Ammonia Technology Roadmap

Towards more sustainable nitrogen fertiliser production

International Energy Agency

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Abstract

Ammonia is the starting point for all mineral nitrogen fertilisers, forming a bridge between the nitrogen in the air and the food we eat. Around 70% of ammonia is used to make fertilisers, with the remainder used for a wide range of industrial applications, such as plastics, explosives and synthetic fibres. Ammonia may also serve as a low-carbon energy vector in the future, but that application is not considered within the core analytical scope of this technology roadmap. Ammonia production accounts for around 2% of total final energy consumption and 1.3% of CO_2 emissions from the energy system. An increasingly numerous and affluent global population will lead to growth in ammonia production, during a period in which governments around the world have declared that emissions from the energy system must head towards net zero.

This technology roadmap uses scenario analysis to explore three possible futures for ammonia production. In the Stated Policies Scenario the industry follows current trends, making incremental improvements but falling well short of a sustainable trajectory. In the Sustainable Development Scenario the sector adopts the technologies and policies required to put it on a pathway aligned with the goals of the Paris Agreement. The Net Zero Emissions by 2050 Scenario describes a trajectory for the ammonia industry that is compatible with reaching net zero emissions globally for the energy system by 2050. The roadmap concludes with a chapter outlining the necessary roles and actions of key stakeholders, namely governments, producers, and financial and research institutions, and establishes milestones and decision points.

Acknowledgements

This report was prepared by the Energy Technology Policy Division within the Directorate on Sustainability, Technology and Outlooks of the International Energy Agency. The study was designed and directed by Timur Gül (Head of the Energy Technology Policy Division). The analysis and production was co-ordinated by Araceli Fernández Pales (Head of the Technology Innovation Unit) and Peter Levi. The main authors were Sara Budinis, Alexandre Gouy, Peter Levi, Hana Mandová and Tiffany Vass.

Several colleagues across the agency contributed analytical input, including Julien Armijo, Jose Miguel Bermudez Menendez, Tomás de Oliveira Bredariol, Uwe Remme and Jacopo Tattini. Valuable comments and feedback were provided by IEA senior management and other colleagues within the IEA, in particular, Tanguy de Bienassis, Ilkka Hannula, Paul Hugues and Keisuke Sadamori. Thanks also go to Jon Custer, Astrid Dumond, Tanya Dyhin, Merve Erdem, Grace Gordon, Jad Mouawad, Jethro Mullen, Rob Stone, Julie Puech, Therese Walsh and Wonjik Yang of the IEA Communications and Digital Office for their help in producing the report. Caroline Abettan, Reka Koczka, Diana Louis and Per-Anders Widell provided essential support.

Justin French-Brooks carried responsibility for editing.

The work could not have been undertaken without the financial support provided by the European Bank for Reconstruction and Development via the Shareholder Special Fund.

The International Fertilizer Association and the European Bank for Reconstruction and Development provided valuable feedback and support throughout the project, in particular by facilitating communication with fertiliser companies and other experts, including at multiple in-person and online workshops. They also provided analytical feedback during the modelling phase and submitted detailed comments during the peer review process.

Many experts from outside the IEA reviewed the report and provided comments and suggestions of great value. They include:

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The individuals and organisations that contributed to this study are not responsible for any opinions or judgements it contains. The views expressed in the study are not necessarily views of the IEA's member countries or of any particular funder or collaborator. All errors and omissions are solely the responsibility of the IEA.

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Executive summary

Ammonia makes an indispensable contribution to global agricultural systems through its use for fertilisers. Ammonia is the starting point for all mineral nitrogen fertilisers, forming a bridge between the nitrogen in the air and the food we eat. About 70% of ammonia is used for fertilisers, while the remainder is used for various industrial applications, such as plastics, explosives and synthetic fibres. While the use of ammonia as a fuel shows promise in the context of clean energy transitions, this application currently remains nascent. The focus of this roadmap is therefore on existing agricultural and industrial uses of ammonia.

In the future, the world will need more ammonia but with fewer emissions. An increasingly numerous and affluent global population will lead to growth in ammonia demand, during a period in which governments around the world have declared that emissions from the energy system must head towards net zero. This technology roadmap explores three possible futures for ammonia production. In the Stated Policies Scenario the industry follows current trends, making incremental improvements but falling well short of a sustainable trajectory. In the Sustainable Development Scenario the sector adopts the technologies and policies required to put it on a pathway aligned with the goals of the Paris Agreement. The Net Zero Emissions by 2050 Scenario describes a trajectory for the ammonia industry that is compatible with the energy system reaching net zero emissions globally by 2050.

An energy- and emissions-intensive global industry

Ammonia production currently relies heavily on fossil fuels. Global ammonia production today accounts for around 2% (8.6 EJ) of total final energy consumption. Around 40% of this energy input is consumed as feedstock – the raw material inputs that supply a proportion of the hydrogen in the final ammonia product – with the rest consumed as process energy, mainly for generating heat. Just over 70% of ammonia production is via natural gas-based steam reforming, while most of the remainder is via coal gasification, leading to 170 bcm of natural gas demand (20% of industrial natural gas demand) and 75 Mtce of coal demand (5% of industrial coal demand). Oil and electricity combined account for just 4% of the sector's energy inputs.

Ammonia production is emissions intensive. Direct emissions from ammonia production currently amount to 450 Mt CO_2 – a footprint equivalent to the total energy system emissions of South Africa. Indirect CO_2 emissions are around 170 Mt CO_2 per year and stem from two main sources – electricity generation and the chemical reaction that takes place when urea-based fertilisers are applied to soils. Ammonia is one of the most emissions-intensive commodities produced by heavy industry, despite coal accounting for a much smaller share of its energy inputs than in other sectors. At around 2.4 t CO_2 per tonne of production, it is nearly twice as emissions intensive as crude steel production and four times that of cement, on a direct CO_2 emissions basis.

Ammonia is produced and traded around the world. China is the largest producer of ammonia, accounting for 30% of production (and 45% of CO_2 emissions), with the United States, the European Union, India, Russia and the Middle East accounting for a further 8-10% each. Ammonia is traded around the world, with global exports equating to about 10% of total production. Urea, its most common derivative, is traded even more widely, at just under 30% of its production. The availability of feedstock and process energy is a key determinant of where and how ammonia is produced. Low-cost natural gas in the United States, Middle East and Russia explain the prominent roles of these regions and their natural gas-based plant fleets. China's abundant coal reserves explain its heavy reliance on the fuel, which accounts for around 85% of its production.

Absent a change in course, ammonia production would continue to take an environmental toll

The industry's current trajectory is unsustainable. In the Stated Policies Scenario, ammonia production increases by nearly 40% by 2050, driven by economic and population growth. CO_2 emissions grow by 3% by 2030, before entering a decline that is mainly spurred by increases in energy efficiency and a decline in the proportion of coal use. In 2050, emissions are 10% lower than today. Cumulative direct emissions from ammonia production under current trends amount to around 28 Gt between now and 2100, equivalent to 6% of the remaining emissions budget associated with limiting global warming to 1.5 °C.

Existing assets give the industry's emissions momentum. Ammonia production facilities have long lifetimes of up to 50 years. The current average age of installed capacity is around 25 years since first installation, but this figure is subject to significant regional variation. Plants in Europe are around 40 years old on average, compared with 12 years in China, which is home to around 30% of global capacity. Depending how long these plants operate, the existing global stock could produce up to 15.5 Gt CO_2 over their remaining lifetime, which is the equivalent of 35 years' worth of ammonia production emissions in 2020.

Non-CO_2 environmental impacts should not be neglected. In addition to CO_2 emissions, the production of nitrogen fertilisers also results in nitrous oxide emissions. Nitrous oxide and CO_2 are also generated in the use phase during and after fertiliser application. While exact quantities are hard to measure accurately, it is estimated that use-phase emissions are upwards of 70% of the total life-cycle greenhouse gas emissions of nitrogen fertilisers. The over-application of mineral fertilisers can damage ecosystems, but the higher crop yields enabled by fertilisers can also reduce the conversion of natural ecosystems to agricultural production. Methane emissions generated during the extraction and transport of fossil fuels pose a further challenge – as they do for the energy system more broadly – but order-of-magnitude reductions can be achieved with commercially available technologies, a significant proportion of them at zero net cost.

Towards more sustainable ammonia production

Encouraging progress on near-zero-emission technologies is already being made. Near-zero-emission production methods are emerging, including electrolysis, methane pyrolysis and fossil-based routes with carbon capture and storage (CCS). These emerging routes are typically 10-100% more expensive per tonne of ammonia produced than conventional routes, depending on energy prices and other regionally varying factors. Existing and announced projects totalling nearly 8 Mt of near-zero-emission ammonia production capacity are scheduled to come online by 2030, equivalent to 3% of total capacity in 2020.

Two pathways outline a range of desirable futures for the ammonia industry. In the Sustainable Development Scenario, direct CO_2 emissions fall by over 70% by 2050 relative to today. The Net Zero Emissions by 2050 Scenario describes a trajectory where emissions fall by 95% by 2050. The difference between the components of these scenarios is one of degree, not of direction.

Using ammonia more efficiently – reducing demand growth without compromising the end-use services it provides – eases the burden on technology deployment. Slower growth in total production is the outcome of strategies such as increasing the efficiency of nitrogen fertiliser application and increased recycling and re-use of plastics and other durable ammonia-derived goods. By 2050, ammonia production in the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario is 10% lower than in the Stated Policies Scenario.

Using technology to improve the performance of existing equipment is important, but alone is not sufficient to deliver the emission savings required. The global average energy intensity of ammonia production today is around 41 GJ/t on a net basis, compared with best available technology (BAT) energy performance levels of 28 GJ/t for natural gas-based production and 36 GJ/t for coal-based production. The universal adoption of BAT, in combination with operational improvements and a structural shift in the processes used to produce ammonia, together yield a reduction of around 25% in the average energy intensity of production by 2050 in the Sustainable Development Scenario and the Net Zero Emissions by 2050 Scenario.

Near-zero-emission ammonia production requires new infrastructure, innovation and investment

The heavy lifting with respect to emission reductions is done by deploying near-zero-emission technologies. Their deployment contributes the largest share of emission reductions in both the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario. In the Sustainable Development Scenario, the share of near-zero-emission technologies reaches nearly 70% of total production[1] by 2050, up from less than 1% today. Natural gas-based production equipped with CCS accounts for around 20% of production, while for electrolysis the share of total production is more than 25%. In the Net Zero Emissions by 2050 Scenario, near-zero-emission technologies achieve nearly 95% of total production by 2050. Natural gas-based production with CCS accounts for around 20% of production, and electrolysis for more than 40%.

Most near-zero-emission technologies are not yet available at commercial scale in the marketplace. CO_2 separation is an inherent part of commercial ammonia production, but permanent storage of the CO_2 is not yet widely adopted. Electrolysis-based ammonia production has already been conducted at scale using high-load-factor electricity, but challenges remain in the use of hydrogen produced from variable renewable energy (such as solar PV and wind) directly in captive installation arrangements. Nearly 60% of the cumulative emission

[1] Calculated excluding the portion equipped with carbon capture for providing CO_2 for urea production.

reductions in the Sustainable Development Scenario stem from technologies that are currently in the demonstration phase.

New infrastructure must be deployed at a rapid clip. The Sustainable Development Scenario requires more than 110 GW of electrolyser capacity and 90 Mt of CO_2 transport and storage infrastructure by 2050. This means installing on average ten 30 MW electrolysers (the largest facility in operation today) per month and 1 large capture project (annual capture, transport and storage capacity of 1 Mt CO_2) every four months between now and 2050. In the Net Zero Emissions by 2050 Scenario, the additional emission reductions require an even more rapid deployment of these technologies.

Overall investment needs for a sustainable pathway are roughly equivalent to those associated with current trends. The Sustainable Development Scenario requires USD 14 billion in annual capital investment for ammonia production to 2050. Of this, 80% is in near-zero-emission production routes. The Net Zero Emissions by 2050 Scenario requires only slightly higher annual investment – USD 15 billion to 2050. In the Sustainable Development Scenario, it is only after 2040 that the investment per tonne of ammonia produced increases above that of the Stated Policies Scenario. Prior to 2040, the avoidance of continued capital-intensive investment in coal-based production in China yields significant savings, and the lower quantity of ammonia produced yields further savings in overall investment needs.

Enabling more sustainable ammonia production

The industry is primed for change. Governments, producers and other stakeholders have already begun taking action to reduce emissions from the ammonia industry. Some governments have adopted carbon pricing regimes and are funding innovation, while producers have set emission reduction targets and are undertaking RD&D projects. Despite these efforts, emissions continue to rise, and greater ambition is needed.

Governments' role is central. Governments will need to establish a policy environment supportive of ambitious emission cuts by creating transition plans underpinned by mandatory emission reduction policies, together with mechanisms to mobilise investment. Targeted policy is also required to address existing emissions-intensive assets, create markets for near-zero-emission products, accelerate RD&D and incentivise end-use efficiency for ammonia-based products. Governments should ensure that enabling conditions are in place, including a level playing field in the global market for low-emission products, infrastructure for hydrogen and CCS, and robust data on emissions performance.

Other stakeholders also have a crucial part to play. Ammonia producers will need to establish transition plans, accelerate RD&D, and engage in initiatives to develop supporting infrastructure. Farmers and agronomists should prioritise best management practices for more efficient fertiliser use. Financial institutions and investors should use sustainable investment schemes to guide finance towards emission reduction opportunities. Researchers and non-governmental organisations can help develop labelling schemes, continue research on early-stage technologies and galvanise support for key technologies.

Time is of the essence. The current decade – from now to 2030 – will be critical to lay the foundation for long-term success, with around 10% of cumulative emission reductions to 2050 taking place by then in both the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario. Vital near-term actions include establishing strong supportive policy mechanisms, taking early action on energy and use efficiency, developing supporting infrastructure, and accelerating RD&D.

Chapter 1. Ammonia production today

Highlights

- Ammonia makes an indispensable contribution to global agricultural systems through its use for mineral nitrogen fertilisers. About 70% of ammonia is used for fertilisers, while the remainder is used for various industrial applications, such as plastics, explosives and synthetic fibres. Ammonia may also serve as a low-carbon energy vector in the future, but that application is not considered within the core analytical scope of this roadmap.
- Ammonia production today is highly energy and emissions intensive. In 2020 global ammonia production accounted for around 2% (8.6 EJ) of total final energy consumption and 1.3% (450 Mt) of CO_2 emissions from the energy system. How to reduce these CO_2 emissions is the focus of this roadmap.
- The People's Republic of China (hereafter "China") is the largest producer of ammonia today, accounting for 30% of production, with Russian Federation (hereafter "Russia"), the Middle East, the United States, the European Union and India accounting for a further 8-10% each. Ammonia is traded around the world, with global exports equating to about 10% of total production. Urea, its most common derivative, is traded even more widely, at just under 30%.
- Ammonia production currently relies on fossil fuels. Just over 70% of ammonia production is via natural gas-based steam reforming, while most of the remainder is via coal gasification. Near-zero emissions production methods are emerging, including electrolysis, methane pyrolysis and fossil-based routes with carbon capture and storage. The routes are typically 10-100% more expensive per tonne of ammonia produced than conventional routes, depending on energy prices and other regional factors.
- Ammonia production facilities have a long lifetime of typically 20-50 years. Depending how long they operate, existing plants could produce 3.9 to 13.5 Gt CO_2 over their remaining lifetime, which is the equivalent of 9 to 30 years' worth of ammonia production emissions in 2020. Strategies to address existing assets will be an important part of the industry's energy transition.
- In addition to CO_2 emissions from production, nitrogen fertilisers also result in nitrous oxide and CO_2 emissions when applied to soils. While their over-application can damage ecosystems, the higher yields enabled by fertilisers can reduce the conversion of natural ecosystems to agricultural production.

Ammonia and society

The main interaction between ammonia and society is via the world's agricultural systems. Ammonia is the starting point for all mineral nitrogen fertilisers, forming a bridge between the nitrogen in the air and the food we eat. While ammonia is applied directly to pastures in a minority of cases (less than 3% of total usage globally, mainly in North America), it is much more commonly converted to urea and other nitrogen fertiliser products before use. While nitrogen fertilisers are critical inputs to the production of food, feed and fibre, it is ammonia that sits directly at the interface between global agriculture and energy systems. Hence ammonia is the focus of this IEA technology roadmap (see Box 1.1 for a full description of the scope of this publication).

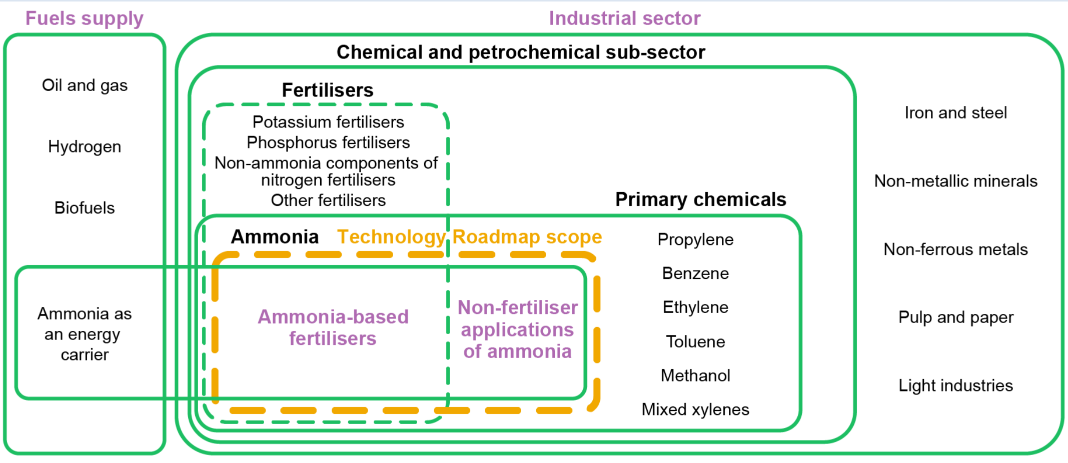
Ammonia is not only used to produce nitrogen fertilisers. Approximately 30% of global demand is for a range of industrial applications. Ammonia is the main input to nitric acid production, which is in turn used to make different grades of ammonium nitrate. Aside from its use as a fertiliser, ammonium nitrate is also used as an industrial explosive for mining, quarrying and tunnelling, and as an input to other chemical products. Urea is a direct derivative of ammonia. Besides its main use as a fertiliser, around a fifth of urea production is also used for a series of industrial applications. It is used as an intermediate in the manufacture of durable resins (e.g. urea formaldehyde) and as a chemical agent to reduce nitrogen oxide (NO_x) emissions from power plants and diesel engines.

Ammonia is also used as an input to acrylonitrile production, which is an intermediate for a range of durable chemical products, including plastic (e.g. polyacrylonitrile and isocyanates for polyurethanes), rubber (e.g. nitrile butadiene) and fibres (e.g. hexamethylenediamine for nylon 66 and caprolactam for nylon 6). While ammonia may in the future be used as a low-carbon energy vector, the focus of this publication is on the production of ammonia to satisfy present and future demand for existing agricultural and industrial applications (see Box 1.1).

Box 1.1 Scope of this technology roadmap

This technology roadmap focuses primarily on the energy consumption and CO_2 emissions associated with the production of ammonia. Other nitrogen fertilisers and industrial products are considered to the extent that they help explain present and future demand for ammonia, and where they have a direct impact on the technology portfolio that is used to produce it, such is the case with urea. Global ammonia production for both fertiliser and industrial applications was 185 Mt in 2020. This roadmap covers the total demand for all existing applications, but does not include within its core scope the potential future use of ammonia as an energy carrier at commercial scale. This topic is addressed in brief in Box 2.2, and in further detail in two separate IEA publications: the *Global Hydrogen Review 2021* and *The Role of Low-Carbon Fuels in Clean Energy Transitions of the Power Sector*.

Scope of this technology roadmap



IEA, 2021.

Energy consumption

The industrial activities associated with producing ammonia fall under the United Nations (UN) International Standard Industrial Classification (ISIC) Rev. 4 Class 2012. These activities are in turn encompassed within the wider chemical and petrochemical sector boundary, which corresponds to UN ISIC Rev. 4 divisions 20 and 21. The latter boundary is the most granular level at which the IEA compiles energy statistics that cover ammonia production, alongside other chemicals such as methanol and high-value chemicals. This roadmap therefore relies heavily on bottom-up modelling of energy consumption, including the use of fuels both for feedstock (essentially raw material inputs that provide much of the hydrogen required) and process energy (electricity and fuel used to provide heat and pressure to drive various process units).

Emissions

The core analytical focus of this roadmap is on CO_2 generated from the production of ammonia. *Direct* CO_2 emissions (often referred to as Scope 1 emissions) from ammonia production include both energy-related CO_2 emissions from the combustion of fossil fuels, and process CO_2 emissions that result from the difference in the carbon content between the feedstock used (typically natural gas or coal) and the ammonia produced.

Two categories of *indirect* CO_2 emissions (often referred to as Scope 2 and 3 emissions) are also addressed within the core analytical scope. The first is CO_2 emissions that are generated during the production of electricity that is used directly to produce ammonia. The second is the CO_2 emissions that are released downstream during the application of carbon-containing nitrogen fertilisers, predominantly urea. The rationale for including this latter category within the core analytical scope stems from the fact that all of the CO_2 used to make urea and its derivatives is sourced indirectly from the fuels that are used as feedstocks to produce ammonia. Nitrous oxide (N_2O) emissions, both from the production phase (e.g. during nitric acid production) and the use phase, are addressed tangentially in Chapter 1, but are excluded from the core analytical scope. Emissions associated with the transport and distribution of fertilisers are also outside the scope of this technology roadmap.

Nitrogen fertilisers: An indispensable input to our modern agricultural systems

Fertilisers are a source of nutrients used by plants to grow, constituting an integral input to the world's agricultural systems. Plants obtain carbon, hydrogen and oxygen directly from water and the atmosphere. Nutrients are also sourced from the environment, with fertilisers being used to supplement those that naturally occur in a given locality. While the diverse range of plant species cultivated for human use require a wide range of nutrients,[1] three key macronutrients are essential to virtually all plant life: nitrogen (N), phosphorus (P) and potassium (K).

No macronutrient is more or less important in the context of agriculture, but in the context of the energy system, nitrogen fertilisers are of preeminent concern. Within the agricultural sector, nitrogen is consumed in the largest volume of the three nutrient categories (in 2018, 104 Mt, compared with 46 Mt of phosphorus and 37 Mt of potassium on a nutrient basis)[2], and it is also the most energy-intensive to produce. While the raw ingredients to produce phosphorus and potassium fertilisers are sourced from deposits of naturally occurring minerals in the earth's

[1] In addition to the three key macronutrients: sulphur, magnesium, calcium, iron, manganese, zinc, copper, boron, molybdenum, chlorine, nickel. Additional elements may be beneficial to a certain plant species, e.g. sodium, silicon and cobalt.
[2] The fertiliser industry uses nitrogen content, potassium oxide (K_2O) content and phosphorous pentoxide (P_2O_5) content to compare fertilisers on a nutrient basis. For example, ammonia (NH_3) is 82% nitrogen by weight.

crust, the nitrogen in mineral nitrogen fertilisers is sourced from air. Nitrogen is the most abundant element in the atmosphere, accounting for 78% in the form of dinitrogen (N_2). But most plants are unable to absorb it directly due to its strong triple bond, and require reactive nitrogen compounds (ammonium and nitrate) to be present in the soil.

There are five key mechanisms by which nitrogen in the air can be converted into a usable form for plants, known as reactive or fixed nitrogen:

- First is natural biological nitrogen fixation. On land, nitrogen diffuses naturally into the soil from the air, and bacteria can convert it to plant-available organic forms. Nitrogen-fixing bacteria exist freely in the soil in many cases. Natural biological fixation on land accounts for an estimated 14% of annual global nitrogen fixation, while similar processes in the ocean account for about 34%.
- Second is agricultural biological nitrogen fixation. Some plants have symbiotic relationships with nitrogen-fixing bacteria, enabling more direct nitrogen uptake – for example, legume roots have nodules in which nitrogen-fixing bacteria can operate. Agricultural production of such crops accounts for about 15% of annual nitrogen fixation.
- Third, lightning can convert nitrogen in the air to nitrous oxide, which then reacts with oxygen to form nitrogen dioxide, which in turn reacts with water in clouds to form nitrates (NO_3), which are transported to the soil by rain. This pathway accounts for only a small amount – around 1% – of total nitrogen fixation.
- Fourth, combustion processes (such as in internal combustion engines or in industrial facilities) lead to nitrogen fixation through a pathway similar to lightning, and fixed nitrogen can be made available to plants through atmospheric deposition. This pathway accounts for an estimated 7% of nitrogen fixation.
- Fifth, production of mineral nitrogen fertilisers accounts for the remaining approximately 29% of nitrogen fixation. Mineral fertilisers are the most significant means by which humans increase the availability of nitrogen to plants in the modern global agricultural system.

In addition to nitrogen fixation from the air, reactive nitrogen can be made available to plants through recycling. Animals and plants can return nitrogen to the soil through nitrogen contained in excrement and decomposing organic matter. In agricultural systems, organic fertilisers composed of animal manure and other excreted wastes make a considerable contribution to providing nitrogen to plants. The amount of nitrogen applied to soils from manure is equal to about one quarter the amount of nitrogen delivered by mineral fertilisers.

Mineral nitrogen fertilisers comprise a group of products (Table 1.1) that deliver nitrogen in plant-available form to soils and aquacultures. Since the chemical composition of each nitrogen fertiliser is different, they are not directly comparable on a “per tonne of product” basis. Instead, nitrogen fertilisers – as with potassium and phosphorus products – are typically measured in terms of their nutrient content. When making comparisons between nitrogen fertiliser products or referring to quantities of demand, it is typically the N content, or “tonnes N”, that is relevant for application in agriculture. When discussing the production of a specific substance, such as ammonia (82% nitrogen), it is typically the overall tonnage of the product that is more often referred to.

Table 1.1 Key nitrogen fertilisers and their characteristics

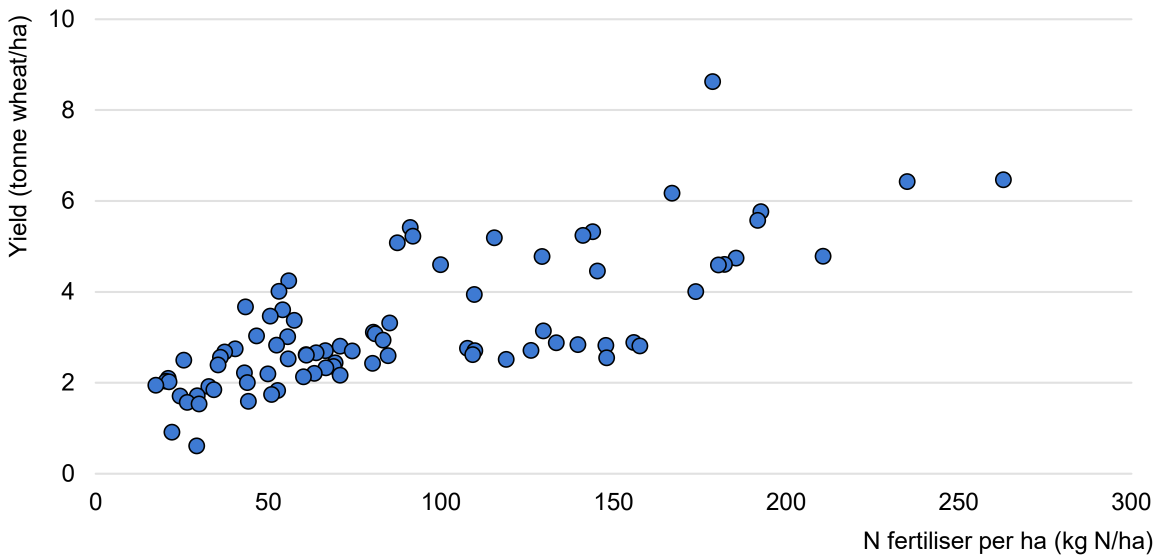
Nitrogen fertiliser product	N	Precursors	Global annual production	
	% by weight		Mt product	Mt nutrient
Ammonia	82%	Hydrogen, nitrogen	183	150
Urea	46%	Ammonia, CO_2	177	81
Ammonium nitrate	34%	Nitric acid, ammonia	49	17
Calcium ammonium nitrate	27%	Calcium carbonate, ammonium nitrate, water	14	4
Urea ammonium nitrate	30%	Ammonium nitrate, urea, water	25	8
Diammonium phosphate	18%	Ammonia, phosphoric acid	9	2
Monoammonium phosphate	11%	Ammonia, phosphoric acid	7	< 1
Ammonium sulphate	21%	Ammonia, sulphuric acid	12	2

Notes: Global production values are the latest available values for each fertiliser in 2019. N content given is a typical percentage by weight, but actual N content can vary by a few percentage points depending on the fertiliser purity. All fertilisers listed other than ammonia are derivatives of ammonia, and some fertilisers are further derivatives (for example, calcium ammonium nitrate and urea ammonium nitrate are derivatives of ammonium nitrate); as such, the global annual production values are not additive.
Sources: Data sourced from the IFA, the FAO and the European Commission, rounded to the nearest 1 Mt.

There is no universal approach to farmers’ selection of mineral fertiliser product. Multiple factors influence the decision in a given context, including weather conditions, soil types and existing nutrient levels, crop types, existing and targeted yields, availability in regional markets, cost, subsidies, environmental regulations, handle ability and safety considerations. There is some variation between different nitrogen fertiliser product prices on a per tonne N basis, with products requiring more transformation steps usually being more expensive. Furthermore, fertiliser prices can differ considerably in a given local context depending on supply, demand and trade dynamics, including whether the product is produced locally or would need to be imported. Some fertilisers deliver two or more nutrients at once (e.g. ammonium phosphate provides nitrogen and phosphorus), whereas others deliver a single nutrient in different forms (e.g. nitrate vs ammonium). Each nitrogen fertiliser product has its own nitrogen content, volatilisation rate, impact on soil acidity and product form (e.g. liquid, granular, crystalline, prilled).

The primary purpose of fertilisers is to achieve and maintain high crop yields and replenish soils with the nutrients that are depleted when plants grow. Since the early 20th century, mineral fertilisers have formed an integral part of our food system. Researchers estimate that around half of the global population is sustained by mineral fertilisers. Wheat, an illustrative case, is one of the largest-volume cereal crops and consumes more nitrogen fertiliser than any other single crop globally. Comparing the yield of wheat fields and the amount of nitrogen fertiliser used per unit area of agricultural land specifically for this crop in different countries shows that yields tend to rise with increased levels of application (Figure 1.1).

Figure 1.1 Fertiliser use and crop yield for wheat production



IEA, 2021.

Note: Each data point represents the average fertiliser use and yield of wheat fields in a specific country for the years 2006, 2007, 2010 and 2014.
Sources: Data sourced from the IFA and the FAO.

Nitrogen fertiliser application to arable land raises yields of crops such as wheat, but sustainable nutrient management is key to realising high yields per unit of fertiliser applied.

Naturally, there is a limit to the extent that increased application of nitrogen will increase crop yields. The goal of fertiliser application is to narrow the gap between actual and attainable crop yields. As the crop approaches the attainable yield, there is a diminishing return measured as the proportion of added nutrients that are taken up by the plants, such that adding more of a given nutrient can become wasteful and lead to environmental damage. It is therefore essential to first establish the attainable yield for a given crop, location and season. From a fertiliser perspective, this is defined as the maximum yield that is achievable when the macronutrient (nitrogen, potassium and phosphorus) needs of the crop are met. Nitrogen cannot compensate for the absence of other nutrients or other requirements such as water and sunlight. This principle is embodied within the law of the minimum, whereby the plant yield is proportional to the amount of the limiting nutrient.

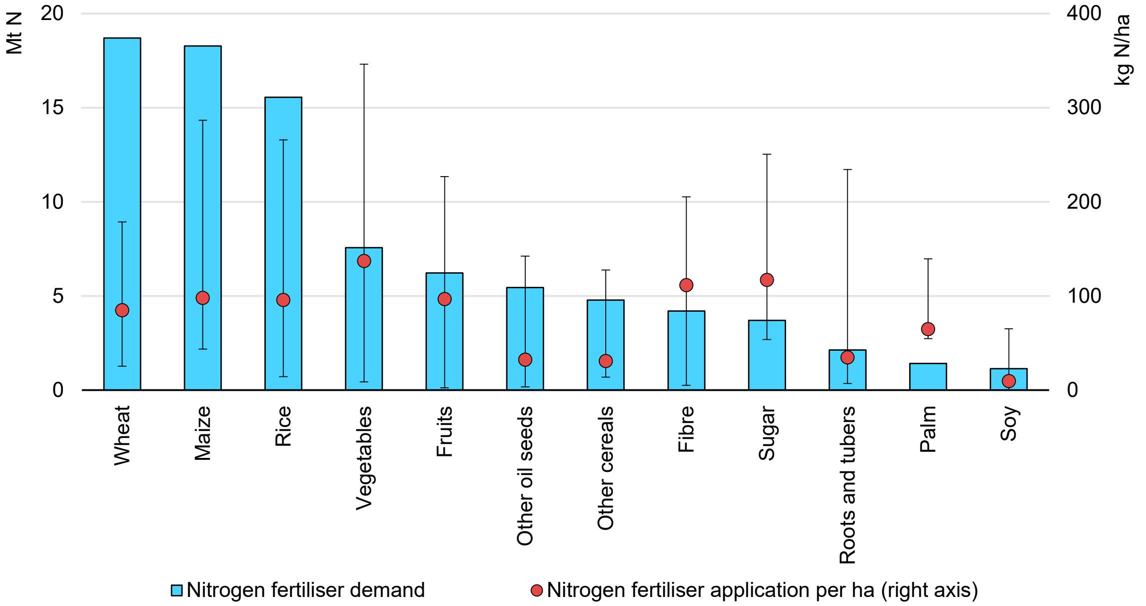
Soil fertility, climate and weather conditions vary widely across the world, and so a wide range of yields are attainable for a given crop, resulting in a wide range of fertiliser requirements. Crop uptake of nitrogen fertiliser varies in the range of 30-60% for most major crops depending on these local factors, the extent to which fertilisers are under- or oversupplied and other management practices. Nitrogen uptake can be 50-60% for wheat grown in temperate climates and around 30% for lowland rice grown in coarse-textured soils, although management practices can lead to considerable variability within crop types. Crops can have dramatically different rates of nitrogen uptake – at the high end, soybeans are estimated to have an average uptake rate of 80%, while fruits and vegetables fall at the lower end with efficiencies of about 15%. The range of application rates for nitrogen fertilisers seen across different countries for major crops are illustrative of the combined impact of site-specific factors and nutrient management practices on the amount of fertiliser required.

All crops consume nitrogen, but just three cereals – wheat, rice and maize – account for over 50% of the total global demand for nitrogen fertiliser, largely because they are three of the four largest-volume crops grown globally[3]. Rice and maize are among those with the widest range of fertiliser application rates observed across countries, with the world average at 96 kg N per hectare (country averages ranging between 14 kg and 266 kg) and 98 kg N per hectare (country averages between 44 kg and 287 kg), respectively. Some crops, such as soybeans, peanuts and clover, are able to fix nitrogen directly from the

[3] While sugar cane is the crop grown in the largest volumes globally, it has high yields per area of cropland. As such, it requires less total nitrogen fertiliser, despite requiring somewhat more fertiliser per hectare compared to wheat, maize and rice.

atmosphere, leading to lower (or zero, in some instances) fertiliser application requirements. These crops can even form a supply of nitrogen to the soil in specific circumstances, excreting nitrogen compounds via their roots, and are often planted specifically for this purpose.

Figure 1.2 Nitrogen fertiliser demand and application rate by crop



IEA, 2021.

Note: Ranges for fertiliser application rate reflect the variation at the country level.
Sources: Data for 2014, sourced from the IFA and the FAO.

Three cereals account for more than 50% of all the nitrogen fertiliser demand for agriculture, with wheat alone accounting for around 20%.

Beyond site- and crop-specific factors that are key to determining the appropriate quantity of fertiliser to apply, it is critical to adopt best fertiliser management practices in order to optimise nutrient use efficiency.[4] These practices are embodied in the "4Rs" of nutrient stewardship: applying the right fertiliser source, at the right rate, at the right time, in the right place. In each of these areas, a variety of technologies can help achieve greater understanding of what the agricultural system needs, and optimise the rate, time and place of fertiliser application and nutrient provision. Such technologies include slow-release fertiliser coatings that can maintain nutrient availability for a significantly longer period of time, global positioning and geographic information systems to target precisely where to apply,

[4] There are varying definitions of nutrient use efficiency, including partial factor productivity, agronomic efficiency, recovery efficiency, removal efficiency and physiological efficiency. In this report we adopt the partial factor productivity definition, of crop yield per unit of nitrogen fertiliser applied.

and monitors and sensors that can facilitate the adjustment of application rates in real time. Policy is also critical. While fertiliser subsidies and trade policies are often applied with the good intentions of reducing food prices or improving the balance of trade, if poorly applied they have the potential to increase wasteful fertiliser application practices and consequently exacerbate negative environmental impacts. Reforming such policies can be a critical enabler of improved nutrient management.

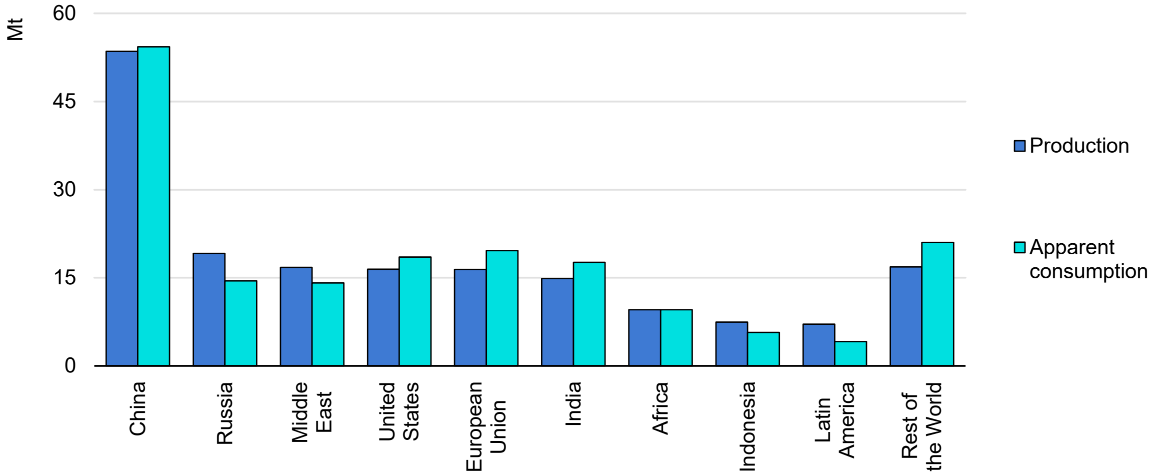
Demand, supply and trade

Between 1990 and 2019,[5] global ammonia demand increased broadly in line with the rise in the population. On a regional basis, true demand for the services provided by ammonia would be best measured through the components of food consumption and industrial products that have ammonia or ammonia-derived products as an input. Given that it is difficult to trace the consumption of these numerous products, apparent consumption – production, plus imports, less exports – is often used as an alternative indicator of broad trends in regional demand levels. Since apparent consumption constitutes demand by direct users of ammonia, such as fertiliser producers, farmers and downstream chemical industries, the indicator is influenced by growth in the relevant industries in the countries rather than directly correlated with population and economic development trends.

China is currently the largest ammonia producer, accounting for 29% of global production in 2019, followed by Russia (10%), the United States (9%), the Middle East (9%), the European Union (8%) and India (8%). Over the past three decades, the structure of the supply side has not changed drastically in market share terms – the main producers in the global economy have remained the same, even as their order has shifted. In 1990 China was the largest producer (19%), followed by today's members of the European Union (17%), the United States (13%), today's Russia (10%), and India (7%), while the Middle East was only at 3%. The regions with the largest increase in apparent consumption of ammonia over the past two decades are the Middle East, Africa and Russia, with demand increases of approximately 140%, 110% and 80% respectively. In the meantime, demand roughly stagnated in the European Union, the United States and South America.

[5] 2019 data are used in this section to reflect the global supply and demand situation before the start of the Covid-19 pandemic.

Figure 1.3 Apparent consumption and production of ammonia in 2019



IEA, 2021.

Notes: The apparent consumption of a region is equal to its production plus imports minus exports.
Source: Data from IFA.

China is the largest ammonia producer at 53.5 Mt in 2019 (29% of global production), and the largest consumer at 54.3 Mt.

Ammonia is traded around the world. In 2019 global trade was almost 20 Mt, or about 10% of production. Principal exporting countries and regions are Russia, Trinidad and Tobago and the Middle East, representing respectively 24%, 23% and 15% of global ammonia exports in 2019. Principal importing regions and countries are the European Union, India and the United States, at 24%, 14% and 13% of global imports respectively. Urea, the single largest derivative product of ammonia, saw an even greater share of its total production volume traded in global markets, at around 28% in 2019.

The main reason for the large volumes of trade in ammonia and its derivatives is the difference in cost of production in different regions of the world. Countries with abundant natural gas reserves and access to nearby centres of demand can produce ammonia at relatively low cost and may specialise in ammonia production as a product for export. For example, Trinidad and Tobago converts around 20%[6] of the natural gas it produces locally into ammonia, rather than exporting the gas itself, increasing the value addition generated in the country. The country's large ammonia industry relative to the size of its economy was also driven by a historical drive to build up a lower-cost offshore source to meet demand in the United States – today, the United States remains its largest trading partner, importing 1.5 Mt of

[6] Number is calculated by applying the average energy intensity of ammonia production via the gas route to Trinidad and Tobago's production volume and comparing it to the country's annual natural gas production. This number assumes that all ammonia in the country is made using natural gas.

ammonia per year from Trinidad and Tobago alone in 2019. The country exports another 3 Mt to more than 25 other countries. Other countries have also adopted an export-focused model, often as a way to make use of the natural gas that is produced in tandem with oil extraction, particularly in the Middle East and North Africa. Saudi Arabia's production has more than doubled since 2005 (compared to a global increase in production of 26%), and Algeria's production quadrupled over the same period. These countries now export around 30% and 40% of their production, respectively.

An important network of ports, pipelines and storage facilities dedicated to ammonia supports this trade. The United States alone has over 10 000 ammonia storage sites, many of which are connected to a pipeline network stretching more than 3 000 km and connecting the Gulf of Mexico to the Midwest. The longest ammonia pipeline in the world is the Tolyatti-Odessa pipeline, running from Russia to Ukraine, at a length of 2 471 km.

Before the 2008 financial crisis, the global volume of ammonia trade was growing at an average rate of 5% per year. In 2009 it decreased by 7%, despite overall production remaining stable between 2007 and 2009 at 150 Mt per year. Since 2010 the total volume of ammonia trade has fluctuated between 18 Mt and 20 Mt. Global ammonia production remained relatively robust during the Covid-19 pandemic, with 2020 production (185 Mt) estimated to be similar to that of 2019 (182 Mt). Overall food demand was not affected to the same degree as other aspects of the economy (such as international travel), despite more of it being consumed at home rather than in restaurants and other public spaces affected by lockdowns and other control measures.

Fertiliser prices stayed broadly stable since the 2008 financial crisis, although they have been rising since January 2021, reaching their highest levels since 2012 in July of this year. Capacity additions to respond to the continuing rise in demand are well underway, with around 9 Mt of output under development. Ammonia, urea and their derivatives can be transported and stored fairly cheaply and easily relative to some other large-volume industrial chemicals. Appropriate handling is imperative to ensure safety. Although these substances are not explosive in and of themselves, they can be brought to explosion when exposed to high temperatures or with the help of additional materials such as oxidisers, fuels and detonators.

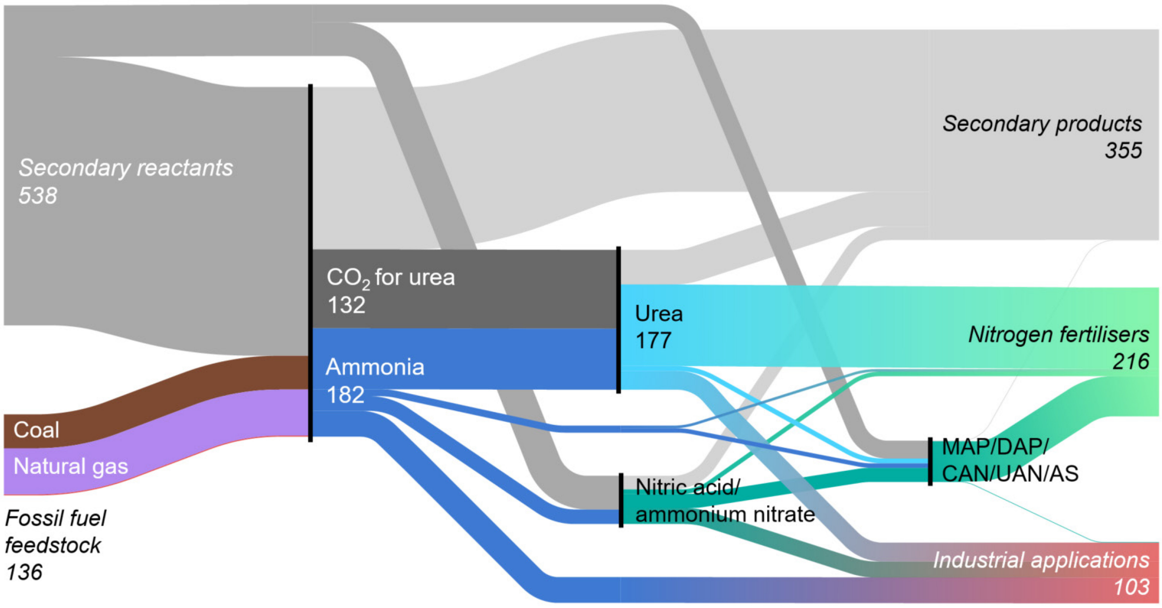
The handling requirements vary depending on the particular product. Ammonium nitrate is classified as an oxidiser (Class 5.1) under the United Nations Recommendations on the Transport of Dangerous Goods Model Regulations, and as such requires handling and storage according to special regulations. Urea is not classified as a hazardous substance, although still requires attention to handling since it could be dangerous if exposed to high temperatures or mixed with other chemicals. The handling requirements for urea are, however, less demanding overall compared to ammonium nitrate, which can be a major factor motivating the selection of urea as a fertiliser in several regions.

Each year millions of tonnes of nitrogen fertilisers and other nitrogen-based products are safely transported, stored and used without incident. Over the years, however, a number of accidents have demonstrated the perils of handling these substances inappropriately. Some of the largest incidents include the Texas City disaster of 1947 and the Beirut explosion of 2020, both involving ammonium nitrate. Accidents in the past have been among the catalysts for the stringent safety regulations and guidelines that governments and industry have put in place in many countries and regions. Examples of such measures include: in the European Union the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation; in the United Kingdom the voluntary Fertiliser Industry Assurance Scheme (FIAS); and in Canada the Ammonium Nitrate Code of Practice (AN Code). At the international level, the International Fertilizer Association's Protect and Sustain programme helps to set standard global reference points for product stewardship, including for safe fertiliser handling.

Ammonia production fundamentals

Ammonia production involves two main steps: first, isolating hydrogen, and second, the Haber-Bosch process in which the hydrogen is reacted with nitrogen from the air to produce ammonia. Currently close to 100% of ammonia production obtains the required hydrogen from fossil fuel feedstocks (together with the steam used to transform them in certain process arrangements). Process energy, comprising fossil fuels and electricity, is needed in addition to the feedstock inputs to generate the heat and pressure required for the production process, and to separate nitrogen from the air. In 2020 ammonia production accounted for 8.6 EJ of energy consumption, equivalent to 2% of total final energy consumption globally. Of this energy, 40% was consumed as feedstock and the remainder as process energy. Natural gas accounts for 70% of the ammonia industry's total energy consumption, coal 26%, oil 1% and electricity the remaining 3%.

Figure 1.4 Mass flows in the ammonia supply chain from fossil fuel feedstocks to nitrogen fertilisers and industrial products



IEA, 2021.

Notes: The thickness of the lines in the Sankey diagram are proportional to the magnitude of the mass flows. All numeric values are in million tonnes per year of production using production data for 2019. Only the fossil fuel quantities consumed as feedstock are shown; the diagram does not represent process energy inputs. MAP = monoammonium phosphate; DAP = diammonium phosphate; CAN = calcium ammonium nitrate; UAN = urea ammonium nitrate; AS = ammonium sulphate.

Sources: Production volumes sourced from the IFA. Process characterisations and yields from Levi and Cullen (2018).

Ammonia is the precursor to all mineral nitrogen fertilisers, which together account for just under 70% of total ammonia demand, including the downstream usage of its derivatives.

For the bulk of its eventual use, ammonia production is only the first step in nitrogen fertiliser production. Just over 2% of total ammonia demand is for direct application to pastures. The majority of ammonia is combined with other inputs to produce other nitrogen-based fertilisers and industrial products in subsequent transformation steps. Urea is chief among these. The production of urea accounts for around 55% of ammonia demand, which is in turn used directly as a fertiliser (around 75%) and to produce urea ammonium nitrate (5%), the remainder being for a range of industrial applications. The other major use of ammonia is for nitric acid and ammonium nitrate production. Around 80% of nitric acid is used to produce ammonium nitrate, two-thirds of which is used for fertiliser applications, including via further transformation into monoammonium and diammonium phosphate, ammonium sulphate, calcium ammonium nitrate and, in conjunction with urea, to produce urea ammonium nitrate. Tracing all of these uses of ammonia downstream to their end uses reveals that just under 70% of ammonia is used for nitrogen fertiliser applications, with the remainder being used for industrial applications.

Aside from these primary products of the ammonia value chain, the various transformation steps also involve the significant use and generation of secondary reactants and products respectively. Around 540 Mt of secondary reactants, comprising steam, oxygen, phosphoric and sulphuric acids and calcium carbonate, are used across the ammonia supply chain, dwarfing the estimated 136 Mt of fossil fuels that are used as the key raw material inputs to ammonia production. Around 355 Mt of secondary products are also produced, comprising mainly steam and process CO_2 emissions – this does not include the CO_2 that is generated during the combustion of fossil fuels used to provide process energy inputs. One important interaction between the primary and secondary mass flows in the ammonia supply chain is the use of CO_2 generated during ammonia production for urea synthesis. Of the roughly 250 Mt CO_2 generated directly from the use of fossil fuel feedstocks (direct process CO_2 emissions), around 130 Mt CO_2 are used directly to produce urea. However, this CO_2 is only temporarily sequestered in the urea and urea ammonium nitrate products – it is rereleased downstream in the agricultural sector when urea decomposes during the use phase.

Current and emerging production pathways

A brief history of ammonia production

The Birkeland-Eyde process was one of the first methods used to produce ammonia at industrial scale, developed in 1903. No longer in use, the process used an electric arc to convert nitrogen, oxygen and water into nitric acid. This method was energy intensive, requiring around 400 GJ of energy per tonne of ammonia. Ten years later the Haber-Bosch process was first deployed at scale, emerging as the dominant method of production. The method greatly improved energy efficiency, requiring around 100 GJ per tonne of ammonia at the time it was first employed. During World War I, the Haber-Bosch process was significantly developed as a means to produce munitions. By the 1930s it had become the main method to produce ammonia, and it remains so today.

The key aspect of the process that has evolved since the early 20th century is the method of producing the hydrogen required to feed the Haber-Bosch process. In the first few decades of industrial fertiliser production, electrolysis using hydropower was commonly used to produce hydrogen for ammonia synthesis via the Haber-Bosch process. A considerable proportion of fertilisers sold in Europe until the 1960s were produced at two hydropower electrolysis plants in Norway. Coal gasification was another early source of hydrogen. By the middle of the 20th century, continued improvements had reduced the minimum energy requirement for ammonia production to about 60 GJ per tonne of ammonia. In the 1960s and 1970s wider availability of natural gas at competitive prices led to increasing use of natural gas-based steam reforming for hydrogen production, due to its lower overall production costs. Most of the electrolysis-based plants shut down over time. Following the closure of a plant in Egypt in 2019, only one known hydropower electrolysis-based ammonia plant remains in the world: a small facility in Peru using a 25 MW electrolyser.

In 2020, of the 185 Mt of ammonia produced, 72% relied on natural gas-based steam reforming, 26% on coal gasification, about 1% on oil products, and a fraction of a percentage point on electrolysis. We estimate[7] that producing one tonne of ammonia in 2020 on average used 46 GJ of energy on a gross basis and 41 GJ on a net basis, accounting for the generation of excess steam in modern process arrangements. This compares to best available technology (BAT) energy intensity for production via natural gas of 32 GJ/t and 28 GJ/t on a gross and net basis respectively, and theoretical minimum energy requirements of 20.9 GJ/t (gross) and 18.6 GJ/t (net) via pure methane. A major contributing factor to reduced energy needs since the middle of the 20th century has been the shift away from coal gasification and towards more efficient natural gas-based production. Other contributors include the introduction of large centrifugal compressors, better process control and maintenance scheduling, a higher degree of process integration to make better use of waste heat, and catalyst improvements. Efficiency gains have slowed considerably since 1990, as production has come increasingly close to the theoretical minimum energy intensity.

The Haber-Bosch ammonia synthesis process operates in the same manner regardless of the hydrogen source. The overall reaction that takes place in the ammonia synthesis step is exothermic, and a high temperature (typically 400-650°C) and pressure (typically 100-400 bar) are needed to activate the reaction in the presence of a catalyst, enabling the reaction to occur at a speed that is economical for industrial production. Most of the energy needed for the process is generated by the reaction itself, although a small amount of electricity is required to power motors, heat exchangers and other equipment to control the pressure and temperature. Under normal operating conditions, only a proportion of hydrogen is converted into ammonia after one cycle through the reactor. A condenser separates ammonia from the remaining hydrogen, the latter being

[7] Average global and regional energy intensities in this section are estimated using reported national average energy consumption data where available, supplemented by best available technology and energy efficiency metrics derived from the IEA's World Energy Balances dataset. The results of an IFA benchmarking analysis using real plant data from 2018 were used to inform and calibrate the results.

cycled back through the reactor until virtually all (> 98%) the hydrogen and most of the nitrogen (around 95%) is converted to ammonia.

Natural gas reforming

Producing hydrogen through natural gas-based steam reforming involves a number of steps. The first step is natural gas desulphurisation, which cleans sulphur impurities from the natural gas feedstock. The second step is steam reforming, which has two main options: 1) regular steam methane reforming (SMR); or 2) auto-thermal reforming (ATR), which combines SMR with partial oxidation (POX). SMR requires process heat (endothermic process) and involves reacting methane and steam to produce a syngas consisting of carbon monoxide (CO) and molecular hydrogen (H_2). ATR reacts hydrocarbons (typically methane) with steam and pure oxygen to produce a syngas consisting of CO, H_2 and CO_2. In ATR, SMR and POX occur simultaneously in a reactor. POX involves internal combustion of part of the methane using oxygen. It is an exothermic reaction that provides the heat required for the SMR reaction, and therefore only minimal external energy inputs are required in ATR for preheating the inputs.[8]

The third step in natural gas reforming is a water gas shift reaction, which reacts water vapour with the CO in the syngas to produce CO_2 and more H_2. The fourth step is CO_2 removal in order to separate the hydrogen from the syngas. Amine-based scrubbing is used for CO_2 removal in many ammonia plants. In this process, the syngas containing CO_2 and H_2 is passed through an amine solution, which absorbs the CO_2 and then releases it when heated. Other CO_2 removal options are used in some plants, such as hot potassium carbonate scrubbing. The high-purity CO_2 stream generated during ammonia production is sometimes utilised for other industrial processes, such as urea production (typically in the same or an adjacent facility) or elsewhere in industry (such as the food and beverage sector). CO_2 from ammonia production is also captured for permanent storage, mostly during the process of enhanced oil recovery (see Box 1.2). The final step of hydrogen production is a methanation process to remove any residual CO and CO_2. Using a catalyst, CO_x reacts with hydrogen to produce methane. This step is necessary as CO and CO_2 can degrade the catalysts used in the Haber-Bosch synthesis step.

The SMR arrangement (as opposed to the ATR) is the most common process for producing ammonia from natural gas. If BAT is used, SMR-based production

[8] An additional difference between SMR and ATR is that ATR requires an air separation unit to isolate oxygen and nitrogen, whereas SMR can use air directly.

consumes 32 GJ of natural gas per tonne of ammonia produced, on a gross basis. The vast majority of energy inputs are natural gas used for the hydrogen production step. A small amount of electricity – about 0.3 GJ – is also needed to power the CO_2 removal stage of hydrogen production and the ammonia synthesis processes. About 5 GJ of excess steam is produced that could be exported for uses outside the ammonia production process, which results in a net energy intensity of 28 GJ per tonne of ammonia. About 1.8 tonnes of CO_2 are generated per tonne of ammonia produced via SMR using BAT.

In the SMR route, typically more than 60% of the natural gas inputs are used as feedstock. The feedstock proportion of the natural gas results in a concentrated CO_2 stream, as CO_2 removal from the syngas is a fundamental part of the commercial production process as it exists today. This CO_2 only needs to be compressed before it can be utilised or prepared for permanent geological storage. Utilisation is commonplace today – in 2020, about 130 Mt of CO_2 was utilised for urea production, most of it supplied from ammonia production. This is equivalent to about a quarter of the CO_2 generated from ammonia production. The additional natural gas used for process energy inputs results in a dilute flue gas CO_2 stream that would require the use of additional CO_2 capture equipment were it to be utilised or stored.

If capture were applied to both concentrated and dilute CO_2 streams and the CO_2 were permanently stored, SMR production would become near-zero emissions, depending on the CO_2 capture rate realised. With current technology costs for amine-based capture, the optimum CO_2 capture rate is in the range of 85-90%. With further economic incentives, capture rates of up to around 99% could become viable in future. Applying carbon capture, utilisation and storage increases energy requirements, for separating and compressing the CO_2. Capture on both the concentrated and dilute streams would require approximately a further 0.7 GJ of electricity per tonne of ammonia produced.

Box 1.2 An overview of carbon capture, utilisation and storage

Carbon capture, utilisation and storage (CCUS) refers to a suite of technologies that can play an important and diverse role in meeting global energy and climate goals. CCUS involves the capture of CO_2 from large-scale point sources, including power generation plants and industrial facilities that use either fossil fuels or biomass for fuel. CO_2 can also be captured directly from the atmosphere, so-called direct air capture (DAC). If not utilised (CCU) on-site or in an adjacent facility, captured CO_2 can be compressed and transported by pipeline, ship, rail or truck and then injected into deep geological formations (including depleted oil and gas reservoirs or saline formations) which trap the CO_2 for permanent storage, avoiding its release to the atmosphere. This is carbon capture and storage (CCS).

Current large-scale CO_2 capture capacity for injection and storage in geological formations is on the order of 40 Mt CO_2/yr. Around two-thirds of this capacity is in natural gas processing facilities and the remaining third comprises roughly equal shares of power generation, synthetic fuel, ammonia and hydrogen applications, with smaller quantities being captured from bioethanol and steel production. Of the 40 Mt figure quoted above, around 20% of the captured gas is directed to dedicated geological storage sites, with the remainder used for enhanced oil recovery (EOR). Virtually all of the CO_2 injected for EOR is ultimately retained in the reservoir over the life of the project, but monitoring and verification is needed to confirm permanent storage. An increasing share of planned projects intend to store CO_2 in dedicated storage sites as opposed to via EOR.

Interest in CCUS has been expanding globally in recent years, with a renewed momentum driven by strengthened climate commitments from governments and industry, including ambitious net zero targets. The improved investment environment has seen more than 40 new commercial projects announced around the world in the first eight months of 2021. Pilot and demonstration-scale carbon capture installations are currently operating or planned in several key sectors where CCUS plays an important role in achieving clean energy transitions: the cement sector; steel furnaces besides those producing direct reduced iron; chemical facilities; and carbon removal facilities (DAC and bioenergy with CCS [BECCS]).

CCUS includes a portfolio of technologies and applications at various stages of development. There are many carbon capture technologies, several of which are mature, such as chemical absorption of CO_2 during hydrogen production in ammonia plants. There are also many CCU applications proposed, including cement and synthetic fuels, but urea synthesis with CO_2 from ammonia plants is the only one that operates at very large scale today (around 130 Mt CO_2/yr). The environmental benefits of CCU depend on the eventual fate of the product in which the CO_2 is utilised – CCU for urea only results in temporary sequestration. Permanent geological storage is conceptually more straightforward. Globally, theoretical CO_2 storage resources are vast, but some reservoirs will not be suitable or accessible. Detailed site characterisation and assessments are still needed to identify the feasibility and scope of permanent CO_2 storage in many regions.

SMR is the arrangement of choice for new-build natural gas-fuelled plants today. This is because ATR plants tend to be slightly less energy efficient overall, on a net basis. ATR does not produce excess steam for possible export (e.g. to power an adjacent urea plant), and requires significantly more electricity than an SMR arrangement, mainly to supply the air separation unit that sources nitrogen from the air. At 1.6 t CO_2 per tonne of ammonia, the direct CO_2 emissions intensity of ATR is 13% lower than that of SMR, but this does not reflect any emissions credit for the additional steam that is produced in the SMR route, which can avoid the need for fuel inputs to utilities that would otherwise be required to generate it.

Another major difference relative to the SMR arrangement is that over 90% of the natural gas inputs to an ATR are for feedstock. This means that a higher proportion of the CO_2 produced is concentrated (a lower proportion is dilute flue gas CO_2) and so is more amenable to the application of CCUS. Because capturing CO_2 from the concentrated feedstock-derived stream of an ammonia production facility is less energy- and capital-intensive, ATR arrangements may become the preferred technology for new-build natural gas facilities where the aim is to achieve near-zero emissions ammonia production. Capturing the concentrated emissions alone would reduce ammonia production emissions via the ATR route by 90%. If higher reductions were targeted, it could be an option to increase the capacity of the ATR unit to produce additional hydrogen that could be used to provide the process heat, rather than using fossil fuels and generating dilute CO_2 in flue gas.

Table 1.2 Energy needs to produce one tonne of ammonia for each route using BAT

Production route	Energy intensity (GJ/t)						Direct CO_2 intensity (t CO_2/t)
	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
Electrolysis	0.0	0.0	36.0	-1.6	36.0	34.4	0.0
Biomass gasification	18.6	16.5	1.4	0.0	36.5	36.5	0.0
Methane pyrolysis	40.5	0.0	8.4	-1.6	48.9	47.3	0.0

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 are for a future commercial-scale installation. CO_2 is generated from the use of bioenergy, but does not contribute towards direct CO_2 emissions from the energy system, following IEA emissions accounting conventions.

Source: Data gathered and reviewed in collaboration with the IFA and its members.

Coal gasification

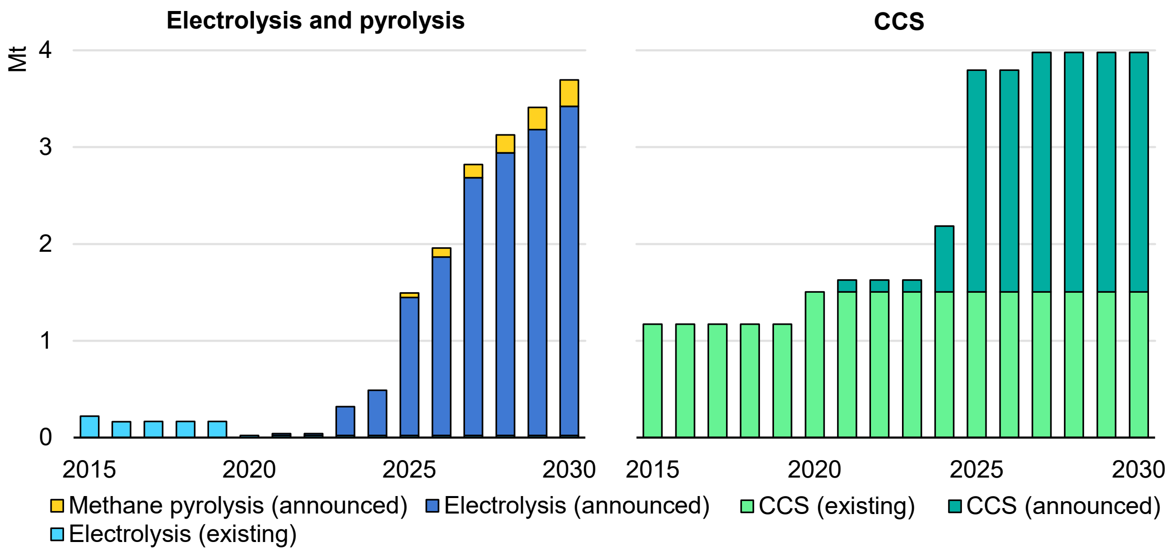
Nearly all ammonia production from coal is in China. About 85% of the country's ammonia production is via coal gasification. Much smaller amounts of ammonia are produced via coal gasification in the United States, South Africa and Indonesia. Producing hydrogen via this method requires a number of steps. First, an air separation unit is used to isolate oxygen from the air. Second is the gasification step, in which coal is heated in the presence of oxygen and water, creating a syngas composed of hydrogen, CO, CO_2, methane and other hydrocarbons. Heating can be internal or external depending on the configuration. Next, a syngas clean-up step removes impurities, to avoid poisoning the catalysts used and to meet air pollutant emission requirements. The remaining steps include a water gas shift reaction that converts CO to CO_2 and hydrogen, CO_2 removal and sulphur removal. Biomass gasification for ammonia production, were it to be pursued in the future, would follow a similar series of steps.

Ammonia production via coal gasification is considerably more emissions-intensive than natural gas-based production. Considering BAT energy performance for facilities using a standard-grade thermal coal input, the route uses 37 GJ per tonne of ammonia produced, on a gross basis, 36 GJ/t on a net basis. This includes 34 GJ of coal, more than half of which is used as feedstock. Electricity needs are higher than for natural gas-based processes, at about 4 GJ per tonne of ammonia. About 1 GJ of excess steam is produced. The emissions intensity using BAT is 3.2 t CO_2 per tonne of ammonia produced by coal gasification, which is nearly double that of BAT SMR-based production. As with natural gas-based routes, CCS can be applied to coal gasification, enabling close to near-zero-emission production if applied to both the concentrated and dilute CO_2 streams generated from the feedstock and process energy inputs, respectively.

Near-zero-emission production routes currently being pursued

In the future, in addition to more widespread application of CCS in existing production routes, other methods of hydrogen production for ammonia synthesis are likely to become more common in order to meet energy and climate goals. In recent years electrolysis-based ammonia production has been regaining interest for this reason. After decades of decline, multiple projects are scheduled to come online in the coming years, bringing total electrolytic ammonia production for conventional uses to more than 3 Mt of capacity by 2030, considering announced projects as of June 2021. A key difference compared to past production is that a considerable proportion of planned capacity will use variable renewable electricity as opposed to dispatchable large-scale hydropower.

Figure 1.5 Current and announced projects for near-zero-emission ammonia production



IEA, 2021.

Notes: CCS = carbon capture and storage. Near-zero-emission ammonia production capacity from CCS projects is estimated based on the quantity of emissions that would be avoided from an ammonia plant with BAT energy performance, whether process-related or energy-related emissions are captured. Emissions utilised for producing urea are not included. Electrolysis projects producing ammonia explicitly for use as an energy carrier are not included. Announced projects include those under construction, with a final investment decision or with a feasibility study completed; those currently at the concept stage are not included.

Despite a decline in near-zero-emission production in recent years, announced projects totalling nearly 8 Mt of ammonia production are in the pipeline for 2030.

Electrolysis involves the splitting of water molecules using an electric current to produce hydrogen, with oxygen as a by-product. Several different types of electrolysers exist, including designs that are commercially available and others that are still under development. Alkaline electrolysers have been used in the chemical industry since the middle of the 20th century. They use an alkaline solution where ions in the water can conduct the current, allowing electrolysis to happen. The catalysts used are generally less expensive and more durable compared to alternative designs. Polymer electrolyte membrane (PEM) electrolysers are a much more recent design, offering the potential to respond even more rapidly than alkaline electrolysers to required changes in capacity factor. In early 2021 Air Liquide inaugurated the largest PEM electrolyser in the world to date, with 20 MW capacity and the ability to generate 8.2 tonnes of hydrogen per day. Solid oxide electrolyser cells (SOEC) are also under development, but have yet to be deployed at scale. A core advantage of SOEC designs is the potential for considerably higher conversion efficiencies compared to other designs, and the ability to operate in reverse (as a fuel cell) when required.

Electrolysis-based ammonia production requires a standalone air separation unit to separate nitrogen from the air, as is the case for ATR natural gas-based arrangements. In SMR arrangements, oxygen from the air is consumed in the reaction with methane, leaving behind pure nitrogen that can be used for ammonia synthesis. A standalone Haber-Bosch synthesis unit is also required, but like the air separation unit, this process can also be powered by electricity. Electrolysis thereby opens a pathway to fully electrified ammonia production, requiring 36 GJ of electricity per tonne of ammonia produced for the process as a whole, with an efficiency of 64% on a lower heating value basis for the electrolyser. Most of the electricity (95%) is used for hydrogen production, with the remaining 5% used to power the air separation and Haber-Bosch synthesis units. This route produces ammonia with zero direct CO_2 emissions. Substantial indirect CO_2 emissions will be incurred upstream in the power sector using this route if the electricity feeding the installation is not low carbon. For a grid-connected electrolysis plant to have lower indirect emissions than the direct emissions from a natural gas-based SMR plant using BAT, the CO_2 intensity of the grid electricity must be 180 g CO_2/kWh or less; the current global average is 475 g CO_2/kWh (see Box 1.3).

Box 1.3 Electrolysis-based ammonia production: Grid connection versus dedicated variable renewable energy capacity

Electricity is the energy source behind electrolytic ammonia production. The way the electricity is produced and delivered has implications for plant operation, costs and indirect CO_2 emissions. Electricity can be produced from virtually any other energy source, including dispatchable low-carbon energy sources such as hydro, geothermal and nuclear power, and variable renewable energy (VRE) sources such as solar PV and wind. Electricity can of course be generated using fossil fuels, as the majority is today globally, but if fossil fuels are to be used for ammonia production, it is more efficient to use them directly (e.g. via an SMR) than to first use them to produce electricity for use in the electrolysis route. There are two main ways that electricity can be obtained: either via a connection to the electricity grid or from dedicated electricity generation capacity, which involves captive, on-site power generation specifically for the ammonia plant. Any electricity source can be paired with either approach.

Projects under development to produce electrolytic ammonia include those using a grid connection and others using dedicated capacity. For example, Yara's project in Norway and CF Industries' project in the United States will be grid-connected, while Yara's projects in the Netherlands and Australia and Enaex's project in Chile will be powered by dedicated solar or wind power (see Chapter 2 "An array of technology options at differing levels of maturity" for more project examples).

A key difference between ammonia production using grid-connected and dedicated VRE capacity is the way the plant is operated. Ammonia production using the Haber-Bosch process requires a relatively stable supply of hydrogen. Electricity grids are designed to provide a constant and reliable flow of electricity by drawing on multiple generation units and multiple sources of flexibility. This reliable provision of electricity enables an electrolyser to operate at high capacity factors (typically > 90%) and produce hydrogen at a steady and consistent rate for ammonia synthesis. Dedicated dispatchable capacity would have attributes relatively similar to grid-connected capacity, given that it would enable electrolysers to operate at a high capacity factor.

In contrast, dedicated VRE capacity would not provide a stable flow of electricity day to day or hour to hour. Capacity factors for VRE vary widely depending on the site. While higher capacity factors can be achieved in some locations, typical solar and wind installations may operate at capacity factors in the range of 15-50%. As a result, VRE generation and electrolyser capacity typically need to be oversized to compensate for the intermittency of a dedicated VRE capacity arrangement. Hydrogen or electricity storage can be used to ensure that a stable supply of hydrogen can be provided to the Haber-Bosch process unit. An alternative or complementary option to storage could be to increase the flexibility of the Haber-Bosch process, thus facilitating some degree of ramping or periods of ceased production. Firm-up electricity can also be provided via a connection to the grid to provide a minority of the electricity input at times when it is more cost-effective to do so.

Electricity costs are a critical factor in determining the cost of ammonia produced from electrolysis-based installations. For grid-connected installations, the cost of grid electricity can vary widely by region – national average electricity prices for industrial users varied widely, with a range of USD 22-240 per MWh and a global average of about USD 100 per MWh. The electricity cost for dedicated VRE installations will also vary widely depending on the renewable resources (e.g. solar irradiance, wind speed) at a given site. Some of the lowest-cost solar and wind sites today have levelised costs of around USD 30/MWh, assuming an 8% discount rate, and with further cost declines this could reach as low as USD 20/MWh within a decade. Many sites will have considerably higher costs, but given that no large dedicated VRE installations for ammonia production currently exist, regions with lower costs are likely to be the most attractive targets.

With regard to electrolyser costs, grid-connected capacity with electrolysers operating at high capacity factors would require less electrolyser capacity to provide the same amount of hydrogen, in comparison to dedicated VRE installations operating at lower capacity factors. Hydrogen storage would only be required for dedicated VRE installations. At sites in close proximity to naturally occurring geological storage (e.g. salt caverns), the costs of storage may be very low. However, geological storage is unlikely to be available in many instances, and the alternative would be expensive high-pressure steel tanks (up to 40 times more costly than geological storage). Demand-side flexibility can also incur additional costs, due to lower utilisation and increased maintenance costs for the Haber-Bosch synthesis unit.

The CO_2 intensity of the electricity generation, and in turn the indirect emissions of ammonia production, can vary significantly between grid-connected and dedicated VRE installations. For grid-connected installations, the CO_2 intensity of the grid varies by region and over time. In a sustainable future for the energy system, electricity generation would need to decarbonise rapidly, likely approaching near-zero emissions in most locations within a few decades. Furthermore, the locations with the lowest electricity prices that would favour electrolytic ammonia production currently tend to have large proportions of low-cost large-scale hydropower in the electricity mix, which is already a zero-emission form of electricity generation. With regard to dedicated VRE capacity, no CO_2 emissions will be produced given that renewable energy is used directly, although the use of firm-up electricity, where required, has the same implications as those mentioned for the grid-connected installations.

Methane pyrolysis is another potential route to produce near-zero-emission ammonia. As no commercial-scale installations currently exist, and the technology is still under development, techno-economic parameters for the process remain highly uncertain. The process involves using very high-temperature heat provided by electrical plasma to split methane into its constituent hydrogen and carbon atoms, without burning it. Producing one tonne of ammonia via methane pyrolysis requires around 40 GJ of natural gas feedstock along with around 8 GJ of electricity. Instead of CO_2, the carbon output is in the form of solid carbon, which can be sold for use in certain carbon black applications, if of the appropriate grade. However, if the product in which the carbon is used is then combusted, during use or at the end of its lifetime, the indirect emissions of the methane pyrolysis route are similar to natural gas-based production. Each tonne of hydrogen produced results in around 3 tonnes of solid carbon, such that one tonne of solid carbon is produced for about every 1.9 tonnes of ammonia. The first commercial facility producing ammonia from methane pyrolysis-derived hydrogen is expected to come online by 2025. Announced projects equating to around 0.3 Mt of ammonia production capacity are scheduled to come online by 2030.

Natural gas-based production with CCS is also likely to become increasingly common in the future in order to meet CO_2 emission reduction targets. CCS projects are typically measured by the quantity of CO_2 that they capture. For a given capture project, the near-zero-emission ammonia production capacity can be estimated as being equal to the capacity of an unabated plant emitting that quantity of CO_2, assuming energy performance levels based on BAT. Using that approach, we estimate that just over 1 Mt of ammonia is currently produced each year with near-zero emissions via the application of CCS in projects located in the United States, Canada and China. All of the CO_2 currently captured in these projects is used for EOR. Announced CCS projects, if realised, would increase near-zero-emission ammonia production capacity via CCS to around 4 Mt by 2030.

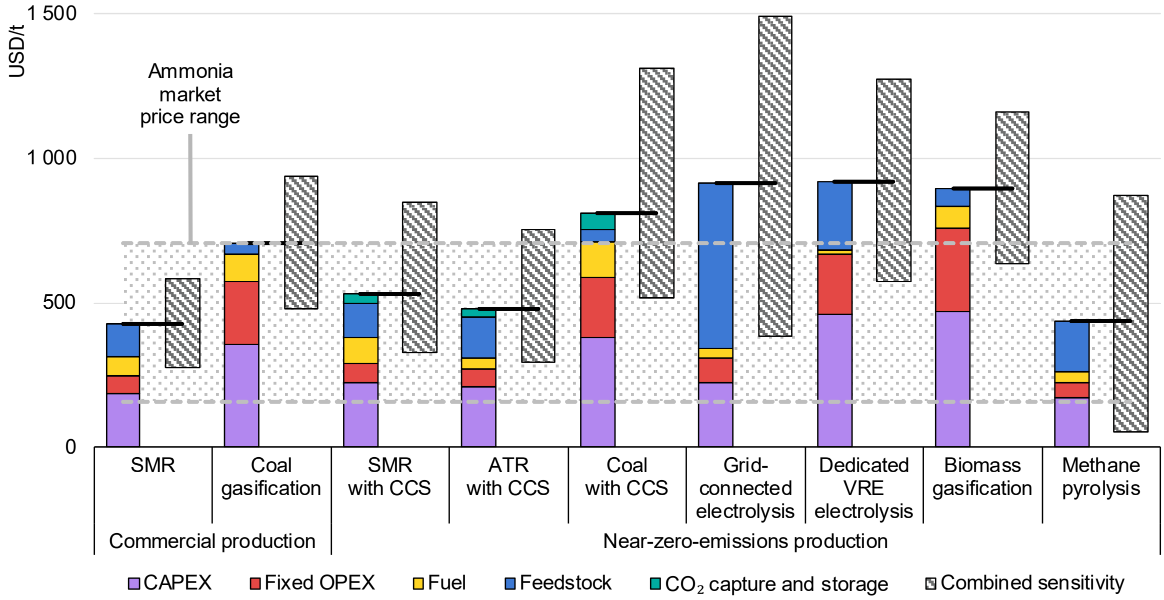
Economic considerations

The cost of producing ammonia is highly dependent on the cost of the main inputs, particularly the cost of energy used for both process energy and feedstock. Using the simplified levelised cost metric as a proxy for the cost of producing one tonne of ammonia, these raw material and energy inputs typically account for 20-40% of the total for commercial routes in operation today. The annualised cost of capital expenditure (CAPEX) and the fixed operational expenditure[9] account for the remainder. The techno-economics of three important near-zero-emission routes are explored in more detail at the individual plant level in Box 1.4.

The prices of the main energy inputs for feedstock and process energy (natural gas, coal and electricity) are key determinants of the overall levelised cost of production. The higher CAPEX of the coal gasification route is offset by the abundance and low-cost of coal relative to natural gas in certain regions, especially China. Avoiding the need to increase relatively expensive natural gas imports, which could potentially hamper efforts to improve energy security, is another factor at play when it comes to the prevalence of the coal-based route in China.

[9] The fixed OPEX boundary used in this analysis includes maintenance, replacement parts and the associated engineering, procurement and construction. Variable OPEX, such as the labour required for operating the plant, is not included. Energy costs are accounted for separately.

Figure 1.6 Simplified levelised cost of ammonia production for commercial and near-zero-emission production routes in 2020



IEA, 2021.

Notes: SMR = steam methane reforming; ATR = auto-thermal reforming; CCS = carbon capture and storage; VRE = variable renewable energy. The simplified levelised cost is calculated using a discount rate of 8% and a design life of 25 years for all equipment, with the exception of the electrolyser stack (11 years) and system (28 years). CAPEX includes core equipment costs, corresponding to the plant battery limit (including CO_2 capture equipment in the case of CCS-equipped routes, electrolysers in the case of electrolysis-based routes, and hydrogen storage in the case of the dedicated VRE electrolysis route), and includes engineering, procurement and construction costs, equating to 70% of core equipment costs. A 95% capacity factor is used for all equipment apart from the dedicated VRE electrolysis route, where a 50% capacity factor is used. The combined sensitivity includes the impact on the total levelised cost of varying the regional coefficient for CAPEX and fixed OPEX (a factor of 73-127% of the CAPEX cost estimated for the United States), energy cost variation for natural gas (USD 3-8.2/GJ), coal (USD 1.3-2.9/GJ), electricity (USD 4.5-30.2/GJ) and bioenergy (USD 2.2-4.4/GJ). The dedicated VRE electrolysis route uses a narrower electricity cost range (USD 2.8-11.1/GJ). Where relevant, the central values for the column series are calculated based on an output weighted average of the fuel prices faced across regions today. For the electrolysis routes, electrolyser cost = USD 1477/kW_e, electrolyser efficiency = 64% and feedstock refers to the electricity used for electrolysis. For CCS-equipped routes, the CO_2 capture rate is 90%, the CO_2 transport and storage costs vary by region from USD 5/t CO_2 to USD 100/t CO_2. CCS is applied to both concentrated and dilute emissions streams for SMR with CCS route, and just the concentrated emissions stream for the ATR with CCS route. No CO_2 emissions price is imposed. A range of revenues for the solid carbon by-product is assumed (USD 0-500/t) for the methane pyrolysis route. CCS in this instance refers to long-term storage. The dotted grey area represents the range of average monthly ammonia prices for 2010-2020, using US Gulf, Middle East and Western Europe spot prices.

Source: Ammonia price data from Bloomberg Terminal.

Energy costs typically account for 20-40% of the levelised cost of ammonia production for the dominant routes used today. Near-zero-emission production routes are typically 10-115% more costly than the incumbent routes.

Among the key emerging routes to produce ammonia with near-zero emissions, two categories can be established based on the relative contributions to levelised cost: CCS-equipped routes and electrolysis-based routes. At the lower end of the cost range, CCS-equipped routes are similar in cost to their unabated counterparts because they are in regions with the lowest CAPEX and energy costs. The slightly higher cost for the CCS-equipped route (10-25% for the natural gas-based routes and 15% for coal gasification) is attributable to slightly higher energy consumption, CO_2 transport and storage costs, and the increased cost of CAPEX and operating expenditure (OPEX) for the capture equipment. The cost of the electrolysis pathways is in large part dependent on the cost of the electricity used, over 90% of which is consumed by the electrolyser. For the case using dedicated VRE capacity, the proportion of cost attributable to CAPEX is much higher than for the grid-based case (95% capacity factor), due to the much lower capacity factor (50% considered here, although this will vary significantly from site to site).

For the methane pyrolysis and biomass gasification routes, the levelised cost is significantly more uncertain due to the lack of a commercial-scale plant in operation today. Cost premiums for the biomass-based route appear to be very large, owing to the very high energy intensity (37 GJ/t including feedstock) and the relatively high cost of bioenergy assumed for a representative sustainable supply (USD 3.3/GJ). The cost of the methane pyrolysis route is highly dependent on the revenue obtained for the carbon black, which is co-produced alongside the hydrogen (and in turn ammonia). At a revenue assumption of around USD 360/t for carbon black, it appears the route could produce ammonia at costs competitive with conventional routes. However, there is a limit to the amount of carbon black that can be absorbed by existing markets for the product (tyres, other rubber products, fillers, pigments), and the grade of carbon black produced significantly affects the revenue that can be obtained. If no revenue, or even a cost, was associated with producing the carbon black, the competitiveness of this route would be severely affected.

Box 1.4 What might a typical near-zero-emission ammonia plant look like in practice?

The world's fleet of ammonia plants numbers around 550, constituting about 250 Mt per year of ammonia production capacity in total. While no two of these plants are exactly the same, a typical natural gas-based ammonia plant built today – the most common choice outside China – uses one of a handful of licensor designs employing SMR technology. Typically, ammonia plants range in size between around 200 kt and 1 200 kt per year (600-3 300 tonnes per day). A reference-scale plant of 875 kt per year (2 400 tonnes per day) is used here.

Characterising the size of a typical near-zero-emission ammonia plant is more speculative, as no such installation exists today at the scale that would be needed in a more sustainable future for the ammonia industry. Two CCUS-equipped plant arrangements can be considered: a typical SMR configuration with full CO_2 capture retrofit to both the concentrated and dilute streams; and a new-build ATR plant with capture of its concentrated stream. These plant configurations would likely operate at a similar scale to commercial plants today. For electrolysis-based plants, announced projects range from 10 kt to 510 kt per year, and commercial electrolysis-based plants have operated at the 150 kt per year scale in the past.

The CAPEX for a typical SMR plant, including engineering, procurement and construction (EPC) costs, is around USD 1 675 million for the core equipment for the 875 kt per year reference-scale plant. Fixed annual OPEX, excluding energy costs, would be around 2.5% of the total initial capital outlay per year, so around USD 50 million per year. For the CCUS retrofit configuration, CAPEX of around USD 335 million would be required (excluding the cost of the existing plant), and annual fixed OPEX for the plant as a whole would rise by around 20%. The ATR configuration is estimated to be just under 10% less expensive than the retrofit configuration when including the cost of the original SMR plant, so would be the likely choice for new-build plants. The fixed annual OPEX for the capture component of the process would also be around 10% lower than the SMR configuration.

The electrolysis-based plant would be the most expensive of the three near-zero-emission options explored here (CAPEX of USD 2 065 million for the reference-scale plant, including EPC costs), considering today's electrolyser costs of around USD 1 477/kW_e. However, electrolyser costs are expected to fall significantly in the coming years, as manufacturing volumes rise to meet increasing capacity additions. The efficiency of the units is also expected to climb, which will make an important contribution to lowering the energy costs. With today's electricity prices in most regions (see Box 1.3), energy costs would make the plant significantly more expensive to operate than the CCUS-equipped configurations, despite similar levels of fixed OPEX.

Assuming BAT energy performance levels, a typical new-build SMR plant consumes around 7 810 GWh of natural gas per year for the reference-scale plant. Electricity inputs are much smaller, at around 75 GWh per year. Around 1 170 GWh of high-temperature steam is produced as a by-product, which is generally put to use on site for preheating and other thermal needs. For CCUS-equipped configurations, natural gas consumption would be broadly similar, but with 3-5 times higher electricity needs owing to the operation of the compressors and separation processes that make up the capture equipment. For the CCUS-equipped SMR retrofit configuration, a proportion of the steam generated by the core process equipment is used to fulfil the heat requirements of the dilute stream capture unit. The electrolysis-based plant does not consume any natural gas, but 20-120 times more electricity, or 8 750 GWh per year for the reference-scale plant.

An SMR plant of the reference-scale size would generate around 1 580 kt CO_2 per year, if operated around the clock. The CCUS configurations would yield a reduction in direct CO_2 emissions of 90-95%, while the electrolysis-based plant would have zero direct CO_2 emissions. Indirect CO_2 emissions from electricity generation depend entirely on the technologies and fuels used in the power sector, and should tend rapidly towards zero in the context of a sustainable future for the ammonia industry. However, taking the global average CO_2 intensity of power generation today, the indirect CO_2 emissions generated equate to around 35 kt of

CO_2 for the SMR-based plant, around 110-175 kt for the CCUS-equipped configurations, and 4 150 kt for the electrolysis-based plant – the latter being significantly more than double the direct emissions from an unabated SMR plant of the same reference scale.

Indicative techno-economic parameters for near-zero-emission ammonia plant configurations

Parameter	Unit	SMR	SMR with CCS retrofit	ATR with CCS new-build	Electro-lysis plant
Typical plant size	kt/year (t/day)	220-1 205 (600-3 300)	220-1 205 (600-3 300)	220-1 205 (600-3 300)	10-510 (30-1 400)
Reference capacity	kt/year (t/day)	875 (2 400)			
CAPEX incl. EPC costs	USD million	1 675	335	1 850	2 065
Fixed OPEX	USD million /year	50	10	55	65
Natural gas consumption	GWh/year	7 810	7 810	6 790	0
Net steam generation	GWh/year	1 170	760	0	390
Electricity consumption	GWh/year	75	235	365	8 750
Direct CO_2 generated	kt CO_2/year	1 580	105	170	0
Indirect CO_2 generated	kt CO_2/year	0-35	1-110	2-175	50-4 150

Notes: SMR = steam methane reforming; ATR = auto-thermal reforming; CCS = carbon capture and storage; EPC = engineering, procurement and construction. Figures are rounded and constitute indicative quantities; realised costs and performance will vary by geography and licensor. Typical plant sizes are stated on a 365-day operational basis and correspond to contemporary new-build plants for the natural gas-based routes and to those of announced projects for electrolysis plants. The reference capacity is used to calculate the quantities in all subsequent rows of the table, to present equivalent quantities for each plant. Energy intensities based on BAT energy performance levels, assuming a typical arrangement with respect to net steam generation. Natural gas consumption includes feedstock. The indirect CO_2 range uses values for the CO_2 intensity of electricity of 6-474 g CO_2/kWh, with the lower end of the range corresponding to the lowest national average grid CO_2 intensity seen in 2020, and the upper end of the range to the global average. Electrolyser parameters, corresponding to a grid-connected arrangement in 2020, as follows: CAPEX including EPC costs = USD 1 477/kW$_e$, efficiency = 64% on a lower heating value basis.

Ammonia and the environment

While nitrogen fertilisers are essential to modern society, their production and use have considerable impacts on the environment. The energy used for fertiliser production leads to considerable CO_2 and other greenhouse gas emissions, and fertiliser use leads to further emissions in the agriculture sector, alongside other impacts on ecosystems and air quality.

Future emissions from nitrogen fertiliser *production* will depend on:

- The level of demand that must be satisfied, which is influenced by many factors including nutrient management strategies.
- The fate of existing production capacity.
- The technology adopted for new capacity additions.
- The type of fertiliser that dominates the market.

Future emissions from fertiliser *use* also depend on a myriad of factors, including:

- The types and amounts of crops that need to be produced.
- Soil, crop and nutrient management practices.
- Local climate and soil conditions.
- The choice of which fertiliser to produce for new capacity, such as whether to produce urea or other fertilisers.
- The availability of various nitrogen fertiliser products in regional markets.

The relationship between sustainability and ammonia-based products is complex. The path the sector takes during the current decade can contribute to achieving several of the United Nations Sustainable Development Goals (SDGs) by 2030, including the following:

- **SDG 2 – End hunger, achieve food security and improved nutrition, and promote sustainable agriculture:** nitrogen fertilisers facilitate food production, and as such their production and use can contribute to ending hunger.
- **SDG 3 – Ensure healthy lives and promote well-being for all at all ages:** since production and consumption of ammonia-based products is one of many contributors to air pollution, reducing pollutants can contribute to improved human health.
- **SDG 7 – Ensure access to affordable, reliable, sustainable and modern energy for all:** since ammonia production uses a substantial amount of energy, shifting to technologies with improved energy efficiency and more renewable energy can contribute to more sustainable energy use.
- **SDG 9 – Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation:** given that ammonia production is a part of the industrial sector, development and deployment of more sustainable technologies will contribute to the broader goal of sustainable industrialisation.
- **SDG 12 – Ensure sustainable consumption and production patterns:** improving the efficiency of use of nitrogen fertilisers and other ammonia-based products will contribute to improved resource efficiency and more sustainable consumption. Additionally, the target to reduce food waste can help contribute to reducing growth in demand for fertilisers.

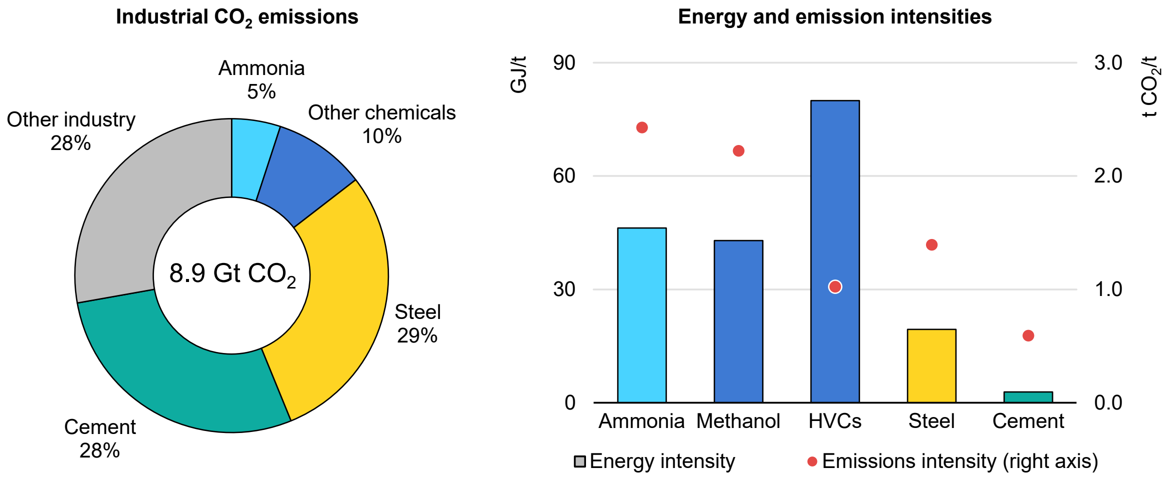
- **SDG 13 – Take urgent action to combat climate change and its impacts:** since a substantial amount of greenhouse gases is emitted as a result of producing and consuming nitrogen fertilisers and other ammonia-based products, switching to near-zero-emission technologies and improving use efficiency will contribute to tackling climate change.
- **SDG 14 – Conserve and sustainably use the oceans, seas and marine resources for sustainable development:** nitrogen fertiliser use contributes to nutrient pollution of waterways and oceans, and therefore more efficient use can improve the health of marine ecosystems.
- **SDG 15 – Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss:** since fertiliser use improves yields, more widespread use can reduce the land needed to produce the same amount of crops, and thus help reduce the need to convert natural ecosystems to agricultural production. Meanwhile, improving fertiliser use efficiency can help reduce ecosystem impacts that arise from air pollution.
- **SDG 17 – Strengthen the means of implementation and revitalise the global partnership for sustainable development:** through finance and technology transfer related to sustainable ammonia production, the global community can help improve sustainability and well-being in emerging-market and developing economies.

There are interlinkages and interactions between the various SDGs, calling for a balanced approach to reap the benefits of using fertilisers and other ammonia-based products, while also minimising their environmental impacts. This section discusses these environmental impacts and begins to look towards a more sustainable future for the sector. A more in-depth look at the future can be found in Chapter 2, including an outline of what the IEA's Sustainable Development Scenario would entail for ammonia production. This scenario focuses in particular on achieving the three SDGs most closely related to energy: to achieve universal access to energy (SDG 7), to reduce the severe health impacts of air pollution (part of SDG 3) and to tackle climate change (SDG 13).

An energy- and emissions-intensive sector

In 2020 global ammonia production accounted for around 8.6 EJ of final energy consumption – over 95% of which was fossil fuels – and around 450 Mt of CO_2 emissions. This is around 20% of the energy consumption of the wider chemical sector and around 35% of its CO_2 emissions. Measured against the energy sector as a whole, ammonia production accounts for around 2% of final energy consumption and 1.3% of energy sector emissions (including energy-related and industrial process emissions). If the ammonia industry were a country, it would be the 16th largest emitter in the world, between South Africa and Australia.[10]

Figure 1.7 Energy consumption for and emissions from ammonia production in context, 2020



IEA, 2021.

Notes: HVCs = high value chemicals, including ethylene, propylene, benzene, toluene and mixed xylenes. Energy intensities shown on a gross basis to facilitate comparison between products and sectors, i.e. excluding the quantities of steam and other energy carriers that are produced as by-products. Industrial energy consumption includes energy used in blast furnaces and coke ovens and chemical feedstock. Industrial CO_2 emissions include process emissions.

Energy demand and direct CO_2 emissions from ammonia production are estimated to have risen by 30% since 2000, while production volumes have increased by 40%.

Three heavy industry sectors – steel, cement and chemicals – account for 70% of industrial CO_2 emissions globally. Emissions from steel production (2.6 Gt CO_2 in 2020) stem primarily from the use of carbon-based reduction agents (coke and coal) and the generation of high-temperature heat during the ironmaking process. Around two-thirds of the emissions generated by the cement sector (2.5 Gt CO_2) stem from the chemical reaction that is employed to make clinker from limestone in a kiln. The remaining third is generated from the burning of fossil fuels (mainly coal) to produce the heat required to sustain this reaction. The chemical sector comprises thousands of complex value chains, most of which start with the production of seven primary chemicals – high-value chemicals (which in turn comprise ethylene, propylene, benzene, toluene and mixed xylenes), methanol and ammonia – which altogether account for around two-thirds of the energy consumption in the sector. Ammonia is by far the largest contributor to emissions

[10] This comparison only takes into account the energy-related emissions of countries in 2019.

within the chemical sector, at 450 Mt CO_2 in 2020, with methanol contributing a further 220 Mt CO_2 and high-value chemicals a further 250 Mt CO_2.

While the steel and cement sectors dwarf the emissions from ammonia production in absolute terms, they are significantly less energy and emissions intensive on a tonne-for-tonne basis. Steel and cement are produced in far higher volumes globally, at 1 877 Mt and 4 281 Mt in 2020 respectively, compared with 185 Mt of ammonia. When considering direct CO_2 emissions from the production of these commodities, steel and cement generate 1.4 t CO_2/t and 0.6 t CO_2/t respectively, compared with 2.4 t CO_2/t for ammonia. This difference is owing to the significant energy intensity differential between the materials, which for steel and cement are around 19 GJ/t and 3 GJ/t respectively, compared with around 46 GJ/t for ammonia on a gross basis (41 GJ/t on a net basis). Within the chemical sector, the energy intensity of methanol is broadly similar to that of ammonia, whereas for high-value chemicals the energy intensity is nearly double, at around 80 GJ/t on average. This is because high-value chemicals consume large quantities of fuel (mainly oil products like ethane and naphtha) as feedstock, which are not combusted during production – this explains their comparatively low emissions intensity of 1 t CO_2/t, less than half that of ammonia.

Non-CO_2 environmental impacts

While this roadmap focuses primarily on the CO_2 emissions from ammonia production, the production and use of nitrogen fertilisers also have wider environmental implications. Negative impacts include:

- Further contributions to climate change by nitrous oxide (N_2O) emissions from nitric acid production and both N_2O and CO_2 emitted from soils following fertiliser application.
- Air pollution associated with ammonia (NH_3) and nitrogen oxides (NO_x) emitted from soils, as well as pollutants emitted from production facilities.
- Soil and water quality degradation and biodiversity loss from excess nitrogen in aquatic and terrestrial ecosystems.

Conversely, fertiliser use enables higher crop yields, thus reducing the need to convert natural ecosystems to agricultural production. This can result in positive impacts on ecosystems and biodiversity, including reduced deforestation and land degradation.

A balance needs to be reached between the benefits and impacts of using nitrogen fertilisers and other ammonia-based products. Researchers have suggested that the degree of human modifications to the nitrogen cycle, including a large contribution from fertiliser production and use, already exceeds the boundary of a sustainable, safe operating space for humanity. This boundary largely pertains to impacts on aquatic ecosystems from excess nitrogen, as well as the greenhouse gases that result from nitrogen use. Reducing these environmental impacts will evidently be important in the shift to more sustainable ammonia-based value chains.

A comprehensive assessment of these non-CO_2 environmental impacts is outside the scope of this analysis. However, an overview is provided here as a broader picture of the sustainability implications of ammonia-based products. Additionally, these other environmental impacts are highly relevant to one of the strategies discussed in this roadmap – improving nutrient use efficiency. Both ammonia production CO_2 emissions and other environmental impacts are reduced when fertilisers are used more efficiently, regardless of the motive behind efficiency improvements. The link between CO_2 and non-CO_2 impacts is thus of interest when considering more sustainable ammonia production.

Non-CO_2 greenhouse gas emissions from fertiliser production and use

Besides CO_2 and methane (see Box 1.5), nitrous oxide (N_2O) is emitted as a result of both the production and use of nitrogen fertilisers. N_2O is a potent greenhouse gas, with a global warming potential 298 times higher than CO_2 over a 100-year period.[11] It is also now the top contributor to ozone depletion, following large-scale phase-outs of chlorofluorocarbons (CFCs). The nitrogen cycle is highly complex, with a multitude of natural and anthropogenic sources and sinks, and as such calculating N_2O emissions is prone to uncertainty. It has been estimated that on average between 2007 and 2016 around 17 Mt of nitrogen from N_2O were emitted to the atmosphere each year, around 7.3 Mt (43%) of which was due to anthropogenic activities and 3.8 Mt (52% of the anthropogenic total) specifically from the agricultural sector. Naturally occurring nitrous oxide sinks reduced the annual increase of nitrogen in the atmosphere to 4.3 Mt. In 2018 N_2O accounted for about 5% (2.8 Gt CO_2-eq) of total global anthropogenic greenhouse gas emissions (excluding land use change emissions). Human induced N_2O emissions have increased by 30% since 1980, with nitrogen additions to cropland being the largest contributor to growth.

[11] Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) has assessed the global warming potential of different greenhouse gases with and without climate–carbon feedbacks. The global warming potential of nitrous oxide is 298 with feedbacks and 265 without. IPCC states that, “Though uncertainties in the carbon cycle are substantial, it is likely that including the climate–carbon feedback for non-CO_2 gases as well as for CO_2 provides a better estimate of the metric value than including it only for CO_2.”

With regard to fertiliser production, nitric acid (HNO_3) is the main contributor to fertiliser-related N_2O emissions. Nitric acid is an important precursor for the production of certain fertilisers, namely ammonium nitrate, calcium ammonium nitrate and urea ammonium nitrate. About 75-80% of nitric acid is used in fertiliser production. Nitric acid is produced by the reaction of ammonia and oxygen. During the process, N_2O is also produced at a rate usually between 6 kg and 9 kg of N_2O per tonne of HNO_3. With the adoption of abatement technologies, emission rates have been observed at least as low as 0.12 kg of N_2O per tonne of HNO_3. While recent robust global data are not available on the quantity of N_2O emissions from nitric acid production, extrapolations using available data would put an estimate at around 120 Mt CO_2-eq in 2020[12] for nitric acid and adipic acid combined (adipic acid is a chemical used in nylon and PVC production; it is derived from nitric acid and its production process also emits N_2O). This is about one-third of the nitrous oxide emissions from the industrial and waste management sectors, and equivalent to about 30% of global CO_2 emissions from ammonia production.

Multiple abatement technologies already exist to limit nitrous oxide emissions from industrial facilities. Primary abatement methodologies prevent N_2O from forming in the first place, such as by using different materials for the ammonia oxidation catalyst. Secondary N_2O abatement technologies involve placing the catalyst inside the ammonia oxidation reactor to control N_2O immediately after it is formed. Abatement efficiency can be as high as 98%, although it varies by plant and is usually somewhat lower than this. Tertiary N_2O abatement technologies consist of a separate reactor dedicated to reducing nitrous oxide further downstream, but before being vented. Abatement efficiency can be between 95% and 98%. Costs of these technologies are relatively low at EUR 0.90-3.20 (USD 1.10-3.80) per t CO_2-eq.

In some parts of the world, N_2O abatement catalysts have been installed on most nitric acid plants. This includes in Europe, largely due to policies such as the EU emissions trading system, as well as in China and a number of other developing economies through the Clean Development Mechanism under the Kyoto Protocol. Largely as a consequence of these technologies, nitrous oxide emissions from nitric acid and adipic acid production fell by 55% from 1990 to 2010. Further deployment of such N_2O abatement technologies, particularly in regions where they are not yet widespread, will be an important and relatively easy-to-implement step in reducing the overall greenhouse gas footprint of

[12] In 2010 N_2O emissions from nitrous oxide and adipic acid production combined were 104 Mt CO_2-eq according to the IPCC. This is the latest available value for nitric acid and adipic acid production. 2020 N_2O emissions from these activities were estimated by comparing the level of nitric acid demand for ammonium nitrate production between now and then, as well as the level of N_2O emissions from industrial processes and product use published by the FAO. The estimate assumes no particular improvement in abatement in this period, which is a conservative assumption and may mean that emissions are somewhat overestimated.

nitrogen fertilisers. Limiting N_2O emissions from nitric acid production will become even more important if fertilisers that require it as an input are increasingly chosen over urea in order to reduce urea's use-phase CO_2 emissions (discussed below).

N_2O emissions from fertiliser use are considerably larger than those from fertiliser production. While quantifying N_2O emissions from agriculture involves considerable uncertainty, and a range of estimates exist, approximately 50-60% of anthropogenic N_2O emissions are estimated to come directly from agriculture. This includes emissions from direct application of mineral and manure fertilisers, cultivation of organic soils, crop residues left on fields, manure left on pastures, manure management and aquaculture. The FAO estimates that in 2019 the application of mineral fertilisers led to emissions of about 2.3 Mt of N_2O (or 0.7 Mt of nitrogen from N_2O), of which 1.7 Mt N_2O were direct and 0.6 Mt indirect emissions. This is equivalent to 670 Mt CO_2, or 50% more than the 440 Mt CO_2 emitted from ammonia production in that year.

N_2O emissions from the application of fertilisers to soil occur through a number of processes. N_2O is emitted directly from agricultural soils as a by-product of two processes by which soil microbes convert ammonia back to nitrogen gas: 1) nitrification, which converts ammonium (NH_4^+) to nitrate (NO_3^-); and 2) denitrification, which converts nitrate (NO_3^-) to nitrogen gas (N_2). Two indirect pathways also lead to N_2O emissions from fertiliser application: 1) nitrogen leaching and run-off from soils leads to later N_2O emissions from ground and surface waters; and 2) NH_3 and NO_x is volatised into the air from soils, then later redeposited onto other soils and waterways, from which N_2O is emitted.

A complex array of factors affect how much N_2O is emitted from soils as a result of fertiliser application. There is a natural flux of N_2O into the atmosphere as part of the nitrogen cycle. Both mineral and organic fertilisers add to the total amount of nitrogen in the soil, as does leaving crop residues on fields. The rate of N_2O emissions is higher when the total amount of nitrogen available exceeds that taken up by plants. Other factors influencing N_2O emissions include soil characteristics (moisture, temperature, pH, salinity, carbon availability), soil microbial populations, and irrigation and tillage practices. As of 2019 the IPCC's default factors for direct N_2O emissions from mineral fertilisers (the percentage of nitrogen applied in mineral fertiliser inputs that is later directly emitted as N_2O) are 1.6% in wet climates, 0.5% in dry climates and 0.3-0.5% for flooded rice fields. However, actual emissions may vary considerably by site depending on the factors mentioned above.

The quantity of greenhouse gas emissions from fertiliser application also varies by the type of fertiliser. Based on the range of typical practices employed across the world today, greenhouse gas emissions from the use phase of the nitrogen fertiliser life-cycle account for roughly 25-70% of total direct and indirect emissions from nitrogen fertiliser production and use.[13] As fertiliser production emissions decrease in the future, fertiliser use emissions – and thus the choice of fertiliser – will become increasingly important for reducing the overall greenhouse gas impact of fertilisers. N_2O emissions from soil per unit of nitrogen fertiliser are highly dependent on application practices, soil type and conditions, humidity and other weather conditions, and the use of additional compounds such as nitrification inhibitors. Different fertiliser types can also react distinctly depending on the conditions. For arable soils and particularly when conditions are dry, nitrate-based fertilisers result in similar or lower N_2O emissions compared to urea and fertilisers containing only ammonium. Meanwhile, for grasslands, peat soils and clay soils, when there are wet conditions, urea and ammonium-based fertiliser may lead to lower N_2O emissions relative to nitrate-based fertilisers.

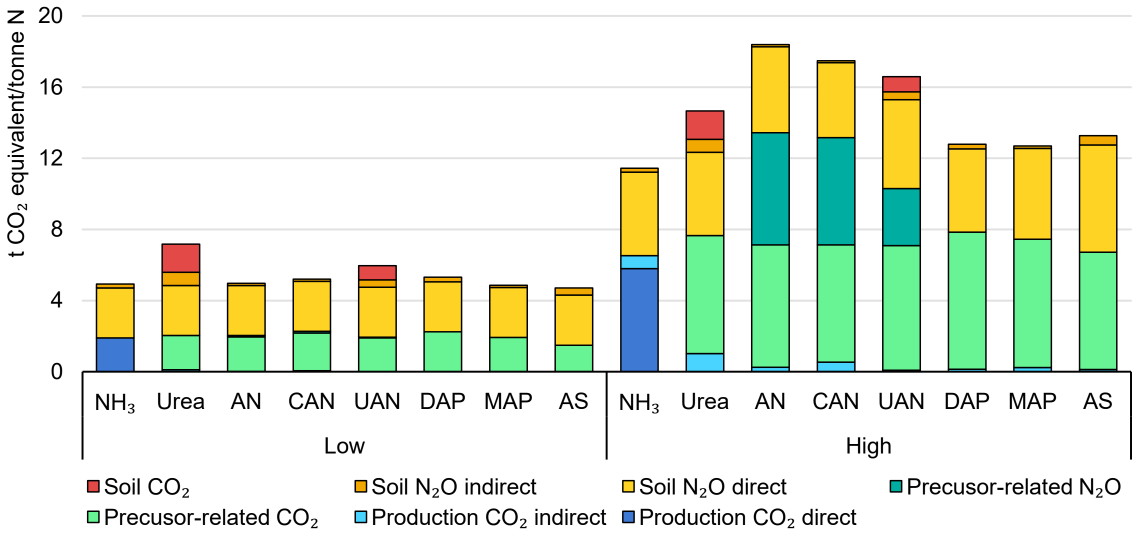
Fertilisers also differ in their direct CO_2 emissions. Urea (and its derivative, urea ammonium nitrate) is a carbon-containing fertiliser ($CO(NH_2)_2$) synthesised from ammonia and CO_2. The CO_2 used to manufacture it is released when it is applied to soil. When the CO_2 is sourced from fossil fuels, as it is today, this adds to the total CO_2 emissions from fertiliser use. If in future the CO_2 were sourced through DAC or biogenic sources, this CO_2 release would be carbon neutral and not add to the total. In 2020 the use of urea fertiliser led to around 130 Mt CO_2 use-phase emissions, or equivalent to about a quarter of the CO_2 emissions from the production of ammonia. Due to the contribution of these CO_2 emissions during application (which cannot practically be captured), urea greenhouse gas emissions from the use phase are about 40% higher than that of the next most common fertiliser, ammonium nitrate.

Various measures can be taken to reduce N_2O emissions from fertiliser application. Nutrient use efficiency measures, such as the 4Rs (right source, right rate, right time and right place), help minimise nitrogen losses to the environment, including direct and indirect N_2O emissions, and in the case of urea reduce CO_2 emissions by lowering the amount of fertiliser applied. Particular techniques that can significantly reduce fertiliser N_2O emissions include variable-rate fertiliser application, precision farming and soil microbe inhibitors. Other management strategies not directly related to fertiliser application can also help reduce N_2O emissions, such as crop residue management, improved irrigation and drainage techniques to reduce excess water in soils and, depending on the conditions of the particular site, limiting tillage to enable more oxygen flow (N_2O production is highest in wet, low-oxygen conditions). It should be noted, however, that while

[13] See notes to the figure below for a description of the boundaries and calculations in this estimate of direct and indirect emissions.

N_2O emissions from mineral fertilisers can be reduced, no method is currently available to eliminate these emissions without also eliminating fertiliser use. In a net zero world, any remaining emissions from fertiliser use would need to be offset by carbon removal, whether in the energy sector, in soils or elsewhere.

Figure 1.8 Ranges of emission factors by fertiliser product for current process technology and application practices



IEA, 2021.

Notes: NH_3 = ammonia; AN = ammonium nitrate; CAN = calcium ammonium nitrate; UAN = urea ammonium nitrate; DAP = diammonium phosphate; MAP = monoammonium phosphate; AS = ammonium sulphate; N_2O = nitrous oxide. The real emission factors for nitrogen fertilisers in a given instance are highly uncertain; ranges are shown here using standard emission factors and are illustrative. For the direct CO_2 emission intensity of ammonia production, low and high values are based on a range of energy intensities and feedstocks: natural gas-based steam methane reforming with gross natural gas consumption of 28 GJ/t NH_3 (low), and coal gasification with gross coal consumption of 45 GJ/t NH_3 (high). Indirect CO_2 emissions from ammonia production include emissions from electricity generation with emission intensities of 6 g CO_2/kWh (low) and 933 g CO_2/kWh (high). Precursor-related N_2O emissions include those generated during nitric acid production, using a range of emission factors (0.12-9 kg N_2O/t nitric acid) from Brentrup et al. 2016 and Ecofys. Precursor-related CO_2 emissions refer to the production-phase emissions generated from upstream products (e.g. the emissions from the production of ammonia used to produce urea). Emissions from phosphoric acid, sulphuric acid and calcium carbonate production and liming are not included, but are estimated to be negligible on a per tonne N basis. Soil N_2O direct and indirect emissions (stemming from nitrification and denitrification reactions) are calculated using emission factors from the IPCC and the EEA respectively. For direct emissions, the default IPCC factor of 0.01 kg N_2O-N/kg N (high) is used along with a reduced value of 0.006 kg N_2O-N/kg N (low), which assumes the use of nitrification inhibitors. This emission factor can vary widely depending on the conditions and application methods, so this value is only an average. Soil CO_2 emissions (stemming from urea hydrolysis) (0.73 t CO_2/t urea and 0.26 t-CO_2/t UAN) are calculated using emission factors from the IPCC. This CO_2 is often sourced from ammonia production, but is accounted for during the fertiliser use stage (application to soils) rather than production is often sourced from ammonia production, but is accounted for during the fertiliser use stage (application to soils) rather than production .

Upwards of 70% of the life-cycle greenhouse gas emissions from fertilisers take place after the fertiliser is applied to the soil. Around 90% of the emissions from the production phase are attributable to ammonia production.

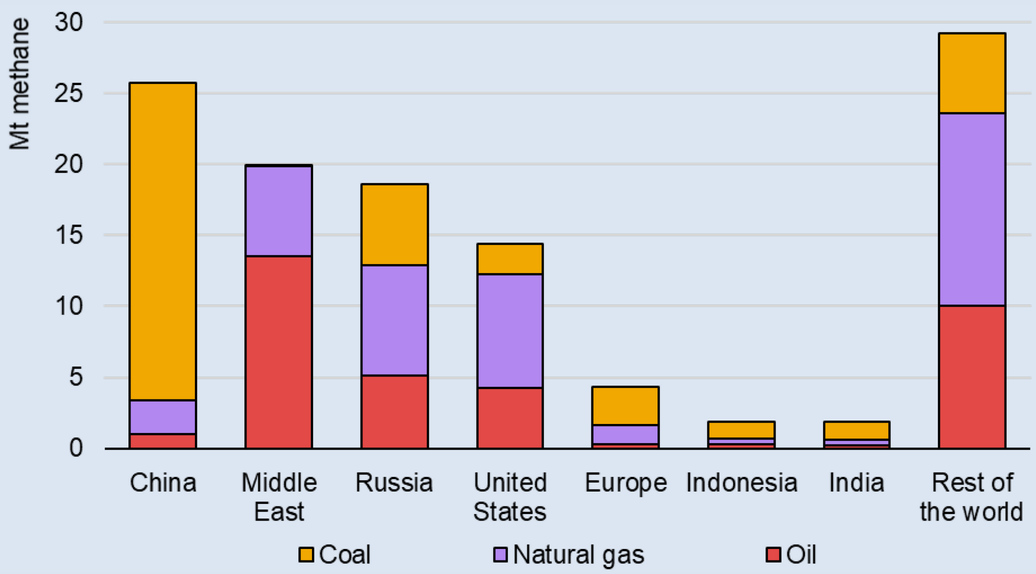
Box 1.5 Methane emissions from fossil fuel operations

Oil, natural gas and coal supply account for nearly one-third of anthropogenic methane emissions and over 90% of methane sources from the energy sector. Tackling methane emissions from fossil fuel operations represents one of the best near-term opportunities for limiting the worse effects of climate change because of its short-lived nature in the atmosphere and the large scope for cost-effective abatement.

In 2020 fossil fuel operations released over 115 Mt of methane to the atmosphere, equivalent to almost 3.5 Gt of CO_2-eq,[14] around 10% of global energy-related CO_2 emissions. Coal, oil and natural gas account for similar shares of methane emissions, but this varies greatly by region. Almost 90% of methane emissions in China are from coal supply, whereas leaks along the natural gas supply account for close to half of related emissions in the United States.

It is complex to allocate methane emissions to a specific end-use like ammonia production accurately, as fossil fuels are widely traded around the world under various contractual arrangements. Using global average emission factors for methane emissions from fossil fuels results in an estimate of 2.3 Mt (70 Mt CO_2-eq) attributable to the fuel inputs to ammonia production. This is equivalent to 0.4 t CO_2-eq per tonne of ammonia, or 15% of the CO_2 directly emitted during production on average.

Methane emissions from fossil fuel operations in key ammonia-producing regions, 2020



IEA, 2021.

[14] Methane global warming potential is considered at 30 over 100 years based on the latest values from the IPCC.

Nearly 75% of oil and gas methane emissions can be abated with existing technologies. These can often be deployed at a relatively low cost. Considering natural gas prices so far in 2021, we estimate that almost 50% of oil and gas methane emissions can be avoided with measures that would have no net cost because the value of the captured methane is sufficient to cover the costs of the abatement measure. The technical solutions available to avoid emissions of coal mine methane are more limited, especially after the start of operations, and often entail higher costs due to the dispersed nature of coal mine methane. However, actions to minimise leaks in coal mines can drive a reduction of almost 45% in the methane intensity of coal supply.

This topic is covered in more detail in other IEA analyses, including Curtailing Methane Emissions from Fossil Fuel Operations

Impacts on water, soil, air and ecosystems

Inefficient use of fertilisers – including both mineral and organic fertilisers – has considerable impacts on water quality and aquatic ecosystems. Run-off from agricultural fields carries excess nutrients to lakes and oceans, leading to eutrophication of freshwater and marine ecosystems. In the process of eutrophication, a high influx of nutrients into a body of water leads to a large increase in growth of plant organisms such as phytoplankton, more commonly known as algae. When the phytoplankton die, bacterial decomposition of the dead phytoplankton depletes oxygen levels in the water. This creates a low-oxygen (hypoxic) environment that is inhospitable to fish and other animal life.

Researchers have found that more than 500 sites in coastal waters have reported hypoxic conditions since 1950. An example of the impact is the Gulf of Mexico hypoxic zone, which has become an annual summer occurrence. The Mississippi River drains a 3.2 million km^2 catchment area from Canada down through the central United States – the third-largest in the world – into the gulf. Nitrogen and phosphorus fertilisers, animal manure, human waste and industrial waste all contribute to the nutrient enrichment. The size of the hypoxic zone can vary considerably from year to year. Over the past 36 years of measurement, the average size has been 14 000 km^2, approximately the area of Northern Ireland. Other examples around the world abound, from the world's largest hypoxic zone in the Baltic Sea to algal blooms in one-third of China's lakes. In addition to their impacts on oxygen availability, algal blooms can have direct toxic effects. The toxins created can affect smaller fish and shellfish that consume the algae, and they can also be passed up the food chain to other fish, birds, marine mammals, and reptiles.

Nitrogen pollution can also have impacts on soils and terrestrial ecosystems. Long-term excessive fertilisation can cause soil acidification and salinisation, reducing crop productivity and potentially resulting in loss of arable land. Nitrogen pollution also contributes to acid rain and direct ammonia deposition, which can damage forests and grassland ecosystems, in addition to negatively affecting aquatic ecosystems. Ammonia – both when applied directly on agricultural fields, and when volatised and redeposited further away – can have localised effects directly toxic to soil organisms.

Nitrogen fertiliser use also contributes to air pollution. The air pollutants involved include: nitrogen oxides (NO_x), which are directly emitted from agricultural fields; particulate matter, which can be formed from NH_3 emitted from agriculture; and ground-level ozone, which can be formed from NO_x emitted from agriculture. These air pollutants contribute to a variety of human health problems, including cardiovascular and respiratory disease.

Various efforts are underway to improve nutrient use efficiency and thus reduce the environmental impacts of nitrogen fertiliser use, including efforts led by the industry itself. Nonetheless, according to the United Nations, much stronger efforts are needed to reduce nutrient pollution. See Chapter 3 for examples of existing initiatives and recommendations for accelerating progress.

The environmental benefits that arise from using fertiliser should also be acknowledged. Fertilisers enable higher crop yields relative to organic agriculture, and thus can produce the same amount of food and fibre from a smaller land area. As a result, less land needs to be brought into agricultural production when using mineral fertilisers. Preserving more natural ecosystems, such as forests and grasslands, has the benefit of preserving biodiversity and maintaining natural carbon sinks. Reduced land use requirements can also prevent agriculture from encroaching on less suitable land, thus reducing degradation of soils and desertification.

This is not to say that organic agriculture should not be pursued due to its higher land use requirements. Indeed, researchers point out that there are other ways to reduce land use requirements. Measures could be taken to reduce food wastage, and diets could be shifted towards lower reliance on animal products, thus reducing livestock feed requirements. As such, total crop production requirements could be lowered while sustaining the same human population. All things considered, moving towards a more sustainable agricultural system will require effort on many fronts and finding a balance between the benefits and impacts of different agricultural production methods. In all likelihood, agricultural production with mineral fertilisers and with organic methods will both play a role in a sustainable future, and maximising efficiency across agricultural value chains will help minimise the various aforementioned environmental impacts.

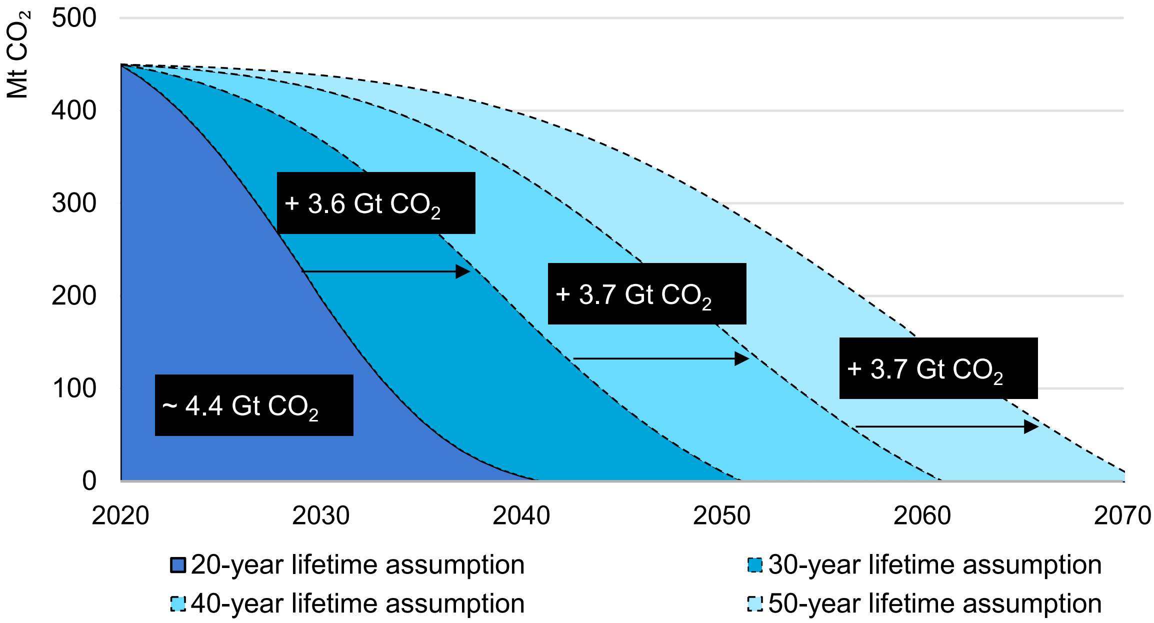
What will happen tomorrow to today's CO_2 emissions from ammonia production?

The ammonia industry's infrastructure is like a container ship – it has inertia and is slow to change direction. While producers are constantly responding to price fluctuations and changes to their order books, short of major disruption to the economy, the behaviour of the system tends to maintain fairly stable trends. Understanding the main pieces of equipment that comprise the emissions-intensive components of the industry's infrastructure is critical to assessing the underlying momentum in the system. Existing infrastructure certainly presents challenges for reducing emissions, but there are also technology opportunities to be seized.

The amount and type of energy that the industry uses at any given time are the consequence of past investments in ammonia production facilities. It is not possible to predict accurately the future energy consumption and subsequent emissions of these installations, as there is scope for adjusting both the quantities and types of energy carriers that they will use and the length of the period they will actually remain in operation. In the end, decisions about whether to cease, continue or extend the operation of a given facility will be based predominantly on its operational cost relative to existing or emerging alternatives, and/or the ability to obtain a sufficient return in a given economic and regulatory context. However, examining potential trajectories of various emission streams, under a stated set of assumptions, is a useful starting point to examine the challenge posed by existing assets and our room to manoeuvre in the coming decades.

The current age profile and typical lifespan of the world's ammonia plants can provide a guide as to the rate at which the existing stock of equipment in the ammonia industry will be decommissioned. Without any further investment in new capacity, emissions from ammonia production would decline, but not as fast as one might think. If operated under the conditions typically observed in recent years (similar energy intensities, capacity factors and fuel mixes), existing ammonia capacity could lead to between 4.4 Gt and 15.5 Gt of CO_2 emissions, considering a typical plant lifetime range of 20-50 years. This is equivalent to 10-35 years' worth of emissions from ammonia production in 2020, and excludes any emissions from the new capacity needed to replace existing facilities and meet rising demand in the future.

Figure 1.9 Projected emissions from existing ammonia plants under different lifetime assumptions



IEA, 2021.

Emissions from existing ammonia production facilities could amount to 4.4-15.5 Gt CO_2, equivalent to 10-35 years' worth of emissions based on ammonia production in 2020.

A key factor in estimating the future emissions from existing ammonia facilities is their current age. A plant built in one year is highly unlikely to be decommissioned the next, but equally no facility is designed to operate indefinitely, so the starting point is of critical importance in estimating the period over which these assets might continue to operate. Using data provided by the International Fertilizer Association,[15] the global average age of ammonia plants in 2020 is estimated to be around 24 years. Figure 1.10 shows the average age and output of global facilities by country. The oldest plants in the world still operating today were installed just under a century ago, although these are clearly outliers when viewing the national average age data available with this study.

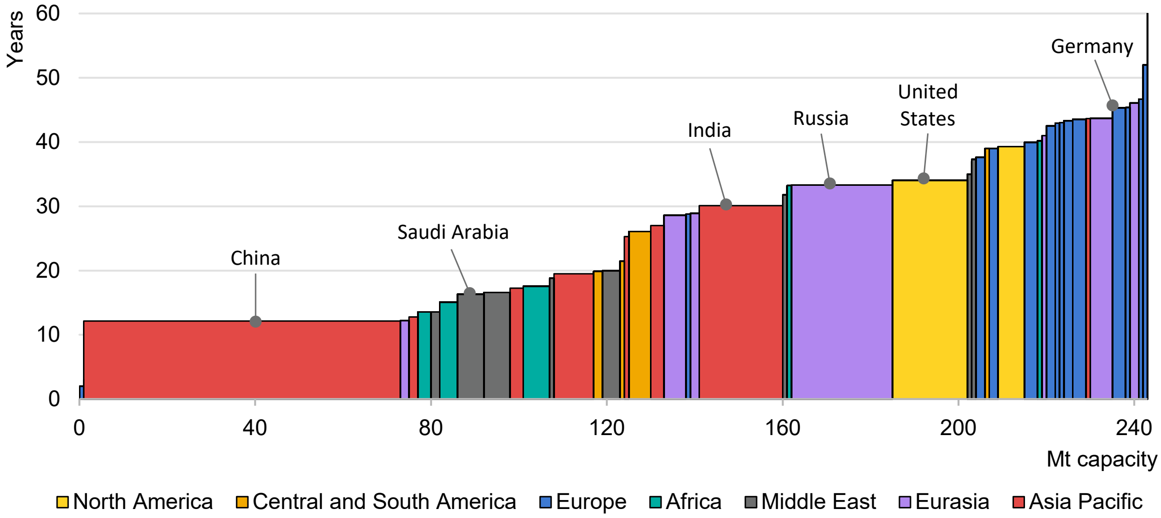
China accounts for 30% of ammonia production capacity globally, and these assets are both young (around 12 years old on average) and emissions-intensive

[15] Plant-level data held by the International Fertilizer Association are confidential. National averages were calculated and provided for use in this study.

(85% are coal gasification units). The age of individual plants within the country will vary considerably, but China's growth in output over the past 20 years (more than 60%) shows the relatively short timeframe over which most of these installations have been added. Industrial facilities in China also tend to be replaced more frequently than in other regions of the world, often owing to mandates targeting the replacement of inefficient capacity. Typical asset lifetimes in the power and heavy industry sectors tend to be in the range of 25-35 years, compared with 30-50 years globally. The average age of the world's ammonia plants excluding China was around 29 years in 2020.

On the right-hand side of the large share of Chinese capacity is significant variation in average age across the other regions. At one end are the recently installed plants in Africa (less than 18 years on average) and capacity in Europe at the other (around 40 years on average). Plants in the Middle East tend to be at the lower end of the age profile, at 19 years old on average, and plants in the Americas towards the upper end (35 years).

Figure 1.10 Geographic distribution and average age of ammonia production facilities in 2020



IEA, 2021.

Source: National average age data provided by the IFA.

Around 30% of the existing stock of ammonia production capacity is based in China, with an average age of 12 years, compared with a global average age of around 24 years.

The average age since installation only tells part of the story, however. Like Theseus' ship, the extent to which many of the older plants have been refurbished and upgraded may render them unrecognisable relative to their original installation arrangement. Many of their parts will have been refurbished and replaced as they wear, and in order to maintain competitiveness and meet evolving regulatory standards, owners are likely to have upgraded them over time to improve energy performance and reduce pollution. A detailed maintenance and upgrade record for every plant in the world was not available for this study, explaining the range of prospective lifetimes (20-50 years) we have used in estimating the potential emissions from the existing stock of plants.

To the extent that much of the existing capital stock will still be in operation decades into the future, the associated CO_2 emissions are often considered to be "locked in". However, these emissions are by no means destined to take place, and there are several strategies and technologies that can be deployed to varying extents to help "unlock" emissions from existing infrastructure:

- **Early retirement or interim underutilisation of assets**, either because of a change in market conditions that makes them uneconomic, or because of laws and regulations that force early closure or partial operation.
- **Refurbishment and retrofitting**, such as enhanced process integration to boost energy efficiency, or the application of emission reduction technologies such as replacing a portion of the natural gas inputs with electrolytic hydrogen or applying CCS.
- **Fuel switching and incremental blending**, sometimes combined with a degree of retrofitting, to allow assets to use less carbon-intensive fuels or recovered fuels.

In the regions where industrial capacity is generally older, earlier retirement than might otherwise be desirable without efforts to reduce emissions will be less painful economically, as the plants would already have provided a substantial return on their original investment. In the countries with younger assets, greater emphasis is likely to be placed on retrofitting with more energy-efficient and less carbon-intensive technologies, where it is economic to do so.

Beyond applying the mitigation strategies above, existing production facilities can be used to bridge the gap to deployment of innovative near-zero-emission technology. This is especially important for the sustainable transition of the assets used to produce ammonia, where readily available alternatives for dramatic reductions in emission intensity are not yet widely accessible to the market. Strategically timed investments to partially renew existing infrastructure – or a decision to forgo investment – can form an important strategy to avoid investment in new capacity occurring just at the wrong time.

The estimates of emissions from existing assets associated with the 20-50-year lifetime range explored above can be used to illustrate the potential impact of misalignment between the phase-out of existing facilities and the availability of near-zero-emission technologies to replace them. The 30-year difference in the lifetime range could be considered equivalent to a full cycle of new or renewed investments in emissions-intensive production capacity, leading to around 10 Gt CO_2, or more than 20 years' worth of emissions from ammonia production in 2020.

Chapter 2. The future of ammonia production

Highlights

- In the Sustainable Development Scenario – a pathway fully aligned with the "well below 2°C" goal of the Paris Agreement – direct CO_2 emissions from ammonia production fall by over 70% by 2050 relative to today. The Net Zero Emissions by 2050 Scenario describes a trajectory for the ammonia industry that is compatible with reaching net zero emissions globally for the energy system by 2050, where emissions fall by 95% by 2050. In contrast, the Stated Policies Scenario, projecting forward current trends, sees emissions decline by only 10%.
- In the Stated Policies Scenario, ammonia production increases by 37% by 2050, driven primarily by economic and population growth. Strategies to improve end-use efficiency (e.g. nitrogen fertiliser application) lead to slower growth in total production (23%) in the Sustainable Development Scenario, thereby accounting for 20% of the emissions reductions achieved.
- Energy efficiency contributes about 25% of emission reductions in the Sustainable Development Scenario, including adoption of BAT, operational improvements and switching from coal to less energy-intensive natural gas-based production. 10% of emission reductions in this scenario stem from substitution of coal with less emissions-intensive fuels.
- The deployment of near-zero-emission technologies contributes the largest share of emission reductions in the Sustainable Development Scenario, including electrolytic hydrogen (30%) and CCS (15%) technologies. This requires more than 110 GW of electrolyser capacity and 90 Mt of CO_2 storage by 2050. In the Net Zero Emissions by 2050 Scenario, the additional emission reductions are driven by even more rapid deployment of these technologies.
- Near-zero-emission technologies are not yet available at commercial scale in the marketplace. CO_2 separation is an inherent part of ammonia production today, but permanent storage of the CO_2 is not yet widely adopted. Electrolysis-based ammonia production has already been conducted at scale using high load factor electricity, but challenges remain to use hydrogen produced from VRE. The Sustainable Development Scenario requires USD 14 billion in annual capital investment for ammonia production to 2050. Of this, 80% is in near-zero-emission production routes. The Net Zero Emissions by 2050 Scenario requires only slightly higher annual investment – USD 15 billion to 2050.

Three contrasting futures for the ammonia industry

The future development of the ammonia industry will depend on, among other factors, advances in production technology, energy and climate policies, population growth and economic progress. Scenario analysis is a useful tool to help understand how ammonia production may evolve in the future and allows us to gain insights into the implications for the energy system and our climate goals. Understanding the current trajectory of the sector and the implications of alternative pathways can help inform decision makers in the technology, policy and consumer realms.

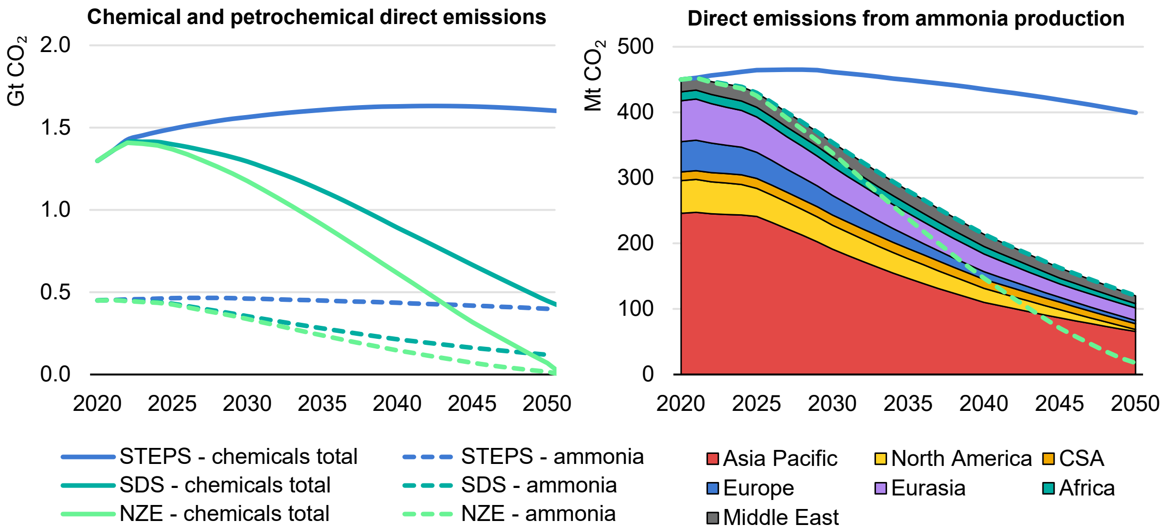
This chapter presents three scenarios for the future of ammonia production in the period 2020-2050 (see Box 2.1). The **Stated Policies Scenario** reflects the sector's current trajectory, influenced by existing and announced policies. The **Sustainable Development Scenario** presents a pathway with regional detail that puts the energy system as a whole on a trajectory compatible with the goals of the Paris Agreement. The **Net Zero Emissions by 2050 Scenario**, modelled regionally but presented globally, lays out a pathway to net zero emissions from the energy system by the middle of the century. None of these scenarios aims to predict the future, but together they can help us explore a range of possible futures that are compatible with stipulated outcomes.

Ammonia production currently accounts for around 450 Mt of CO_2 emissions per year globally, equivalent to the territorial CO_2 emissions from fossil fuel combustion of South Africa. Ammonia accounts for almost a third of emissions produced within the chemical and petrochemical sector, more than any single other industrial chemical. The Stated Policies Scenario shows that under current and announced policies and technology trends, emissions from ammonia production would peak in the next 10 years at around 460 Mt CO_2 and gradually decline to around 400 Mt CO_2 by 2050 (Figure 2.1). In the Sustainable Development Scenario emissions from ammonia production fall by at least 70% by 2050 relative to 2020. These levels are to be achieved while global ammonia production for existing agricultural and industrial applications increases at an average annual rate of 0.7% per year, from 185 Mt today to 230 Mt in 2050, a somewhat slower rate than the 1.5% annual growth over the previous three decades.

The regional pace of emissions intensity reductions in the Sustainable Development Scenario is broadly similar between regions, except for those in countries that have pledged to reach net zero emissions (e.g. the European Union and several other countries in Europe, and the United States and Canada in North America), or carbon neutrality (in the case of China) by a specific date. In the Net Zero Emissions by 2050 Scenario the global pace of emission reductions is even more ambitious, declining by 95% by 2050.

The reduction in emissions from ammonia production is broadly similar to the emissions trajectory of other industrial sectors. For example, in the Sustainable Development Scenario total chemical sector emissions decline by 65% by 2050. Similarly, in the same period emissions in the cement and steel sectors drop by 70% and 60% respectively. However, emission reductions across heavy industry take place at a slower pace than in other areas of the energy system, such as in electricity generation, where emissions are reduced by 95% within the same timeframe in the Sustainable Development Scenario, and reach net zero by 2040 in the Net Zero Emissions by 2050 Scenario.

Figure 2.1 Direct CO_2 emissions from the chemical sector and ammonia production by scenario and region



IEA, 2021.

Note: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario; CSA = Central and South America.

In the Sustainable Development Scenario emissions from ammonia production are reduced by 75% by 2050, accounting for around 30% of direct emissions from the chemical sector through to 2050.

Deep emission reductions in the industrial sector, including ammonia production, face a different set of challenges to the power sector and other sectors of the energy system. Key challenges for heavy industry include the need to provide high-temperature heat, the use of fossil fuels as chemical feedstocks, the prevalence of process emissions (particularly in cement and ammonia production) and the need for chemical reduction agents (in iron and steel production). At present there is limited availability of technologies in the market to address these challenges and achieve deep reductions in emissions. Long-lived assets are a further challenge, slowing the potential pace of technology change that is possible without early retirements. The high degree of competition faced by many industrial products makes it difficult for early adopters to invest in near-zero-emission technologies while maintaining viability. The hydrogen production step in ammonia manufacture, in particular, is one of the single most emissions-intensive processes in the chemical industry. Reducing its emissions will be necessary to achieve deep emission reductions across industry as a whole, and to contribute to the broader energy system transition outlined in the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario.

Box 2.1 Scenario definitions and the broader energy system context

This *Ammonia Technology Roadmap* is part of the Energy Technology Perspectives (ETP) series, which since 2006 has been providing insights into technology, energy and environmental issues and their interdependencies. In 2020 the IEA revamped the ETP series with its launch of *ETP 2020*, the key focus of which was technology opportunities for reaching net zero emissions from the energy sector, and the related energy technology development and innovation needs.

To explore a range of possible futures for ammonia production over the next three decades, this technology roadmap follows three scenarios, two of which are explored at the energy system level in *ETP 2020*:

The **Stated Policies Scenario** projects forward current trends in the energy sector, taking into account existing and announced policies, including the nationally determined contributions established under the Paris Agreement. This scenario is not the key focus of this technology roadmap, but rather is used to provide a baseline for analysis.

The **Sustainable Development Scenario** comprises a pathway for the energy system that is compatible with achieving the goals of the Paris Agreement and is the analytical focus of this technology roadmap. This scenario reaches “net zero” CO_2 emissions for the global energy system as a whole by 2070. Alongside these climate-related goals, the scenario addresses other key elements of the United Nations Sustainable Development Agenda embodied in its Sustainable

Development Goals (SDGs), including obtaining universal access to modern energy and a dramatic reduction in energy-related air pollution.

The rising number of net zero emissions targets announced by different countries was reflected within *ETP 2020* using the Faster Innovation Case, which evaluated opportunities for reaching net zero emissions across the whole energy system by 2050 through technology innovation. In May of 2021 the IEA published *Net Zero by 2050: A Roadmap for the Global Energy Sector*, which provides in-depth analysis of the necessary milestones for the energy system as a whole to achieve the goal stipulated in its title. This technology roadmap builds on the global results presented in that publication using the **Net Zero Emissions by 2050 Scenario**.

None of the scenarios above should be treated as predictions or forecasts, but rather as possible pathways for the energy system, given a series of pre-stipulated goals and assumptions. The aim is that they collectively provide insights into the potential impacts and trade-offs that can occur, assisting decision makers in government and other stakeholders. For the latest information on the broader energy system context of the scenarios presented in this technology roadmap, please see the chemical sector and overall energy system analysis presented in Chapter 4 of ETP 2020 and Chapter 3 of Net Zero by 2050: A Roadmap for the Global Energy Sector.

The outlook for demand and production

Demand for ammonia is driven in large part by demand for mineral nitrogen fertilisers (around 70% of current ammonia production), with the remainder of demand stemming from a range of industrial applications (see Chapter 1). With respect to examining the potential future demand for fertilisers in particular, it is the nitrogen (N) nutrient content that is of most interest, irrespective of the specific fertiliser product that is used. Industrial N demand can also be quantified in the same units. In this technology roadmap we only deal with demand for mineral N, which is initially produced in the form of ammonia – demand for nitrogen as part of the broader naturally occurring nitrogen cycle or in future uses for energy applications are not included within our core scope (see Box 1.1).

In 2020 annual global N demand reached 152 Mt. In the Stated Policies Scenario demand for nitrogen grows by almost 40% by 2050 relative to today, reaching 208 Mt, driven largely by economic and population growth. A stronger push on nutrient use and material efficiency strategies leads to slower growth in the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario, such that nitrogen demand is about 10% lower in 2050 relative to the Stated

Policies Scenario, but still 25% higher than today. In both scenarios Asia Pacific continues to dominate global ammonia production, even as its production share declines from 47% today to 42% in 2050. Strong growth is seen in the Middle East, Africa, and Central and South America, each of which roughly doubles its production levels by 2050.

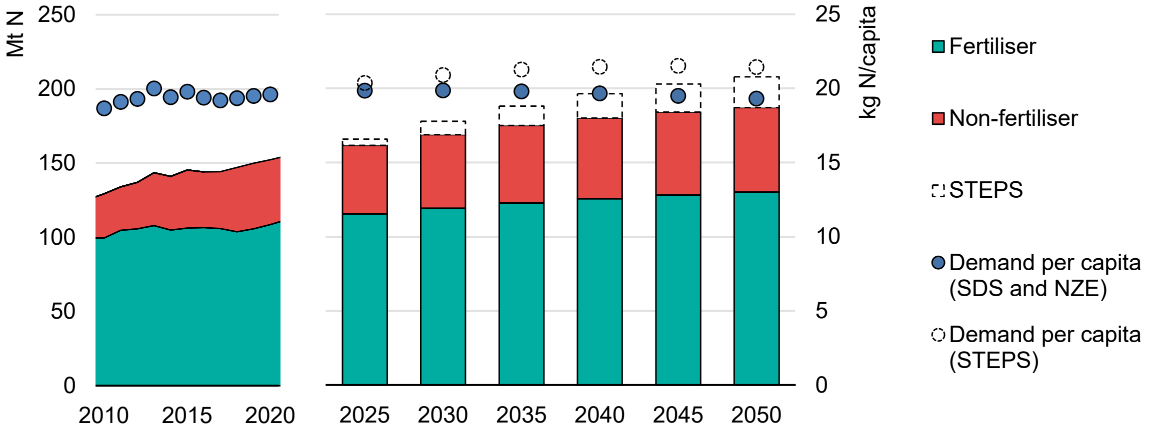
The outlook for nitrogen demand, nutrient use efficiency and material efficiency

Nitrogen demand drivers

Total demand for nitrogen-based products as well as nitrogen demand per capita have been steadily increasing, driven by increasing demand for fertilisers and for other uses. Since 2010 global demand for nitrogen has grown on average by 1.7% per year, reaching 152 Mt in 2020. Fertiliser demand has grown at an annual average rate of 0.9% since 2010. The remaining non-fertiliser portion of demand grew at a considerably faster rate of 4% per year. Apart from fertilisers, nitrogen products are used in a wide range of industrial applications, including: explosives, plastics, textiles, pharmaceuticals and dyes; for removing impurities from stainless steel in construction and manufacturing processes; as a refrigerant; as a cleaning agent; and in agents for reducing nitrous oxide emissions (see Chapter 1).

In the Stated Policies Scenario demand for nitrogen for conventional uses grows by almost 40% by 2050 relative to today, reaching 208 Mt. Total demand grows at a rate of 1.0% per year, a somewhat slower rate than in the 2010-2020 period. The slower growth can be attributed to the non-fertiliser demand segment, whose growth rate falls to 1.3% per year. China's rapid industrial expansion following the turn of the millennium is not repeated in our projection horizon, as its economy shifts towards higher-value manufacturing and a larger share of consumption-led growth – this is the main cause of slower growth in the non-fertiliser demand segment. Meanwhile, demand for fertiliser production grows at a similar rate compared to the past decade (around 0.9% per year), driven by increasing food, feed and fibre demand in developing economies. The split between the different nitrogen-based products used in agriculture for fertilisation remains broadly similar to today – urea remains the most common nitrogen-based product, accounting for 60% of the nitrogen applied to soils via fertilisers.

Figure 2.2 Nitrogen demand by market segment and per capita



IEA, 2021.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. Non-fertiliser includes industrial nitrogen use, losses during manufacturing processes and stored ammonia or ammonia products. Ammonia used as an energy carrier is not included.

By 2050 the demand for nitrogen per capita increases by 10% in the Stated Policies Scenario. In the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario, the demand per capita is similar to today, despite total nitrogen use increasing by 25%.

In the Stated Policies Scenario the global population increases by 25% between 2020 and 2050, and global GDP by 150%, compared with growth in nitrogen fertiliser demand of 40%. Growing populations require higher agricultural production to sustain them. Economic development changes the nature of both food production and food consumption. On the production side, economic development proceeds in tandem with an increasing shift away from smaller-scale subsistence farming towards larger-scale industrial farming, the latter of which tends to be more intensive and rely more heavily on fertilisers and other chemical inputs. On the consumption side, increasing wealth tends to drive higher consumption of meat and dairy products, together with the feed that animals require. The human consumption of animal products requires more crop production per calorie compared to obtaining a calorie directly from plants, due to the conversion ratio of livestock feed to animal product. As such, animal products are more fertiliser-intensive overall. Due to these factors, as economies grow, their per-capita fertiliser demand tends to increase. As economies reach maturity, however, per-capita demand tends to saturate, and fertiliser demand growth slows even with continued economic growth.

Measures to improve nutrient use efficiency also have a moderating impact on demand growth (see the following sub-section). Such measures tend to be applied most assertively in advanced economies with stringent environmental regulations. Meanwhile, increasing use of bioenergy may contribute to higher fertiliser demand. This could result either from the use of crops grown specifically for biofuels or the use of agricultural residues that would otherwise have been left on the fields and contributed nutrients to the soil.

At the global level, nitrogen demand per capita has grown modestly over the past decade to reach just under 20 kg per capita in 2020. At the country level, per-capita demand varies considerably, tending to be higher in advanced economies than in emerging and developing economies. The level and nature of agricultural activity in the country also has an influence. Countries that are major exporters of agricultural products will tend to have higher fertiliser consumption per capita, while importers have lower consumption. Other factors can contribute to regional variability in fertiliser application rates, including fertiliser prices, availability of manure and other alternatives, the types of crops grown, soil and climate conditions, application practices and environmental policies.

At the global level, nitrogen demand for fertilisers – the key driver of total nitrogen demand – was 14 kg per capita in 2018. To provide a sense of demand in some of the largest agricultural-producing countries, per-capita demand was 35 kg in the United States, 22 kg in Brazil, 20 kg in China and 13 kg in India. Countries with the highest consumption per capita are generally those that have large volumes of net agricultural exports relative to domestic production. These include New Zealand, Ireland and Canada, all with per-capita demand of 75 kg or more. Meanwhile, many countries in Africa have per-capita demand of 5 kg of less.

In the Stated Policies Scenario per-capita nitrogen demand from all sources grows slightly to reach about 21 kg in 2050. Underlying the relatively flat demand per capita at the global level are more complex regional dynamics. In general, mature economies see declining demand per capita. They have reached a saturation point in the economic growth-related factors that drive up consumption. At the same time they are increasingly pursuing nutrient use efficiency measures out of both economic and environmental motivations. Conversely, many emerging and developing economies continue to see growth in demand per capita, as they transition to larger-scale agricultural operations, increase meat consumption and are able to afford more fertiliser inputs. The net effect is relatively flat demand per capita globally. With a growing population, however, this does lead to growth in total nitrogen demand.

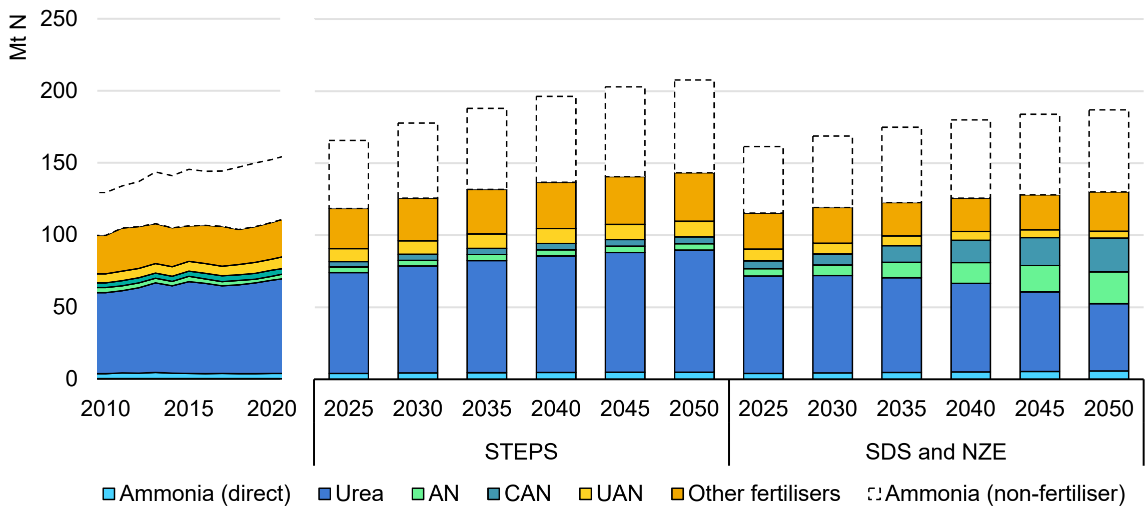
In the Sustainable Development Scenario the more assertive pursuit of measures to improve nitrogen use efficiency leads to slower total nitrogen demand growth of 0.7% per year and a total nitrogen demand increase of 25% by 2050. Global nitrogen demand per capita stays broadly constant relative to today, at around 20 kg per capita. Other activity shifts in this scenario will also affect demand for nitrogen-based products. With regard to explosives used for mining, some activities will decrease, including mining for coal and for certain minerals and metals (e.g. iron ore, limestone used for cement) due to the pursuit of material efficiency strategies. Meanwhile, mining for a variety of critical minerals (e.g. lithium, copper, rare earth elements) will increase for clean technologies such as batteries and renewable energy. The build-out of more rail systems will require more explosives (for underground metros, tunnelling in mountainous areas, etc.), while decreased demolition due to building reuse and lifetime extension will reduce explosives demand. Requirements for agents to reduce nitrous oxide emissions in power plants and diesel engines will decrease with the shift away from fossil fuels. Not every aspect of this demand profile for ammonia in industrial applications could be assessed individually in the context of this technology roadmap. In the context of the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario, we have assumed that the increases and decreases mentioned above offset each other, and identify this area as deserving further study. Nitrogen demand in the Net Zero Emissions by 2050 Scenario is very similar to the Sustainable Development Scenario. Fertiliser-related nitrogen use efficiency measures are already fully exploited in the Sustainable Development Scenario.

In the Sustainable Development Scenario the use of urea-based fertilisers declines by 28% by 2050 compared to today, replaced by ammonium nitrate and calcium ammonium nitrate. Urea is dominant today due to its high nitrogen content (46%) and greater convenience for storage, transport and application relative to the other derived fertiliser products. However, in the context of a sustainable future for energy and agricultural systems, urea has the disadvantage that its production requires CO_2 that is later released during hydrolysis after its application to the soil. Urea therefore moves CO_2 from where it can be managed (i.e. captured or avoided) in the production phase of nitrogen fertilisers to the use phase, where, when it is released, it is very difficult to fully mitigate.

This CO_2 from urea use – around 130 Mt CO_2 in 2020 – adds to the total CO_2 emissions of the agricultural sector if derived from fossil fuels, as it is currently. For context, this is equivalent to about 30% of the total emissions generated from ammonia production, a substantial quantity when considering global objectives to reach net zero emissions. While the CO_2 could be sourced from climate-neutral non-fossil sources – via direct air capture or capturing CO_2 from biogenic sources – doing so would make urea less cost-competitive compared to other fertilisers in many instances. Thus, the Sustainable Development Scenario sees greater uptake of ammonium nitrate and calcium ammonium nitrate, which do not release CO_2 during their use. While urea use declines considerably, it continues to be used in some contexts, particularly for applications where nitrated-based fertilisers would lead to higher nitrous oxide emissions (e.g. in wet conditions on heavy soils) and in developing economies where infrastructure for safe handling and transport of nitrate-based fertilisers may not be yet fully developed. Certain industrial applications for urea, such as durable resins (e.g. urea formaldehyde) also see continued growth in the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario, whereas others see significant declines (e.g. urea used to reduce nitrogen oxide [NO_x] emissions from diesel engines).

Aside from conventional applications, the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario see growth in ammonia demand for use as an energy carrier, primarily as a maritime fuel and in the power sector. In addition to the 230 Mt of ammonia demand from conventional uses in 2050, 125 Mt of ammonia is used as an energy carrier – this brings total ammonia demand to 355 Mt, about twice the 185 Mt produced in 2020. The use of ammonia as an energy carrier is outside the scope of this roadmap (these quantities are not included within the core scenario results presented in this chapter), but the main considerations and results from a broader energy system analysis are summarised in Box 2.2. The topic is addressed in more detail in other IEA publications, including the *Global Hydrogen Review 2021* and *The Role of Low-Carbon Fuels in Clean Energy Transitions of the Power Sector*.

Figure 2.3 Nitrogen demand by final product by scenario



IEA, 2021.

Notes: AN = ammonium nitrate; CAN = Calcium ammonium nitrate; UAN = urea ammonium nitrate; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. Ammonia used as an energy carrier is not included.

In the Sustainable Development and Net Zero Emissions by 2050 Scenarios nitrogen provided through the use of urea and urea-containing fertilisers falls by 29% by 2050, substituted mainly by ammonium nitrate and calcium ammonium nitrate.

Box 2.2 The potential use of ammonia as an energy carrier

Ammonia has the potential to be used as a low-emission energy carrier in a variety of applications. Ammonia has the potential to be used as a low-emission energy carrier in a variety of applications. At 18.65 GJ/t and 12.7 GJ/m^3 – on a lower heating value basis and when in liquid state – it has around 40% of the energy density of gasoline, and it contains no carbon atoms, so produces zero CO_2 emissions when combusted. At 18.6 GJ/t and 12.7 GJ/m^3 on a lower heating value basis, it has around 40% of the energy density of gasoline on a mass basis and 40% on a volumetric basis, and it contains no carbon atoms, so produces zero CO_2 emissions when combusted.

The key advantage ammonia has over pure hydrogen as a low-emission fuel is its higher volumetric energy density and liquefaction temperature, making it much easier to transport and store. In 2020, 185 Mt of ammonia were produced and around 20 Mt of it globally traded. This means that for ammonia, when compared to hydrogen, the infrastructure and practices to support safe and reliable storage, distribution and export are already highly developed. It is for these reasons that ammonia is gaining attention for its potential role in reducing emissions in specific sub-sectors of the energy system, particularly in power generation and as a maritime fuel. These uses of ammonia are outside the core analytical scope of this technology roadmap (see Box 1.1), and are covered in more detail in other IEA publications, including the the *Global Hydrogen Review 2021* and *The Role of Low-Carbon Fuels in Clean Energy Transitions of the Power Sector*.

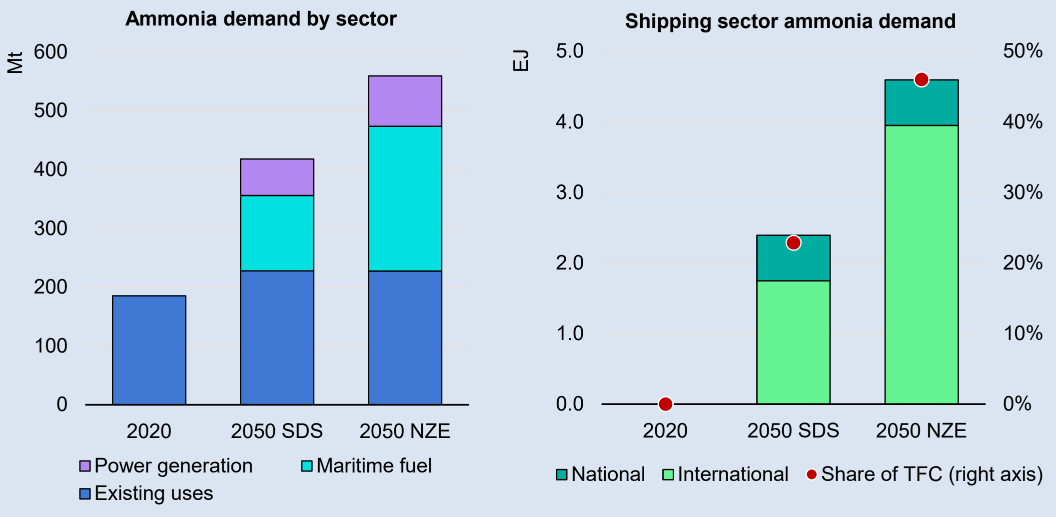
Ammonia can be used for many purposes in the power sector in the context of a low-carbon transition. Countries with limited direct access to sources of low-carbon electricity could use ammonia as a vector for hydrogen imports. Ammonia can be produced in regions with abundant renewable resources, or with low-cost natural gas twinned with CO_2 transport and storage infrastructure, and shipped at relatively low cost to importing regions. Then the ammonia can be cracked to yield pure hydrogen for use in gas turbines, or used directly by being fed into existing coal power plants in a co-firing arrangement.

Co-firing a 1% share of ammonia was successfully demonstrated by Chugoku Electric Power Corporation at one of its commercial coal power stations in 2017. JERA, another Japanese utility, plans to demonstrate a 20% co-firing share of ammonia at a 1 GW coal-fired unit by 2025. The direct use of ammonia in gas turbines has to date been successfully demonstrated only in micro gas turbines with a power capacity of up to 300 kW. The low combustion speed of ammonia and flame stability have been identified as issues preventing its use in larger gas turbines, alongside the matter of increased NO_x emissions. However, Mitsubishi Heavy Industries has announced plans to commercialise by 2025 a 40 MW gas turbine directly combusting 100% ammonia. NO_x and nitrous oxide (N_2O) emissions can and must be managed with end-of-pipe technologies (such as scrubbers) – the resulting air pollution and climate impact of these gases would significantly erode the benefits of adopting ammonia as an energy carrier if they were not.

Ammonia can also be used as a seasonal storage medium for the power sector, whereby electricity can be converted into ammonia when it is in surplus, and burned in power plants at times when solar PV and wind are scarce. Ammonia is an order of magnitude cheaper than batteries for storing energy for inter-seasonal periods. Siemens demonstrated the use of ammonia for electricity storage during 2018 in the United Kingdom by converting wind electricity via electrolysis into hydrogen and then into ammonia for storage. The stored ammonia was then used in an internal combustion engine to produce electricity at a time of need.

Ammonia is particularly well suited to serve as a fuel for ocean-going vessels. Almost 200 harbours worldwide have ammonia terminals that serve the international trade of around 20 Mt of ammonia every year. The main hurdles for using ammonia as a marine fuel is that it is toxic, and its use can lead to NO_x and N_2O emissions. The fact that ammonia has been used as a refrigerant gas for decades highlight that industry actors have gained significant expertise in handling it safely.

Ammonia use as an energy carrier in the Sustainable Development Scenario and the Net Zero Emissions by 2050 Scenario



IEA, 2021.

Notes: SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario; TFC = total final energy consumption in the maritime shipping sector. "Existing uses" refers to current agricultural and industrial uses, coinciding with the core analytical scope for this technology roadmap.

Two of the world's leading maritime engine manufacturers (MAN and Wärtsilä) are developing ammonia-fuelled internal combustion engines and are expecting to make them commercially available by 2024. MAN stated that by 2025 it plans to make an ammonia retrofit package commercially available, which will facilitate the conversion of an existing fossil-fuelled vessel into a low-emission one. "Ammonia-ready" is becoming established as a designation for vessels that are designed to be converted to run on ammonia in the future.

In the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario, ammonia-fuelled maritime vessels start to be adopted in the mid-2020s. Container shipping is the first sector to see ammonia-powered vessels enter the fleet, because the routes these ships operate on are fairly consolidated and the additional cost can be spread across many customers. Other early movers are expected to be tankers carrying energy commodities that already have the storage capacity and operational experience of handling fuels.

In the longer term, ammonia is considered to be the "destination fuel" for ocean-going vessels in these scenarios, accounting for around one-quarter of total final consumption in national and international maritime shipping in 2050 in the Sustainable Development Scenario, and around 45% in the Net Zero Emissions by 2050 Scenario. By then, the total tonnage of ammonia used as a shipping fuel – which does not exist today at a commercial scale – is equivalent to more than half the volume used for conventional agricultural and industrial uses in the Sustainable Development Scenario and 110% in the Net Zero Emissions by 2050 Scenario.

The use of ammonia for co-firing in coal power stations climbs to 60 Mt per year and 140 TWh of electricity generation by 2050 in the Sustainable Development Scenario. In the Net Zero Emissions by 2050 Scenario the use of ammonia for this purpose reaches 85 Mt. This is up from a handful of pilot and demonstration scale projects today. Despite providing only around 0.2% of global electricity generation in 2050 in the Sustainable Development Scenario (and also only 0.2% in the Net Zero Emissions by 2050 Scenario), this application accounts for around a third of the consumption of ammonia for purposes other than its established uses today (25% in the Net Zero Emissions by 2050 Scenario).

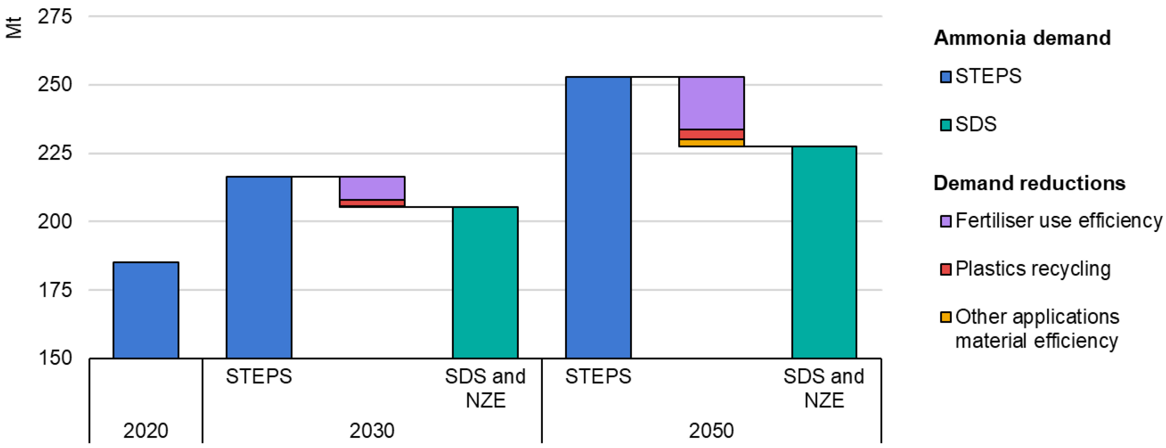
Measures to improve nitrogen use efficiency

Considerable potential exists to reduce nitrogen demand through measures to improve use efficiency. It has been estimated that nutrient use efficiency across the full nitrogen chain globally is currently only about 20%. That is, out of all the nitrogen fixed through industrial production and by crops, only 20% ends up in human food and durable products. The percentage varies depending on location and application. For example, for the food system, nutrient use efficiency in different European countries has been estimated to range from 10% to 40%. The

UN Colombo Declaration on Sustainable Nitrogen Management of 2019 has called for a halving of total nitrogen losses to the environment by 2030, a target mirroring similar calls from scientists.

In the Sustainable Development Scenario various measures are adopted to use nitrogen more efficiently across value chains. Consequently, nutrient use efficiency improves considerably and global demand for ammonia for conventional uses is 5% lower in 2030 and 10% lower in 2050 compared to the Stated Policies Scenario. This reduction in ammonia demand relative to the Stated Policies Scenario occurs while meeting the same demand for the services that ammonia provides – for example the same provision of nutrition – since more efficient systems result in fewer nutrient losses prior to final consumption. The greatest potential for demand reduction comes from the largest end use, fertilisers, accounting for 65% of the reduction in 2050. Plastics recycling accounts for about 10% of the reduction, driven by an increase in the average plastics collection rate to 50% by 2050, relative to 16% today. Other measures in industry and other end uses account for the remaining demand reduction.

Figure 2.4 Contribution of use and material efficiency to ammonia demand by scenario



IEA, 2021.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. Ammonia used as an energy carrier is not included.

In the Sustainable Development Scenario use efficiency measures reduce demand for ammonia by 10% in 2050 relative to the Stated Policies Scenario; fertiliser use efficiency contributes 75% of the reduction.

Estimates of global nitrogen nutrient use efficiency (NUE) at the crop level – including nitrogen from mineral fertilisers, manure application, biological fixation and atmospheric deposition – vary by source, with estimates from key sources ranging from 45% to 60% in 2017-2018.[1] Over the past half century there have been substantial shifts in NUE. In 1961 global nitrogen NUE was higher than it is today, with estimates averaging at 59% (ranging across 49-75%). Since then, nitrogen inputs to crop production have quadrupled, about two-thirds of which were from mineral fertilisers. This increased nitrogen provision has undoubtedly led to benefits from improved crop productivity, but has contributed to a lower global NUE. Improved nutrient management can help ensure that NUE is optimised in tandem with increasing crop yields. Following a considerable decline in global NUE in the 1960s and 1970s, nutrient management has been gaining traction and there has been an upward trend in NUE in recent decades. Estimates of the NUE increase at the global level range from 5 to 9 percentage points since 2000, and 4 to 5 percentage points since 2010.

At the regional level, nitrogen NUE varies considerably, influenced by various factors including the mix of crops grown, the ratio between fertiliser and crop prices, nitrogen fertiliser subsidies and policies to reduce nitrogen pollution. According to FAO data, Asia Pacific currently has a relatively low NUE of around 35%, although there has been an upward trend in the past decade, particularly in China. In Europe, NUE has been improving over the past several decades, at least in part due the introduction of the EU Nitrates Directive in 1991, and is currently at around 45%. Meanwhile, the Americas and Africa are at the higher end of NUE, in the range of 50-60%, although in Africa this may be in part due to under-application of fertilisers in some regions rather than successful nutrient management.

Sustainable agricultural systems must balance the benefits of high crop yields for food provision with the environmental impacts of nitrogen losses to the environment and greenhouse gas emissions from the production and use of mineral fertilisers. In the Sustainable Development Scenario global nitrogen NUE on croplands improves by about five percentage points overall by 2050. Underlying this is a higher increase in the NUE for mineral fertilisers. Improved nitrogen management also leads to higher nitrogen recycling through increased use of livestock manure. Since manure has a lower use efficiency, its increased use results in a smaller increase in overall cropland NUE, even as it reduces nitrogen losses within the full nitrogen system.

Optimal NUE will vary between farms, depending on factors such as the specific crop and the local physical environment. There will always be some losses of

[1] Key data sources for global NUE include the FAO and IFA. Note that the IFA's current methodology does not include atmospheric nitrogen deposition, leading to higher estimates of NUE compared to the FAO and other sources.

nitrogen in agricultural systems. In fact, a very high NUE (over about 90%) may actually be harmful, signalling depletion of soil nutrients or "soil mining". Conversely, a very low NUE is not only harmful to the environment, but may also not be good economically. Additional fertiliser application results in diminishing returns beyond a certain point; the cost of additional fertiliser will outweigh the financial benefit of increased yields. An ideal NUE target for a given system would consider this economic optimum as well as environmental objectives, and for most systems is likely to fall in the range of 50-90%.

The "4Rs" have become a common set of guiding principles for agricultural nutrient management over the past few decades, encouraging farmers to apply "the right nutrient source at the right rate, at the right time and in the right place" so that nutrient losses are minimised while still meeting crop nutrient requirements. Examples of management practices include timing fertiliser application according to weather conditions (such as not before major rainfall), and using precision agriculture and variable-rate application technologies to better match fertiliser application to crop needs. A switch in the fertiliser type can also help. For example, farmers may choose to use enhanced-efficiency fertilisers, which are coated with polymers or have characteristics that slow the release of nutrients or inhibit reactions in the soil that could lead to losses. Switching from urea to nitrate-based fertilisers or other fertiliser forms may also help, since urea is more prone to nutrient losses through ammonia volatilisation on fields.

Increasing use of organic fertilisers is also an option if they are available. This is closely connected to adopting circular economy practices – maximising reuse of waste nitrogen where possible (from crop residues, livestock excreta, food waste, etc.) can help make more efficient use of nitrogen inputs. Other beneficial complementary management practices may include using cover crops, conservation tillage, nitrification inhibitors, crop rotation, biostimulants and crop varieties that use nitrogen more efficiently. Best management practices will vary according to the cropping system, climate, soil and other site-specific conditions.

Additional measures along food value chains can also reduce the need for fertilisers by reducing demand for crops. Potential exists to reduce post-harvest losses and food waste at multiple stages, including at food manufacturing facilities, during transport and storage, at grocery stores and restaurants, and in the homes of consumers. Additionally, shifting towards greater reliance on plant-based proteins can reduce total fertiliser needs, assuming that plant-based proteins are replacing animal protein from livestock whose feed comes from fertilised crops or pastures (as opposed to unfertilised pastures). Reducing consumption of animal proteins would reduce requirements for livestock feed and improve full chain NUE, since humans would obtain protein more directly from plants.

Other strategies can help improve use efficiency for other nitrogen-containing products. Plastics recycling and efforts to reduce overall plastics demand will lower the need for ammonia as an input to certain types of plastics, even as plastics account for a relatively small share of total ammonia demand. For other industrial uses, areas of overuse or waste can be identified and addressed. This could include, for example, reducing over-application of pesticides, using industrial cleaners with lower concentrations of ammonia where that is sufficient for the intended purpose, extending the lifetime of textile products and switching from chemical to natural dyes. Given that nitrogen is present in such a wide range of products, a diversity of actions from manufacturers to final consumers would be needed to optimise efficiency across these various end uses.

Box 2.3 IEA demand projections for nitrogen fertilisers in context

This roadmap focuses on the most energy- and emissions-intensive step in the nitrogen fertiliser value chain: ammonia production. About 70% of ammonia is used for fertilisers with agricultural applications. Of these, about 85% are applied to croplands, while the rest are applied to other areas such as forests, grasslands, fish farms and golf courses. Outside agriculture, ammonia demand comes from various other industrial and commercial applications. Given these various demand sources, we have developed demand projections for the nitrogen-based products discussed in this roadmap using information from two organisations with widely recognised expertise in these different areas: the International Fertilizer Association (IFA) and the United Nations Food and Agriculture Organization (FAO).

The FAO is tasked with improving food security and fighting hunger around the world. The organisation provides detailed information on all types of fertiliser used across the world, for both cropland and non-cropland purposes, in its extensive databases on the food system and regularly published reports on the future of agriculture. In its 2018 publication, The future of food and agriculture – Alternative pathways to 2050, the FAO published a number of future scenarios for the agricultural system. We have used the FAO Business As Usual Scenario to estimate non-cropland fertiliser demand in the Stated Policies Scenario in this roadmap. The underlying assumptions behind these two scenarios, most importantly with respect to population growth, are broadly similar. The FAO also has a Towards Sustainability Scenario in which proactive measures are taken towards more sustainable food and agricultural systems, through measures such as reducing food waste and more resource-efficient food production.

For nearly 100 years the IFA has been working with actors across the fertiliser value chain, from production to application, to promote best management practices and reduce environmental impacts. The IFA collects statistics on fertilisers, focusing on fertilisers applied to croplands, and also develops scenarios for future demand. We used the IFA Business As Usual Scenario for fertiliser demand as a baseline to define cropland fertiliser demand in the Stated Policies Scenario in this roadmap. Specifically we used the FAO Business As Usual Scenario's agricultural production levels and medium-level ambition on improving nutrient management. The IFA has also developed a composite scenario to inform cropland fertiliser demand in the Sustainable Development Scenario in this roadmap. It is informed by agricultural production levels from a combination of the FAO Business As Usual Scenario and Towards Sustainability Scenario (depending on the region) and has higher ambition on improving nutrient management.

We have used the outputs from these work streams – together with those of the OECD's own work in this area – to inform the IEA's long-standing framework for material demand projections, including the projections for nitrogen, ammonia and urea demand and production developed for use in this technology roadmap. Demand is driven by industrial value added and population growth, with saturating per-capita demand once an advanced level of economic development is reached. We have also used the IEA's evaluation of stocks of materials in society and material efficiency opportunities that can reduce non-fertiliser ammonia use, including increased plastic reuse and recycling.

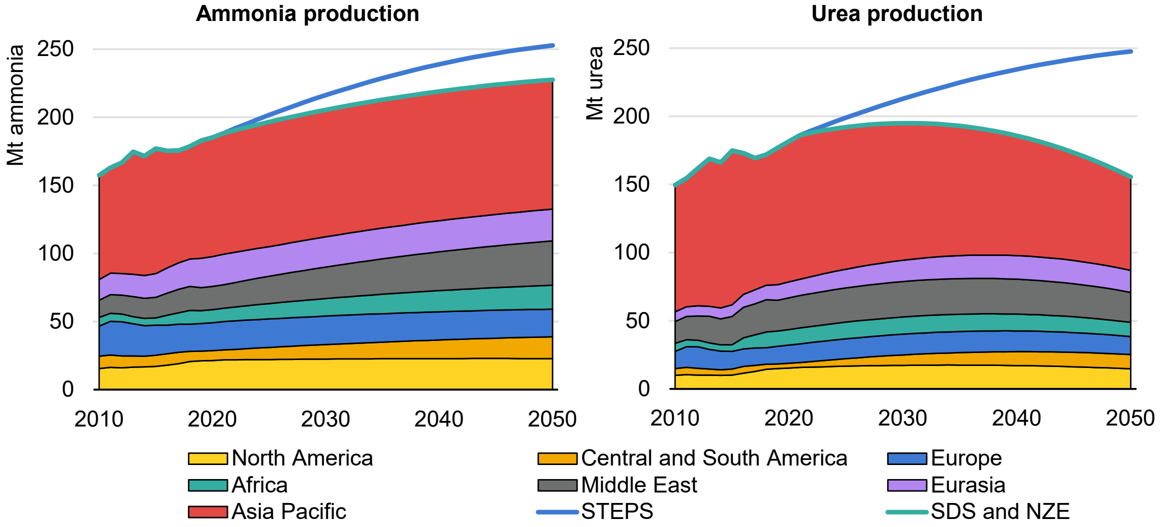
The outlook for production

Increasing demand for nitrogen – driven by a growing population, higher living standards and increased protein consumption – sees global ammonia production grow by 37% in the Stated Policies Scenario relative to today to reach 253 Mt NH_3 (208 Mt N) by 2050.[2] At an average annual rate of 1.1%, this growth is somewhat slower than the 1.5% annual growth seen in the previous three decades. In the Sustainable Development Scenario ammonia production is 10% lower in 2050 compared to the Stated Policies Scenario due to the greater adoption of nutrient use and material efficiency strategies. Thus, production grows by 23% to reach 228 Mt NH_3 in 2050 (0.7% average annual growth). While total urea production

[2] Production projections here comprise ammonia produced for established applications. Ammonia production for use as an energy carrier is not included, given that it is outside the scope of this roadmap.

grows by 36% by 2050 in the Stated Policies Scenario, it declines by 14% during the same period in the Sustainable Development Scenario. This results from lower demand for urea fertilisers in order to reduce the release of CO_2 when urea is applied to soils, as discussed above.

Figure 2.5 Ammonia and urea production by region for Stated Policies Scenario and Sustainable Development Scenario



IEA, 2021.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. Ammonia used as an energy carrier is not included.

In the Sustainable Development Scenario ammonia production grows moderately while urea production declines. Growth is strongest in the Middle East, Central and South America, and Africa.

The ammonia market is currently dominated by Asia Pacific, which produced 47% of the world's ammonia in 2020. China alone accounted for 30% of global production. Following rapid growth of 4% per year from 1990 to 2010, production in China has grown at a slower rate of 1% per year since 2010, which is below the global average rate of growth. In the Sustainable Development Scenario, Asia Pacific remains the largest ammonia-producing region, even as its share declines somewhat to 42% of global production in 2050. Production in China peaks in the next 5 to 10 years and then declines by almost 35% by 2050, as a result of restructuring shifting the economy away from heavy industry towards higher value-added industries and sectors. Still, it remains the largest producing country in 2050, at 16% of global production. Meanwhile, production in India grows over twofold to reach 15% of global production and Southeast Asia by 1.7 times to reach 8% of global production, as part of increasing industrial activity in these rapidly growing economies. This more than makes up for the decline in China such that total ammonia production in Asia Pacific grows by 10% by 2050.

The remainder of current global production is spread more evenly across the other regions. Leading ammonia-producing countries include those with access to natural gas supplies at competitive prices, including the United States, Russia and Middle Eastern countries, as most ammonia outside China is currently produced from natural gas, and energy inputs are one of the main contributors to production costs. In the Sustainable Development Scenario access to competitive natural gas supplies remains a key factor determining where production occurs, even as natural gas-based capacity is increasingly paired with CCS (see Chapter 2, “Technology pathways towards net zero emissions”).

Advanced economies see relatively flat levels of production in the Sustainable Development Scenario. In Europe and North America, production growth is less than 10% by 2050 relative to today, although both regions maintain about 10% of global market share. Meanwhile, strong growth occurs in the Middle East, Africa, and Central and South America, all of which see roughly a doubling of production by 2050 relative to today. These regions account for 14%, 8% and 7% of global production respectively in 2050. The factors contributing to high growth in these regions include economic development, industrialisation, and increasing agricultural output to feed growing populations.

The regional distribution of urea production today and in the future is similar to that of ammonia production, given the close link between production of the two commodities. In the Sustainable Development Scenario a key difference from ammonia is that since urea production is declining globally, most regions have either flat or falling urea production. Southeast Asia and the Middle East see modest growth until about 2030, followed by eventual declines in production. This contrasts with the Stated Policies Scenario where most regions continue to see growing urea production, broadly in step with growth in ammonia production.

Box 2.4 Technology modelling methodology

The technology model used to generate the results for ammonia in this technology roadmap forms part of the IEA chemical sector model, which is one of the IEA’s six detailed industry sub-sector models. The five other models cover the iron and steel, cement, pulp and paper, aluminium and other industry sub-sectors. The models interact with other models in the IEA via price signals (e.g. for fuels), availability of resources (e.g. biomass) and user constraints (e.g. CO_2 emission trajectories and the availability of CO_2 storage).[3]

The industry modelling architecture used for this publication consists of three main components: activity modelling (production and demand), capacity modelling (examining the existing stock of production equipment) and technology modelling (the selection of technologies used to meet the required production levels). This industry modelling framework sits within a broader energy system modelling architecture, with various cost signals and constraints being taken from other sub-sector model results. The aim of the modelling is to present energy, emissions and investment implications of least-cost technology pathways for a given scenario definition.

The technology modelling is at the heart of the model, with the other models creating intermediate results with which to inform its inputs and constraints. The technology model is implemented in the TIMES (The Integrated MARKAL-EFOM System) model generator, using 40 model regions to obtain global coverage. The chemicals model selects from a range of ammonia production technologies with a technology readiness level (TRL) of five and above (for discussion of the IEA TRL scale, see Box 2.6). The technology choice is performed in annual time steps, based on constrained optimisation that aims to minimise system cost while satisfying demand for ammonia. System cost includes capital expenditure (CAPEX) and fixed operating expenditure (OPEX), along with energy and feedstock costs where relevant. Cost and energy parameters for technologies at an early stage of development are obtained in consultation with industry experts.

Ammonia demand and production projections are based on country-level macro-economic data and historical production levels, informed by FAO and IFA projections for fertiliser demand (see previous box). The technology model must satisfy these production levels while conforming to various scenario-specific constraints, such as limits on the availability of certain energy carriers and constraints on CO_2 emissions, as well as other constraints to reflect the regional political economy and other circumstances.

The capacity model provides a signal of the existing capacity of ammonia production facilities, along with a projection of their phase-out rate over time. The capacity model takes account of the regional variation in the predominance of specific technology types, as well as the timeframe since the installation or last major refurbishment of each individual plant, to provide region-specific phase-out rates for existing facilities.

[3] More detailed documentation of the full ETP Model is found in the *ETP 2020* annex.

Technology pathways towards net zero emissions

Energy consumption and CO_2 emissions

Ammonia production is a highly energy-intensive process, accounting for 2% of global final energy consumption in 2020. It is the third-largest single consumer of energy among industrial bulk materials, after steel (9%) and cement (3%) respectively. Fossil fuels account for virtually all of the process energy and feedstock inputs to ammonia production today. In 2020 the consumption of natural gas for ammonia production stood at around 170 bcm, or around 50% of the wider chemical industry's demand. Coal also plays an important role, particularly in China, with ammonia production using around 75 Mtce in 2020, or 44% of the coal consumed by the global chemical industry. Ammonia production currently consumes negligible quantities of oil, which accounts for around 1.4% of total energy inputs. Electricity use is also relatively modest today, at around 70 TWh, or 5% of the chemical industry's total electricity consumption.

Of the energy consumed for ammonia production, 40% is used as feedstock.[4] Natural gas and coal account for 72% and 26% of the sector's feedstock energy inputs, with oil accounting for the remainder. Bioenergy and water (split into its constituent hydrogen and oxygen atoms) can be used as a source of feedstock, although they form miniscule contributions to the sector's overall inputs today. Process energy inputs (the remaining 60% of energy consumption) comprise fuels (68% natural gas and 25% coal) and electricity (5%).

Under current trends, global energy demand for ammonia production increases by 8% by 2050 in the Stated Policies Scenario relative to 2020, but energy intensity declines by 21%. The global average energy intensity of ammonia production today is estimated to be around 50% higher than BAT energy performance levels, assuming the same share of each route in total production. In the Stated Policies Scenario all regions are on track to reach current BAT energy performance levels soon after 2050, as plants are upgraded and replaced to meet stringent energy performance standards in several regions (e.g. the Perform

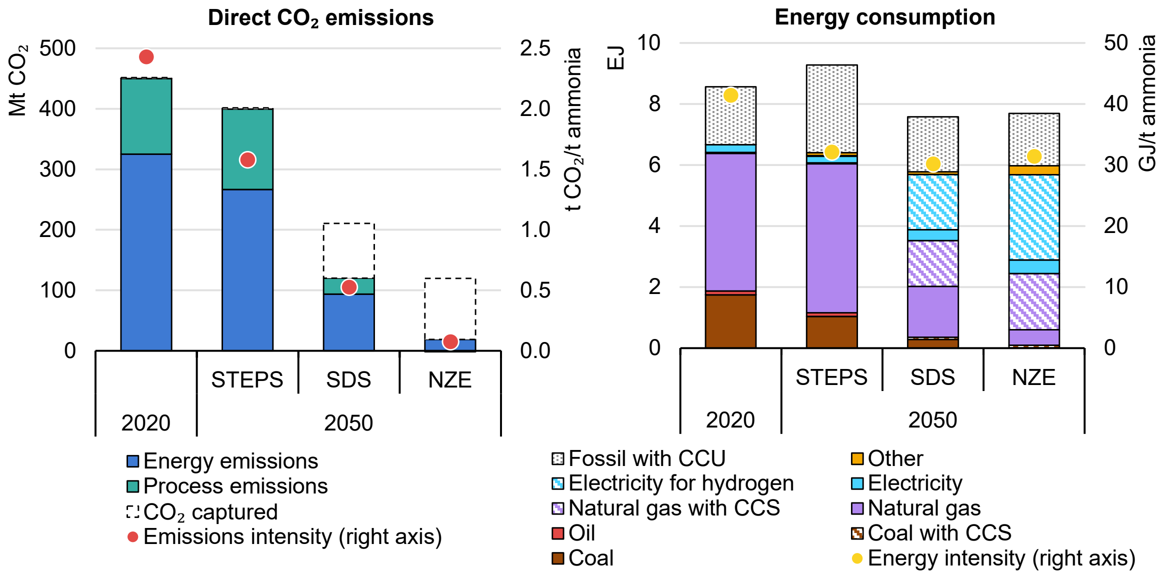
[4] The share of feedstock energy use is approximated using the lower heating value (LHV) of the ammonia produced, following IEA energy accounting conventions. The LHV approximation (18.6 GJ/t of ammonia) is kept constant over time and between process routes. This does not affect the overall accounting of total energy consumption, but tends to underestimate the share of feedstock energy use in the sector and allocates all efficiency gains to the process energy inputs. In practice, the shares of feedstock and process energy will vary depending on the efficiency and precise process arrangement of a given plant. For example: the BAT plant characterisations presented in Chapter 1 consume between 55% and 92% of their fuel inputs as feedstock. For plants with higher process energy consumption than a BAT plant, these shares are lower.

Achieve Trade scheme in India) and to maintain competitiveness in others. Continued improvements in process energy efficiency are outweighed by increasing demand for ammonia, pushing up overall energy consumption in this scenario. No energy intensity improvements take place for the consumption of feedstock, as process yields are already close to their theoretical maximum. The share of feedstock in total energy inputs therefore rises over time in the Stated Policies Scenario, from 40% in 2020 to 50% in 2050.

With respect to its fuel mix, the sector sees an overall shift from coal- to natural gas-based routes for ammonia production over time as a result of shifting regional market dynamics. China, the largest producer today, remains heavily reliant on coal-based production in the Stated Policies Scenario, but its share of global production decreases as its economy shifts towards a service-driven model and other economies industrialise. China's output of ammonia production declines by 25% between 2020 and 2050, whereas growth in other regions that predominantly use natural gas, such as India, the Middle East and Africa, grow by 100-150%. The result of these shifts is an increase in global energy demand for ammonia production, but a decline in the share of coal from 26% today to 15% in 2050, and an increase in the share of natural gas from 70% in 2020 to 80% in 2050. Overall CO_2 emissions slightly drop in 2050 relative to today, despite ammonia output rising by nearly 40%.

Achieving the goals of the Paris Agreement and other SDGs requires a complete change of course in the way ammonia is produced today and in the trajectory outlined in the Stated Policies Scenario. In the Sustainable Development Scenario CO_2 emissions in the sector are 73% lower in 2050 than in 2020. Energy savings achieved through the faster adoption of BAT – all regions reach today's BAT energy performance levels between 2040 and 2050 – and better operational practices roughly equate to the additional energy needed to sustain growing ammonia demand and to operate CO_2 capture equipment. In 2050 in the Sustainable Development Scenario the energy intensity of ammonia production reaches a similar level to that reached in 2050 in the Stated Policies Scenario, but with a very different energy mix. Electricity demand undergoes the largest increase (more than eightfold, relative to 2020 levels) at the expense of coal and natural gas, which drop by 75% and 20% respectively.

Figure 2.6 Direct CO_2 emissions and energy consumption for ammonia production by scenario



IEA, 2021.

Notes: CCU = carbon capture and utilisation; CCS = carbon capture and storage; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. "Other" is comprised mostly of bioenergy, as well as a small amount of hydrogen-based synthetic methane imported via blending in the natural gas grid. Ammonia used as an energy carrier is not included. Energy consumption includes that used as feedstock. Energy intensities are shown on a net basis.

A 78% drop in the emissions intensity of ammonia production by 2050, as in the Sustainable Development Scenario, hinges on electrolysis and CCS routes. Such dependency is even more important to reach the 96% reduction in the Net Zero Emissions by 2050 Scenario.

The main shifts in energy consumption in the Sustainable Development Scenario stem from the deployment of innovative near-zero-emission technologies. In this scenario 83% of the total electricity demand for ammonia production in 2050 is used to produce hydrogen via electrolysis, with the remainder supplying ancillary units (e.g. air separation units) and carbon capture equipment. This requires 110 GW of electrolyser capacity by 2050, assuming an average capacity factor of 50%. Around 31% of the natural gas-based production of ammonia is equipped with CCS by 2050 and a further 33% with CCU, the latter owing to the need to capture CO_2 for urea synthesis. This results in 83 Mt CO_2 captured for storage and 89 Mt CO_2 for use in 2050. This is around 36% of the total CO_2 capture in the chemical sector by that time, with a much larger extent of deployment taking place in methanol and high-value chemicals installations. A further 5% of natural gas consumption is used for methane pyrolysis, and 26% of the remaining coal capacity is also equipped with CCS. A small amount of carbon removal takes place in the Sustainable Development Scenario, owing to the CCS applied to process energy natural gas streams that in many regions comprise significant amounts of biogas by 2050. The overall carbon removal impact is around 2 Mt CO_2 by 2050, but this is outweighed by residual energy-related emissions.

For the ammonia industry to play its part in the overall energy sector reaching net zero emissions by 2050, further emission reductions would need to take place. In the Net Zero Emissions by 2050 Scenario, by 2050 overall emissions are 96% lower than today, production is 23% higher and the average CO_2 emissions intensity of ammonia is 97% lower than today (compared with 73% lower, 23% higher and 78% lower, respectively, in the Sustainable Development Scenario).

Given that production levels and the pace of energy efficiency improvements are very similar in the Net Zero Emissions by 2050 Scenario and the Sustainable Development Scenario, the faster pace of emissions decline is achieved primarily through more rapid deployment of innovative near-zero-emission technologies. By 2050, 41% of ammonia is produced via electrolytic hydrogen in the Net Zero Emissions by 2050 Scenario, compared with 27% in the Sustainable Development Scenario. CO_2 capture for permanent storage from ammonia production would rise to 100 Mt CO_2 by 2050 in the Net Zero Emissions by 2050 Scenario, with almost 50% of the fossil-based capacity equipped with CCS.

Innovation cycles (see Chapter 2, "Readiness, competitiveness and investment") are compressed in the Net Zero Emissions by 2050 Scenario, meaning that innovative technologies can be deployed sooner and to a greater extent by 2050. Technologies that are at too early a stage of development to be deployed within the 2050 time horizon in the Sustainable Development Scenario see some comparatively small-scale deployment in the Net Zero Emissions by 2050 Scenario. A key example is biomass gasification, which although costly, provides a source of biogenic carbon in its feedstock that can be used for carbon removal. Process emissions that are captured from this route result in around 6 Mt CO_2 of carbon removal by 2050 in the Net Zero Emissions by 2050 Scenario. Together with the contribution of emissions captured from the biogas that is blended with natural gas, the gross carbon removal impact is around 8 Mt CO_2 in 2050, about five times that of the Sustainable Development Scenario. However, emissions are still positive on a net basis at the global level, owing to the residual fossil energy-related and non-biogenic process emissions.

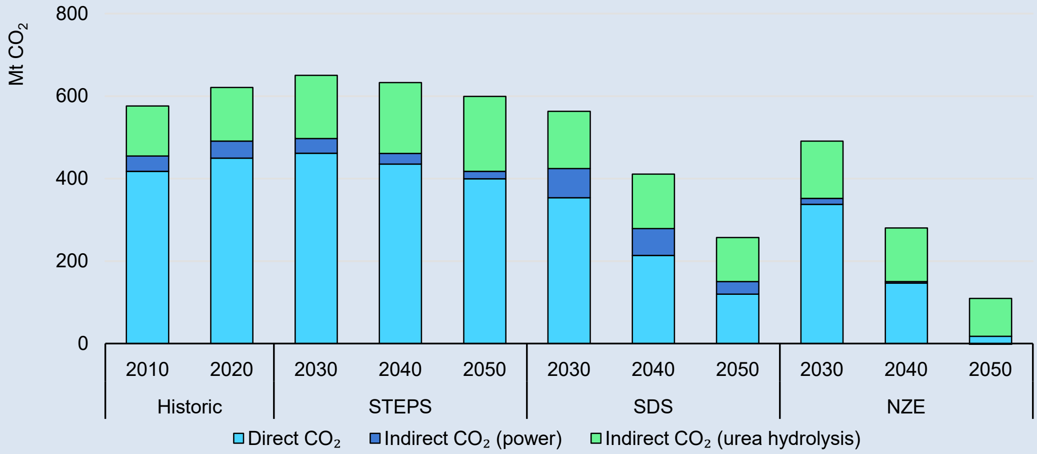
Box 2.5 How are indirect CO_2 emissions tackled?

The production and use of nitrogen fertilisers lead to greenhouse gas emissions during both the production and use phases. Non-CO_2 greenhouse gas emissions are beyond the core analytical scope of this roadmap, but Chapter 1 provides some context on this topic. In this scenario analysis we consider three main categories of CO_2 emissions from the sector: 1) direct CO_2 emissions from fossil fuel combustion and process CO_2 emissions from the use of fossil fuel feedstocks; 2) indirect CO_2 emissions from generating the electricity that the sector uses; and 3) indirect CO_2 emissions in the agricultural sector that result directly from the use of fossil fuel feedstocks in the production phase. We address the first category throughout the analytical content of this chapter, while the latter two (indirect emissions) categories are explored here.

Indirect CO_2 emissions from electricity generation for ammonia production totalled around 40 Mt CO_2 in 2020. This reflects a global power sector that runs on around 70% fossil fuels, with huge variation between ammonia-producing countries in the CO_2 intensity of the power they use. For example Norway, which produces less than 0.5 Mt of ammonia, has an average power sector CO_2 intensity of less than 10 g CO_2/kWh. China, which accounts for 29% of global production, has an average power sector CO_2 intensity of 621 g CO_2/kWh. In the Sustainable Development Scenario the global average power sector CO_2 intensity declines by 98%, from around 474 g CO_2/kWh today to 9 g CO_2/kWh in 2050. This results in just a 27% decline in the indirect CO_2 emissions from power generation for ammonia production by 2050, to 30 Mt CO_2, due to eightfold increase in electricity demand.

A principal feature of the demand profile for nitrogen fertilisers in the Sustainable Development Scenario is reduced reliance on urea. As discussed in Chapter 1, urea leads to significant CO_2 emissions as it undergoes hydrolysis in the agricultural sector, where these emissions cannot be practically captured. Urea demand declines from 181 Mt in 2020 to 155 Mt in 2050 globally in the Sustainable Development Scenario, compared to an increase in overall nitrogen demand of 25%. The indirect emissions from urea decline proportionately with its use to 110 Mt CO_2 in 2050, around 40% lower than the 180 Mt CO_2 they reach by the same year in the Stated Policies Scenario, which does not undergo the same shift away from the use of urea. This shift contributes 22% of total (direct and indirect) emission reductions in 2050 in the Sustainable Development Scenario relative to the Stated Policies Scenario.

Direct and indirect CO_2 emissions from ammonia production and use by scenario



IEA, 2021.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. Ammonia used as an energy carrier is not included.

A portfolio of mitigation options

Like the wider energy system, the fertiliser sector cannot rely on one technology or mitigation lever alone to make progress on its climate goals – it must pull on all levers that can make a difference to allow its transition to zero emissions to take place as quickly as possible. However, the relative importance of different mitigation options evolves over time.

More efficient use of nitrogen fertilisers is an important strategy pursued to reduce the overall quantity of ammonia demand in the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario. Around 20% of the cumulative emission reductions from ammonia production to 2050 in the Sustainable Development Scenario are made possible by avoiding the production and use of up to 25 Mt of fertilisers in that year (14% of today's global annual production) compared with the Stated Policies Scenario, while delivering the same agricultural output. Strategies within the agricultural sector involve minimising nutrient losses by applying fertilisers at efficient rates and with appropriate timing and placement, often aided by precision agriculture technologies and specialised fertilisers. Outside agriculture, measures are also taken to improve material efficiency, such as increased plastics recycling and reuse (see Chapter 2, "The outlook for demand and production" for more details).

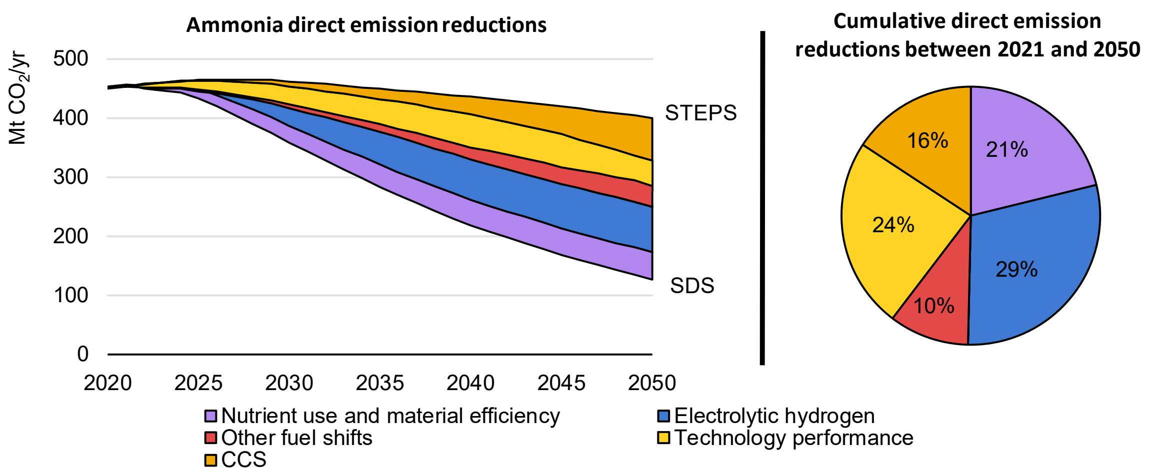
Energy efficiency is a win-win strategy to enhance competitiveness in an industry that is as energy-intensive and exposed to international trade as the fertiliser industry. The amount of process energy required to produce a tonne of ammonia from natural gas on average globally was about 40% higher in 2020 than BAT energy performance levels. The remaining gap is narrow and producers exploiting it in some regions face practical (e.g. physical constraints on existing assets) and economic barriers that are overcome in the Sustainable Development Scenario. The adoption of BAT, improved operating and maintenance routines, and increased levels of process integration lead to all regions achieving BAT energy performance levels for each process route in the period 2040-2050 in the Sustainable Development Scenario.

The type of feedstock determines the lowest amount of process energy required per unit of output: even with BAT, coal-based ammonia production is around 15% more energy intensive than natural gas-based production (and twice as emissions intensive). Thus, a shift towards the natural gas-based route, as takes place in the Sustainable Development Scenario, contributes to further lowering energy intensity, beyond the progression towards BAT energy performance levels for each process route. Conversely, some innovative near-zero-emission routes require additional equipment beyond the core ammonia production process, which increases the energy demand per unit of output even if BAT is adopted. For instance, 3.5 GJ/t CO_2 (or 2.4 GJ/t ammonia) are needed to capture CO_2 from flue gases resulting from the combustion of fuels in ammonia production compared to the overall 28 GJ of process energy needed per tonne of ammonia in best performing natural gas-based plants today. After accounting for these opposing trends, overall technology performance improvements deliver 24% of the cumulative emission reductions in the Sustainable Development Scenario.

A further 10% of cumulative emission reductions in the Sustainable Development Scenario stem from shifts towards less CO_2-intensive feedstocks and fuels. A shift at the global level from coal to natural gas-based routes is the main contributor, stemming primarily from an underlying regional dynamic in which coal-intensive Chinese ammonia production decreases and production in natural gas-intensive regions increases. In the Sustainable Development Scenario existing energy distribution infrastructure repurposed to the extent possible facilitates the delivery of low-carbon fuels. Gaseous biofuels and hydrogen are injected into natural gas distribution grids to lower their overall CO_2 intensity by 5% on average globally by 2050, which constitutes an indirect form of fuel switching.

About 45% of the emission reductions to 2050 in the Sustainable Development Scenario come from deploying near-zero-emission technologies, comprising CCS-equipped and electrolysis-based hydrogen production. Almost 30% of the CO_2 savings through to 2050 result from ammonia production via electrolytic hydrogen growing to 27% of total ammonia production in 2050, from a position of initial projects about to start operating today. Similarly, another 16% of emissions are saved cumulatively via permanent storage after capture from ammonia production, a greater than 50 times increase by 2050 relative to today's storage volumes from this CO_2 emissions source.

Figure 2.7 Ammonia direct CO_2 emission reductions in the Sustainable Development Scenario by mitigation strategy



IEA, 2021.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; CCS = carbon capture and storage.

Only an array of mitigation measures can significantly reduce emissions from ammonia production. Nutrient use and material efficiency, electrolytic hydrogen and CCS account for two-thirds of the cumulative emission reductions in the Sustainable Development Scenario.

Innovative technology pathways

Overview of global and regional technology trends

Whether in natural gas-based[5] or coal gasification-based routes, the CO_2 emissions stemming from the feedstock energy use for hydrogen production (process emissions) are inherently captured as part of the ammonia manufacturing process, which makes CCS a particularly competitive option for substantial emission reductions from ammonia production (see Chapter 2,

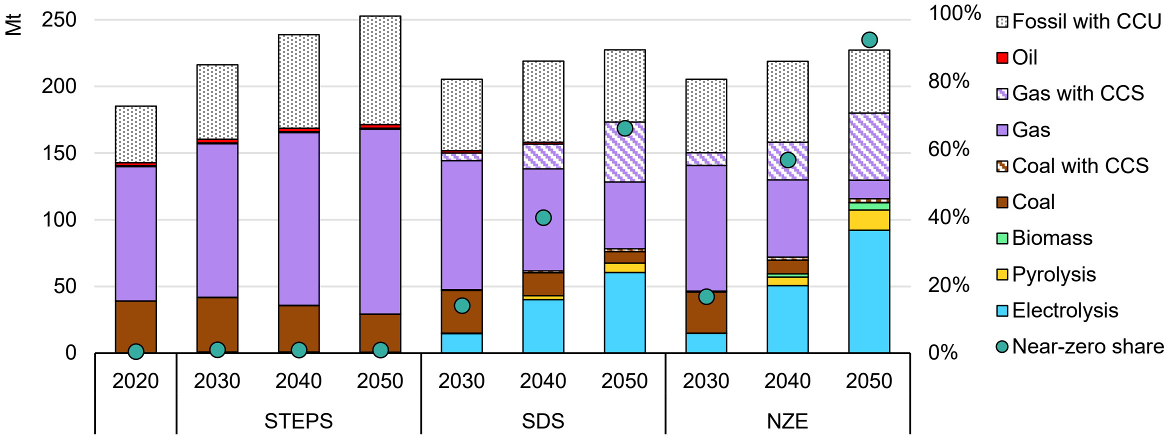
[5] Applicable both to steam methane reforming (SMR) and auto-thermal reforming (ATR) technologies.

“Readiness, competitiveness and investment”). The resulting CO_2-rich stream only requires purification and compression to make it suitable for transporting and geological storage. By 2050 in the Sustainable Development Scenario, 200 Mt CO_2 are captured, 17% of which are energy-related emissions and 83% process emissions. Of the process emissions captured, 65% are utilised for urea production, and 35% are permanently stored. In the Net Zero Emissions by 2050 Scenario a higher share of energy-related emissions is captured (33% of total capture), as the process emissions are nearly fully abated in many regions.

In both scenarios some of the CO_2 required for urea has to be obtained from sources other than the process CO_2 emission streams of ammonia plants. These volumes, at around 4% of total CO_2 capture in the Sustainable Development Scenario and 11% in the Net Zero Emissions by 2050 Scenario in 2050, could be sourced from the energy-related emissions of ammonia production that are captured for permanent storage, or more sustainably from an indirect emissions perspective, from the power and fuel transformation sector, through the use of DAC or from biogenic CO_2 sources.

The concentration of CO_2 in energy-related emissions from ammonia production (3-13% by volume) is typically significantly lower than that of process emission streams (> 95% by volume), which increases the energy requirements to separate it from the flue gas stream. This is particularly relevant for SMR plants. Virtually all current natural gas-based production uses SMR. Existing SMR facilities have a higher proportion of their total CO_2 emissions as flue gas relative to ATR technologies – the likely choice for new-build CCS-equipped plants – which generate around 90% of their emissions in a concentrated stream as process emissions. The CO_2 capture unit that is integrated into conventional ammonia plants to handle the concentrated CO_2 generated from feedstock is typically specified for that process stream and not able to treat the additional volumes from flue gases. The expansion of such a unit or the integration of an additional capture unit (depending on the possibilities at each individual site) would be needed to allow for full capture of the CO_2 generated at a site using an SMR. Another option for retrofitting SMR plants could be to meet the process energy requirements using electrolytic hydrogen, generated on site or imported from merchant hydrogen plants. Process CO_2 emissions capture would still be required, but this would avoid the need to capture the more dilute energy-related flue gas stream, which would no longer contain CO_2.

Figure 2.8 Global ammonia production by technology and scenario



IEA, 2021.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario; CCS = carbon capture and storage; CCU = carbon capture and utilisation for urea production. Near-zero share = aggregated share of near-zero-emission routes, excluding CCU.

Near-zero-emission ammonia production routes account for 50% of total production by 2050 in the Sustainable Development Scenario and 73% in the Net Zero Emissions by 2050 Scenario.

Electrolysis is the other innovative technology pathway that plays a major role in the Sustainable Development Scenario and the Net Zero Emissions by 2050 Scenario. Water electrolysers[6] have been used in several industrial plants commercially over the past century, including for ammonia production using hydropower (see Chapter 1), although their use is not widespread today due to their higher cost relative to fossil fuel-based ammonia production. For this route to achieve substantial reductions in both direct and indirect emissions, it needs to be powered by low-carbon electricity. In the Sustainable Development Scenario the CO_2 intensity of grid electricity drops by 56% by 2030 (75% in the Net Zero Emissions by 2050 Scenario, in which electricity generation would already be at net zero in 2048). In addition to grid-connected arrangements, dedicated VRE installations for ammonia production are also attracting growing interest (see Table 2.2). These could lead to zero-emission production, including both direct and indirect emissions. In the Sustainable Development Scenario 27% (60 Mt) of the ammonia produced globally in 2050 relies on electrolysis, more than China's current annual ammonia production. In the Net Zero Emissions by 2050 Scenario this share reaches 41% by 2050 (92 Mt), limited from going further in many regions by the need to provide CO_2 from carbon-containing feedstocks for urea production.

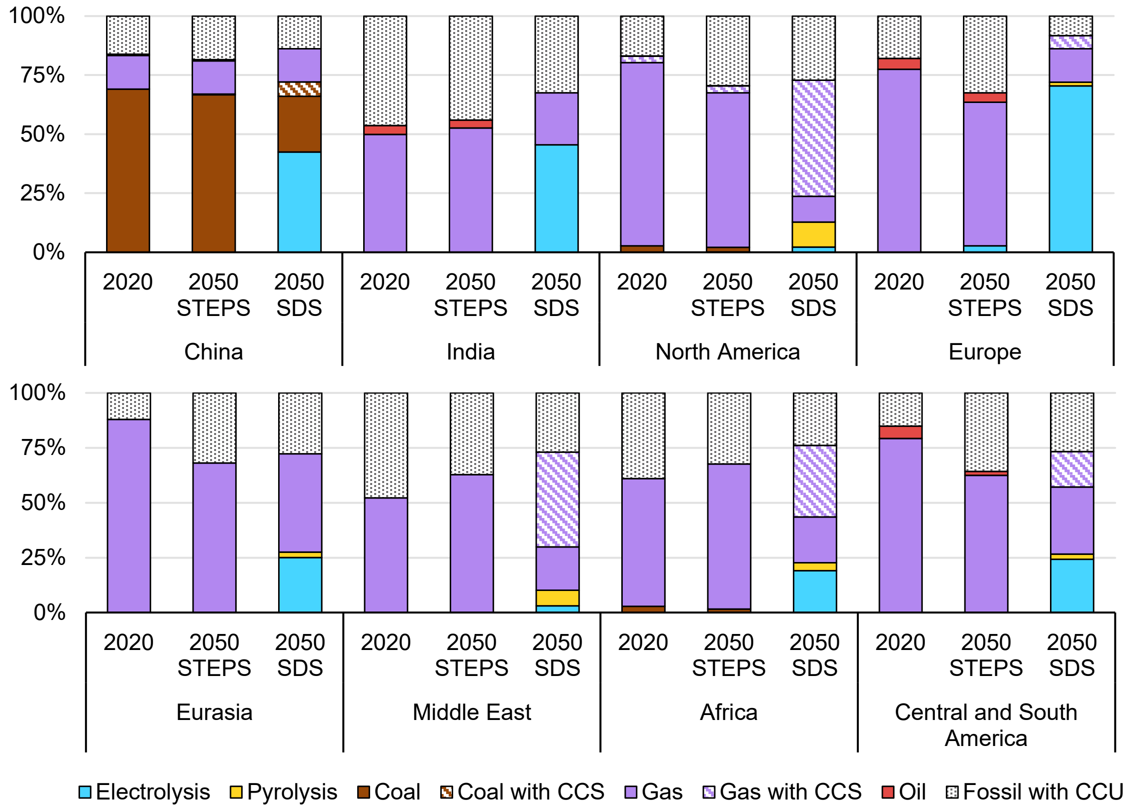
Methane pyrolysis also plays an important role in specific regions, accounting for around 7 Mt of ammonia production by 2050 in the Sustainable Development

[6] This is aside from the use of brine electrolysis to produce chlorine, which is the dominant pathway in this industry.

Scenario. Biomass gasification is a technology that is not deployed in any region in this scenario due to its high projected costs and low technology maturity (no plants are being pursued using this technology today). In the Net Zero Emissions by 2050 Scenario methane pyrolysis reaches production of 15 Mt by 2050, and as the innovation cycles of early-stage technologies are compressed in this scenario, biomass gasification plays a minor role (production of around 6 Mt by 2050 globally). This occurs in regions with access to plentiful supplies of sustainable bioenergy to alleviate the sourcing of carbon for urea production, which becomes more difficult as the carbon-intensive routes are phased out more quickly.

Underlying these technology pathways at the global level are important regional nuances. Both the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario are modelled regionally, but the results for the latter are only presented globally in this technology roadmap. We use the Sustainable Development Scenario to shed light on some of the major regional dynamics.

Figure 2.9 Ammonia production by process route and scenario in major ammonia-producing regions



IEA, 2021.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; CCS = carbon capture and storage; CCU = carbon capture and utilisation for urea production.

The electrolysis route makes important inroads in certain regional markets with access to low-cost renewable electricity and relatively high natural gas prices.

China

In September 2020 at the United Nations General Assembly, President Xi Jinping announced that China will "aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060". This bold new vision for China's future development comes in the midst of a groundswell of ambition among the world's major economies, recognising the need to achieve net zero emissions by mid-century. Achieving carbon neutrality means that CO_2 emissions from heavy industry, including ammonia production, cannot be ignored. The decline in China's emissions from ammonia production is just over 80% in the Sustainable Development Scenario by 2050, compared with a 73% decline for the world as a whole. Output declines by 34% during this period, resulting in an emissions intensity decline that is broadly in line with the global trajectory.

China's technology portfolio for ammonia production is unique. Notably, the country relies heavily on coal gasification technology. Replacing this large, young fleet (estimated at 12 years old on average) with near-zero-emission capacity is the principal challenge China faces in the context of the Sustainable Development Scenario. A wholesale switch to natural gas at the country's coal ammonia plants would halve the country's CO_2 emissions from ammonia production without deploying any innovative technologies. However, this would result in a substantial increase in natural gas imports, as the fuel is a scarce commodity (and expensive at the margin) in China. This would also renew the life of an already young fleet of fossil-fuelled plants well into the 2030s, and still retain the need for CCS retrofits in the long term.

The evolution of China's technology portfolio in the context of the Sustainable Development Scenario can be characterised by the rapid build-up of electrolysis capacity, supported by the continued rollout of carbon capture – already underway – to prolong the life of the youngest coal-based plants and avoid early retirements. By 2050 China accounts for 15 Mt of electrolysis-based ammonia production (requiring 124 TWh or 1% of total industrial electricity demand by that point), equating to 42% of China's output and 25% of global electrolysis-based ammonia production in this scenario. CCS-equipped plants account for around 6% of ammonia production in China in 2050, while its unabated coal-based ammonia capacity declines by more than 70% by 2050 to account for less than one-quarter of production. The strong push for electrolysis also alleviates pressure on the rapid CCS rollout (and associated infrastructure requirements) that is required across China's industrial sector as a whole. For process emissions from methanol and high-value chemical production in the chemical sector, and for clinker production in the cement sector, the alternatives to CCS for achieving significant emission reductions are limited or non-existent. Over 600 Mt CO_2 are captured across China's heavy industry sectors by 2050, compared with the 3 Mt CO_2 captured by industry globally today. The deployment of electrolysis-based ammonia capacity by 2050 avoids the need for a further 50 Mt CO_2 capture capacity by 2050 that would be required if the coal-based plants were retained.

India

Ammonia production in India more than doubles in the period between 2020 and 2050 in the Sustainable Development Scenario. The country accounts for over 40% of the global increase in ammonia output, and is the fastest-growing major producing region, followed closely by the Middle East. This large increase in output means sustained capacity additions are required throughout the projection horizon, particularly in the period 2030-2050. Despite this large increase in output, emissions decline by 28%, requiring an almost 70% reduction in the direct CO_2 intensity of ammonia production.

Existing ammonia production capacity in India is more than 90% natural gas-based, with the remaining share provided by comparatively less efficient oil-based production facilities. Like China, India faces constraints in its indigenous production of natural gas, with the country needing to rely on imports for any substantially higher future demand. Imported liquefied natural gas is expensive in India, with prices of around USD 7-8/MBtu in recent years (compared with USD 2-3/MBtu in the United States). Combined with the uncertainties and expense associated with building up CCS infrastructure in the near future, this makes continued growth in the natural gas-based production fleet a less attractive prospect than in some other regions.

India has vast potential for low-cost renewable electricity generation. Solar PV installations, in particular, have rapidly declined in cost over the last decade, and the country is projected to be one of the largest markets for renewables deployment in the coming years. These factors explain the large role played by electrolysis in meeting the capacity additions required in the Sustainable Development Scenario, where India accounts for 25% of global electrolysis-based capacity by 2050, the same share as China, in a domestic market that is almost equal in size by then. Natural gas-based capacity still grows modestly to account for 18 Mt of ammonia production in 2050 (25% increase by 2050, or a net addition of approximately three large new plants over that period), while around 30 GW of electrolysis is deployed – a technology that currently exists only at the multi-megawatt scale for ammonia production today – such that electrolytic-based production accounts for 15 Mt (45%) of ammonia production in 2050.

North America

North America, a region comprising the United States, Canada and Mexico, is a region of plateauing ammonia output in the Sustainable Development Scenario. Current production levels are around 21 Mt, with this quantity rising slightly to 23 Mt by 2050. Mexico accounts for all of the growth in production, and offsets very slight declines in the United States and Canada. The latter two countries have in place ambitious net zero-emission commitments for 2050, which leads the region as a whole to decarbonise at a faster pace than the world as a whole. Emissions from ammonia production decline by almost 95%, with the decline in emissions intensity at roughly the same rate. This is broadly in line with the pace of emission reductions in advanced economies, many of which have similar net zero targets in place.

The CCS-equipped natural gas pathway provides the majority of emission reductions in the Sustainable Development Scenario. Low natural gas prices, established policy frameworks (e.g. the 45Q tax credit system in the United States) and experience with several existing projects (e.g. the Alberta Carbon Trunk Line in Canada) mean the region is poised for a rapid rollout of this technology. For the region's older SMR plants, some continued unabated operation and eventual replacement with a new-build ATR installation is the most effective strategy, given the lower costs of capturing a large percentage of the CO_2 generated with this reformer arrangement. For the younger plants in the region, and particularly any unabated plants built in the next decade in Mexico, SMR retrofits with CCS would be the natural choice to avoid early retirements and replacements.

Methane pyrolysis technology, though not yet deployed commercially at scale for ammonia production, is being pursued in the United States in Nebraska. From an initial commercial-scale plant in the early 2020s, this route expands to reach more than 10% of ammonia production in 2050. The constraint on further expansion via this pathway is the co-production of solid carbon, which if produced at a sufficiently high grade would start to saturate the domestic carbon black market in North America, and need export markets if it is to generate its cost-offsetting revenue. The alternative may be to store the solid carbon – a solid-phase form of CCS – although this is an uncertain prospect given it is yet to be tested or regulated and would significantly affect the cost-competitiveness of the technology relative to the regionally more dominant natural gas with CCS pathway.

Europe

Similar to North America, Europe is a mature market for ammonia, and its overall production stays flat at around 20 Mt through to 2050 in the Sustainable Development Scenario. The European Union, which makes up around three-quarters of the output of the region, has in place an ambitious net zero greenhouse gas emissions target for 2050. Emissions from ammonia production decline by around 90% for the region as a whole, with EU emissions declining virtually to zero by 2050.

The region's existing fleet of ammonia plants comprises mainly natural gas-based production. Around 5% of output is via comparatively less efficient oil-based facilities, which are the first candidates for substitution by electrolysis in this region's rapid rollout of the technology. The EU hydrogen strategy, and a significant degree of momentum behind electrolytic hydrogen projects on the supply side, lay the groundwork for the near wholesale replacement of the region's existing natural gas stock by 2050 in the Sustainable Development Scenario, when 70% of Europe's ammonia production is via electrolysis. The region accounts for a share of global electrolysis capacity similar to China and India by 2050.

CCS-equipped capacity deployment in the region is very limited for ammonia production in the Sustainable Development Scenario, given the low levels of public acceptance in many EU countries and several false starts for the technology over the past two decades. This is a major area of uncertainty in the scenario results, as the policy framework in Europe is subject to change in the future, and a large CCS project in Norway may do much to alter the current prospects for the technology once fully operational in the early 2020s. The United Kingdom and the Netherlands are other countries where CCS technology and the required infrastructure is undergoing serious discussion and development, but as with China, there will be many competing CO_2 sources for the transport and storage infrastructure that ends up being realised. The cement industry is a key example of an industry that is likely to be retained in some form in the region, so this and other sectors with few or no alternatives to CCS technology for deep emission reductions are expected to take priority.

Other key regions

The regions discussed above account for approximately 60% of current ammonia production, this share falling to around 50% in 2050 in the Sustainable

Development Scenario. The regions that account for the remainder generally follow a similar trajectory to one of those outlined above, or a combination thereof.

A broad distinction can be made between regions according to their growth trajectory. Emerging and developing economies, particularly in Africa, the Middle East, Central and South America, and Asia Pacific (aside from China and India, addressed above), tend to see the highest growth rates in ammonia production in the Sustainable Development Scenario, although in absolute terms they still account for relatively small shares of global production. By 2050 the Middle East accounts for 14% of global production (up from 9%), Africa for 8% (up from 5%) and Central and South America for 7% (up from 4%). Other countries in the Asia Pacific region, besides India and China, account for most of the rest. Advanced economies and mature regions, such as Japan and most of Eurasia, see plateauing or declining ammonia output. In contrast to the regions with strong growth trajectories, these regions pursue technology strategies that are compatible with falling output, such as retrofit technologies and strategically timed replacements. High-growth regions are attractive prospects for new capacity and infrastructure development, as the costs of production are likely to be lower and they generally have growing domestic markets to serve.

The natural gas-based route equipped with CCS is the dominant near-zero-emission solution deployed in these other key regions, particularly in the Middle East, which account for nearly one-third of CCS-equipped output by 2050. The methane pyrolysis route, following successful scale-up in North America where it is currently most advanced, is a complementary technology for deployment in these regions, which tend to have low natural gas prices. Small amounts of electrolysis are also deployed in these regions, but natural gas tends to win on cost where it is available indigenously (it is abundant in the Middle East, many parts of Central and South America and North Africa), and where there are no barriers to CCS in the regulatory and public acceptance spheres.

Considerations for the main innovative technologies

Dedicated VRE electrolysis

The electrolysis pathway for ammonia production plays a critical role in the Sustainable Development Scenario. By 2050 the route accounts for around one-fifth of ammonia production globally (up from less than 0.01% today), the share rising to above 40% in regions such as Europe, India and China. In the Net Zero Emissions by 2050 Scenario the global share is significantly higher, more than

40%. These quantities of electrolytic ammonia production would most likely be produced in a combination of two possible arrangements: grid-connected installations operating at high capacity factors (typically > 90%) and installations fed by dedicated VRE generation that operate on a flexible basis, with lower average capacity factors (typically around 50%). To explore in more detail the opportunities for the electrolytic route in the latter of the two arrangements, we present results from analysis of specific sites and process arrangements to complement the core scenario results, which comprise the aggregate of the two arrangements, as presented above.

Assuming a reliable source of grid electricity, and therefore a high capacity factor at the installation (95%), the levelised cost of ammonia production via the electrolytic route is determined in large part by the cost of electricity powering the process. Levelised costs of ammonia production in the range of USD 525-1 170 per tonne are achievable via this route today, assuming a grid electricity price range of USD 10-40 per MWh and an electrolyser cost of USD 1 477 per kW (including EPC). The lower end of this cost range puts the electrolytic pathway within the range of historic ammonia prices, even in the absence of a specific policy to promote its use. However, USD 30 per MWh is a low electricity price for grid electricity providing a near-100% capacity factor, with relatively few countries seeing prices at this level for much of the year. Most regions seeing wholesale electricity prices at this level today would achieve this using low-cost fossil fuels – and ammonia produced using such electricity would be significantly more emissions intensive than producing it directly from natural gas. Hydropower-rich countries would be the key exceptions, but the potential to expand hydropower is limited in most cases, and demand for low-carbon grid electricity is projected to rise dramatically in both the Sustainable Development Scenario and the Net Zero Emissions by 2050 Scenario. Ammonia would be just one of many demands for hydropower and other low-cost, low-carbon, high capacity factor generation.

An alternative approach to using grid electricity is to harness VRE directly in a dedicated installation. Using a discount rate of 8%, solar PV generation costs are as low as USD 35/MWh today at utility-scale installations, and are projected to drop to around USD 20/MWh by 2030 in regions with the highest potential in the Sustainable Development Scenario. It is a similar story for onshore wind power. While our core scenario results are not prescriptive as to the geospatial location of future installations, this low cost of VRE is an important explanatory factor behind the critical role that the electrolytic pathway plays in reducing emissions from ammonia production.

In addition to its low cost, VRE is an attractive energy vector for ammonia production via the electrolytic route because this electricity can be generated emissions-free. While a small amount of grid electricity (or some other form of dispatchable power generation, such as a hydropower plant, a battery, or a diesel or ammonia generator) is still likely to be required in an installation run on VRE, the CO_2 intensity is lowered substantially relative to a 100% grid electricity installation. Direct use of VRE in ammonia manufacturing and other industrial processes could also ease the burden facing the electricity grid by accommodating the variability directly, or by varying the proportions of grid electricity consumed at times of supply shortage or surplus.

This utilisation of low-cost and ultra-low CO_2 intensity VRE does impose constraints. Because of the mismatch between the variability of VRE and the need for stable operating conditions for large-scale industrial processes, flexibility is a major cost driver. It can either be provided on the supply side (principally through the use of hydrogen buffer storage or battery electricity storage) or on the demand side (tolerance of a certain degree of ramping of the Haber-Bosch synthesis unit, or periods of suspended production). Both options result in additional cost, either in the form of additional equipment (e.g. hydrogen or electricity storage) or lower utilisation and therefore lower efficiencies and increased maintenance costs for core process equipment (e.g. the electrolyser, air separation unit and standalone Haber-Bosch synthesis unit).

To explore the implications for production costs of harnessing VRE directly to produce electrolytic ammonia, we have examined nine specific locations across the world that display significant potential for low-cost VRE from both solar PV and wind. The key parameters that characterise these sites are presented in Table 2.1 and are based on data for 2020 and 2030 in the Sustainable Development Scenario. The locations selected all have good or very good solar and wind resources. With respect to the levelised cost of electricity, in 2020 the locations in Chile, Spain, the United States and Saudi Arabia have lower-cost solar resources; those in China and Morocco have a cheaper wind resource, and the locations in India, South Africa and Australia are more balanced. In 2030, however, solar PV becomes cheaper than wind power in all locations except the site in China.

Table 2.1 Parameters for low-cost VRE sites in 2020 and 2030 in the Sustainable Development Scenario

Site	Year	Solar PV CF	Wind CF	Solar PV LCOE (USD/ MWh)	Wind LCOE (USD/ MWh)	Hydrogen LCOH (USD/ kg)	Electricity curtailment
Calama, Chile	2020	32%	36%	41	55	4.3	8%
	2030	32%	36%	26	51	2.2	7%
Hebei, China	2020	18%	47%	51	33	3.8	14%
	2030	18%	47%	32	31	2.3	13%
Karnataka, India	2020	24%	44%	35	33	3.7	7%
	2030	24%	44%	23	30	2.0	5%
Andalucia, Spain	2020	23%	42%	39	51	4.4	15%
	2030	23%	42%	27	48	2.6	16%
Assa, Morocco	2020	26%	51%	67	48	4.8	16%
	2030	26%	51%	40	44	2.9	9%
Kleinsee, South Africa	2020	28%	38%	62	65	5.5	11%
	2030	28%	38%	38	59	3.1	15%
Port Headland, Australia	2020	25%	42%	50	50	4.5	14%
	2030	25%	42%	35	46	2.6	4%
Aqaba, Saudi Arabia	2020	27%	48%	37	45	4.1	18%
	2030	27%	48%	20	41	2.1	16%
Nevada, United States	2020	26%	26%	55	83	6.0	16%
	2030	26%	26%	34	79	2.9	19%

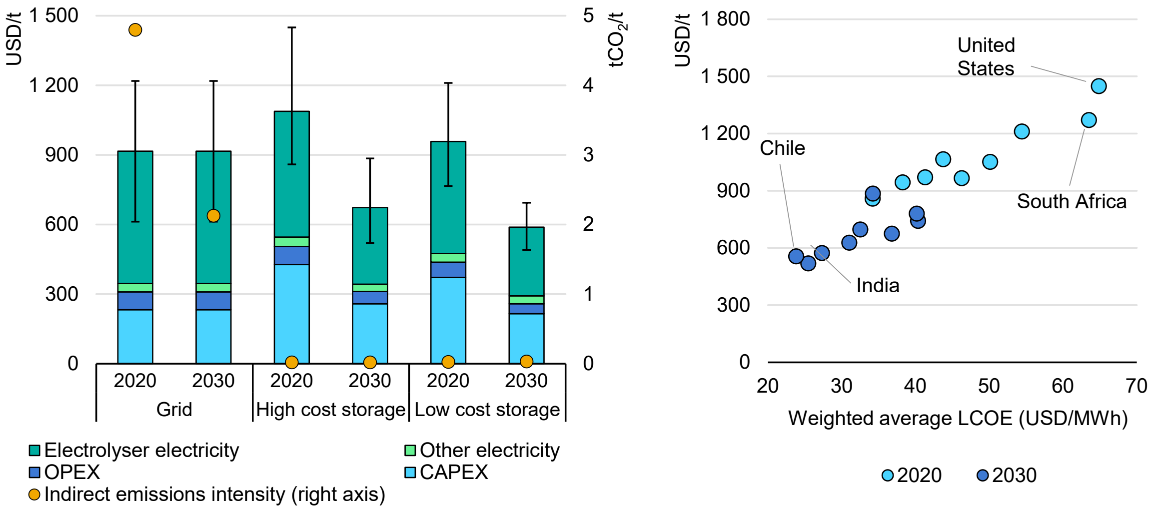
Notes: CF = capacity factor; LCOE = levelised cost of electricity; LCOH = levelised cost of hydrogen. For each site, hourly data for one year are used for the calculation of all parameters. The LCOH and electricity curtailment result from an optimisation of a hybrid wind/solar system. Main cost assumptions (incl. EPC): solar PV CAPEX (varies by country) = USD 580-1 140/kW in 2020, USD 310-657/kW in 2030; wind CAPEX (varies by country) = USD 1 039-1 737/kW in 2020, USD 955-1 597/kW in 2030; electrolyser CAPEX = USD 1 477/kW in 2020, USD 559/kW in 2030.

The flexibility of the process arrangement – specifically that of the Haber-Bosch synthesis and air separation units – is a key uncertainty in this analysis. It is assumed that the synthesis process can ramp down to 60% of its rated capacity, at a maximal rate of 20% per hour. The electrolyser is assumed to be 100%

flexible; thus, the production of hydrogen is fully variable. As the synthesis unit can operate with only partial flexibility, buffer storage of hydrogen is required between the electrolyser output and the synthesis unit. These flexibility assumptions may be deemed to be at the conservative end of what is possible once experience is gained with large-scale installations of this type. But, to date, no electrolytic ammonia projects are operating at the scale of a single commercial ammonia plant (> 500 kt per year of production) fed by VRE directly, so to some extent this is uncharted territory and a conservative approach is warranted.

We consider two costs of hydrogen storage: "Low-cost hydrogen storage", which corresponds to naturally occurring geological storage; and "High-cost hydrogen storage", which corresponds to high-pressure steel tanks. Our analytical approach aims to minimise the levelised cost of ammonia production by optimising the size and utilisation of the main process units used in ammonia manufacture. They include the solar PV and wind installations used to generate the electricity, and the core process units (the electrolyser, the air separation unit and the Haber-Bosch synthesis unit).

Figure 2.10 Levelised cost of electrolytic ammonia production with VRE at nine key sites for a range of storage cost assumptions



IEA, 2021.

Notes: On the column chart, the nine sites summarised in Table 2.1 are presented in aggregate in the "High-cost storage" and "Low-cost storage" VRE result groupings, with the top of the columns showing the midpoint of the range of sites, and the error bars displaying the range from the lowest to the highest cost sites. The weighted average LCOE is a function of the costs and shares of solar PV and wind electricity at each selected site. Emissions intensities of electricity generation in 2020 and 2030 are the global average values in the Sustainable Development Scenario: 474 g CO_2/kWh and 210 g CO_2/kWh respectively. See Table 2.1 notes for the main techno-economic parameters used.

Dedicated VRE installations offer the possibility of producing ammonia at or below the cost of an arrangement connected directly to the grid, and at much lower indirect CO_2 intensities.

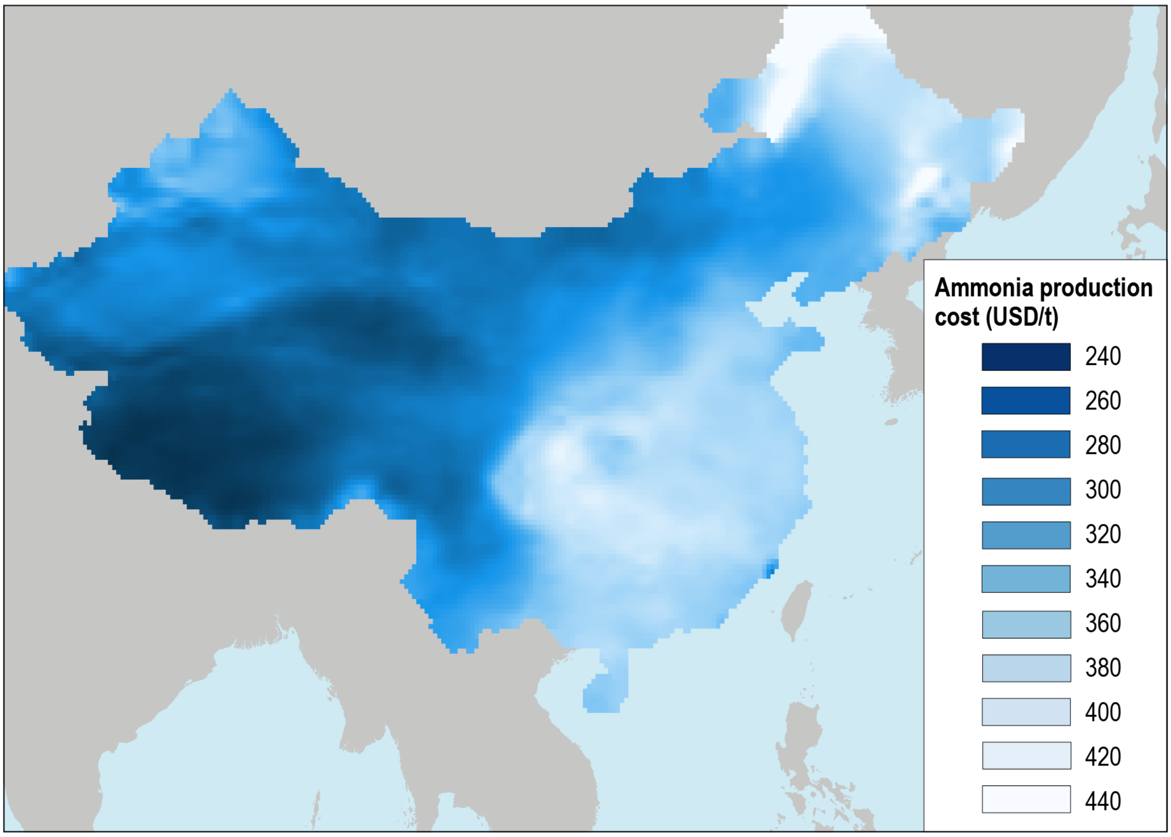
Process flexibility is a prerequisite for dedicated VRE ammonia production, and the more that is available, the lower the cost of production. Low-cost hydrogen buffer storage offers the potential for significant further cost reduction, by 8-15% relative to the cases with high-cost storage. Low-cost buffer storage is unlikely to be available in many instances, so expensive high-pressure steel tanks (up to 40 times more costly than cavern storage) become the fallback option, significantly raising the cost of stabilising the supply of hydrogen to the Haber-Bosch synthesis unit to within the bounds of the flexibility constraints considered. Advances in hydrogen storage (cost reductions) will be critical to making this cost advantage less site-specific, but geological variation between sites is always likely to create an imbalance.

The CO_2 intensity of electrolytic ammonia production (including indirect emissions from power generation) is almost completely reduced – by about 97-99% – by harnessing VRE directly, compared to utilising grid electricity at the global average values of the Sustainable Development Scenario. This is because electrolysis accounts for 93% of the electricity consumption, and thanks to its high flexibility it can fully rely on VRE power. The residual need for grid power only stems from the need to “firm up” the less flexible Haber-Bosch and air separation units, which can operate only semi-flexibly during most of the year, and consume only 7% of the power, which can also be sourced from VRE in most hours of the year. Battery electricity storage, or electricity generation using hydrogen or ammonia, could further reduce this reliance on grid electricity, and thus the residual indirect emissions of VRE-based ammonia production, perhaps with a slight increase in overall costs.

Producing ammonia flexibly using zero-carbon VRE also provides value at the energy system level, as few large producing countries and regions will have a fully decarbonised electricity grid in the short to medium term, and demand for low-carbon grid electricity is projected to increase dramatically in the Sustainable Development Scenario. In the longer term, costs of VRE-based ammonia are expected to drop such that the route can achieve parity with traditional fossil fuel routes. Figure 2.11 displays a geospatial cost analysis of China in 2050 in the Sustainable Development Scenario, providing insights as to the very low levelised costs that can be achieved in the long term. Costs drop as low as USD 260-340/t in huge swathes of the country, which even with significant exclusion zones (cities, areas of natural beauty) would provide ample potential.

The most favourable sites would be located in the dryer western and northern provinces where radiation and wind energy are high, and competition for rural land is less than in the more humid and agriculturally productive provinces of the east and the south. Water availability for electrolysis can be a limiting factor in locations that are remote from the sea, or where desalination is not possible at reasonable cost. This could result in many of the most favourable sites being far from established industrial and consumption centres, which would mean a restructuring of the country's industrial infrastructure. China is just one illustrative case, but similar themes are likely to be present in other regions.

Figure 2.11 Simplified levelised cost of ammonia production via electrolysis for optimal mixes of wind and solar PV in China in 2050 in the Sustainable Development Scenario



IEA, 2021.

Notes: This map is without prejudice to the status of or sovereignty over any territory, to the elimination of international frontiers and boundaries, and to the name of any territory, city or area. Main cost assumptions (incl. EPC): solar PV CAPEX = 280 USD/kW; wind CAPEX = 930 USD/kW; electrolyser CAPEX = 405 USD/kW$_e$.

Dedicated VRE-based ammonia production plants in the long term offer the prospect of cost-effective production, requiring gigawatt-scale VRE capacity in remote locations.

CCUS-equipped pathways

CO_2 is routinely captured during the process of producing ammonia and used on site for urea synthesis. Such installations have been operating commercially in this way for decades because of the inherent need to separate the CO_2 from the hydrogen required for ammonia production, and the relatively high share of ammonia that is converted to urea. Because this inherent capture takes place and produces a highly concentrated CO_2 stream, applying CCUS to any remaining CO_2 beyond the portion needed for urea synthesis just requires compression and dehydration to ready it for transport and storage. Consequently, this is one of the cheapest options available to reduce a substantial share of the CO_2 emissions arising from ammonia production (see Chapter 1, "Fertiliser production fundamentals" on production pathways and cost considerations).[7] To capture CO_2 from the dilute flue gas streams of ammonia production, the same technology (chemical absorption) used to separate the CO_2 from the feedstock stream can be employed; however, this requires additional investment in capture equipment beyond that incorporated in a commercial ammonia plant today.

While CO_2 capture is widespread in the ammonia industry, with more than 130 Mt CO_2 captured in 2020, only a small fraction of the captured CO_2 is geologically stored (around 2 Mt CO_2 per year). This fraction comes from the only four large-scale ammonia CCS projects that are currently operating worldwide (two based in the United States, one based in Canada and one based in China), transporting CO_2 via pipeline and using it for EOR. The rest of the captured CO_2 is utilised for urea synthesis.

In the Stated Policies Scenario only limited deployment of CCS-equipped routes takes place, the previously mentioned large-scale ammonia CCS projects being joined by a handful of further installations that are expected to come online in the next few years (Table 2.1). In the Sustainable Development Scenario 15 Mt CO_2 are captured for storage in 2030 globally, with this quantity rising to 41 Mt CO_2 in 2040 and almost twice as much in 2050 (91 Mt CO_2), while in the Net Zero Emissions by 2050 Scenario 101 Mt CO_2 are captured for storage in 2050.

In the Sustainable Development Scenario North America captures the largest share in 2050 (23% of total CO_2 captured for storage), while more than half of the growth in CCUS deployment between 2030 and 2050 takes place in the Middle East and in Asia Pacific, together capturing more than 50 Mt CO_2 in 2050 (Figure 2.11). The conditions for CCUS in these regions are more favourable than in others, and include low natural gas prices, existing oil and gas infrastructure that could be converted for use in CCUS applications, abundant storage capacity and experience with the technology.

CCUS technologies increase the energy intensity of the ammonia production process by around 1-2% for partial capture applications and by around 3-7% for

[7] CO_2 captured during ammonia production and used to make urea will be re-released into the atmosphere once the urea is applied to the field.

full capture applications.[8] The increase in CAPEX depends on the final configuration of the integrated plant, with limited increases in cost for retrofitted solutions (around 5% for partial capture and 20% for full capture) and a wider range of costs for new plant configurations (around 5% for partial capture and 10-30% for full capture, with natural gas reforming at the lower end of the range and coal gasification at the higher end of the range).

For large-scale applications CO_2 is transported via pipeline or by ship, while tanks transported by truck and rail are better suited for small-scale applications and short distances (for instance, within the same industrial hub). Pipelines represent a cost-effective solution, on average between USD 1.5-16/t CO_2/250 km, with the most economic opportunities where the transport capacity need is high, the location is onshore and the area sparsely populated. Repurposing existing pipelines can substantially decrease (by 90-99%) the cost of transporting CO_2 in regions where such infrastructure is available (e.g. United States, Canada and the North Sea region).

CO_2 storage costs vary significantly depending on the rate of CO_2 injection and the characteristics of the storage reservoir, as well as the location of the storage site, particularly with respect to whether it is situated onshore or offshore. Costs can vary from just a few dollars to more than USD 50/t CO_2 for storage reservoirs with less favourable storage conditions. The costs can even be negative if the oil revenue from EOR applications is taken into account. In the United States more than half of onshore storage is estimated to cost below USD 10/t CO_2, while about half of offshore storage is estimated to be available at costs below USD 35/t CO_2. The regional availability of CO_2 storage potential differs considerably by region, with substantial capacity expected to exist in Russia, North America, Africa and Australia, and global capacity far exceeding storage needs for the full energy system over the period 2020-2050 in the Sustainable Development Scenario.[9] Therefore, regional availability of CO_2 storage capacity would not be a limiting factor for the deployment of this technology in the ammonia industry.

The levelised cost of CCUS-equipped ammonia production pathways depends on multiple factors, with the main components being the CAPEX and fixed OPEX of the core production and capture equipment, the feedstock and fuel costs. Natural gas-based CCUS-equipped ammonia production starts to compete with that via

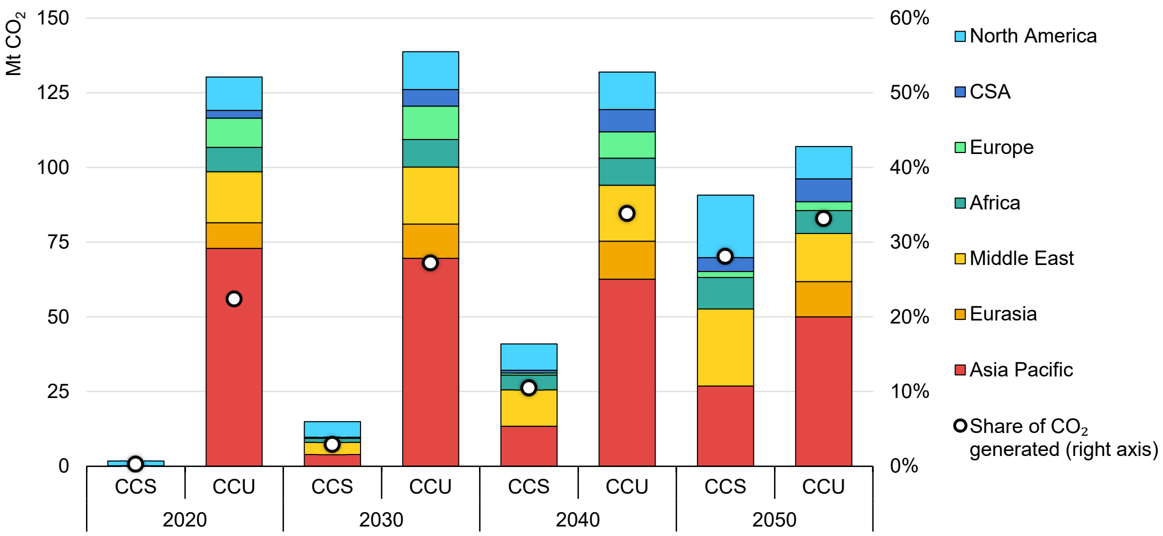
[8] Partial capture involves capturing only process emissions, which are highly concentrated and only require compression and dehydration before being transported and stored. Full capture targets both process and energy-related emissions, with the latter being much more dilute and requiring higher energy inputs for CO_2 capture. The CO_2 capture rate (equivalent to the captured CO_2 as a percentage of the generated CO_2 to which the capture is applied) for partial capture configurations is around 95% of process emissions, while for full capture configurations is around 90% of combustion emissions (plus 95% of process emissions).

[9] Total global storage capacity is estimated at between 8 000 Gt CO_2 and 55 000 Gt CO_2. While potential storage volumes are considerable, a smaller fraction will most likely prove to be technically or commercially feasible.

unabated natural gas when CO_2 emissions are priced above USD 30/t CO_2 (Figure 2.14). While global average transport and storage costs are estimated at around USD 20/t CO_2, even a threefold increase to USD 60 /t CO_2 (say, due to low capture volumes, a large distance between the CO_2 source and sink, only offshore storage availability) would increase the levelised cost of ammonia by only around 10-15%. This would still leave CCUS-equipped production competitive with electrolysis-based production at moderate-to-high electricity prices.

The development of CCUS hubs with shared CO_2 transport and storage infrastructure could play a critical role in accelerating the scale-up of CCUS in the fertiliser sector, for which dedicated infrastructure may be both impractical and uneconomic. Previously identified potential CCUS hubs to co-locate fertiliser production within larger industrial clusters include the Skagerrak/Kattegat area in Scandinavia (lying between southern Norway, Sweden and northern Denmark). Granular geospatial analysis can identify early opportunities for ramping up CCUS around industrial hubs, reducing costs by exploiting economies of scale and making it feasible to capture CO_2 at smaller industrial facilities.

Figure 2.12 Captured CO_2 for storage and utilisation in the Sustainable Development Scenario



IEA, 2021.

Notes: CCS = carbon capture and storage; CCU = carbon capture and utilisation for urea production; CSA = Central and South America.

In the Sustainable Development Scenario, the regions with the largest CO_2 storage requirements for the ammonia industry are Asia Pacific, the Middle East and North America.

Readiness, competitiveness and investment

Near-zero-emission technologies for the ammonia industry are currently at different stages of development. They include technologies that are ready to be deployed by industry today, and those that still have innovation hurdles to overcome before being fully placed on the market. Which technologies are ultimately deployed will be context-specific, depending on factors such as energy costs, availability of supporting infrastructure and the policy environment. The future is uncertain, and factors such as the pace of innovation and extent of technology cost reductions may affect technology deployment. Regardless, achieving deep emission reductions in the ammonia industry will require a massive shift in investment towards near-zero-emission technologies and the infrastructure to support them.

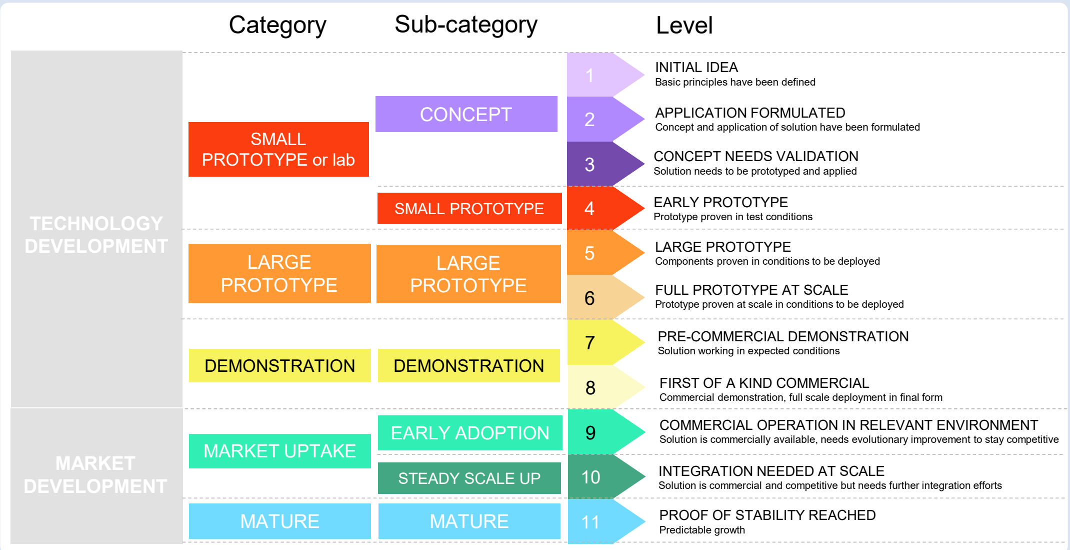
Box 2.6 The TRL scale

One way to assess where a technology is on its journey from initial idea to market is to use the TRL scale. Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s and used in many US government agencies since the 1990s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale. The US Department of Defense has been using the TRL scale since the early 2000s for procurement, while the European Space Agency adopted it in 2008. In 2014 the TRL was applied for the first time outside the aerospace industry to assess EU-funded projects as part of the Horizon 2020 framework programme. It is now widely used by research institutions and technology developers around the world to set research priorities and design innovation support programmes.

The scale provides a common framework that can be applied consistently to any technology, to assess and compare the maturity of technologies across sectors. The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology now enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4), followed by testing of components in the conditions it will be deployed (TRL 5), through to testing the full prototype in the conditions in which it will be deployed (TRL 6). The technology then moves to the demonstration phase, where it is tested in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards full commercial operation in the relevant environment (TRL 9).

Arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. Beyond the TRL 9 stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; other supporting technologies may need to be developed, or supply chains set up, which in turn might require further development of the technology itself. For this reason, the IEA has extended the TRL scale it uses in its reports to incorporate two additional readiness levels: one where the technology is commercial and competitive, but needs further innovation for its integration into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11).

Maturity categories and technology readiness levels along innovation cycles



IEA, 2021.

As technologies pass through each stage, the level of risk associated with their performance is reduced, but the level of overall risk rises as capital expenditure requirements grow. However, innovation is rarely a linear progression. Not all technology designs make it to market or are deployed at scale. Stages of development can accelerate or slow down depending on technical or cost factors, and a given technology can be at different stages in different markets and applications. As the development of a technology generates new ideas for improvement, alternative configurations and potentially better components can appear even once a given technology configuration has become competitive. Stages overlap and run concurrently, feeding off one another.

In this report we refer to several broader readiness categories, each of which comprises a different range of specific readiness levels from the full TRL scale:

mature, market uptake, demonstration, large prototype and small prototype (technologies at the small prototype stage of TRL 4 or lower are not included in the Sustainable Development Scenario). Each technology type is assigned to one of these higher-level categories based on the granular levels of maturity of individual technology designs or components currently associated with that technology:

"Mature" for technologies that have reached market stability, and the number of new purchases or installations are constant or even declining in some environments as newer technologies start to compete with the stock of existing assets, for example ammonia production via SMR.

"Market uptake" for technologies that are being deployed in a number of markets. This category includes the sub-categories "early adoption" for technologies that have a cost and performance gap with established technologies and "steady scale-up" for technologies that are competitive but barriers to reaching their full market potential remain, such as integration with existing infrastructure or consumer preference. Policy attention is needed in both cases to stimulate wider diffusion to reduce costs and to overcome existing barriers, with more of the costs and risks being borne gradually by the private sector. An example is ammonia production via SMR with CCS.

"Demonstration" for technologies where the first examples of a new technology are being introduced at the size of a full-scale commercial unit, for example ammonia production via methane pyrolysis.

"Large prototype" for technology types for which prototypes are being developed at a considerable size, as in pilot plants.

"Small prototype or lab" for technology types for which designs are being developed into lab-scale prototypes. This category includes the sub-categories "small prototype" for technologies that have been proven in test conditions and "concept" for technologies still needing to be prototyped.

An array of technology options at differing levels of maturity

Technologies that are not yet mature in the marketplace will be critical to achieving deep emission reductions in the ammonia industry. Most of these technologies either capture CO_2 from fossil fuels for permanent storage or rely on electricity as an important input. Within both categories there are several different technology options with varying levels of readiness.

With regard to CCS, the ammonia industry has an advantage over many other industrial sectors in that CO_2 separation is already an integral part of conventional ammonia production processes. In conventional reforming to produce hydrogen from natural gas, process CO_2 from the feedstock is removed using either chemical or physical absorption technologies. Thus the CO_2 capture technologies are mature (TRL 11) for application to the concentrated CO_2 stream from feedstock energy. Many ammonia plants are already utilising the captured CO_2, often for urea production.

It is not a huge leap from a technology standpoint to take the extra steps to permanently store the already-captured CO_2. It simply needs to be compressed and transported to the storage site. For several decades a number of fertiliser plants in the United States have been providing their CO_2 for EOR (through which virtually all of the CO_2 injected is ultimately retained in the reservoir over the life of the project, although monitoring and verification is needed to confirm permanent storage). A similar project came online in 2020 in Canada, with additional projects in the construction or planning stages in the United States, the United Kingdom and China. At least two of these projects are specifically intended to reduce emissions, with the CO_2 stored in dedicated geological storage sites rather than being used for EOR. Given that the technology is ready, but deployment is not yet widespread, the full chain of CCS for ammonia production – including CO_2 transport and storage infrastructure – is considered to be at the market uptake stage (TRL 9) and would still benefit considerably from policy support for further deployment.

Unlike the process emissions, CO_2 emissions from fuel combustion to provide process heat are not already captured as part of conventional production processes. Thus a second capture unit would be needed, or the existing unit would need to be expanded with some reconfiguration. Given the lower concentration of CO_2 in the combustion flue gas, chemical absorption is a probable technology choice. This technology is being used to capture fuel combustion CO_2 in two known ammonia plant in Bahrain and Pakistan (the CO_2 being used for urea and methanol production) and for CO_2 streams with comparable concentrations in the power sector (TRL 9-10 for the capture technology and CO_2 use). There are no known ammonia plants capturing the dilute stream for permanent storage, although transport and storage requirements would not present a technology challenge given experience in other applications (TRL 8 for the full CCS chain). The potential for applying CCS to ammonia fuel combustion emissions is less a question of technology readiness than a question of cost – using current technologies, capturing CO_2 from fuel combustion is about two to four times costlier than from the process stream, and the CO_2 capture from the process stream is already part of the costs of the ammonia plant’s costs anyway.

Various options exist to reduce fuel stream emissions to less than 10% of total emissions, such as using ATR technology or diverting a proportion of the hydrogen produced in the reforming process for use in the furnace. Thus, some operations may opt out of capturing the small amount of remaining dilute fuel combustion CO_2. However, at least one known company is working towards full CO_2 capture ammonia production. The setup would use a cryogenic CO_2 capture system together with a process that displaces steam requirements by making use of high-pressure CO_2. The company is working towards a first commercial plant in New Zealand that is expected to come online in 2024 (TRL 7).

Table 2.2 Status of main near-zero-emission technologies in ammonia production

Technology	TRL, year available, importance for net zero emissions	Deployment status (selected projects)
Carbon capture, utilisation and storage		
Chemical absorption – partial capture (concentrated CO_2 stream)*	9 Today Very high	Capture technology widely used commercially as part of the SMR hydrogen production process (TRL 11 for capture technology) Multiple commercial plants in operation capture CO_2 for use, often for urea (TRL 10-11 for CCU). For example: • Petronas Fertilizer; Kedah, Malaysia; operational 1999; 60 kt CO_2/yr • Indian Farmers Fertilizer Co-op; Aonla, India; operational 2006; 0.2 Mt CO_2/yr Several commercial plants in operation, using captured CO_2 for EOR (TRL 9 for full CCS chain). Known projects are: • Koch Nitrogen; Enid, OK, United States; operational 1982; 0.7 Mt CO_2/yr • Nutrien (formerly Agrium); Geismar, LA, United States; operational 2013; 0.25 Mt CO_2/yr with capacity up to 0.6 Mt CO_2/yr • PCS Nitrogen (subsidiary of Nutrien); Geismar, LA, United States; operational 2013; 0.3 Mt CO_2/yr • Sinopec; Zhongyuan, Henan Province, China; operational 2015; 0.1 Mt CO_2/yr • Some projects are also in the development stages, for example: • CF Fertilisers; Ince, United Kingdom; at early development stage; 0.33 Mt CO_2/yr; part of the Hynet North West industrial cluster that will store CO_2 in a dedicated geological storage site • Horisont Energi; Hammerfest, Norway; concept study has begun, expected to be operational by 2025; 1 Mt ammonia/yr capacity, ammonia may be used for fuel rather than fertilisers; dedicated geological storage.

Technology	TRL, year available, importance for net zero emissions	Deployment status (selected projects)
Chemical absorption – full capture (dilute CO_2 stream)	8 Today Medium	Full capture involves additional capacity to capture the dilute CO_2 stream from fuel combustion for heat provision. Chemical absorption would be a likely candidate for this CO_2 stream. It is already being applied commercially to the concentrated process emissions stream in ammonia plants, as well as to dilute CO_2 streams in a more limited number of cases in the power sector (TRL 9-10 for capture technology). However, it is likely currently being applied to the dilute stream in only a very limited number of ammonia plants. Two known ammonia plants are capturing dilute emissions for use (TRL 9 for CCU): • GCIP; Sitra, Bahrain; operational 2010; 0.16 Mt CO_2/yr • Engro; Daharki, Pakistan; operational 2010; 0.12 Mt CO_2/yr No known ammonia plants are capturing dilute emissions for permanent storage, although based on other related experience there would be no major technology hurdles to overcome (TRL 8 for full CCS chain).
Physical absorption – partial capture (concentrated CO_2 stream)	9 Today Very high	Capture technology widely used commercially as part of the SMR hydrogen production process (TRL 11 for capture technology) Several commercial plants in operation, using captured CO_2 for EOR (TRL 9 for full CCS chain). Known projects are: • Coffeyville Resources Nitrogen Fertilizers; Coffeyville, KS, United States; operational 2013; 1 Mt CO_2/yr • Nutrien; Redwater, AB, Canada; operational 2020; 0.3 Mt CO_2/yr; part of the Alberta Carbon Trunk Line project.
Cryogenic – full capture (dilute CO_2 stream)	7 2025 Medium	Pouakai NZ (subsidiary of eight Rivers Capital) is developing a zero-emission hydrogen project in Taranaki, New Zealand, set to come online in 2024 capturing 1 Mt CO_2/yr. It will produce fertilisers, hydrogen and power. Through use of a cryogenic CO_2 capture system and a process called the Allam-Fetvedt Cycle, which uses high-pressure CO_2 instead of steam, the project is aiming to store 100% of CO_2 generated.

Technology	TRL, year available, importance for net zero emissions	Deployment status (selected projects)
Electricity		
Electrolytic hydrogen supplied by VRE	8 2025 Very high	Electrolysers have been used commercially over the past century, including for ammonia production using hydropower. However, their use is not widespread today, putting the electrolyser itself at TRL 9-10. Only one known ammonia plant using electrolytic hydrogen from hydropower remains, operated by Industrias Cachimayo in Cusco, Peru, since the 1970s. The full chain of VRE-powered electrolysis to produce ammonia is being developed, with several large-scale demonstration or first commercial plants in the development stages (TRL 8 for full chain). Some of the projects that are most advanced and/or most relevant to fertilisers and other current uses of ammonia include: • Fertiberia and Iberdrola; Puertollano, Spain; under construction, due to be online by end of 2021; 20 MW electrolyser, solar-powered; for use in fertiliser plant to enable 10% reduction in natural gas requirements; three additional projects planned between 2023 and 2027 in Puertollano and Palos de la Frontera for a total of 800 MW electrolysis • Yara, NEL Porsgrunn, Norway, 25 MW electrolyser expected online in 2023; expanded electrolyser capacity to fully shift 0.5 Mt/yr of ammonia production away from natural gas in 2026-2028 (in partnership with Statkraft and Aker Clean Hydrogen); grid-connected hydropower • Yara and Ørsted; Sluiskil, Netherlands; at feasibility stage, expected online 2025; 100 MW electrolyser, 70 kt/yr ammonia; powered by offshore wind • Yara and Engie; Pilbara, Australia; 10 MW electrolyser by 2023; solar-powered • CF Industries; Donaldsonville, LA, United States; construction to begin in 2021, completion by 2023; 20 MW electrolyser, 20 kt/yr ammonia; grid-connected • Enaex and Engie (Hyex project); Mejillones district, Chile; pilot with 26 MW electrolyser and 18 kt/yr ammonia expected online by 2024; full-scale operation with 1.6 GW electrolyser and 700 kt/yr ammonia by 2030; solar-powered • Balance Agri-Nutrients and Hiringa Energy; Kapuni, New Zealand; expected online mid-2020s; 7 kt urea/yr; wind-powered Other pilot to commercial-scale projects are also at various stages of planning and development, including some that would use ammonia for fuel. They are located around the world, including in Australia (Queensland Nitrates; Dyno Nobel; H2U; BP; Fortescue Metals Group; Origin Energy), Denmark (Skovgaard Invest; Copenhagen Infrastructure Partners), Trinidad and Tobago (Kenesjay Green Ltd), Germany (RWE), Chile (AES Gener; CORFO; Austria Energy), Oman (ACME) and Morocco (OCP Group).

Technology	TRL, year available, importance for net zero emissions	Deployment status (selected projects)
Methane pyrolysis	7 2025 High	Several projects are working towards using methane pyrolysis to produce hydrogen. While some are already planning to use the hydrogen to produce ammonia, for others the intended use of hydrogen is not yet determined. Projects include: • Monolith completed pilot testing in Redwood City, CA, United States during 2013-15. First commercial unit - Olive Creek 1, 14 kt/yr carbon black capacity; Hallam, NE; construction completed in 2020 with production expected to start in 2021. Second phase to begin construction in 2021 on same site, Olive Creek 2; production expected to begin 2023/24; will produce 275 kt/yr ammonia and 180 kt/yr carbon black • BASF is pilot testing in Ludwigshafen, Germany; first industrial-scale plant expected around 2030; technology expected to be used for producing chemicals such as ammonia and methanol • Hazer Group is preparing for construction of a commercial demonstration project in Munster, Australia • C-Zero is working on commercialising a methane pyrolysis technology developed at the University of California, Santa Barbara in the United States; in early 2021 funds were raised for a first pilot plant • A number of other companies and research institutions have done lab-scale testing, with a few – including HiiROC in the United Kingdom, TNO in the Netherlands and KIT in Germany – working towards pilot plants.
Bioenergy		
Biomass/ waste gasification	5 - Low	Techno-economic evaluation of producing ammonia via biomass gasification completed, but suggests it is not yet economically viable. Higher TRLs for other applications (for example biomethane, ethanol and methanol production), but not yet applied to ammonia.

*For CO_2 capture projects, if information on the type of capture technology was unavailable, the project was listed under chemical absorption.

Notes: TRL = technology readiness level; SMR = steam methane reforming; CCU = carbon capture and utilisation; CCS = carbon capture and storage.

Electrolytic hydrogen has already been used commercially for ammonia production, powered by large-scale hydropower. In fact, ammonia production from electrolytic hydrogen was quite common until around the 1970s when cheap natural gas led to the technology's replacement by SMR plants. Only one electrolytic ammonia plant remains in the world, a plant built in the 1960s in Peru. While electrolytic ammonia production in itself is a commercially proven technology, producing ammonia from electrolysis powered by VRE has the added challenge of adapting the production chain to the variability of electricity infeed.

Producing ammonia from electrolytic hydrogen has regained interest in recent years due to the need to reduce CO_2 emissions. Numerous projects around the world are at various stages of integrating electrolytic hydrogen into ammonia production, including in Europe, the United States, Chile, Australia and New Zealand. Several will use the ammonia for fertiliser production, some for explosives and some for energy. Many are beginning with smaller electrolysers (10-25 MW) to meet a proportion of the plant's hydrogen input requirements, and have plans to scale up in the subsequent years to gigawatt-scale electrolysers providing 80-100% of hydrogen requirements. The first small-scale electrolyser for ammonia production is scheduled to come online by the end of 2021, with larger electrolysers coming online in the mid to late 2020s. While some will use grid electricity, many will be powered directly by dedicated VRE. Given that several projects to produce ammonia with electrolytic hydrogen from VRE are at advanced stages, but the VRE integration challenge remains, the full chain of ammonia from VRE is assessed at TRL 8.

Innovation of the electrolysers themselves also continues, which will bring down capital costs and improve efficiency. Alkaline electrolysers have already been used commercially (TRL 9). Polymer electrolyte membrane (PEM) electrolysers are less commercially developed, but have been scaled up to industrial size with commercial projects in operation (TRL 9) and have several advantages, such as the potential to respond rapidly to required changes in capacity factor even more rapidly than alkaline modules. Solid oxide electrolysers that could considerably reduce electricity input requirements – although provide less flexibility than PEM and alkaline electrolysers – are at the pilot stage (TRL 6). Of course, nitrogen fertiliser production can benefit from technology learnings in the many other sectors where electrolysers are being advanced to produce hydrogen.

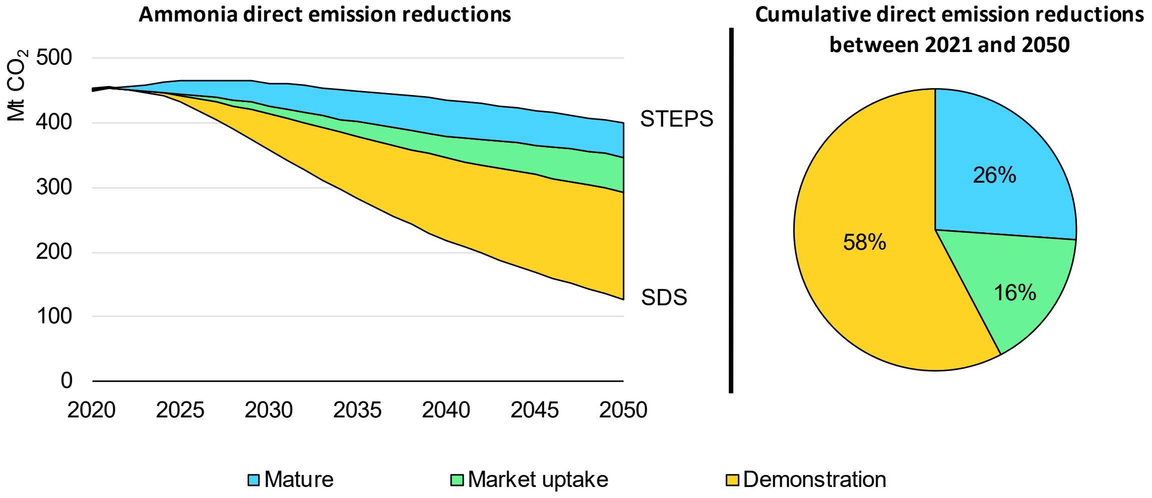
Methane pyrolysis is also approaching market readiness. What is expected be the first methane pyrolysis unit to produce ammonia at commercial scale is due to come online in the United States in 2023 or 2024, putting the technology at TRL 7. Other companies and research institutions – primarily in Europe, the United States and Australia – are also developing technologies to produce hydrogen from methane pyrolysis, some of which are likely to be used for ammonia production. Within the broader category of methane pyrolysis, there are three main technologies, plasma, thermal and catalytic, and different variations of these technologies are at different stages of readiness.

Gasification of biomass or waste is also a possible technology option for near-zero-emission ammonia production. While techno-economic evaluations have been completed and biomass gasification is used for other applications, no known projects are pursuing scale-up specifically for ammonia production. This puts biomass gasification for ammonia still at the prototype stage (TRL 5). High costs and competition for sustainable biomass resources from other sectors make this technology route unlikely to play a large role.

R&D is also underway on a variety of other technologies for low-emission ammonia production. Some involve modifications to producing ammonia with Haber-Bosch, while others are based on processes other than Haber-Bosch. These technologies are at the small prototype or lab phase (TRL 4 or lower) and would require considerable further development to reach market readiness. As such, they are not included in the scenarios discussed in this technology roadmap. However, the innovation process involves many uncertainties and advances could occur more rapidly than anticipated. Thus, it is a possible that they could play a role in sustainable ammonia production in the future. Major categories of earlier-stage technologies being researched include:

- **Electrified SMR:** hydrogen could be produced using a combination of natural gas for feedstock – for which process emissions are more easily captured – and using electricity to provide process heat. This is challenging given the high-temperature heat required. Other renewable direct heat sources, such as concentrated solar power or geothermal, could also be an option. The Haber-Bosch process would be maintained for ammonia synthesis.
- **Biological enzymes:** such processes would replace Haber-Bosch with biological enzyme catalysts – produced by genetically modified bacteria – that synthesise ammonia directly from water and nitrogen in the air. As such, they would mimic natural biological nitrogen fixation.
- **Electrochemical production:** such processes would replace Haber-Bosch by electrolysis using specific electrolytes and electrocatalysts to synthesise ammonia directly from water and atmospheric nitrogen in the air.
- **Chemical looping:** such processes would produce ammonia as a by-product of chemical and electrochemical reactions, while recycling the core reaction chemicals. Some of these processes would avoid hydrogen production and thus replace Haber-Bosch, while others would produce hydrogen for ammonia synthesis via Haber-Bosch.
- **Low-temperature catalytic synthesis:** such processes would use innovative catalysts at low temperatures (around 50°C) to drive ammonia synthesis, increasing yield and reducing process energy requirements relative to conventional high-temperature Haber-Bosch using an iron catalyst.

Figure 2.13 CO_2 emission reductions in the Sustainable Development Scenario by technology maturity category



IEA, 2021.

Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. See Box 2.3 for a description of the technology maturity categories. Ammonia used as an energy carrier is not included.

Almost 75% of the emission reductions in the Sustainable Development Scenario come from technologies that are currently at the market uptake or demonstration stage.

CCS and electrolytic hydrogen from VRE are likely to play a critical role in near-zero-emission ammonia production. As such, most emission reductions in the Sustainable Development Scenario are from technologies that are currently at the market uptake and demonstration stages – they account for 16% and 58% of the emission reductions until 2050, respectively. Technologies and strategies to improve ammonia use efficiency are already mature from a technology standpoint, although there are cost, behavioural and co-ordination barriers remaining to be overcome. These strategies, along with energy efficiency improvements within conventional routes, account for most of the remaining 26% of emission reductions from mature technologies. There is also a small contribution from the structural shift at the global level in which natural gas-based production modestly increases while coal-based production decreases. This is driven by China's declining share of global production, given that most coal-based production today occurs in China.

Exploring key uncertainties

While the results presented in the Sustainable Development Scenario take into account many factors, including variations in regional circumstances, these figures do not constitute a forecast and are subject to much uncertainty. Major aspects of uncertainty include the future costs of production and the pace of technology innovation, which are interconnected due to the potential for innovation to bring down technology costs. These factors, which are explored in this section, can affect the extent to which different technologies are deployed and could determine what a sustainable future for the ammonia industry looks like.

Future production costs

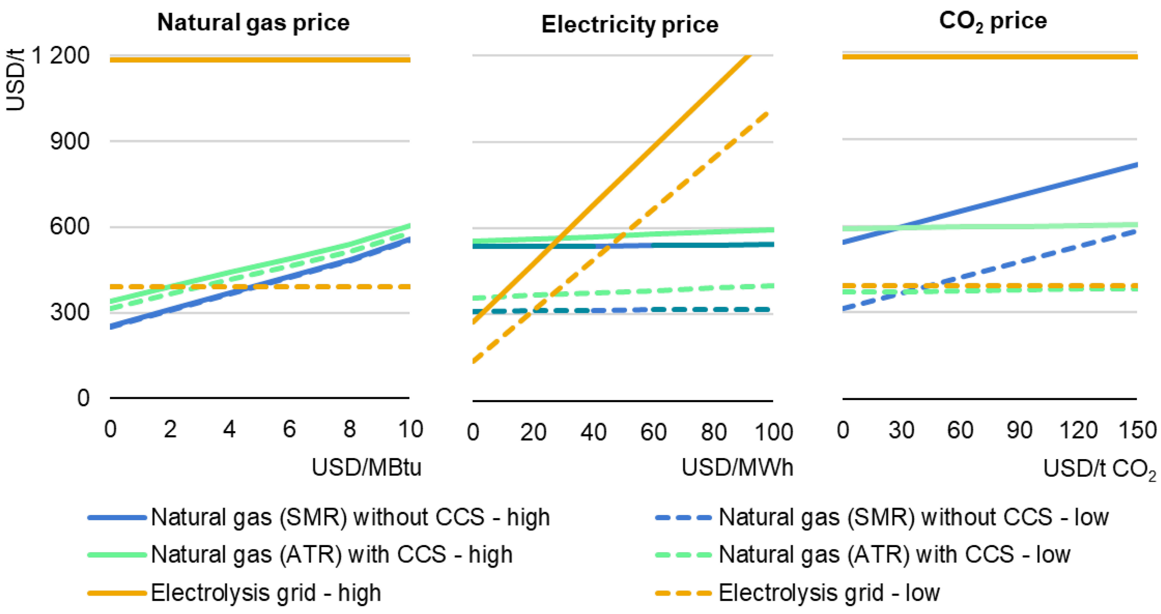
The simplified levelised cost can be a helpful metric to compare the relative sensitivity of production pathways to variations in their input costs. Two of the key factors likely to affect future costs of ammonia production are energy costs and technology CAPEX. CO_2 emission reduction policies, such as CO_2 prices, would also affect total production costs.

When comparing natural gas-based reforming production with and without CCS and electrolytic-based ammonia production, natural gas-based reforming without CCS is unsurprisingly the least-cost option in most energy price contexts and in the absence of a CO_2 price. The cost of adding CCS to natural gas-based reforming is relatively modest. It increases the levelised cost of ammonia production by about 25% in typical energy price contexts and would require a CO_2 price of about USD 30/t CO_2 to start being cost-competitive with unabated natural gas reforming. Policies other than explicit carbon prices could similarly spur the addition of CCS, such as CO_2 emission regulations or technology subsidies.

Electrolysis-based ammonia production is able to compete with natural gas reforming in a more limited range of contexts, but is most likely to when electricity prices are low, natural gas prices are high and electrolyser costs low. Even in the case of low electrolyser costs, electricity prices of USD ‘40/MWh or lower are needed for electrolysis to become competitive. In regions with high natural gas prices (USD 10/MBtu), electrolysis could already become competitive with electricity prices of around USD 40/MWh. Such low electrolyser costs require considerable reductions in the cost of electrolysers relative to today – on the order of 60% reductions to reach about USD 400/kW_e electrolyser capacity. Without such reductions in electrolyser costs, even lower electricity prices of USD 20-25/MWh would be needed. In regions with lower natural gas prices, electrolysers at today’s costs may require electricity prices below USD 5/MWh to be cost-competitive.

The CO_2 price at which electrolysis becomes competitive with natural gas reforming with or without CCS is highly dependent on the energy price context and electrolyser costs, and could range anywhere from no carbon price to several hundred dollars per tonne of CO_2.

Figure 2.14 Levelised cost of ammonia production pathways at varying gas, electricity and CO_2 prices



IEA, 2021.

Notes: SMR = steam methane reforming; ATR = auto-thermal reforming; CCS = carbon capture and storage. Presented costs account for regional variation. For left and right graphs: electricity costs = USD 90/MWh (USD 25/GJ) for electrolysis high and USD 30/MWh (USD 8/GJ) for electrolysis low; electrolyser cost = USD 1 477/kW$_e$ for electrolysis high and USD 405/kW$_e$ for electrolysis low. For middle and right graphs: natural gas costs = USD 10/MBtu (USD 9/GJ) for natural gas high and USD 2/MBtu (USD 2/GJ) for natural gas low. For left and middle graphs no price on CO_2 is imposed. CO_2 transport and storage costs = USD 20/t CO_2 captured. Electrolyser LHV efficiency = 64% for electrolysis high and 74% for electrolysis low. CO_2 streams are captured with a 95% capture rate. CAPEX comprises process equipment costs (including air separation units, carbon capture equipment and electrolysers where applicable) plus engineering, procurement and construction costs. For all equipment: discount rate = 8%; lifetime = 25 years; capacity factor = 95%.

Electricity prices of about USD 40/MWh or lower are required for electrolysis to be cost-competitive with natural gas-based ammonia production with or without CCS. Application of CCS to natural gas-based production becomes competitive at CO_2 prices of USD 30/t CO_2.

Regions with electricity prices today in the range needed to make electrolytic ammonia production competitive (USD 40/MWh or below) achieve low prices either through low-cost fossil fuels that would make ammonia production even more emissions-intensive than natural gas reforming, or through large-scale hydropower that has limited potential for future expansion to supply new uses. However, costs of solar and wind have fallen rapidly in recent years and are likely to continue to fall. In regions with strong potential for wind and solar, for example parts of Africa and Australia, electrolytic-based ammonia could indeed become cost-competitive, including through strategically placed dedicated VRE capacity. Furthermore, in regions expected to have quite high natural gas prices in the future – such as parts of Europe, a number of Asian countries such as China, Korea and Japan, and parts of Latin America – electrolysis could become increasingly appealing. Beyond costs, other factors may lead to choosing electrolysis-based production, such as lack of access to CO_2 transport and storage infrastructure needed for natural gas reforming with CCS. Moreover, as discussed in the next section, it may well turn out that technology costs fall more rapidly than expected, enabling more widespread competitiveness for electrolysis.

Uncertainty in technology innovation

Technology innovation is a process of experimentation, often involving decades to successfully bring technologies from the lab to market readiness. Many technologies will never make it out of the lab, while others may fail to scale-up to commercial scale, often due technical complications or cost challenges. Even after a technology reaches industrial scale, its longer-term uptake may depend on whether continued innovation is able to bring costs down to competitive levels. Conversely, some technologies can progress rapidly through the innovation stages. Characteristics that facilitate rapid innovation include: small enough unit size to be mass produced for rapid testing; modularity that enables sequential addition of units; and synergies with technology advances elsewhere to enable learning spillovers.

Due to the uncertainties inherent in technology innovation, the exact roles of different technologies in a sustainable future for the ammonia industry are also uncertain. The Sustainable Development Scenario provides one possible path, but there are others. The main uncertainties are the pace of development and extent of cost reductions for the electrolytic and methane pyrolysis routes. As mentioned in the previous section, while current estimates of future cost developments suggest that natural gas-based ammonia production with CCS may continue to be the most cost-competitive option in many regional contexts, it could well turn out that innovation on electrolysis and/or methane pyrolysis leads to greater cost reductions and their more widespread cost-competitiveness.

Aside from technology innovation, other uncertainties also exist that could affect the deployment of different production routes. For example, CCS-based production could have lower deployment in some regions due to insufficient build-out of CO_2 transport and storage infrastructure. This could result from challenges related to public acceptability of CCS, the co-ordination of infrastructure planning and construction, or other factors.

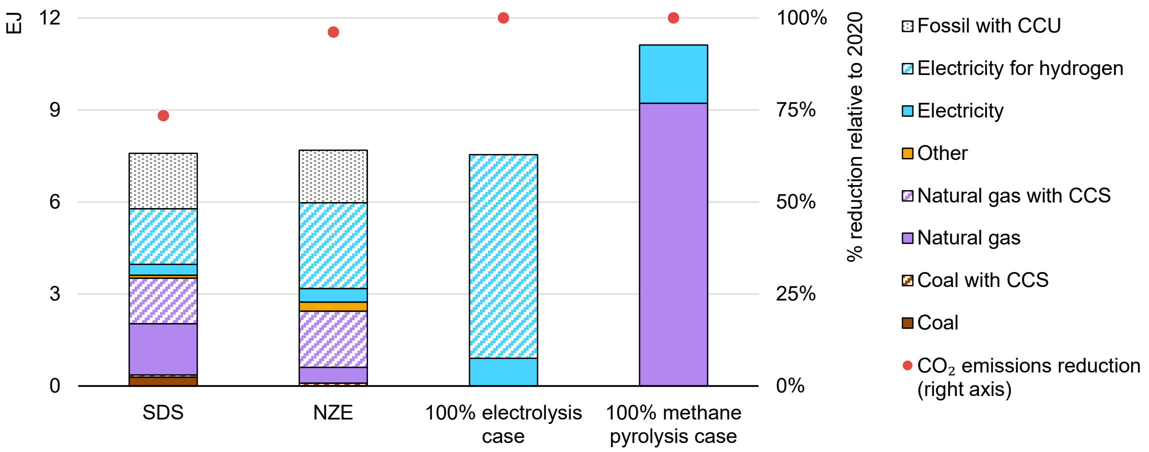
To appreciate the range of the uncertainties, it can be useful to consider the extreme cases in which 100% of ammonia production in 2050 would be via the electrolytic or methane pyrolysis routes. This is not to suggest that such an extreme case would occur in the real world – in all probability a mix of different technologies is likely. Rather it is to illustrate the outer bounds of the various possibilities, to provide a sense of the implications if particular technologies took more or less market share. In both of these cases, CO_2 emissions from ammonia production would be reduced to close to zero by 2050, which is more comparable to the level of emission reductions reached in the Net Zero Emissions by 2050 Scenario than in the Sustainable Development Scenario.

In the case of 100% electrolysis-based ammonia production, 2.5 times more electricity would be required in 2050 for ammonia production compared to the Net Zero Emissions by 2050 Scenario (3.5 times more than the Sustainable Development Scenario). This is an additional 1 200 TWh of electricity, roughly equivalent to half today's electricity demand in the European Union. Considering that in a sustainable future electricity demand will increase substantially in all end-use sectors, pursuing 100% electrolytic-based ammonia production could be challenging. It would put additional pressure on the electricity system to build out even more near-zero-emission generation and distribution capacity. Equally, however, it would eliminate the need to build CO_2 transport and storage infrastructure for the sector. It is notable that total energy requirements for this case would be similar to that in the Sustainable Development Scenario or Net Zero Emissions by 2050 Scenario. This is largely as a result of improvements in electrolyser efficiency through technology learning, which reaches about 75% efficiency in 2050 compared to about 65% today.

In the case of 100% methane pyrolysis-based ammonia production, compared to the Sustainable Development Scenario, total energy requirements would be about 45% higher and electricity requirements about 10% lower in 2050; compared to the Net Zero Emissions by 2050 Scenario, total energy requirements would again be about 45% higher, but electricity requirements about 40% lower in 2050. As in the case of 100% electrolysis-based production, infrastructure for CO_2 capture and storage would not be needed. However, a solution would be needed to deal with the 120 Mt of carbon black than is co-produced through methane pyrolysis.

Carbon black is solid carbon that is currently produced in dedicated facilities for various industrial uses. Its primary use is as reinforcement and pigment in tyres; other uses include as an agent for reinforcement, pigmentation, UV stabilisation, conductivity and insulation in other rubber products, inks, coatings and plastics. The market for carbon black is about 13 Mt per year, and with population and economic growth, demand from current uses could be expected to grow to about 20 Mt by 2050. Thus, producing all ammonia through methane pyrolysis would alone co-produce about six times as much carbon black as is likely to be needed globally. Even for the 20 Mt of demand, ammonia producers that co-produce carbon black are likely to face competition with the output of dedicated carbon black producers, as well as hydrogen producers using methane pyrolysis to produce hydrogen for use in other sectors. As such, market prices for carbon black are likely to be depressed, and the quantity of carbon black ammonia producers can sell will be less than 20 Mt. Unless other uses can be found for carbon black, the unsold quantity would likely need to be landfilled. The absence of a market for much of its carbon black may hurt the competitiveness of methane pyrolysis, as the revenue from carbon black is currently a key aspect of the technology's economic case. Once the carbon black market is saturated, even greater technology cost reductions through innovation would be needed for methane pyrolysis to cost-competitively gain a larger market share.

Figure 2.15 Ammonia production energy requirements and CO_2 emission reductions in 2050 in different technology contexts



IEA, 2021.

Notes: CCU = carbon capture and utilisation; CCS = carbon capture and storage; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. "Other" is comprised mostly of bioenergy, as well as a small amount of hydrogen-based synthetic methane imported via blending in the natural gas grid. Ammonia used as an energy carrier is not included.

Producing all ammonia from electrolysis would quadruple electricity requirements in 2050. Alternatively, producing all ammonia from methane pyrolysis would lead to a 45% increase in total energy requirements.

An additional consideration if all ammonia were produced via either electrolysis or methane pyrolysis is that neither route would generate CO_2 for use in urea production. In the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario about 155 Mt of urea are produced in 2050. This is even as urea's share of total nitrogen fertiliser production declines, stemming from efforts to reduce the CO_2 that is released after urea is applied to agricultural fields. In both scenarios the 110 Mt of CO_2 required to produce urea is supplied from natural gas SMR-based ammonia production. If using the most efficient technologies, this quantity of CO_2 in a concentrated stream would be generated from 75 Mt of ammonia production, or about one-third of total ammonia production in 2050.

If this ammonia production were displaced by electrolysis- or methane pyrolysis-based production, another CO_2 source would be needed for urea. The CO_2 could be supplied by other industries, or could be sourced from direct air capture (DAC). Using CO_2 from DAC would have an advantage that its later release during urea application on fields would be carbon neutral, given that the CO_2 was just recently extracted from the air. However, DAC has not yet been demonstrated at large scale and costs are currently very high – major developments are needed to bring the technology to full scale and bring down costs. Furthermore, DAC has substantial electricity and land use requirements compared to an ammonia plant. About 265 TWh of electricity would be needed to capture the 110 Mt of CO_2, roughly equivalent to all the electricity consumed in Indonesia today. An alternative option could be to further reduce the share of urea and instead produce other forms of nitrogen fertiliser.

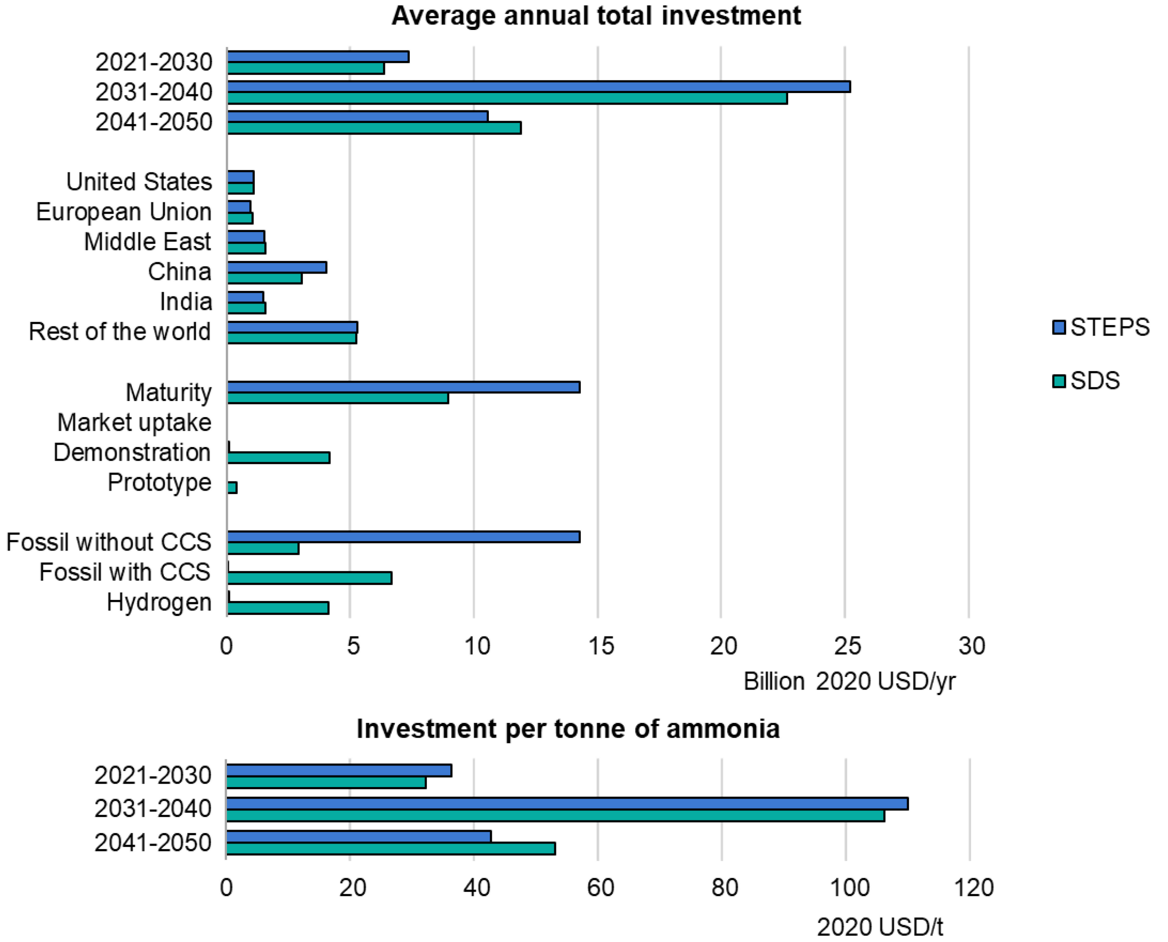
Investment

For the ammonia sector, the CO_2 emission reductions in the Sustainable Development Scenario translate into a massive overhaul of a large industrial sector that has been built up over many decades and for which conventional technologies are well established. It calls for large-scale investment in new, near-zero-emission processes and supporting infrastructure. By 2050 the global fertiliser sector will need to install 155 GW of electrolyser capacity and infrastructure to transport and store 90 Mt CO_2.

At least in the initial stages of deployment, investing in new technologies may be considered riskier, considering the uncertainties involved and given that higher total production costs for near-zero-emission routes may lead to lower profitability for the project. As such, government support mechanisms will be needed to help mobilise the required investment and align incentives to enable near-zero-emission production to be profitable (see Chapter 3). Despite the initial higher risk and uncertainty of investing in near-zero-emission technologies, in the longer term following the Sustainable Development Scenario investment pathway is likely to be lower risk. In a future where the rest of the economy is transitioning towards net zero emissions, investment in high-emitting capacity is at risk of becoming a stranded asset, unable to produce ammonia competitively within the evolving market and regulatory conditions.

The Sustainable Development Scenario will require on average USD 14 billion in capital investment in process technologies for ammonia production each year between now and 2050, of which 80% are in near-zero-emission capacity. The average annual investment required in the Net Zero Emissions by 2050 Scenario is only slightly higher, at USD 15 billion to 2050. For context, in 2019 global GDP was USD 88 trillion, of which USD 21 trillion (about 25%) was for capital investment, of which nearly USD 2 trillion (9%) was for capital investment in the energy sector.

Figure 2.16 Capital investment in process equipment for ammonia production by scenario



IEA, 2021.

Notes: CCS = carbon capture and storage; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Ammonia used as an energy carrier is not included.

While total cumulative capital investment is comparable to the Stated Policies Scenario, the Sustainable Development Scenario requires a massive redirection of investment away from conventional technologies and towards near-zero-emission technologies.

Cumulatively from now to 2050 the global capital investment required for process equipment in the ammonia industry in the Sustainable Development Scenario is comparable to that required in the Stated Policies Scenario – around USD 400 billion. However, the nature of the individual investments is quite different. In the Sustainable Development Scenario a large proportion of investment goes towards near-zero-emission process routes. About 30% is in hydrogen-based routes, including electrolysers and synthesis units to produce ammonia from electrolytic hydrogen, while 50% is in CCS-equipped routes, including the CO_2 capture equipment itself and the equipped SMR units. This means that a considerable proportion of investment goes towards new technologies – a third of cumulative investment is in technologies that are today at the demonstration or prototype stage. In contrast, virtually all investment in the Stated Policies Scenario is in mature technologies. The uncertainty involved in investing in new technologies means the investment in the Sustainable Development Scenario is higher risk, and thus government support will be important.

Many factors contribute to the scenarios' roughly equivalent investment needs – the dynamics in the Sustainable Development Scenario relative to the Stated Policies Scenario include the following:

- **Half as much cumulative capacity addition to coal-based ammonia production.** Since the CAPEX of coal-based ammonia production is about double that of natural gas-based production, this puts a downward pressure on investment.
- **Considerably higher deployment of CO_2 capture technologies.** Since applying these technologies results in additional CAPEX, this puts an upward pressure on investment, even as CO_2 capture costs decline by about 20% throughout the modelling horizon.
- **Considerable deployment of electrolysis- and pyrolysis-based ammonia production.** The costs of electrolysers and methane pyrolysis decline by more than 50% over the course of the modelling horizon due to technology learning as deployment increases across the energy system. As such, in most regions these routes have higher CAPEX than natural gas-based ammonia production until about 2030, whereas in later decades their CAPEX is lower. Regional differences in the cost of capital equipment also affect the relative costs, and since electrolysers are assumed to be more globally traded, they thus have less regional differentiation in cost of capital. Thus, electrolysis and pyrolysis deployment leads to both upward and downward pressures on investment, depending on the time period and region.
- **Lower ammonia production, by 7% cumulatively, due to use efficiency measures.** This means less production capacity is needed, putting a downward pressure on total investment. Note that the average investment per tonne of

ammonia produced over the course of the Sustainable Development Scenario is 1.5% higher than in the Stated Policies Scenario, with a 24% increase in the 2041-2050 time period.

- **Higher capacity turnover in some regions in order to meet CO_2 emission reduction requirements.** Retiring capacity earlier than would otherwise have been the case, so it can be replaced by near-zero-emission technologies, increases capacity additions and puts an upward pressure on investment.

At the global level, these upward and downward pressures balance out to lead to roughly equivalent cumulative investment in the two scenarios.

The share of total investment by region in the Sustainable Development Scenario is aligned closely with the share of production. About 22% of cumulative investment in the Sustainable Development Scenario occurs in China, which is the largest producer. This is followed by 12% in India, 10% in the Middle East, 8% in the European Union and 8% in the United States. Within each region, the difference in investment between the Sustainable Development Scenario and the States Policies Scenario is driven by the variation in technology routes followed and regional cost of capital.

In China cumulative investment is about 25% lower in the Sustainable Development Scenario than in the States Policies Scenario. Investment in coal-based ammonia production capacity is considerably lower, and a significant amount of investment is in the electrolytic route that benefits from major cost declines. In the United States and the Middle East, cumulative investment is comparable in the two scenarios. In both regions, higher investment in CO_2 capture technologies to equip natural gas-based ammonia production is outweighed by a combination of investment in lower-CAPEX pyrolysis-based production in the later decades and lower total capacity additions due to lower demand for ammonia.

Meanwhile, the European Union and India see 10% and 7% higher cumulative investment, respectively, in the Sustainable Development Scenario than in the States Policies Scenario. In the European Union this is driven primarily by early investment in considerable electrolytic-based production prior to 2030, when the CAPEX of that route is still higher than for natural gas-based production. Furthermore, the rapid deployment of electrolytic production capacity along with flat production volumes means a higher turnover of capacity. India also relies primarily on the electrolytic route. Given that India has relatively low capital costs for equipment manufactured domestically, including equipment for natural gas-based ammonia production, the electrolytic route relying on imported electrolysers retains higher CAPEX than the natural gas route throughout the modelling horizon, leading to higher investment needs in the Sustainable Development Scenario.

It is important to keep in mind that capital investment in process technologies is only one component of the costs of a more sustainable ammonia industry. Investment in R&D and demonstration is still needed to bring the required near-zero-emission technologies to market readiness. Production with CCS will require considerable investment in CO_2 transport and storage infrastructure. While the full costs of this infrastructure are likely to be shared with other sectors, the cumulative cost of transporting and storing the CO_2 captured from just the ammonia sector in the Sustainable Development Scenario through to 2050 is an estimated USD 17 billion (assuming current costs of USD 15-55/t CO_2, declining to USD 12-30/t CO_2, depending on the region).

For the electrolytic route, when electricity is produced on site from variable renewables, investment will be needed in electricity generation capacity and hydrogen storage. When electrolytic hydrogen is produced using electricity from the grid, the additional investment in electricity generation capacity and distribution infrastructure is seen by ammonia producers as electricity costs. Given that electricity costs more than natural gas and coal, the shift towards increasing production from electrolytic hydrogen in the Sustainable Development Scenario results in about USD 75 billion in additional cumulative energy costs globally during 2021-2050 relative to the States Policies Scenario, a 5% increase. This increase in total energy costs occurs even though natural gas continues to be used in the Sustainable Development Scenario at lower prices than in the States Policies Scenario, given lower global demand for fossil fuels.

The efficiency measures that moderate ammonia demand in the Sustainable Development Scenario also require investment. With regard to improved NUE on farmland, the costs are associated with planning and implementing nutrient management plans. Some of these investments are for equipment that enables better monitoring of crops and more precise application of fertilisers, such as crop sensors, weather monitors, GPS guidance systems, automatic swathe control technologies (which prevent double application on areas where fertiliser has already been applied) and variable-rate application technologies (which automatically change the application level according to the management zone or information from crop sensors).

Other costs are the expertise and labour required to design and carry out nutrient management, which may include efforts from farmers themselves as well as agronomists/crop advisers, soil scientists, extension agents and fertiliser dealers.

The cost of a comprehensive nutrient management plan can vary considerably by farm – available estimates are several thousand dollars per farm or anywhere from USD 5 to USD 30 per acre (USD 1 000 to USD 7 000 per km^2). These costs would go towards activities such as soil and crop testing (both initially and monitoring over time), developing remote-sensing imagery maps, data analysis to develop site-specific recommendations and plans, developing decision support systems, field scouting, tracking yields and fertiliser application record-keeping.

Fortunately, despite the various costs of nutrient management, there is often a pay-off not only in environmental benefits but also financially. A well-designed nutrient management plan seeks to achieve a nitrogen application rate that optimises profitability at the given site, taking into account the cost of fertilisers and the revenue gained from increased crop yields, while also ensuring environmental objectives are met. By reducing the over-application of fertilisers, one estimate suggests that precision agriculture techniques could save anywhere from 5% to 30% of input costs and would provide a return on investment within a couple of years.

Chapter 3. Enabling more sustainable ammonia production

Highlights

- Governments, producers and other stakeholders have already begun taking action to reduce emissions from the ammonia industry. Some governments have adopted carbon pricing and are funding innovation, while producers have set emission reduction targets and are undertaking RD&D projects. Despite these efforts, emissions continue to rise, and greater ambition is needed.
- Governments have a central role to play. They will need to establish a policy environment supportive of ambitious emission cuts by creating transition plans underpinned by mandatory emission reduction policies and mechanisms to mobilise investment. Targeted policy is also required to address existing emissions-intensive assets, create markets for near-zero-emission products, accelerate RD&D and incentivise end-use efficiency for ammonia-based products. Governments should ensure that enabling conditions are in place, including a level playing field in the global market for low-emission products, infrastructure for hydrogen and CCS, and robust data on emissions.
- Ammonia producers will need to establish their own plans for the transition, for addressing existing capacity and deploying near-zero-emission technologies. Accelerating RD&D on near-zero-emission technologies will help lower costs and ensure the needed technologies are available in the market. Producers and industry associations should engage in initiatives to develop supporting infrastructure and improve data provision on emissions performance.
- Farmers and agronomists should prioritise best management practices for more efficient fertiliser use. The food industry can adopt purchasing practices supportive of low-emission production methods and inputs, based on taxonomies developed by the research community. Financial institutions should use sustainable investment schemes to direct resources towards emission reduction opportunities, while diverting investment from emissions-intensive assets that could become stranded. Non-governmental organisations can raise awareness of the benefits and requirements of near-zero-emission technologies.
- Time is of the essence. The next decade – from now to 2030 – is critical to lay the foundation for long-term success. Vital near-term actions include establishing strong supportive policy mechanisms, taking action on energy and use efficiency, developing supporting infrastructure, and accelerating RD&D.

The current policy, innovation and financing landscape

Governments, producers and financial institutions around the world are putting in place various policies and programmes to kick-start the transition towards a near-zero-emission ammonia industry. These endeavours are a promising start. However, further action is needed to accelerate progress and put the sector on a sustainable trajectory that achieves the goals of the Paris Agreement.

Ongoing efforts by governments

Governments have an integral role to play in the ammonia industry's transition. Without strong policy frameworks in place, it will be very challenging for ammonia producers to achieve large emissions cuts while remaining competitive. Several major ammonia-producing countries already have policies and programmes in place to reduce the sector's emissions (Table 3.1), although none yet has all the elements of a comprehensive strategy to facilitate deep emission reductions. The majority of the policies in place today apply to the broader industrial sector (covering steel, cement, chemicals, etc.), while some elements target fertilisers and ammonia in particular. Broader national climate strategies and emission reduction targets also help signal the need for emission reductions in all sectors of the energy system.

Carbon pricing and energy efficiency measures

Several governments are aiming to reduce industrial-sector emissions through carbon pricing, implemented via an emissions trading system (ETS) or carbon tax. The European Union introduced the EU ETS in 2005, covering large industrial emitters including ammonia production. The system had relatively limited impact on industrial emissions in its early years due to an overabundance of allowances and low prices. However, in recent years prices have risen considerably, exceeding EUR 60 (USD 70) per tonne of CO_2 in 2021. The revised EU ETS Directive for the period 2021-2030 will require the sectors within its scope to reduce their emissions by 43% by 2030 compared to 2005 levels. Ammonia production falls within the ETS scope and includes CO_2 emitted from the ammonia production facility and CO_2 utilised downstream as a chemical feedstock (thus CO_2 emissions that occur from urea decomposition when fertiliser is applied to the fields are attributed back to ammonia producers, given that ammonia is usually the source of the CO_2 used for urea production).

An ETS in China came into force in February 2021, initially only covering the power sector. It is expected that initial prices will be low, equivalent to about CNY 25 (USD 4) per tonne CO_2. There are plans to include several industry sub-sectors, including the chemicals industry, at an unspecified future date. The Chinese administration required key energy-intensive industries to report their emissions in 2020, which signals a move towards better data collection for their eventual inclusion in the ETS. Korea has also had an ETS since 2015, which reached an average price of KRW 32 600 (USD 28) per tonne CO_2 in 2020. A number of other major ammonia-producing countries are making initial steps to trial ETS systems, which could potentially be later applied to ammonia production. Indonesia is considering developing a national ETS, with a voluntary trial for the power sector taking place in 2021. In Russia, the region of Sakhalin is planning to pilot a carbon trading scheme from mid-2020, which the national government has said could serve as an experiment for potential future scaling up at the national level.

Other countries are adopting alternative methods of carbon pricing for industry. Canada, for example, has adopted an output-based carbon pricing system, which resembles a tradeable performance standard. It is applied in those provinces without their own equivalent or more stringent carbon pricing system. The scheme is designed to reduce the impact on trade-exposed producers by only charging for emissions above a specified emission intensity threshold – similar in outcome to the EU's system with its current free allocation. It still provides an incentive for additional reductions by issuing credits for performance improvements beyond what is necessary to stay just under the threshold. The carbon price is CAN 40 (USD 32) per tonne as of 2021 and is set to rise gradually to CAN 170 (USD 135) per tonne by 2030.

As countries are adopting increasingly stringent carbon prices, several are looking into mechanisms to help address the potential impact of carbon prices on competitiveness for trade-exposed industries. Since its inception, the EU ETS has allocated free allowances for emissions equivalent to production at a benchmark emissions intensity to those industries deemed at highest risk of production relocation, including ammonia. The benchmark is set according to the average greenhouse gas emissions of the best-performing 10% of installations producing the product in the European Union and other European Economic Area/European Free Trade Association countries.

As the ETS carbon price continues to rise, the European Union has chosen to explore another method of protecting competitiveness. In July 2021 the European Commission adopted a proposal for a Carbon Border Adjustment Mechanism (CBAM) that will apply a carbon price to imported goods equivalent to the EU ETS price. According to the proposal, starting in 2023 importers in the sectors initially covered – including fertilisers – will be required to report embedded emissions and purchase equivalent certificates starting in 2026, unless the producer has already paid an equivalent carbon price in the country of origin. The proposal must still undergo review and possible modification by the European Parliament and Council of the European Union before being considered final. Allocation of free allowances to sectors covered by the CBAM will be phased out between 2026 and 2035. The United States and Canada are each also in earlier stages of considering carbon border adjustments, as stated by the United States in its Trade Policy Agenda released in March 2021 and by Canada in its 2020 Fall Economic Statement.

A number of notable energy policies applicable to industry have focused specifically on improving energy efficiency, which may include investment in new equipment and enhanced equipment operations. India's Perform, Achieve, Trade (PAT) Scheme, which began in 2012, uses market-based regulation to drive industry energy efficiency towards sectoral targets. The mechanism aims to be economically efficient – entities that reduce energy consumption beyond the required threshold receive certificates, which can be sold to other entities that need to achieve compliance. China's top energy-consuming enterprises programme[1] requires large enterprises to undertake measures to achieve specified energy savings targets, including establishing energy management systems.

Support for near-zero-emission technology RD&D and early commercial deployment

Governments are also funding R&D for near-zero-emission industrial technologies. The EU Innovation Fund, the successor of the NER300 programme, will provide grants to fund projects demonstrating innovative low-emission technologies, including innovative processes in energy-intensive industries and CCS. The first call for large-scale project proposals closed in autumn 2020, with grants to be awarded by the end of 2021. Of the 311 large-scale projects that applied, two-thirds (204) are related to energy-intensive industries, of which one-quarter (56) are related to hydrogen. The second call for large-scale projects is

[1] Referred to as the Top 10 000 Program in the 12th Five-Year Plan and the 100, 1 000, 10 000 Program in the 13th Five-Year Plan; program inclusion and design for the 14th Five-Year Plan may be forthcoming in more specific five-year plans that follow the release of the outline plan.

expected in October 2021. The first call for small-scale projects has already seen 32 successful projects funded, although none are for ammonia or fertiliser production.

In the United States, Advanced Research Projects Agency–Energy (ARPA-E) is supporting a diversity of advanced energy technologies, including a methane pyrolysis cohort launched in 2019 that is funding several projects. The UK Research and Innovation's Industrial Decarbonisation Challenge announced the successful applicants in March 2021, with GBP 171 million (USD 240 million) in funding for nine industrial cluster decarbonisation projects. They include the HyNet hydrogen and CCUS project and the Net zero Teesside CCUS project, both of which include fertiliser production activities. In Australia, the Australia Renewable Energy Agency and the Western Australia Renewable Hydrogen Fund have provided funding for projects aiming to manufacture ammonia from hydrogen produced from renewable electricity, including AUD 1.6 million (USD 1.2 million) for a feasibility study completed in mid-2020 and AUD 2.0 million (USD 1.5 million) for a capital works project, whose initial phase aims to produce 3.5 kt of ammonia by 2022.

Incentives and funding are also being offered for early-stage *deployment* of near-zero-emission technologies and infrastructure, including CCS and hydrogen. CCS projects in the United States are eligible for a tax credit under the Internal Revenue Code Section 45Q, ranging from USD 20 to USD 50 per tonne of CO_2 stored, depending on the year (the credit increases over time) and whether the project involves EOR or dedicated geological storage. The Canadian government's 2021 budget proposed a tax credit for capital invested in CCUS projects, intended to enter into effect in 2022. Also in Canada, the Alberta Carbon Trunk Line, which began operation in 2020 transporting CO_2 captured at a fertiliser plant (0.3 Mt CO_2/yr capture) and a nearby oil refinery, has received close to CAD 500 million (USD 400 million) in funding from the Alberta government and CAD 63 million (USD 50 million) from the Canadian government. In Norway, hydrogen and ammonia produced via electrolysis are supported by exempting the electricity used from taxation.

Creating a market for materials produced with a substantially reduced emissions footprint (near-zero-emission materials) is an area where government support is emerging. Germany is preparing plans to use carbon contracts for difference (CfDs) to support near-zero-emission industrial production, including ammonia, through a guaranteed minimum strike price for near-zero-emission production. The country's National Hydrogen Strategy, released in mid-2020, proposed the launch of a pilot CfD programme, and draft plans for the programme were released in April 2021. Germany is also considering a rising demand quota for near-zero-emission materials. The European Commission is considering use of CfDs as part of its proposal for a revised ETS Directive.

Accelerating efforts to expand and decarbonise hydrogen production in recent years are likely to assist the ammonia industry's transition. Several jurisdictions have developed hydrogen strategies, often covering ammonia and fertilisers. The European Union launched its new "Hydrogen strategy for a climate-neutral Europe" in 2020, which mentions a possible carbon CfD pilot scheme targeting hydrogen use in various industries, including fertilisers. In India, a National Hydrogen Mission for 2021-2022 is under development, and may include mandates to use green hydrogen in key industries such as fertilisers. Japan announced in early 2021 a target to increase the country's demand for ammonia as a fuel from zero to 3 million tonnes by 2030. For a more detailed discussion of policies for the use of low-carbon ammonia as an energy carrier, and other hydrogen-based fuels, consult the IEA publications the *Global Hydrogen Review 2021* and *The Role of Low-Carbon Fuels in Clean Energy Transitions of the Power Sector*.

Policies for improving efficiency of use

On the demand side, many countries have in place policies and programmes targeting more efficient cropland fertiliser application. In many cases, the primary motivations are to reduce nitrogen pollution in aquatic ecosystems or nitrous oxide (N_2O) emissions from nitrogen fertiliser use, rather than to reduce CO_2 emissions from fertiliser production. However, by enabling and incentivising more efficient use of fertilisers, they reduce growth in fertiliser demand and moderate the level of investment needed to deploy innovative technologies to reduce CO_2 emissions during the production phase.

Some of the policies include broader nitrogen and fertiliser-related strategies and targets. The EU Nitrates Directive, which came into effect in 1991 with the aim of protecting water quality, establishes voluntary codes of good agricultural practice, including measures to limit the timing of and set the conditions for fertiliser application. The EU National Emissions reduction Commitments Directive, originally legislated in 2001 and revised in 2016, sets limits on ammonia emissions for its member countries, which should encourage more efficient use of nitrogen fertilisers. In 2020 the EU launched its Farm to Fork Strategy, which includes a target to reduce nutrient losses by at least 50% by 2030, with the expectation of a 20% reduction in total fertiliser use, and states the intent to develop an integrated nutrient management action plan. In 2015 China adopted an Action Plan for the Zero Increase of Fertiliser Use, targeting a halt in the growth of fertiliser use in

2020. Total fertiliser use in China has indeed declined since 2015, perhaps in part thanks to the action plan. Canada's updated climate strategy, "A Healthy Environment and a Healthy Economy" launched in 2020, includes an objective to reduce emissions from fertiliser application by 30% below 2020 levels. Additionally, taxes on nitrogen fertiliser have been under discussion in a number of countries, including France and New Zealand, although the proposals tend to be met with considerable opposition.

A number of countries have requirements and programmes in place focused on more specific aspects of fertiliser use. In India, a requirement has been in place since 2016 for all urea used in the country to be coated with neem oil, which slows the release of nitrogen. While partially motivated by the economic objective of reducing the diversion of subsidised fertiliser into chemical applications, the policy can also help encourage more efficient fertiliser application. Additionally, India's National Biogas and Manure Management Programme helps to reduce the need for chemical fertilisers by supporting the creation of small-scale biogas plants. In addition to producing biogas, the plants also produce a digested slurry that can be used as enriched bio-manure. A number of Indian states are also promoting zero-budget natural farming, which focuses on avoiding external inputs of fertiliser and pesticides to reduce costs for farmers and improve environmental outcomes. In Brazil, the Inovagro programme run by the national development bank, BNDES, helps finance technology innovation in agriculture, including precision agricultural equipment and fertiliser application maps.

A number of policies are also in place that could curb demand for other applications that use smaller amounts of nitrogen, particularly plastics. Many countries have been increasing their plastics recycling activity, including improvements in collection and sorting. Japan and Korea lead the way, having achieved single-digit landfill rates. Several jurisdictions have adopted or are working towards policies to curb single-use plastics, including the European Union, the United Kingdom and Canada.

International collaboration

At the international level, a number of countries came together to launch the Industrial Deep Decarbonisation Initiative in June 2021, focused on stimulating demand for low-carbon industrial materials. An initiative of the Clean Energy Ministerial (CEM) and co-ordinated by the United Nations Industrial Development Organisation (UNIDO), it will initially focus on steel and cement, but could expand to other materials in the future. It could present useful learning opportunities for other efforts to create market demand and harmonise emissions performance data and standards.

The Clean Development Mechanism (CDM) under the Kyoto Protocol provides a mechanism for countries to fund greenhouse gas emission reductions in other countries and to claim the emission reductions towards meeting their own targets under international agreements. Projects to reduce N_2O emissions from nitric acid plants have been a common project type under the CDM, with close to 100 such projects registered under the mechanism. Almost all of these projects, however, were initiated prior to 2013, after which time declining demand and thus considerably lower prices for Certified Emission Reduction units have made N_2O abatement projects under the CDM less economically attractive and caused some projects to be abandoned. Perhaps in future a reform of the CDM or a new mechanism could lead to a revival of international co-operation on N_2O abatement, which is a relatively low-cost, easy-win way of reducing greenhouse gas emissions from fertiliser production. The experience with the CDM provides some important learnings for the design of mechanisms in the future, including the need to provide certainty and stability for producers in order for mitigation measures to be seen through to completion.

Efforts are also under way to address nitrogen pollution at the international level, which could help improve the efficiency of nutrient use. Several existing United Nations multilateral environmental agreements and resolutions are of relevance to nitrogen – including the Paris Agreement, the Montreal Protocol, the Convention on Biological Diversity and the Convention on Long-range Transboundary Air Pollution – but none is dedicated specifically to nitrogen. The UN Environment Programme (UNEP) is working towards developing an Inter-convention Nitrogen Coordination Mechanism (INCOM) to bring together the nitrogen-related aspects of existing initiatives, through the Nitrogen Working Group of the UNEP Committee of Permanent Representatives.

Various initiatives at the international level are moving closer to the goal of a co-ordinated and holistic approach to nitrogen management. In 2016 UNEP and the International Nitrogen Initiative, supported by funding from the Global Environment Facility, launched the International Nitrogen Management System, a platform to bring together stakeholders from the spheres of science, policy and industry to develop guidance on nitrogen management. The initiative is working to produce the first International Nitrogen Assessment, due to be published in 2022. In 2019 member states of the United Nations endorsed the Colombo Declaration on Sustainable Nitrogen Management, a proposed plan for action on nitrogen that includes the objective of halving nitrogen waste by 2030. Additionally, in 2020 the parties to the UN Economic Commission for Europe's Convention on Long-range Transboundary Air Pollution adopted a new Guidance Document on Integrated Sustainable Nitrogen Management. It provides an overview of principles and measures to be taken into consideration when formulating nitrogen management strategies, including promoting a circular economy approach for nitrogen.

Table 3.1 Key current government policies and programmes that could enable progress towards sustainable ammonia production and use

Country or region	Carbon pricing and standards	Energy efficiency policies	R&D programmes for clean technologies	Deployment incentives for clean technologies	Collaboration and knowledge sharing	Efficiency of use policies and targets
China	-	Top 100/ 1 000/10 000 Enterprises Program	National Key Technologies R&D Program	-	-	Action Plan for the Zero Increase of Fertilizer Use
European Union	Emissions Trading System	Energy Efficiency Directive	Innovation Fund; Horizon Europe	-	ZEP and EERA under the SET Plan	Nitrates Directive; Farm to Fork Strategy
United States	-	Energy Star fertiliser plant energy performance indicator and certification	ARPA-E; AMO cost-sharing	Section 45Q tax credit for CCUS		Integrated Farm Management Program Option
India	-	Perform, Achieve, Trade Scheme	-	-	-	National Biogas and Manure Management Programme; Fertiliser neem coating requirement
Canada	Output-based carbon price	-	EIP; PERD; Strategic Innovation Fund	-	Canadian Industry Partnership for Energy Conservation	A Healthy Environment and a Healthy Economy climate strategy
Australia	ERF Safeguard Mechanism	-	ARENA grants	-	-	-

Notes: This table features examples of key policies in a number of countries that are major ammonia producers and/or have ambitious ammonia-related emission reduction policies; it is not intended to be a comprehensive list of all policies in all countries. Policies of subnational governments are not included, nor are proposed programmes (e.g. the China ETS expanding coverage to industry). AMO = Advanced Manufacturing Office; ARPA-E = Advanced Research Projects Agency-Energy; ARENA = Australian Renewable Energy Agency; EERA = European Energy Research Alliance; EIP = Energy Innovation Program; ERF = Emissions Reduction Fund; PERD = Program of Energy Research and Development; SET Plan = Strategic Energy Technology Plan; ZEP = Zero Emissions Platform (a European Technology and Innovation Platform for CCS).

Encouraging progress in the private sector

Private-sector stakeholders are also making efforts to reduce emissions from the nitrogen fertiliser industry. A number of companies that produce ammonia are developing climate plans and setting emission reduction targets. Major ammonia-producing companies with targets for net zero emissions or climate neutrality by 2050 include CF Fertilisers, Yara, Sinopec and BASF, which together account for close to 15% of global ammonia production. Some companies have made shorter-term targets, including Nutrien (30% per tonne reduction by 2030 relative to 2018), CF Fertilisers (25% per tonne reduction by 2030 relative to 2015) and Yara (30% absolute reduction by 2030 relative to 2019). The IFA has also established an ambition to reduce greenhouse gas emissions from nitrogen fertiliser production by at least 30% per tonne by 2040.

Ammonia producers are already starting to implement measures to reduce CO_2 emissions from their operations. Many are adopting energy efficiency measures in their existing and new plants. Another emissions-reducing option that some producers are instigating is to use waste materials as inputs for production, such as ammonium nitrate from wastewater treatment plants. Companies are also taking major steps towards the adoption of near-zero-emission technologies by undertaking R&D and demonstration. See Chapter 2 Table 2.1 for information on activities in this area.

Industry associations can also play a valuable role in promoting and aiding emission reductions among their members, for example by providing comparative metrics and facilitating knowledge exchange. Since 2004 the IFA has offered ammonia energy efficiency and CO_2 emission benchmarks to its members, which they can voluntarily use for tracking progress. Since then, members have achieved a 14.5% reduction in CO_2 emissions per tonne of ammonia produced and 5.5% net improvement in energy efficiency on average. The Fertiliser Association of India (FAI) has been monitoring and benchmarking the energy efficiency of ammonia and urea plants in India for many years, as well as calculating their CO_2 emissions, which can help spur improvements. Through the modernisation of old plants, commissioning of new efficient plants in the 1990s and shift in feedstock from liquid fuels to natural gas in the past 15 years, the FAI estimates that in the past three decades India’s ammonia plants have reduced CO_2 emissions by 45% and energy consumption by 34%.

Fertilizers Europe has developed a Carbon Footprint Calculator, launched in 2014, which enables fertiliser producers to measure and benchmark their CO_2 emissions, as well as to report verified results via a certification scheme developed in partnership with the Carbon Trust. Certified results could be useful for attracting buyers concerned about sustainability, including farmers looking to achieve their own sustainability-oriented certifications under programmes such as the Cool Farm Tool. Some fertiliser producers, such as CF Fertilisers, have already begun certifying and labelling their production to promote their emission reductions to buyers. Industry association product stewardship programmes and requirements, including those of the IFA and Fertilizers Europe, can also help push producers to improve their environmental performance and reduce emissions along the full fertiliser value chain.

NUE is another area of private-sector action. The IFA has worked on promotion and knowledge sharing in this area, including through a set of six Nutrient Stewardship Commitments that affirm its members' goal of working with farmers towards improved NUE. In the spirit of helping accelerate progress, in May 2021 the association adopted an ambition to improve average global nitrogen use efficiency in crop production from the current level of 50% to 70% by 2040. It also seeks to accelerate plant nutrition innovation through its Smart and Green platform, which brings together the plant nutrition industry and the agricultural technology start-up ecosystem. The EU Nitrogen Expert Panel, initiated by Fertilizers Europe in 2014, has developed a nitrogen use efficiency indicator to promote efficiency improvements among famers. The 4R Nutrient Stewardship Initiative was set up by Fertilizer Canada and The Fertiliser Institute, in collaboration with the International Plant Nutrition Institute and the IFA. Its components include a series of online training modules, a research fund to establish indicators and data, and an advocate programme.

Initiatives involving financial institutions and investors

In recent years the financial sector – including public, private and multilateral banks – has been increasingly working on initiatives to channel finance towards sustainable and lower-emitting projects. Providing information about climate risks and sustainability performance is a key component of that. The Task Force on Climate-related Financial Disclosures (TCFD), established by the Financial Stability Board, is helping companies develop voluntary climate-related financial risk disclosures to better inform investors. Various non-profit organisations are encouraging stakeholders to integrate climate risks into their investment strategies and financial regulations. Many financial institutions are now offering sustainability-focused products and services, such as green investment opportunities and incorporation of environmental, social and governance factors into credit ratings.

Various initiatives are endeavouring to define what constitutes "green" or "sustainable" investment. The EU Taxonomy establishes six environmental objectives for determining whether an economic activity is environmentally sustainable, including objectives related to climate change. The Taxonomy Regulation came into force in summer 2020, with a delegated act published in April 2021 defining technical screening criteria for determining whether economic activities have a substantial positive impact on climate change adaptation and mitigation objectives. Under the Taxonomy, ammonia production is considered to have a substantial positive contribution to climate change mitigation if it is produced with hydrogen that has greenhouse gas emissions 73% lower than unabated fossil fuels. Another classification being developed is the International Organization for Standardization's standard for green bonds (ISO 14030), which builds upon the Green Bond Principles established by the International Capital Market Association and other existing classifications. Meanwhile, in 2015 multilateral development banks established a set of Common Principles to define what constitutes finance for climate change mitigation. Dialogue is also ongoing between stakeholders on standards for "transition bonds" for emissions-intensive industries that may not yet be eligible for finance through "green" bonds, but will need finance for their transition towards near-zero emissions.

Multiple international funds and programmes are making use of contributions from numerous governments to finance clean energy transitions. While no funds target ammonia in particular, the sector could be eligible under several of these funds, particularly those that include a focus on the industrial sector. Key funds and programmes – which use various mechanisms such as grants, concessional loans and guarantees – include:

- The Green Climate Fund under the Paris Agreement, which aims to support developing economies in achieving their emission reduction ambitions. Its High Impact Programme for the Corporate Sector, administered by the European Bank for Reconstruction and Development, targets uptake of low-carbon technologies in industry.
- The Clean Technology Fund under the Climate Investment Funds framework, which is administered by several multilateral development banks to finance the demonstration, deployment and transfer of low-carbon technologies in middle-income and developing economies, including industrial energy efficiency projects.
- The Global Environment Facility established at the Rio Earth Summit, which assists developing and economies in transition to meet international environmental convention objectives, including those of the United Nations Framework Convention on Climate Change.
- The European Fund for Sustainable Development, which supports investments to achieve the SDGs in Africa and the European Union's neighbouring countries, including investment in the industrial sector.
- The Nitric Acid Climate Auctions Program, administered by the World Bank in collaboration with the Nitric Acid Climate Action Group initiated by the German government, which provides price guarantees for nitric acid plants to sell carbon credits for their abatement projects.

Many countries also have their own funds and programmes targeted towards domestic and international low-carbon technology investment.

Recommendations for accelerating progress

While encouraging activity is underway, it is far from sufficient. Greater ambition is needed on multiple fronts from a diversity of stakeholders around the world to put ammonia producers on a pathway to achieving deep CO_2 emission reductions. Many of the same components are needed universally for a sustainable transition, even though varied regional circumstances will affect the specifics of planning and policy design. Collaboration among stakeholders – including governments, producers, consumers, technology suppliers, financial institutions, researchers, non-governmental organisations and others – will be integral to accelerating progress (Figure 3.1).

Governments must lead by laying the fundamental groundwork, consisting of a clear, reliable long-term policy signal for emission reductions and financial mechanisms to help mobilise the necessary investment. Additional policies are needed to target specific technology categories, including existing high-emission plants, clean technologies that are market ready and clean technologies at earlier stages of development. In addition, policies should promote improved NUE. Supporting conditions must also be put in place, including establishing a level playing field for producers around the world, developing enabling infrastructure, and improving data collection and reporting.

Figure 3.1 A framework for accelerating the sustainable transition of the ammonia industry

Driving force: stakeholder collaboration

- Leading role: governments, ammonia producers and associations
- Supporting role: farmers, agricultural co-operatives, agribusiness, food processers and suppliers, users of other ammonia-based products, financial institutions, investors, other industries, technology suppliers, trade unions, researchers, non-governmental organisations

Framework fundamentals

Establishing plans and policy for long-term CO_2 emission reductions

- Roadmaps for multiple levels: climate change, sustainable development, industrial sector, ammonia industry, companies, just transition
- Legislated policy: emissions trading systems, carbon taxes, tradeable emissions standards

Mobilising finance and investment

- Direct public funding (e.g. grants, development aid)
- Public financing mechanisms to mobilise private investment (e.g. low-interest and concessional loans, blended finance), including international finance
- Sustainable investment schemes and taxonomies

Targeted actions for specific technologies and strategies

Production technologies

Managing existing assets and near-term investment

- Retrofits and retrofit-ready builds
- Tradeable energy efficiency schemes
- Differentiated policy for existing plants

Creating a market for near-zero-emission ammonia products

- Carbon contracts for difference, public and private procurement
- Minimum content regulations
- Certification and product stewardship initiatives

Developing earlier- stage near-zero-emission technologies

- RD&D funding, public-private partnerships
- Knowledge sharing, innovation co-ordination

Use phase

Improving use efficiency for ammonia-based products

- Nitrogen quotas, fertiliser taxes, mandatory fertiliser application reporting, subsidy reform
- Training, knowledge exchange and decision support systems

Necessary enabling conditions

Enhancing international co-operation and creating a level playing field

- International carbon markets, sectoral agreements, carbon border adjustments, climate clubs, consumption-based emissions policy
- Technology transfer, best practice sharing, international finance

Planning and developing infrastructure

- Co-ordinated planning and public financing for CO_2 transport and storage, and for reliable, decarbonised electricity and hydrogen production and distribution

Tracking progress and improving data

- Increased data collection and reporting
- Low-emission labelling and standards for nitrogen fertilisers and other ammonia-based products

IEA. 2021.

Stakeholders will need to collaborate on multiple fronts to drive the ammonia industry's transition towards a more sustainable future, including long-term planning and policy signals, targeted technology strategies and enabling conditions.

Framework fundamentals

Establishing plans and policy for long-term CO_2 emission reductions

A clear vision of the path ahead, and a commitment to following it, is imperative to accelerate the transition. Governments will be instrumental in providing clarity, certainty and a business case for investing in near-zero-emission technologies. They can help establish a strong and stable market signal for emission reductions by incorporating Paris Agreement-aligned medium- and long-term plans and targets for the ammonia industry within climate, energy, and industrial strategies. The industry should be actively involved in the planning process.

Planning for the ammonia industry's energy transition should take careful consideration of broader strategies to achieve the UN SDGs, including the role of the ammonia industry in addressing climate change (SDG 13), responsible production and consumption (SDG 12), affordable and clean energy (SDG 7), sustainable industrialisation (SDG 9) and zero hunger (SDG 2). Care should be taken that plans and policies are designed in such a way that addressing one objective does not jeopardise another. In particular, given the importance of nitrogen fertilisers in food production, governments should have in place safeguards to ensure the energy transition does not negatively impact the affordability of agricultural production and food. Measures may include monitoring prices, maintaining dialogue with farmers and, if necessary, using carefully designed support mechanisms (perhaps attached to NUE targets, in order to protect affordability but disincentivise inefficient fertiliser use). Additionally, just transition provisions should be incorporated into plans to minimise potential employment and other social impacts, and ensure an orderly transition.

Strategies should be backed by mandatory long-term emission reduction policies, with stringency increasing over time in a predictable manner. This may include carbon pricing in the form of carbon taxes or an ETS, or a tradeable emissions performance standard that would require a decreasing average emission intensity of ammonia production. As discussed above, a number of jurisdictions are already adopting carbon pricing, but increased stringency is needed in those regions, as is coverage of a greater number of countries. For low-cost measures such as N_2O abatement from nitric acid plants, governments could mandate the use of abatement technologies to accelerate near-term progress. While an integral part of the overall strategy, mandatory policies are likely to be insufficient on their own to enable the full sustainable transition, and must be complemented by other components discussed in subsequent sections.

The ammonia industry should also establish corporate strategies for the energy transition and climate governance plans, recognising that transitioning to sustainable production methods will be important for staying competitive in the long run. Such strategies should include long-term targets aligned with the Paris Agreement and a plan for how investment, plant retrofitting and R&D will enable those targets to be achieved. Such planning would help facilitate long-term business planning, bring shareholders and employees together behind a common vision and show commitment to shareholders. Industry support for and input into government policy design and planning processes are also important.

Key actions

- **Governments:** in consultation with industry, develop sustainable transition plans for the ammonia industry; establish long-term emission reduction policies such as carbon pricing or emissions standards.
- **Ammonia industry:** establish long-term corporate strategies for the energy transition; engage in road-mapping exercises and support government policy design.
- **Researchers and non-governmental organisations:** contribute to road-mapping exercises and policy design; galvanise support for industry transition plans.

Mobilising finance and investment

A massive redirection of capital investment will be required for the sustainable energy transition, away from incumbent technologies and towards R&D, demonstration and deployment of near-zero-emission technologies at existing and new plants, and in supporting infrastructure. As discussed in the previous chapter, 80% of cumulative capital investments in the Sustainable Development Scenario are in near-zero-emission capacity. Governments have a role to play in providing funding through direct grants and other subsidies, most likely targeting areas with the highest risk or other barriers to overcome, such as R&D, first-of-a-kind commercial projects and perhaps shared infrastructure. They should also lead the development and application of sustainable finance taxonomies that set a clear standard for sustainable investment in the fertiliser sector, as is being done at the EU level.

Private-sector investment will also be crucial for the full rollout of sustainable technologies. The public sector can help mobilise private investment through mechanisms that take on some of the financial risk of early projects or provide other incentives for investment. Such mechanisms may include concessional and subordinated loans, debt guarantees, early-stage equity investment, tax incentives and blended finance. Removing fossil fuel subsidies would also shorten the timeline for new near-zero-emission technologies to reach cost parity and thus help redirect existing sources of finance to sustainable technologies. Furthermore, governments can help mobilise private investment by ensuring they have a strong policy framework for CO_2 emission reductions in place, via the other policy pillar discussed in this chapter.

The case for governments and banks to provide direct funding and finance mechanisms within their countries is clear, as it enables domestic projects. But there is also a critical need for international finance, particularly to enable a timely transition in emerging markets and developing economies, as well as in other countries where sufficient private-sector finance is not accessible. This could take various forms, including contributions to funds administered by multilateral institutions and development banks, bilateral agreements and official development aid. When adequately backed by their member governments, financing through multilateral development banks is likely to play a key role. While a number of funds that could finance ammonia industry projects already exist, as discussed above, a successful global transition will require advanced economies to massively scale up international finance. There is also a case for more targeted funds focusing on the industrial sector, perhaps with funding allocated specifically to ammonia production to ensure adequate coverage.

The financial sector has a valuable role to play in facilitating access to finance for the energy transition, and it can leverage this finance to push the private sector towards new, more sustainable business models. Financial institutions can help bring sustainability criteria, climate and stranded asset risks, and other environmental, social and governance (ESG) considerations to the forefront of investment decisions among both investors and companies seeking finance. This can be done through products and incentives such as responsible investment schemes, ESG factors incorporated into credit ratings, and financial risk disclosures. Financial institutions should also embed consideration of stranded assets and other ESG risks into their own core risk evaluations. They can also directly help raise capital by issuing green bonds and transition bonds that include opportunities to fund emission reduction projects in the ammonia industry. The financial sector should also work with the public sector in developing sustainable finance taxonomies and delivering blended finance.

Producers in the ammonia industry can take steps to position themselves for access to green and transitional finance, which may include developing clear energy transition strategies, integrating climate risks into their financial planning, and disclosing information on their environmental performance and climate risks.

They can also directly raise capital by issuing their own green and transition bonds in line with established sustainability criteria.

Key actions

- **Governments:** provide direct funding to early-stage near-zero-emission projects; develop finance mechanisms to mobilise private investments in near-zero-emission projects; increase contributions to international low-carbon development funds; develop and apply sustainable finance taxonomies.
- **Financial institutions:** promote investment in low-emission technology deployment among investors through sustainable finance schemes; issue green and transition bonds; work with governments on blended finance mechanisms and sustainable finance taxonomies.
- **Investors:** consider environmental performance and climate risks in investment choices, aided by sustainable investment schemes and taxonomies.
- **Ammonia industry:** provide information to potential investors on environmental performance and climate risks; issue green bonds to raise capital.
- **Researchers and non-governmental organisations:** help define levels of CO_2 emissions performance that align with a sustainable energy transition trajectory.

Targeted actions for specific technologies and strategies

Managing existing assets and near-term investment

Considering the long lifetimes of typically 20-50 years or more for ammonia plants, specific attention is needed on emissions-intensive plants built recently and any added in the coming few years before near-zero-emission technologies are available at commercial scale.

For existing assets, owners can pursue energy efficiency gains through equipment upgrades to incorporate technologies such as waste heat recovery and improved process operations. Efficiency improvements, however, should be balanced with the need for a fundamental shift to new near-zero-emission technologies in the medium term, and should only be pursued to the extent that they do not create investment “lock-in”. Governments can promote improvement through energy benchmarking schemes, energy performance schemes (perhaps with time-limited exemptions for plants close to retirement to avoid investments that will not pay off in the long run) and incentives for energy efficiency improvements. Producers should also consider opportunities to retrofit or convert existing assets to incorporate lower-emitting or near-zero-emission technologies such as CCS or electrolytic hydrogen. In the shorter term, this may include switching to lower-emitting fuels such as from coal to natural gas. Another option may be to convert plants to a hybrid that uses hydrogen produced from electrolysis for process energy while maintaining natural gas for feedstock, using the CO_2 emissions from the feedstock for urea production.

Considering that near-zero-emission technologies for ammonia production are already market-ready (in the case of CO_2 capture) or fairly close to market-ready (in the case of electrolytic hydrogen), whenever possible new investments should employ these near-zero-emission technologies. At the very least, new builds should be retrofit-ready, that is, have the physical space and technical characteristics to easily integrate near-zero-emission technologies at a later date. Siting new plants in industrial clusters can also facilitate easier access to shared supporting infrastructure. Governments can assist by setting mandatory retrofit-ready requirements for new builds in the near term, and specifying a medium-term deadline when they will no longer grant operating licences to new high-emitting plants. Financial institutions and investors can also play a role in directing finance in support of near-zero-emission capacity additions.

Key actions

- **Governments:** develop energy efficiency benchmarking and improvement schemes; adopt retrofit-ready requirements for new-build plants; set a medium-term deadline after which operating permits will not be issued for new high-emission plants.
- **Ammonia industry:** pursue opportunities to improve existing plants through energy-efficient process upgrades and retrofitting to incorporate near-zero-emission technologies; build new plants with near-zero-emission technologies, or at the very least retrofit-ready plants.
- **Financial institutions:** use sustainable finance taxonomies and climate risk assessment frameworks to guide investment away from emissions-intensive technologies to avoid stranded assets.

Creating a market for near-zero-emission nitrogen products

Near-zero-emission ammonia production technologies are likely to be considered higher risk and initially have significantly higher costs than conventional technologies, with production costs anywhere from 10% higher to more than double. Manufacturers may face challenges securing private finance and competing in the market due to their higher of cost production using these technologies. Establishing stable, early market demand for near-zero-emission ammonia-reliant products would give certainty to producers investing in early commercial projects and would facilitate cost reductions through continued technology development.

Niche markets have played a critical role in the deployment of new near-zero-emission technologies in the past, a prominent example being feed-in tariffs for solar and wind. As mentioned above, a number of jurisdictions are considering carbon CfDs to help create early markets for near-zero-emission industrial production. Under such a policy, governments would tender for near-zero-emission production of ammonia, nitrogen fertilisers or other nitrogen products, and fund the difference in the cost of production relative to conventional high-emitting production for a guaranteed quantity of production. In this way CfDs would act as a guaranteed carbon price sufficient for near-zero-emission production to become economically viable. The level of support would gradually fall with increased deployment and declining costs. The certainty provided by a carbon CfD could present a considerable advantage over other instruments that may provide shorter-term, less certain and more fragmented demand pull. Since the cost of long-term support for an initial near-zero plant may be large, governments could join together to share the cost.

Another source of demand pull for near-zero-emission production could be private-sector purchasers. Farmers and industrial agricultural producers could choose to pay a premium for fertilisers produced with near-zero-emission technologies, motivated out of concern for sustainability and to assist in marketing to food purchasers who share the same concern and are willing to pay a higher price for a differentiated product. A number of certification schemes focused on sustainable food production already exist, such as the Farm Sustainability Assessment of the Sustainable Agriculture Initiative Platform and the GLOBALG.A.P. certification for good agricultural practices. The Cool Farm Tool developed by the Cool Farm Alliance focuses in particular on greenhouse gases from agricultural production, including emissions from producing fertilisers.

As corporate sustainability continues to grow in importance, purchasers of agricultural products – in particular, large-scale buyers such as food manufacturing companies and restaurant chains – may choose to procure certified agricultural production, in some cases upon the request of retailers. The use of certification schemes for the final food products could enable food producers to charge a premium, thereby passing on the additional costs of low-emission agricultural and food production to the final consumer. Fertiliser producers could also undergo their own certification and then work with agricultural product certification schemes to increase the incentive for crop producers to use near-zero-emission fertilisers. They could also work directly with fertiliser distributors and buyers to promote near-zero-emission fertilisers, including through product stewardship initiatives. While this could be challenging given that distributors and farmers are very numerous, a larger source of demand might be achieved by targeting large-scale industrial food production companies or farmers already united by agricultural co-operatives and associations. If possible, establishing long-term purchase commitments for near-zero-emission production would facilitate greater certainty for fertiliser producers.

Particularly after the first-of-a-kind commercial plants have been successfully deployed, governments could apply market share regulations to support the rollout of additional plants. Regulations could be formulated as a tradeable quota or certificate system requiring a minimum and increasing share of ammonia, nitrogen fertilisers or other ammonia-based products sold or purchased in the market to have been produced with near-zero-emission technologies. Applying CO_2 regulations or taxes to the life-cycle emissions of agricultural production could be another method to generate demand for near-zero-emission nitrogen fertiliser production, although this would require fairly complex emissions accounting. As near-zero-emission production becomes increasingly widespread over time, earlier-stage regulations may eventually be phased out and carbon pricing would take over as the primary driver of continued deployment.

Establishing clear standards and certification for near-zero-emission production will be important to facilitate market creation mechanisms. This is discussed further under "Tracking progress and improving data". Additionally, governments may need to adapt regulations and permitting procedures as they apply to new technologies, so that the legal framework does not pose a barrier to near-zero-emission technology diffusion.

Key actions

- **Governments:** develop support mechanisms for early deployment of near-zero-emission ammonia production, such as carbon CfDs or minimum market share regulations; adapt permitting regulations to new technologies.
- **Ammonia industry:** certify and label the CO_2 emission footprint of nitrogen fertiliser and other nitrogen products; seek out buyers willing to pay a premium for nitrogen products produced with low-emission technologies; work with agricultural product certification schemes to include incentives for near-zero-emission fertiliser use.
- **Fertiliser distributors and buyers, including farmers:** consider purchasing near-zero-emission fertilisers, possibly through long-term purchase agreements and together with other buyers.
- **Food processors, suppliers and retailers**: consider purchasing food ingredients produced with lower-emission methods and inputs, and adopting sustainability labelling for final food products to promote purchasing by final consumers.

Developing earlier-stage near-zero-emission technologies

Increased R&D is needed to continue developing near-zero-emission technologies for ammonia production. This will contribute to bringing down technology costs and expanding the portfolio of near-zero-emission technology options, enabling technology choices better suited to regional circumstances. R&D is particularly needed for technologies that are not yet market-ready, such as ammonia production from electrolytic hydrogen produced with VRE. For CCS, which has already been deployed in a number of commercial ammonia plants for EOR, continued R&D could help reduce costs, particularly for the capture step and for energy-related emissions, and further optimise the full CCS value chain. The fertiliser industry could benefit from other sectors' learnings from applying and scaling up electrolytic hydrogen production, and CO_2 capture technologies and transport and storage systems. R&D and demonstration efforts in these technology areas should be seen as a common knowledge pool across sectors, with potential for high rewards from collaboration.

Public-sector financial support for R&D is helpful given the level of risk and the uncertainties of bringing technologies to market. While a number of government R&D funding programmes for near-zero-emission technologies are already in place, increased and more targeted funding would enable faster progress. In particular, funding is needed to allow the ammonia industry to demonstrate production via electrolysis and methane pyrolysis at a commercial scale in different regional contexts. Support may take various forms, such as grants, concessional finance, public-private partnerships, procurement or carbon CfDs. Particularly useful are public finance initiatives that unlock additional private-sector finance by reducing the overall level of risk. Non-financial support from governments can also play a role, such as by co-ordinating knowledge sharing and collaboration on innovation. The ammonia industry itself has an integral role to play in leading R&D and in co-ordinating with other producers and equipment manufacturers.

Key actions

- **Governments:** provide R&D funding and financing for commercial-scale demonstration of key near-zero-emission technologies in ammonia production; co-ordinate innovation knowledge sharing.
- **Ammonia industry:** undertake commercial-scale demonstration of near-zero-emission technologies in difference regional contexts; engage with other producers and stakeholders to share innovation learnings where possible.
- **Technology suppliers:** undertake R&D on near-zero-emission technologies to continue improving them and lowering costs.

- **Researchers:** undertake research in relevant technology and strategy areas, including materials for and the manufacture of electrolysers, absorption solvents for carbon capture and more efficient use of fertilisers.

Improving use efficiency for ammonia-base products

By lowering overall demand, optimising the efficiency of use of nitrogen fertilisers and other ammonia products is an important lever to reduce the sector's emissions. Farmers and agronomists have a lead role to play in optimising fertiliser application efficiency on farmland, through the "4Rs" and other best practices (see Chapter 2, section "Measures to reduce nitrogen demand"). Tools that farmers can use to support best practice management include reference databases, simulation models, decision support systems, and soil and crop testing. Agronomists can provide advice and assist with developing nutrient management plans. Knowledge exchange among famers may also prove beneficial. The fertiliser industry and the agricultural technology industry also have a role to play by increasing alternative fertiliser options on the market, such as slow- and controlled-release and stabilised nitrogen fertilisers, as well as biostimulant products and digital tools to facilitate efficient application.

Government policies can help reduce the inefficient application of nitrogen fertilisers, achieving benefits from reduced CO_2 emissions and reduced nitrogen pollution. Countries with policies already in place would do well to examine gaps, and then to fill those gaps through revising their policy framework or improving monitoring and enforcement as needed. Meanwhile, countries without such a framework should adopt suitable policies. Mechanisms may include regulation, such as site-specific limitations on nitrogen application or discharge to the environment, backed by penalties for over-application; requirements to employ catch crops; mandatory reporting on fertiliser application and total nitrogen use; and performance standards requiring increasing use of enhanced-efficiency fertilisers. Researchers have suggested that a possible alternative to solely regulating farmers could be to place nutrient efficiency-related requirements on producers. This would have the advantage of needing to regulate a considerably smaller number of entities. It could take the form of requiring producers to sell a given percentage of enhanced-efficiency fertiliser out of total sales or to achieve a specified nutrient efficiency level upon application. Such policies would take an extended producer responsibility approach and would encourage producers to promote NUE among the farmers who use their product.

Additionally, reform and where possible removal of fertiliser subsidies – which remain quite common today in various countries – will be important. Taxes on fertilisers could also be an option. Subsidy removal and taxes would need to be carefully balanced with the objective of ensuring fertiliser affordability, particularly in developing economies. Where possible, applying taxes and quotas to surplus fertiliser use, rather than total fertiliser use, could help alleviate affordability concerns.

Governments could also assist by developing and funding information, training, monitoring and evaluation programmes for farmers, as well as R&D on improved fertiliser application decision support systems and the adoption of sustainable farming practices. Crop planning and evaluating which lands to allocate for farming can also influence the use of fertiliser in the longer term. Governments could also provide financial incentives for converting to lower-impact farming practices, such as those that rely less on mineral fertiliser inputs and circular economy approaches that maximise the reuse of nitrogen waste (from crop residues, livestock excreta, food waste, etc.).

Actors throughout food supply chains, including final consumers, can also help reduce fertiliser use by reducing food waste. Citizens may also choose to reduce their consumption of animal products, which would reduce fertiliser needs for livestock feed. Users of other products that require ammonia, including commercial cleaners, pharmaceuticals and plastics, can also examine their use and determine opportunities to increase efficiency and reduce consumption where possible. While it may be difficult to reduce demand from particular applications, such as explosives, relevant end users may nonetheless benefit from examining any potential to reduce overuse or wastage of the relevant products. Government efforts to improve plastic recycling and curb single-use plastics can help reduce the demand that comes from plastics. Given that some of these other end uses consume relatively small quantities of ammonia, efforts to improve their efficiency of use will have a considerably smaller impact relative to efforts to reduce fertiliser use.

Another aspect of the fertiliser-related transition that will need addressing is the potentially growing shift away from urea towards other nitrogen fertiliser types, such as ammonium nitrate. This is driven by the desire to reduce the CO_2 emissions that occur when urea decomposes after application to fields. Governments will need to ensure that adequate safety regulations are in place for the transport, handling and storage of ammonium nitrate or other nitrogen fertiliser types. Training for carriers and farmers on the safe handling and use of such fertilisers may also be needed in regions where their use is not common today. Measures in place in regions where they are already more common could be used as models and drawn on for lessons learned when designing similar measures elsewhere.

Key actions

- **Governments:** set policies such as limitations, mandatory reporting and taxes to reduce inefficient use of fertilisers; develop and fund training and evaluation programmes on fertiliser application efficiency; create incentives to promote more efficient use of fertilisers and alternative cropping practices; reform, and phase out where possible, subsidies for fertiliser production and use; ensure robust safety regulations are in place for transport, handling and storage of all fertiliser types, and implement safety training programmes as needed.
- **Farmers:** adopt best management practices for more efficient fertiliser use, including the 4Rs and other conservation measures; monitor soil and crops to aid decision-making; share knowledge and learnings with other farmers.
- **Agronomists:** assist farmers in understanding site-specific crop nutrient requirements and in adopting best management practices.
- **Agricultural technology industry, including plant breeders and crop equipment suppliers:** continue R&D on crop varieties that produce high yields and make efficient use of fertiliser, on equipment and digital tools that facilitate efficient fertiliser application and on other plant nutrition technologies.
- **Fertiliser industry:** increase the market availability of alternative fertiliser options that facilitate NUE, include those suitable to site- and crop-specific conditions.
- **Consumers and other supply chain actors:** reduce post-harvest losses and food waste; reduce overuse and wastage of other ammonia-based products**.**
- **Researchers:** generate knowledge on efficient nutrient use under varying conditions; help create decision support tools and models for efficient fertiliser application.

Necessary enabling conditions

Enhancing international co-operation and creating a level playing field

Nitrogen fertilisers and other ammonia-based products are traded in large volumes in competitive global markets. This means it will be important for policy makers to design emission reduction measures carefully to ensure that uneven policy ambition in different regions does not lead to the relocation of production to countries with lower ambition. Ideally, governments around the world would work together to develop a policy framework that provides a level playing field for fertiliser producers as production increasingly shifts to lower-emission technologies. A least-cost solution from a purely economic perspective would be a uniform international carbon price, although in practice this may be very challenging to achieve (at least in the short to medium term) and may not be the best approach given the diversity of regional circumstances.

Another option could be an international ammonia industry agreement, in which governments and/or producers make a formal commitment to ambitious, commonly agreed-upon – although not necessarily uniform – CO_2 emission reduction objectives. This may also be challenging given the competitive nature of the sector. However, an advantage of a sectoral approach is that a comparatively small number of actors – namely the largest producing countries and companies – would be required to create a critical mass sufficient for a relatively effective agreement. Existing collaborative structures, such as the frameworks for international co-operation under the Paris Agreement or co-ordination by international associations, might provide a helpful starting point for an agreement.

While actors continue to work towards increasing global ambition and co-ordination, a lack of uniform ambition should not be reason to delay action. Initially governments may be able to adopt policies with lower levels of ambition that begin to incentivise change but do not have major impacts on competitiveness. Special provisions for trade-exposed industries may help, such as free allowances for emissions below a benchmark in a cap-and-trade system. As policy ambitions increase, however, other measures will likely be needed.

Some regions are considering adopting carbon border tariffs on imports based on their CO_2 footprint, such as the EU CBAM described above. This would account for both explicit carbon prices and implicit carbon prices applied through other regulations, such that domestic and imported production would face the same CO_2 emission reduction requirements. Robust methods would be needed to certify and track the CO_2 intensities of products, which may entail considerable technical and logistical complexities. “Climate clubs” have also been posited by the research community as an alternative formulation, in which a coalition of willing countries agrees to a common policy ambition and places a blanket tariff on all imports from countries outside the club. Careful design of such tariff policies would be imperative to ensure compliance with international law, notably World Trade Organization requirements. It should also be noted that exports would still face competitiveness challenges, and export subsidies to address this would likely be costly and challenging to apply while remaining compliant with international trade law.

Consumption-based policies could present an alternative and potentially less politically challenging solution than tariffs. Such an approach would place emission requirements on fertiliser users rather than producers, through policies such as a consumption-based CO_2 tax or a regulation specifying a declining average CO_2 intensity for fertilisers sold in the jurisdiction. Since the requirement is on domestic fertiliser use, both domestic and imported product would face the same CO_2 requirements. This approach would also face challenges, including the large numbers of actors (i.e. fertiliser retailers or users) that would need to be regulated, the need for CO_2 intensity tracking and certification systems, and the continued competitiveness challenge for fertiliser exporters, the latter two of which also pertain to tariff-based policies. Consumption-based fertiliser requirements could also lead to increased domestic crop prices relative to imports, although the competitiveness impact for farmers of such as policy would likely be smaller than the competitiveness impact on fertiliser producers of having no policy in place, given that fertilisers account for only a proportion of crop prices.

Increased international co-operation will be an important facilitator of the nitrogen industry's transition, offering benefits both from further emission reductions and by raising global ambition and coherence in approach towards establishing an increasingly level playing field. Important aspects of this are international technology transfer and capacity building, and international climate finance to help emerging and developing economies deploy near-zero-emission technologies. While its rulebook has proved contentious and remains to be agreed upon within the United Nations Framework Convention on Climate Change (UNFCCC) negotiations, Article 6 of the Paris Agreement could provide a valuable framework for various aspects of voluntary international co-operation. Direct bilateral co-operation under Article 6.2 could enable countries leading in near-zero-emission fertiliser production technologies to deploy their technologies in other countries, particular emerging economies. The international carbon market proposed until Article 6.4 could enable fertiliser companies to put their own mitigation measures on the market for international support. Finally, the rulebook for non-market-based co-operation in Article 6.8 could provide a formal basis for initiatives such as an international ammonia industry agreement and technology transfer.

In addition to global co-operation on reducing emissions from producing nitrogen-based products, increased collaboration is needed at the international level on managing the nitrogen cycle. As described above, a number of initiatives, such as the International Nitrogen Management System, are working towards improved co-ordination. Given the scale of the challenges involved, governments would do well to increase their participation and accelerate action.

Key actions

- **Governments:** introduce provisions or mechanisms in CO_2 emission reduction policies that ensure domestic and imported products face the same emission requirements; work towards greater policy coherence and ambition on reducing emissions at an international level; assist international technology transfer and finance; collaborate towards a more holistic and robust international approach to nitrogen management.

- **Ammonia industry:** explore options to work collaboratively to promote global industry emission reductions; participate in government-led efforts to form an international ammonia industry emissions reduction agreement; engage in efforts to transfer near-zero-emission technologies to other countries.
- **Non-governmental organisations:** facilitate international dialogue and collaboration through research networks, events and targeted programmes.
- **Financial institutions:** create green finance mechanisms that incentivise investment in near-zero-emission technologies across countries.

Planning and developing infrastructure

Large-scale, co-ordinated infrastructure planning and development will be needed to enable near-zero-emission ammonia production routes. CO_2 transport and storage infrastructure will be needed for CCS-based production, enabling over 90 Mt of CO_2 to be captured and stored from the sector globally in 2050 in the Sustainable Development Scenario. Electrolytic hydrogen-based production will require infrastructure to generate zero- or near-zero-emission electricity on a large scale, to produce hydrogen, and to distribute the electricity or hydrogen if distant from ammonia plants. The Sustainable Development Scenario requires build-out of over 110 GW of electrolyser capacity at ammonia production sites. The current number of infrastructure projects globally is a mere fraction of what will be required for the energy system transition.

Collaboration between governments, the ammonia industry, other industries and researchers will be needed to plan and develop such infrastructure, positioned around industrial clusters where possible. Considering the large scale and shared nature of supporting infrastructure, it is likely that governments will need to play a leading role in co-ordinating plans, ensuring sufficient financing, establishing a suitable regulatory framework for transporting and storing CO_2 and hydrogen, and ensuring affordable access to infrastructure in all regions. Separate companies could also play a role in building and providing access to infrastructure, such as companies dedicated to CO_2 transport and storage or hydrogen production and distribution.

All stakeholders, including non-governmental organisations in particular, can assist with raising awareness and increasing acceptance of CCS among the public.

Key actions

- **Governments:** co-ordinate planning and ensure financing for infrastructure to transport and store CO_2, and produce and distribute near-zero-emission electricity and hydrogen; establish a clear regulatory framework for infrastructure, particularly for CCS.
- **Ammonia industry:** participate in planning and developing supporting infrastructure; where possible, site new plants in industrial clusters for easier access to infrastructure.
- **Researchers:** provide research into suitable locations for CO_2 storage, near-zero-emission electricity generation, process flexibility and industrial clustering.
- **Non-governmental organisations:** raise awareness and increase public acceptance of CCS.
- **Other industries and dedicated infrastructure companies:** collaborate with governments, the fertiliser industry and other industrial stakeholders in the development of infrastructure for CO_2 transport and storage and hydrogen production and distribution.

Tracking progress and improving data

Robust data on the ammonia industry's emissions, energy use, technology profile and nitrogen use efficiency are essential for identifying best practices and opportunities for improvement. By collecting the right data, stakeholders can monitor progress towards objectives, develop industry-appropriate policies and differentiate near-zero-emission fertilisers. Tracking and evaluation are beneficial both at the individual company and farm level, and at the sectoral level via government and industry-led benchmarks and indicators.

Existing data collection and reporting systems can be improved with greater participation from ammonia producers and farmers, and by making regionally aggregated data available for researchers and governments. Governments might consider implementing mandatory emissions reporting if they do not already have it in place, as well as reviewing competition law to enable improved data accessibility and transparency. International collaboration to increase levels of reporting and transparency on emissions performance would provide greater visibility on where progress is being made and where improvement is needed.

An important aspect of tracking CO_2 performance will be developing and applying standards for labelling the CO_2 intensity of nitrogen fertilisers and differentiating near-zero-emission product, as well as possibly the life-cycle emissions of agricultural production. Ideally government and industry would develop and agree upon practical and uncomplicated standards that can be applied internationally. Such standards and labelling would be useful for regulation, including for carbon border tariffs, and for buyers willing to pay a premium for near-zero-emission product. Aligning data reporting and labelling efforts with sustainable finance classifications would be beneficial to provide consistency and reduce the data reporting burden.

Key actions

- **Governments:** promote better collection and reporting of data on emissions and energy use, perhaps through mandatory reporting; develop improved reporting and performance evaluation schemes; work towards increased transparency and public availability of data, including international efforts to increase data availability across countries; collaborate with industry to define international standards for nitrogen fertiliser CO_2 intensity labelling.
- **Ammonia industry:** track own emissions and energy progress; identify opportunities for improvement and share best practices; improve data reporting to data collection schemes, including timeliness and detail (e.g. production tonnage by product type); engage in efforts to standardise CO_2 intensity labelling.
- **Farmers:** fully participate in data collection initiatives on fertiliser use and efficiency.
- **Researchers and non-governmental organisations:** help develop near-zero-emission nitrogen fertiliser production and sustainable food production labelling schemes.

Key milestones and decision points

The Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario both require a massive transformation of the ammonia industry in only a few decades (Table 3.2). The next decade – from now to 2030 – is a critical window to lay the groundwork for long-term success. Both scenarios require similar actions at a rapid pace, with the pace and degree of progress accelerated in the Net Zero Emissions by 2050 Scenario. Many of the emission reductions in the short term will come from efficiency upgrades to existing emissions-intensive assets, deploying commercially available near-zero-emission technologies and accelerating fertiliser use efficiency. In addition to these short-term reductions, the next ten years require strong and co-ordinated action on multiple fronts to prepare for deeper emission reductions from 2030 onward.

Important actions this decade include the following:

- **Establish long-term CO_2 reduction plans, policies and finance mechanisms:** considering the long lifetimes of ammonia plants and the lead times needed for infrastructure build-out, it is critical to long-term success to establish reliable policies, support mechanisms and planning initiatives as early as possible. This would send a strong market signal on the need for change and enable a smoother transition. Within the next few years, governments should have in place plans for the ammonia industry transition, including a decision on whether to pursue hydrogen or CCS or a combination of both. These plans should be underpinned by policies creating an initial market for near-zero-emission fertilisers and other ammonia-based products, aligning incentives for continued deployment of near-zero-emission technology in the long term and mobilising finance for the necessary investment. Action to create a level playing field internationally also needs to begin in the next few years.

- **Pursue better technology performance and fertiliser use efficiency:** early emission reductions can be achieved through readily available and easier to implement measures. On the production side, energy and emissions can be saved by improving plant process operations and integrating BAT. Meanwhile on the demand side, farmers – supported by agronomists and planning tools – can work to maximise the efficiency of fertiliser use. Not only would this enable shorter-term emission reductions, but it would also lay the foundation for long-term lower demand for fertilisers. This eases the burden by reducing the absolute number of near-zero-emission ammonia plants that need to be deployed.
- **Build supporting infrastructure and incorporate plant readiness:** the co-ordinated planning and development of supporting infrastructure – including for CO_2 transport and storage, low-emission electricity generation and hydrogen production – will take time. Planning should begin immediately, with build-out from the mid-2020s so that infrastructure is ready for use by the end of the decade. Ammonia producers should already begin preparing to use near-zero-emission technologies. Operators of existing plants should make plans in recognition of the decline in CO_2 intensity needed just one investment cycle away – they may include retrofitting to incorporate lower-emission technologies or retiring the plant early. New plants should be built with near-zero-emission technologies, or at a minimum be retrofit-ready, and siting should be considered within industrial clusters that enables easier access to shared supporting infrastructure.
- **RD&D:** large-scale demonstration of ammonia production with electrolytic hydrogen and methane pyrolysis will expand the portfolio of options available for near-zero-emission production. Ongoing R&D can also help bring down the cost of technologies related to low-carbon production routes. Government financial support and co-ordination can give a strong push to innovation over the next decade, enabling smoother technology roll-out thereafter. Additionally, preparations can already begin on demand-pull mechanisms to create a market that supports higher-cost near-zero-emission nitrogen fertiliser production.

Table 3.2 Global ammonia industry technology milestone requirements for meeting the Sustainable Development Scenario and Net Zero Emissions by 2050 Scenario

Technology	2020	2030		2050	
		SDS	NZE	SDS	NZE
Reduction in direct CO_2 emissions relative to 2020	-	21%	25%	73%	96%
Share of production via near-zero-emission routes	0.4%	10%	12%	50%	73%
Share of production with CO_2 utilised for urea synthesis	23%	27%	27%	25%	21%
Hydrogen demand (Mt H_2)	33	37	37	41	41
On-site electrolyser capacity (GW)	0	29	29	112	171
CO_2 captured for storage (Mt CO_2)	2	15	24	91	101
CO_2 captured for utilisation (Mt CO_2)	130	139	139	107	92

Notes: SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. Near-zero-emission routes exclude production with CO_2 captured and utilised for urea production.

Building out near-zero-emission capacity is at the heart of the challenge. Following the Sustainable Development Scenario pathway, in each year between now and 2030, about two ammonia plants would need to be equipped with CCS (each capturing 1 Mt CO_2/yr including both process and fuel emissions, and producing 0.5 Mt/yr ammonia) and four ammonia plants would need to be built with electrolytic hydrogen (each producing 0.5 Mt/yr ammonia). From the early 2030s onwards, nearly all new capacity additions in the ammonia industry should employ near-zero-emission technologies. This entails equipping four ammonia plants with CCS and building about five electrolytic-based ammonia plants each year from 2030 to 2050. Policy stringency and ambition should continue to ramp up over the forthcoming decades, such that by 2050, 50% of ammonia production employs near-zero-emission technologies, in addition to 25% utilising CO_2 for urea production.

The scale of the challenge cannot be understated. Thus, early decisive action and sustained co-operation over the long term among stakeholders – both regionally and internationally – will be critical to making the clean energy transition pathway to 2050 and beyond achievable for the ammonia industry.

Annexes

Abbreviations

ARPA-E	Advanced Research Projects Agency-Energy
ATR	auto-thermal reforming
BAT	best available technology
BECCS	bioenergy with CCS
CAPEX	capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation and storage
CDM	Clean Development Mechanism
CEM	Clean Energy Ministerial
CfD	contract for difference
CO	carbon monoxide
CO_2	carbon dioxide
DAC	direct air capture
EEA	European Environment Agency
EOR	enhanced oil recovery
EPC	engineering, procurement and construction
ESG	environmental, social and governance
ETP	Energy Technology Perspectives
ETS	emissions trading system
FAI	Fertiliser Association of India
FAO	Food and Agriculture Organization of the United Nations
FIAS	Fertiliser Industry Assurance Scheme
GPS	Global Positioning System
HNO_3	nitric acid
H_2	hydrogen
IEA	International Energy Agency
IFA	International Fertilizer Association
INCOM	Inter-convention Nitrogen Coordination Mechanism
IPCC	Intergovernmental Panel on Climate Change
ISIC	International Standard Industrial Classification
K	potassium
LCOE	levelised cost of electricity
LCOH	levelised cost of hydrogen
LHV	lower heating value

N	nitrogen
NASA	National Aeronautics and Space Administration
NH_3	ammonia
NO_x	nitrogen oxides
N_2	dinitrogen
N_2O	nitrous oxide
NUE	nitrogen use efficiency
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OPEX	operational expenditure
P	phosphorous
PAT	Perform, Achieve, Trade
PEM	polymer electrolyte membrane
POX	partial oxidation
R&D	research and development
RD&D	research, development and demonstration
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SMR	steam methane reforming
SOEC	solid oxide electrolyser cells
STEPS	Stated Policies Scenario
TCFD	Task Force on Climate-related Financial Disclosures
TIMES	The Integrated MARKAL-EFOM System
TRL	technology readiness level
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
VRE	variable renewable energy

Units of measure

EJ	exajoule
g	gramme
g CO_2/kWh	grammes of CO_2 per kilowatt hour
GJ	gigajoule
Gt	gigatonne
Gt CO_2-eq	gigatonne of CO_2-equivalent
GW	gigawatt
ha	hectare
kg	kilogramme

km^2	square kilometre
kt	thousand tonnes
kW	kilowatt
kW_e	kilowatt electrical
kWh	kilowatt hour
m^3	cubic metre
MBtu	million British thermal units
Mt	million tonnes
Mtce	million tonnes of coal-equivalent
Mt CO_2-eq	million tonnes of CO_2-equivalent
MWh	megawatt hour
t	tonne
t CO_2-eq	tonne of CO_2-equivalent
TWh	terawatt hour
yr	year

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Typeset in France by IEA – October 2021

Cover design: IEA

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