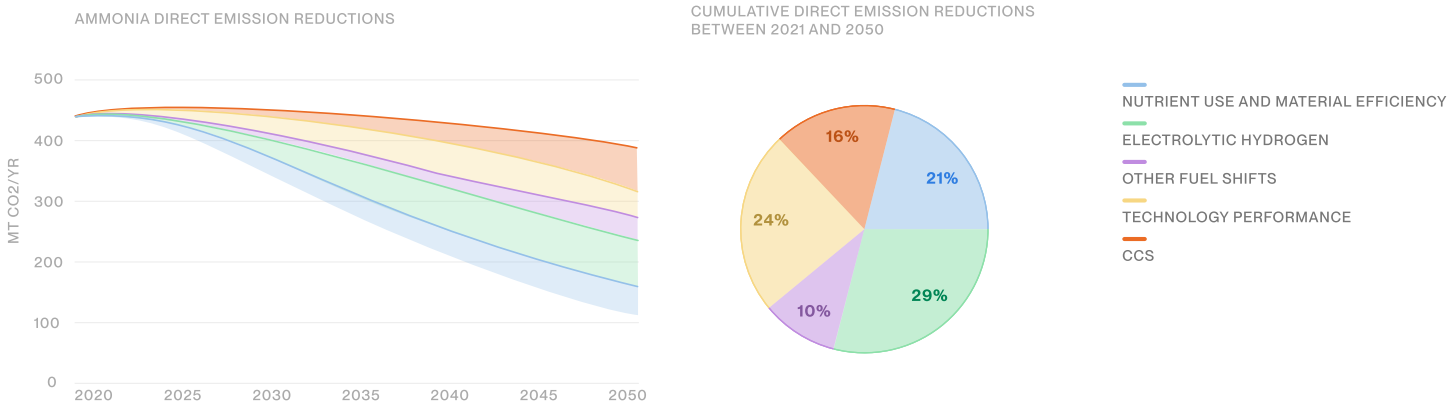


Figure 5. Selection of Strategies to Reduce Demand for (and Emissions from) the Ammonia Value Chain

Note: Roughly half of projected emissions reductions come from clean hydrogen (60% green, 40% blue).

STEAM METHANE REFORMING WITH CCS

This process involves reacting natural gas with high-temperature steam to liberate hydrogen and capture attendant CO_2 emissions in the process. The application of CCS to the fertilizer production process is recognized as a low-cost method (Figure 6) to both reduce emissions and minimize price increases to the end-use product,[83] due in part to the highly concentrated nature of CO_2 (near pure) that is emitted during the process. Emissions reductions of up to 70 percent have been observed using CCS to reduce the emissions intensity of ammonia production for fertilizer synthesis.[84] Much of the cost of conventional ammonia production through SMR (around 70-90 percent) is driven by natural gas prices,[85] for which moving away from natural gas or other fossil fuel feedstocks could help reduce exposure to price volatility in the market.[86] Costs for fossil-based ammonia production is estimated at $110-340 per metric tonne (which increases to $170-465 per metric tonne with CCS). [87] The estimated cost for a first-of-a-kind ammonia plant with CCS is between $22-33 per tonne of CO_2.[88]

ELECTROLYSIS

This process involves using a current of electricity to split water molecules and liberate hydrogen, which needs to be done through the use of low-carbon electricity to elicit an emissions benefit. Costs for renewable ammonia (of which 90 percent of the cost is driven by the cost of clean hydrogen) are estimated at $720 per metric tonne in geographic areas with optimal renewable energy resources, which is expected to decline to $480 per metric tonne by 2030 and $310 per metric tonne by 2050. By 2030, renewable ammonia is expected to be cost competitive with fossil-derived ammonia with CCS (with cost improvements dependent on the electrolyzer, electricity price, and potential for efficiency gains).[89] Electrolytic hydrogen is more cost competitive than CCS for ammonia production if costs are below $35/MWh for greenfield ammonia and below $15/MWh for brownfield ammonia.[90] (Of note is that ammonia synthesis using electrolytic hydrogen is a water-intensive process that requires an estimated nine tonnes of water to produce one tonne of hydrogen, which poses additional considerations regarding project siting and environmental impacts.)[91]

OTHER PRODUCTION PATHWAYS AND TECHNOLOGY INNOVATIONS

There are multiple alternative means to produce ammonia and reduce the emissions intensity of the process that include:

- Biomass can be used in lieu of fossil fuels to help reduce the emissions intensity of ammonia production, but is less cost competitive both as a feedstock for ammonia ($250-400 per metric tonne using biomass compared to ≤$150 per metric tonne using renewables) and compared to other mitigation options.[92,93]
- 'Generation 3' technology involves the production of ammonia through an electrochemical cell without the need to produce hydrogen as a feedstock.[94]
- Methane pyrolysis (or methane cracking) involves the thermal decomposition of methane which yields hydrogen and solid carbon without emissions.[95] There is currently a demonstration plant in Nebraska that is aiming to produce 275,000 metric tonnes of ammonia per year without CO_2 emissions.[96]
- Monash University scientists reported the ability to produce ammonia from renewable energy in reactors that are only the size of refrigerators (and at room temperature), which could allow for greater siting flexibility at the individual farm or community level.[97]
- Solid state ammonia synthesis could combine water electrolysis with ammonia synthesis in a single step using a modified fuel cell technology.[98]
- Thermochemical cycles which leverage a series of chemical steps to split water.[99]
- A scientific advancement found that adding ammonia to a metal catalyst produces nitrogen without the need for additional energy input. This process could be leveraged to produce electricity in an environmentally friendly manner.[100]

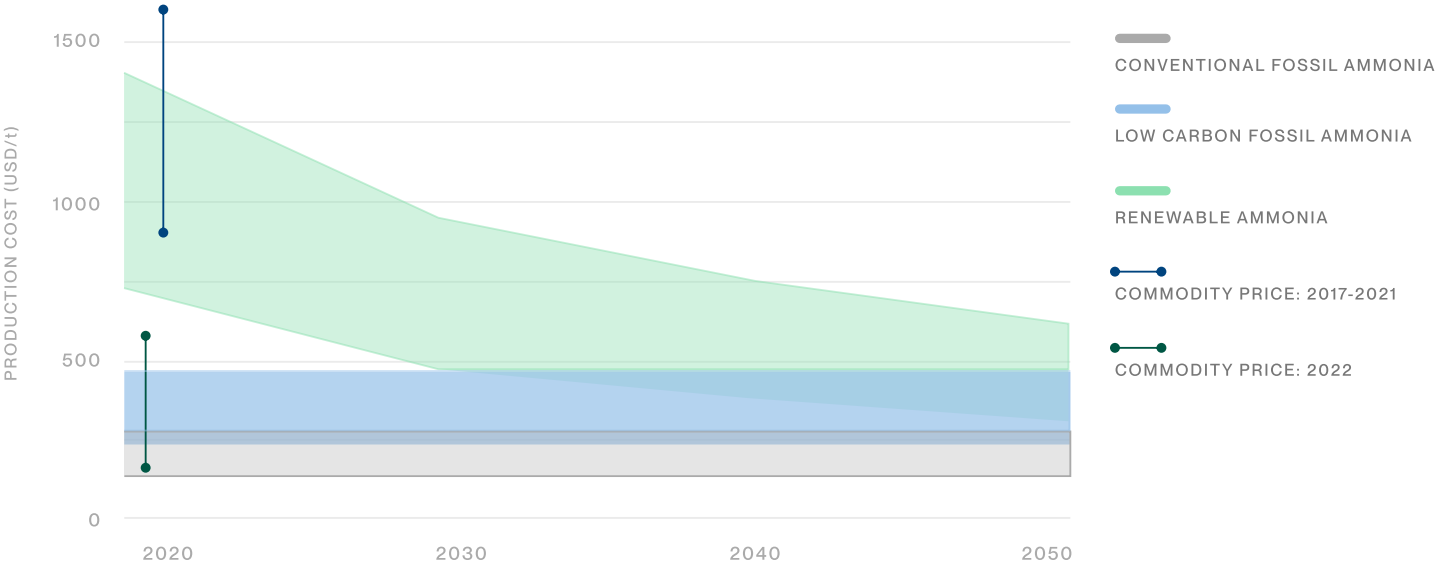


Figure 6. Current and Projected Costs of Low-Carbon Ammonia Production, 2020-2050

Source (adapted) IRENA and AEA (2022), Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn. https://irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia; EIA, May 20, 2022, US Ammonia prices rise with higher natural gas prices, https://www.eia.gov/todayinenergy/detail.php?id=52358

Future Market Potential

Global demand for ammonia could grow by a factor of 3-4 times current levels to an estimated 688 million metric tonnes per year by 2050 in a 1.5°C scenario (80 percent of which would be used for direct consumption with the remainder used as a hydrogen carrier).[102] In the IEA's Sustainable Development Scenario (2°C stabilization), clean ammonia production comes online at a rapid pace. By 2050, the scenario specifically calls for 110 GW of electrolyzer capacity and 90 million metric tonnes of CO_2 transport and storage infrastructure (resulting in an annual capital investment level of $14 billion per year between now and 2050 or approximately $420 billion in total investment).[103] IRENA suggests that the ammonia market will need to scale by a factor of four (compared to current levels) to meet Paris-aligned climate targets, with major demand increases coming from maritime transport (new demand of 197 million metric tonnes from current levels by 2050) and as a hydrogen carrier (new demand of 127 million metric tonnes from current levels by 2050).[104] In the IEA's Net Zero Emissions Scenario, hydrogen and ammonia comprise two percent of total electricity generation and 45 percent of energy demand for shipping by 2050.[105]

MARITIME TRANSPORT

Ammonia could account for around one-quarter of the fuel mix for maritime transport by 2050, with all newly built ships being capable of running entirely on ammonia beginning in the 2040s.[106] Estimates suggest that bringing clean ammonia to scale for use as a primary fuel in maritime transport (and reducing sectoral GHG emissions 50 percent by 2050) would require an investment of approximately $1 trillion, for which 87 percent of investments would be primarily directed toward land-based infrastructure and production facilities (with the remainder used for the maritime vessels themselves). Fully eliminating emissions from the global maritime fleet could cost $1.4-1.9 trillion.[107,108] Of note is that the International Maritime Organization (IMO) has set a target to halve GHG emissions by 2050 (from a 2008 baseline) and fully eliminate emissions as soon as possible during the course of this century, which could help spur new markets for clean ammonia as a fuel for maritime transport.[109]

Market and Engineering Challenges for Ammonia

Ammonia will need to contend with methanol for market share as an alternative low-carbon fuel of choice. Potential advantages of methanol compared to ammonia include a higher volumetric energy density, less toxic, and easier to store and transport. Dual-fuel engines that are capable of running on methanol have already been ordered by or generated interest from Maersk (Denmark), MPCC (Germany), CMA CGM (France), Cosco (China), Eastern Pacific (Singapore), and Pacific International Lines (Singapore).[110] Preliminary estimates suggest that methanol and ammonia dual-fuel newbuild ships could cost 11 percent and 16 percent more than a standard newbuild ship, respectively.[111]

Maritime vessels (whether through retrofit projects or purpose-built ships) will also need to overcome the engineering challenges associated with the onboard storage of ammonia that, despite being more energy dense by volume than hydrogen (by over 50 percent) for ship propulsion (and roughly 10 times more energy dense than lithium-ion batteries), can still occupy a considerable amount of space for fuel storage which will affect cargo space (requires more space compared to diesel).[112,113,114,115]

INFRASTRUCTURE CONSIDERATIONS

The ammonia industry already has an established infrastructure base given its current commercial-scale production, global trade patterns, and enabling transportation infrastructure such as maritime ports (currently produced, stored, and traded in more than 130 ports) and vessels. However, the buildout of a market for clean ammonia to help achieve global climate goals will require major investments in physical infrastructure and supply chains along with policy and regulatory support. Much of this infrastructure buildout could (initially) focus on a subset of countries to help minimize costs and logistics, given that the top 10 ammonia-consuming countries comprise 75-90 percent of total market demand. Considerations to realize this potential include:

- Global electrolyzer production capacity will need to scale rapidly to meet projected demand for renewable ammonia. Estimates suggest that electrolyzer production capacity will need to scale by a factor of 20 from 2.1 GW per year in 2020. The potential to scale will rely in part on improving the energy efficiency of electrolyzers and development of smaller-scale, distributed production processes to optimize siting considerations.
- The costs of ammonia pipelines are cheaper than that of natural gas or hydrogen. Estimates suggest ammonia pipelines are approximately 50 percent less expensive than natural gas pipelines and 75 percent less than hydrogen pipelines. However, the siting of pipelines remains an obvious and considerable challenge. Maritime shipping costs for ammonia are also expected to decline from around $8 per kgH_2 to less than $1 per kgH_2 by 2050 (mostly due to reduction or elimination in conversion and reconversion costs and midstream costs). This could help bolster global markets for trade. From 2020-2021, there were more than 80 projects or collaborations that were announced concerning the global trade of ammonia and hydrogen.[121]
- Infrastructure requirements to help realize ammonia-powered maritime shipping at scale include improved safety mechanisms for propulsion systems (and safety protocols for any toxic exposure to ammonia more broadly), bunkering capabilities at ports to help facilitate refueling, and large-scale clean electricity deployment.[122]
- Ammonia plants are typically large facilities at a scale of up to 1,500 metric tonnes of ammonia per day[123] and have a production lifetime of around 50 years, leading to a relatively slow capital stock turnover (and potential lifetime emissions level between 4-13.5 $GtCO_2$). Estimates suggest that the average age of the current global fleet of ammonia plants is 25 years.[124]
- For large (conventional) ammonia production plants in the United States, the capital costs range from $1,000-1,500 per tonne annual installed capacity (and up to $3,000 per tonne annual installed capacity for smaller plants).[125]
- Continued support across the research, development, demonstration, and deployment spectrum will be required to maximize the opportunity for clean ammonia at scale, such as through the U.S. Department of Energy's Ammonia for H2@Scale program and Advanced Research Projects Agency-Energy's REFUEL PROGRAM.[126,127]
- The Ammonia Energy Association is set to develop a globally harmonized Low-Carbon Ammonia Certificate Scheme that will be piloted in 2023 and become operational in 2024. The aim of the certification is to account for the well-to-gate GHG emissions associated with ammonia production and transport,[128] and allow for the

establishment of a market mechanism by which global producers and consumers can trade low-carbon ammonia through a scientifically validated framework.[129] It is intended that qualifying projects would be approved through the framework and thereby be eligible to issue certificates based on environmental attributes that could then be traded with other entities. The certification scheme is designed to be inclusive in nature across all production pathways, with tailored considerations and life cycle assessments for each approach.[130]

PROJECT AND COMPANY LANDSCAPE

Renewable ammonia projects that are either planned or under development (most of which have not reached a final investment decision) are estimated at 15 million metric tonnes of installed capacity by 2030[131] and 71 million metric tonnes by 2040. To reach a Paris-aligned (2°C) scenario, a further 8x increase to 566 million metric tonnes would be required by 2050.[132]

As of May 2022, roughly 60 clean ammonia projects through water electrolysis had been announced along with 10 clean ammonia projects through SMR and autothermal reforming with CCS.[133]

Note: Carbon Direct Inc. ("Carbon Direct") has compiled an extensive database of current and proposed clean ammonia projects globally (along with production volumes) and will continue to curate the database as more projects are announced and move through the project development pipeline. Please contact us to discuss developments in the ammonia industry.

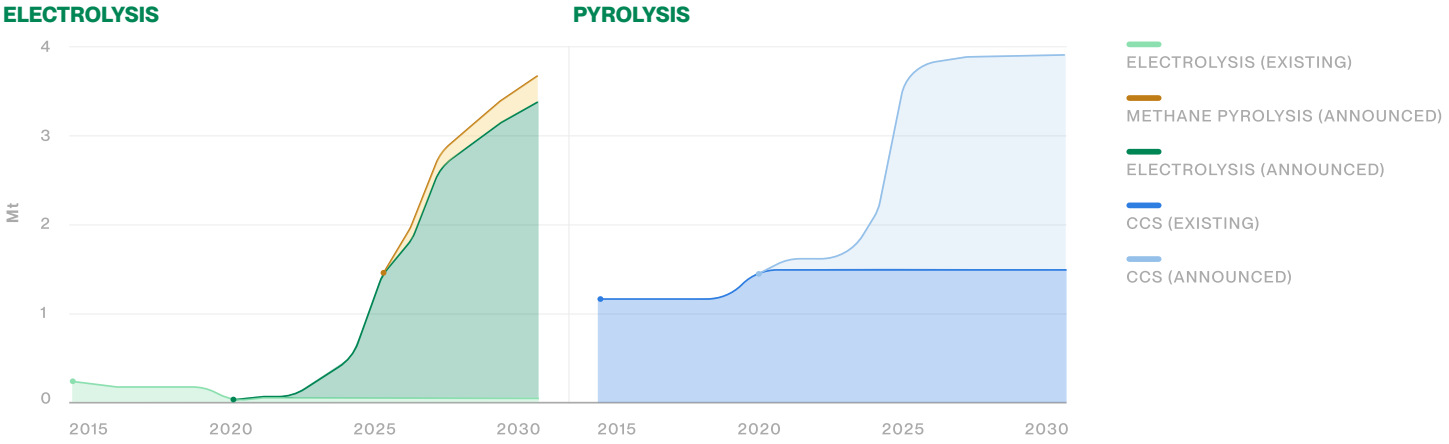


Figure 7. Current and Proposed Clean Ammonia Projects Globally by 2030

Source (adapted) IEA (2021), Ammonia Technology Roadmap, IEA, Paris https://www.iea.org/reports/ammonia-technology-roadmap

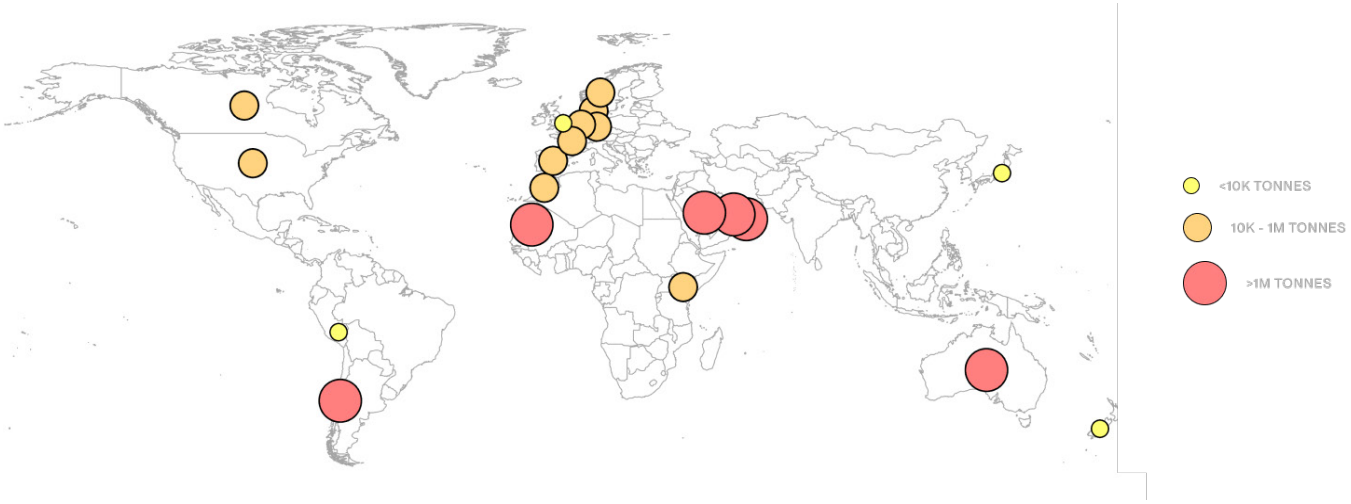


Figure 8. Subset of Current and Proposed Clean Ammonia Projects Globally

Source (adapted) Carbon Direct Inc. (2023). Compiled using data from IRENA and AEA (2022), Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn. Available at: https://irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia

Summary of Findings and Opportunities

The ammonia industry is poised to play an important role in decarbonization efforts across multiple sectors, most notably for fertilizer production and as a fuel for maritime shipping, and potentially into industrial and power sector applications further into the future. However, the emissions-intensive industry must undergo a transformation to low-carbon production to provide an environmental benefit and attract new investment streams. Strict operational controls and attendant regulations will also be needed to manage the release of nitrous oxide and nitrogen oxide gases during transport and use.

The ultimate success of the clean ammonia industry will be predicated on the production of clean hydrogen and ability to use ammonia as a fuel. Commercially viable production options already exist for low-carbon hydrogen through SMR with CCS, biomass gasification, and electrolysis with clean electricity, which can help the clean ammonia industry develop at speed and scale. Of note is that there are already numerous clean ammonia projects that have been announced or are under development. Despite these current industry trends, greater investment will be needed across the entire value chain to meet anticipated demand by midcentury in accordance with global climate goals, as are market standards for carbon footprinting of low-carbon ammonia.

Endnotes

1 IRENA and AEA (2022), Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn. Available at: https://irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia

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