MAKING NET-ZERO AMMONIA POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

AMMONIA TRANSITION STRATEGY / SEPTEMBER 2022

MISSION POSSIBLE PARTNERSHIP

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At current emissions levels, staying within the global carbon budget for 1.5°C might slip out of reach already in this decade. Yet efforts to slow climate change by reducing greenhouse gas (GHG) emissions run into a central challenge: some of the biggest emitters of greenhouse gases into the atmosphere – transportation sectors like aviation, shipping, and trucking, and heavy industries like steel, aluminium, cement/concrete, and chemicals manufacturing – are the hardest to abate. Transitioning these industries to climate-neutral energy sources requires complex, costly, and sometimes immature technologies, as well as direct collaboration across the whole value chain, including companies, suppliers, customers, banks, institutional investors, and governments.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonise these industries. Led by the Energy Transitions Commission, the Rocky Mountain Institute, the We Mean Business Coalition, and the World Economic Forum, MPP has as its objective to propel a committed community of CEOs from carbon-intensive industries, together with their financiers, customers, and suppliers, to agree and, more importantly, to act on the essential decisions required for decarbonising heavy industry and transport. MPP will orchestrate high-ambition disruption through net-zero industry platforms for seven of the world's most hard-to-abate sectors: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals.

The foundation of MPP's approach: 7 Sector Transition Strategies

Transitioning heavy industry and transport to net-zero GHG emissions by 2050 – while complying with a target of limiting global warming to 1.5°C from preindustrial levels – will require significant changes in how they operate. MPP facilitates this process by developing **Sector Transition Strategies** for all seven hard-to-abate sectors.

A Sector Transition Strategy

is a suite of user-friendly tools (including a report, an online explorer, and an open-source model) aiming to inform decision makers from the public and private sectors about the nature, timing, cost, and scale of actions necessary to deliver net zero within the sector by 2050 and to comply with a 1.5°C target.

In line with industry-specific replacement cycles of existing assets (like steel plants or aircraft) and the projected increase in demand, the market penetration of viable decarbonisation measures each sector can draw on is modelled.

The objectives of the MPP Sector Transition Strategies are:

1. **To demonstrate industry-backed, 1.5°C-compliant pathways to net zero,** focusing on in-sector decarbonisation and galvanising industry buy-in across the whole value chain.
2. **To be action-oriented with clear 2030 milestones:** By quantifying critical milestones for each sector in terms of its required final energy demand, upstream feedstock resources, and capital investments, MPP wants to lay the foundation for tangible, quantitative recommendations how these milestones can be achieved through collaboration between industry, policymakers, investors, and customers.
3. **To be transparent and open:** MPP's long-term goal is to fully lay open the internal machinery of the Sector Transition Strategies, that is, to make its Python models open source and all data inputs open access. In addition, MPP is developing online web interfaces that bring the Sector Transition Strategy reports to life: individual users will be able to explore the results of the reports and to customize model input assumptions, explore the impact of individual levers, and dive deeper into regional insights.
4. **To break free from siloed thinking:** The transition of a sector to net zero cannot be planned in isolation since it involves interactions with the broader energy system, (e.g., via competing demands for resources from multiple sectors). All MPP Sector Transition Strategies are based on similar assumptions about the availability and costs of technologies and resources like electricity, hydrogen (H_2), or sustainable biomass. By providing a harmonized, cross-sectoral perspective, we intend to inform decision makers with a fair, comparable assessment of transition strategies for all seven sectors.

On the basis of its Sector Transition Strategies, MPP intends to develop practical resources and toolkits to help operationalize industry commitments in line with a 1.5°C target. Among others, the quantitative results of the Sector Transition Strategies will inform the creation of standards, investment principles, policy recommendations, industry collaboration blueprints, and the monitoring of commitments. These will be developed to expedite innovation, investments, and policies to support the transition.

Goals of the MPP Ammonia Transition Strategy

This publication builds on the work of other organizations that have announced initiatives to reduce emissions. In particular, we acknowledge and appreciate the following important building blocks to shape the ammonia sector's decarbonisation path:

- *Innovation Outlook: Renewable Ammonia*, International Renewable Energy Agency (IRENA), May 2022
- *Renewable Energy Policies in a Time of Transition*, IRENA, April 2018
- *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, Energy Transitions Commission (ETC), April 2021
- *Ammonia Technology Roadmap*, International Energy Agency (IEA), October 2021
- *Global Hydrogen Review*, IEA, October 2021
- *A Strategy for the Transition to Zero-Emission Shipping*, University Maritime Advisory Services (UMAS), October 2021
- *Closing the Gap*, UMAS, January 2022

The Ammonia Transition Strategy is the first of the Chemicals Transition Strategies that MPP is launching. Given the diversity and breadth of the chemicals sector, MPP plans to address key sub-sectors individually and develop multiple transition strategies. This is the first version of an industry-backed global strategy charting multiple pathways to net zero for the ammonia sector while considering both existing and future uses of ammonia in a decarbonising world. The scenarios presented in this report are not forecasts but instead illustrate potential trajectories for the ammonia industry under different assumptions taken at the time of writing this report (February–July 2022). These may be updated as policy, finance, and industry stakeholders move to commercialise and scale the required technologies as well as policy regimes required for this transition.

Through the support of industry stakeholders from the Low-Carbon Emitting Technologies (LCET) initiative, MPP has consolidated the different perspectives of the roadmaps above and has developed **an industry-backed Sector Transition Strategy** that outlines how the global ammonia sector can reach net-zero GHG emissions by 2050, while also complying with a 1.5°C target. Beyond that, **it takes the next step from strategic thinking to near-term milestones and provides recommendations for action for industry, policymakers, and financial institutions on how to unlock the transition in this decade.**

Industry support for MPP's Ammonia Transition Strategy

This report constitutes a collective view of participating organisations in the Ammonia Transition Strategy. Participants have **generally validated the model inputs and architecture** and **endorse the general thrust of the arguments made** in this report but should not be taken as agreeing with every finding or recommendation. These companies **agree on the importance of reaching net-zero carbon emissions** from the energy and industrial systems by mid-century and share a broad vision of how the transition can be achieved.

The fact that this agreement is possible among these industry leaders should give decision makers across the world confidence that it is possible to simultaneously meet global ammonia demand and reduce emissions from the sector to net zero by 2050. It should also provide confidence that the critical actions required in the 2020s to set the sector on the right path are clear and can be pursued without delay, and that the industry is ready to collaborate with its value chain to achieve those goals.

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Mission Possible Partnership (MPP)

Led by the ETC, RMI, the We Mean Business Coalition, and the World Economic Forum, the Mission Possible Partnership is an alliance of climate leaders focused on supercharging the decarbonisation of seven global industries representing 30% of emissions: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030 in a Business-as-Usual scenario. MPP brings together the world's most influential leaders across finance, policy, industry, and business. MPP is focused on activating the entire ecosystem of stakeholders across the entire value chain required to move global industries to net zero. **www.missionpossiblepartnership.org**

Low-Carbon Emitting Technologies (LCET)

The objective of the LCET initiative, hosted by the World Economic Forum, is to accelerate the development and upscaling of low-carbon-emitting technologies for chemical production and related value chains. The initiative is the first CEO-led coalition in the chemical industry focused on transformation towards a decarbonized and circular future with an ambition of accelerating the industry's journey towards net-zero emissions by 2050. To this end the initiative's industry-driven working groups are developing high-impact lighthouse project on prioritized technology, regulatory, funding, and market enablers to decarbonization. **https://initiatives.weforum.org/low-carbon-emitting-technologies-initiative/home**

Energy Transitions Commission (ETC)

ETC is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C. Our commissioners come from a range of organizations – energy producers, energy-intensive industries, technology providers, finance players, and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. **www.energy-transitions.org**

World Economic Forum

The World Economic Forum is the international organization for public–private cooperation. The Forum engages the foremost political, business, cultural, and other leaders of society to shape global, regional, and industry agendas. Learn more at **www.weforum.org**.

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EXECUTIVE SUMMARY

ELEVEN CRITICAL INSIGHTS ON THE PATH TO A NET-ZERO AMMONIA SECTOR

1. Ammonia production currently accounts for ~1% of global emissions and ~33% of global chemical Scope 1 emissions.

With an annual production of ~185 megatonnes (Mt), ammonia (NH_3) is one of the highest-volume chemicals produced globally. It is the single biggest carbon-emitting chemical process, contributing ~1% of global greenhouse gas (GHG) emissions.

The primary use of ammonia is nitrogen-based fertiliser, which accounts for 70% of ammonia production. The rest of the current ammonia production is used as a chemical feedstock (30%) in dozens of industrial applications, including explosives for mining and construction, plastics, cleaning products, and textiles. These uses will remain essential to provide for the growing global population, requiring an additional 24 Mt for chemical feedstock and 44 Mt for fertiliser use by 2050.[i]

Current ammonia production is CO_2 intensive and relies heavily on fossil fuels: It's primarily produced from methane through steam methane reforming (SMR) – 80%, 147 Mt in 2020 – or derived from coal – 20%, 38 Mt in 2020.[ii]

In addition, **Scope 3 emissions** (~0.6 gigatonne [Gt] CO_2-equivalent [CO_2e]/year) account for **more than half of the total GHG emissions from the ammonia sector.**[iii] Around 80% of these Scope 3 emissions is produced downstream in the application of nitrogen-based fertilisers to soil, producing large volumes of nitrous oxide (N_2O) and CO_2 emissions, and 20% upstream in fossil fuel extraction, in the form of fugitive methane. By 2050, if left unmitigated, these emissions could increase substantially.

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[i] In both the Business-as-Usual (BAU) and Lowest Cost (LC) scenarios.

[ii] Natural gas and coal make up over 95% of feedstocks used for ammonia production globally. Oil and naphtha make up the remaining proportion and have been excluded from this analysis based on their low volumes. See International Fertilizer Association, "World Ammonia Statistics by Region", 2021; and US Geological Survey, *Mineral Commodity Summaries 2021*, February 2021.

[iii] Note that estimates of Scope 3 emissions vary widely. Downstream Scope 3 emissions are estimated using standard Intergovernmental Panel on Climate Change (IPCC) emissions factors. See "Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application," in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, IPCC, May 2019, **https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch11_Soils_N2O_CO2.pdf**.

2. Ammonia use could grow dramatically in a decarbonised economy.

Fertiliser production and industrial demand are likely to grow steadily in line with population growth.

- **Agricultural uses of ammonia will remain essential to provide for the growing global population**, requiring an additional 44 Mt for fertiliser use by 2050.[iv]
- **Optimisation of fertiliser use** could result in slower growth in demand while still meeting crop nutrient requirements and ensuring universal food security. An ambitious transformation of our food systems through **efficiency and circularity levers** could result in a more modest fertiliser demand increase of 0–26 Mt of NH_3 by 2050 as compared with today, from two key measures:
  - Increasing nutrient use efficiency (NUE), through improved uptake of agricultural management practices like precision agriculture and regenerative farming
  - Reducing demand for crops through global dietary shifts to less land-intensive diets and strong action to reduce food waste

However, in a decarbonised world, major uses of ammonia as an energy carrier could grow in shipping, power generation, and as a hydrogen carrier. These uses **could accelerate** from 2030 in a highly ambitious policy and investment environment, and provided its production is emissions free. This would enable the long-distance transport of clean energy around the world. Ammonia has relative advantages in transportation and storage as compared with both electricity and hydrogen, with much of the required expertise and infrastructure already in place. The three most likely use cases are:

- As a shipping fuel, 295 to 670 Mt of ammonia could power 55%–90% of long-distance shipping fleets per year, replacing 5–13 exajoules (EJ) of bunker fuel.
- Power generation in renewable resource or land-constrained regions could account for an additional 35–105 Mt of ammonia. Up to 100% of thermal coal power plants in resource-constrained countries like Japan and South Korea could require ammonia to decarbonise power generation.
- The use of ammonia as a hydrogen carrier to transport clean energy over large distances could represent up to 110 Mt of ammonia demand by 2050, with up to 10% of total global hydrogen produced being transported over large distances in the form of ammonia, given the lower cost of shipping ammonia compared with hydrogen.

[iv] In both the BAU and LC scenarios.

3. The key to net-zero ammonia production is to eliminate emissions of the hydrogen input.

The ammonia production process, based on direct synthesis of hydrogen and nitrogen (called the Haber-Bosch [H-B] process), is unlikely to change dramatically in the future. The crucial need is to produce zero-emissions hydrogen, which can be done via:

- **Green hydrogen** via electrolysis of water, powered by renewable energy
- **Blue hydrogen** from a number of variants of SMR or autothermal reforming (ATR), to which carbon capture and utilisation or storage (CCUS) is applied
- **Biomass-based hydrogen** via gasification of biomass or bio-methane reforming
- **Methane pyrolysis,** powered by renewable electricity

To explore the pace at which this can be achieved and the balance between them, this report explores two decarbonisation scenarios, considering new uses of ammonia and combining different sets of decarbonisation measures to reach a 92%–99% reduction in Scope 1 and 2 CO_2 emissions by 2050. The main differences between the two scenarios (Lowest Cost scenario and Fastest Abatement scenario) are the assumed uptake in demand and whether economics or speed of abatement drives the choice of technology.

- **Lowest Cost (LC) scenario:** This is an **ambitious but feasible net-zero scenario** for decarbonising the ammonia sector and, to a moderate extent, shipping and other sectors, **at the lowest cost to the ammonia industry.** Utilising a suite of policy and investment levers including a carbon price starting at US$10/t CO_2 in 2026 and increasing linearly to $100/t CO_2 by 2035, near-zero-emissions production technologies reach cost parity with grey ammonia production. Blue ammonia technologies using CCUS take up a large transitional role, while eventually green ammonia becomes the most cost competitive.
- **Fastest Abatement (FA) scenario:** This is an **ambitious net-zero scenario** for decarbonising the ammonia, shipping, and other sectors **as quickly as possible by employing all policy and investment levers.** New investment is based on the lowest emissions technologies, leading to an extremely rapid and large uptake of green ammonia through electrolyser and renewable energy systems (RES) build-out. This scenario also considers the adoption of circularity and efficiency measures, which could reduce the growth rate of fertiliser demand and reduce emissions from fertiliser use, lowering overall emissions.

Both scenarios have a set of common conclusions. Net zero by 2050 is feasible if:

- **A highly coordinated and ambitious policy and investment effort** provides the necessary combination of regulation and incentives to catalyse new zero-emissions ammonia demand.
- **Retrofits begin immediately** with lower-emissions transitional technologies, including the capture and permanent storage or usage of process CO_2 emissions, eliminating two-thirds of CO_2 emissions generated during production, and the installation of small electrolysers at existing plants to produce ~10% green ammonia alongside conventional grey ammonia.[v]
- **Blue ammonia technologies with high capture rates mature by 2025,**[vi] and CO_2 transport and storage infrastructure begin to develop on a commercial scale, playing a key role in transitioning existing production.
- **Green ammonia achieves cost parity with blue ammonia in lowest-cost locations by 2030** as renewable electricity build-up advances rapidly and electricity prices continue to fall, and sustained scale-up of electrolyser capacity is achieved through large investments, reaching gigawatt (GW) scale by 2025.
- **Green ammonia delivers the largest reduction in emissions intensity** as shown in Exhibit A.
- **For blue and grey ammonia production, upstream Scope 3 emissions from flaring as well as methane leakages are significantly reduced.**
- **Carbon dioxide removal (CDR) solutions are used to remove residual Scope 1 and downstream Scope 3 emissions caused by fertiliser use.**

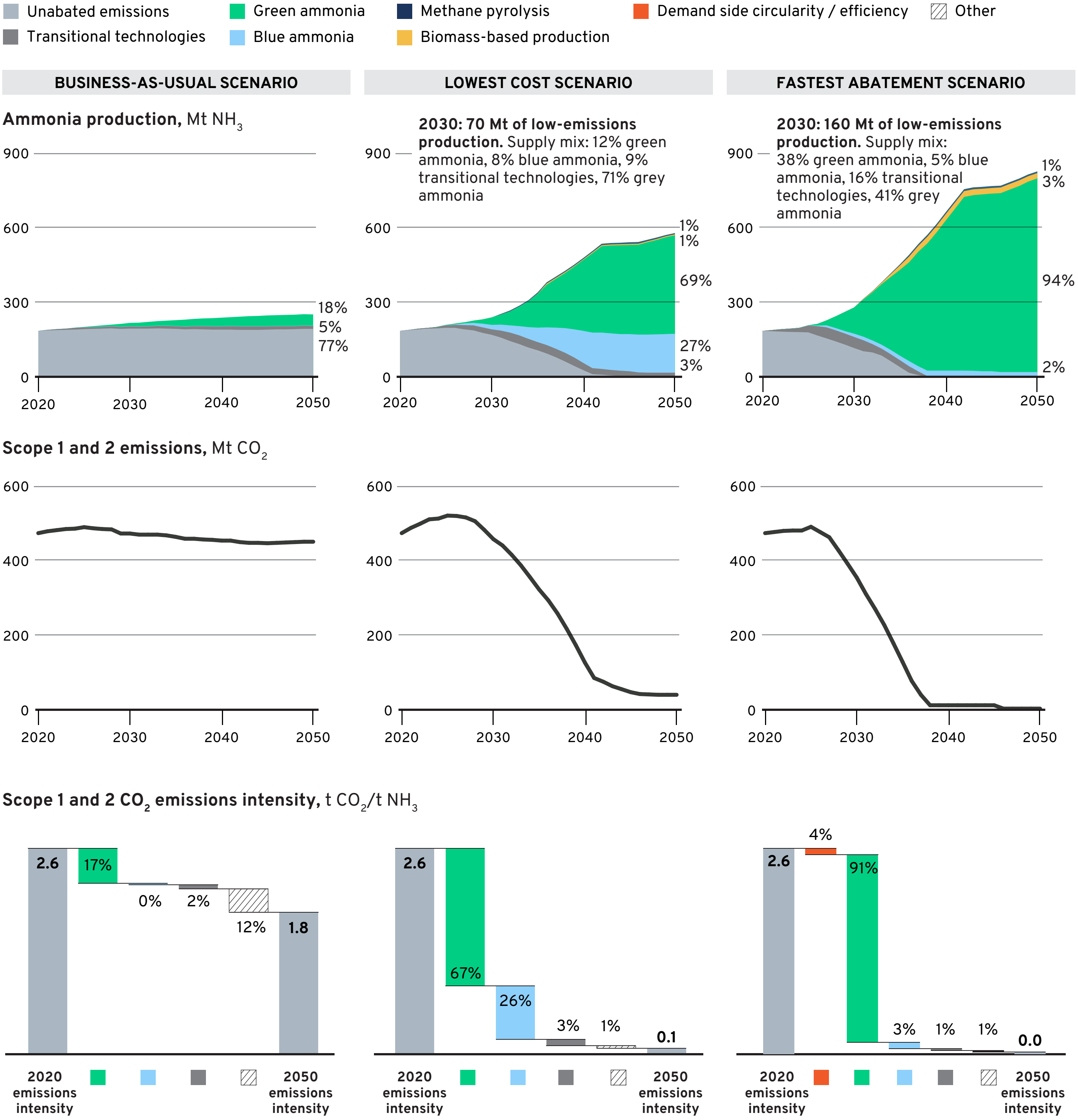
The Business-as-Usual (BAU) scenario, on the other hand, relies on stated polices and the continuation of historical trends which may drive ammonia production emissions down by only 5% between 2020 and 2050.

[v] Usage of CO_2 considers applications where CO_2 is stored for very long periods of time (e.g., in building materials) or where CO_2 is captured at end of life (e.g., incineration of plastics).

[vi] Capture rates of 90% to 96%. The point at which a technology is considered to reach maturity is the year in which it is expected to reach TRL 9 and thus commercial scale.

EXHIBIT A

Green ammonia delivers the largest reduction in emissions intensity across all scenarios



2030: 70 Mt of low-emissions production. Supply mix: 12% green ammonia, 8% blue ammonia, 9% transitional technologies, 71% grey ammonia

2030: 160 Mt of low-emissions production. Supply mix: 38% green ammonia, 5% blue ammonia, 16% transitional technologies, 41% grey ammonia

Note: Numbers may not sum to 100% because of rounding. "Other" includes methane pyrolysis and biomass-based production, as well as the emissions reduction from switching from coal to gas-based grey ammonia production in the BAU scenario. Transitional technologies are supply-side technologies which reduce emissions from ammonia production below conventional production but do not bring emissions sufficiently close to net zero.

Source: MPP analysis

4. Both green and blue ammonia have a role to play, but green is likely to dominate over time.

The ammonia production landscape could shift from being primarily natural gas (80%, 147 Mt in 2020) and coal-based (20%, 38 Mt in 2020)[vii] to multiple net-zero-emissions production routes by 2050.

The endgame is green ammonia. However, it requires rapid scaling this decade to ensure its long-term cost-competitiveness. This in turn depends on improved economies of scale, growth in manufacturing capacity and resource availability, and the ability to compete with grid decarbonisation efforts.

- By 2030, the share of green ammonia production could account for 12%–38% of total ammonia production, increasing to 69%–94% by 2050.
- This uptake is enabled by:
  - The continued decline in wind and solar power generation costs, which have fallen by over 80% since 2010 and, assuming a supportive policy environment, are expected to fall by a further 20%–40% by 2030 and 50%–70% by 2050, relative to 2022.
  - The falling electrolyser capital expenditures driven by economies of scale, which, when combined, reduce green ammonia costs by up to 50%, relative to 2022.
- By 2030, green ammonia produced at a levelised cost of around \$350–\$380/t NH_3 is cost-competitive with blue ammonia in optimal locations within regions with the lowest-cost renewable power (such as Australia, Latin America, North Africa, and the Middle East).[viii] By 2040, green ammonia produced at a levelised cost of around \$300–\$500/t NH_3 is cost-competitive with blue ammonia in almost all regions but will remain more expensive than grey ammonia in most parts of the world, produced at a levelised cost of \$200–\$400/t NH_3.[ix]

[vii] See International Fertilizer Association, "World Ammonia Statistics by Region", 2021; and US Geological Survey, *Mineral Commodity Summaries 2021*, February 2021.

[viii] Note that all costs are given without the inclusion of any carbon tax. This list is not exhaustive. Similar levelised costs of green ammonia production could realistically be achieved in optimal locations within regions that are not listed here. However, to simplify the modelling, optimal locations within these four listed regions were used to represent all low-cost power regions around the world.

[ix] Costs do not include a carbon price. Natural gas prices are based on the IEA Stated Policies (IEA STEPS) scenario: 2020 natural gas prices range from \$1.8 to \$7.8 per metric million British thermal unit (MMBtu); 2050 gas prices range from \$4.3 to \$8.9/MMBtu. 2020 levelised costs of energy (LCOEs) range from \$25 to \$52 per megawatt-hour (MWh); 2050 LCOEs range from \$10 to \$25/MWh.

Blue ammonia offers a transitional abatement option for existing and new assets until green ammonia costs come down in the short to medium term as well as a long-term solution for regions with a combination of low-cost gas, access to geological CO_2 storage, and/or scarcity of renewable resources.

- Its production could amount to 13–18 Mt (5%–8% of total production) by 2030, and 20–156 Mt (2%–27%) by 2050. In early years, retrofitting existing assets with full CO_2 capture is a low-cost, capital expenditure-efficient abatement solution, particularly in current production locations that have access to cheap fossil feedstocks and ready storage such as North America and the Middle East. In these regions, blue ammonia is projected to be produced at a levelised cost of around $350–$400 per tonne (t) of ammonia by 2030.
- In most regions, the lowest-cost decarbonised production route this decade is to retrofit existing SMR assets with carbon capture and utilisation or storage (CCUS).[x]
- By 2030, ATR–based production routes with CCUS, which currently have lower technology readiness level (TRL) compared with SMR with CCUS, emerge as cost-competitive options for new-build blue ammonia sites.[xi] ATR routes also allow for higher capture rates of over 95% to be reached economically given that almost all the CO_2 emissions are highly concentrated.

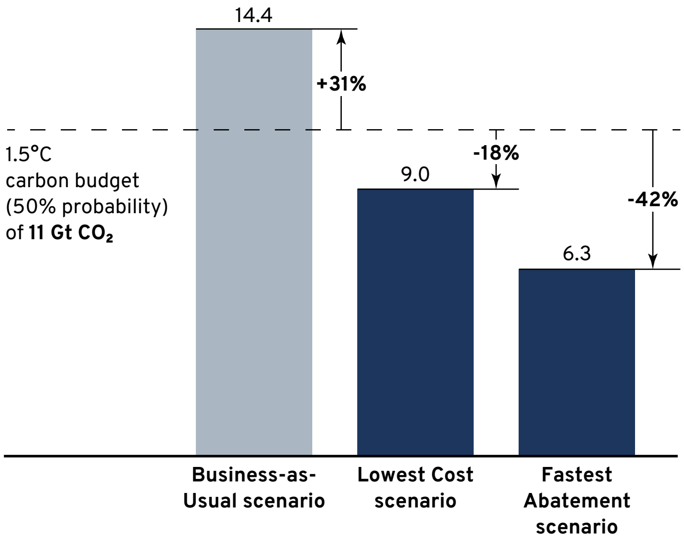
Blue ammonia costs and thus its share of total production by 2050 depend strongly on the **evolution of natural gas prices**. Gas prices in some regions are currently multiple times their long-run average, at over $30/MMBtu. A persistent environment of high natural gas prices could drive the relative attractiveness of alternative feedstock technologies such as green ammonia. However, even in a 1.5°C-aligned world with low gas prices ($1.8–$2.4/MMBtu), green ammonia could account for over 50% of total production by 2050.[xii]

Through the combined application of green and blue emissions reduction measures, Scope 1 and 2 emissions from ammonia production could be reduced by 92%–99% by 2050, and cumulative emissions in this period, amounting to 6.3–9.0 Gt CO_2, could be maintained well within the carbon budget as shown in Exhibit B.

EXHIBIT B

Cumulative emissions in net-zero scenarios remain within the allocated 1.5°C carbon budget

1.5°C carbon budget for global ammonia, from beginning of 2020 in Gt CO_2 vs. cumulative CO_2 emissions of net-zero scenarios between 2020 and 2050



Note: Since the carbon budget figure is based on Scope 1 and Scope 2 CO_2 emissions (excluding non-CO_2 and Scope 3 emissions), it is compared with the sum of the cumulative Scope 1 production emissions and Scope 2 emissions from grid electricity generation. The carbon budget should not be understood as a precise value; it rather provides an indicative figure, and therefore we have accepted slight over- and undershoots.

Source: MPP analysis; Intergovernmental Panel on Climate Change (IPCC) summary for policymakers in *Global Warming of 1.5°C*

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[x] Usage of captured CO_2 should either ensure to store the CO_2 semi-permanently (for example, in building materials) or the emissions should be captured after use (such as in end-of-life incineration of plastics).

[xi] Particularly the ATR plus gas heated reformer configuration in which the recovery and use of waste heat reduces the overall gas consumption, achieving a levelised cost of ammonia (LCOA) that is 5%–10% lower than the traditional SMR route with CCUS.

[xii] This is explored further in a sensitivity analysis in Box 10.

5. In addition, it is crucial to reduce Scope 3 emissions, which lie mostly in the fertiliser sector.

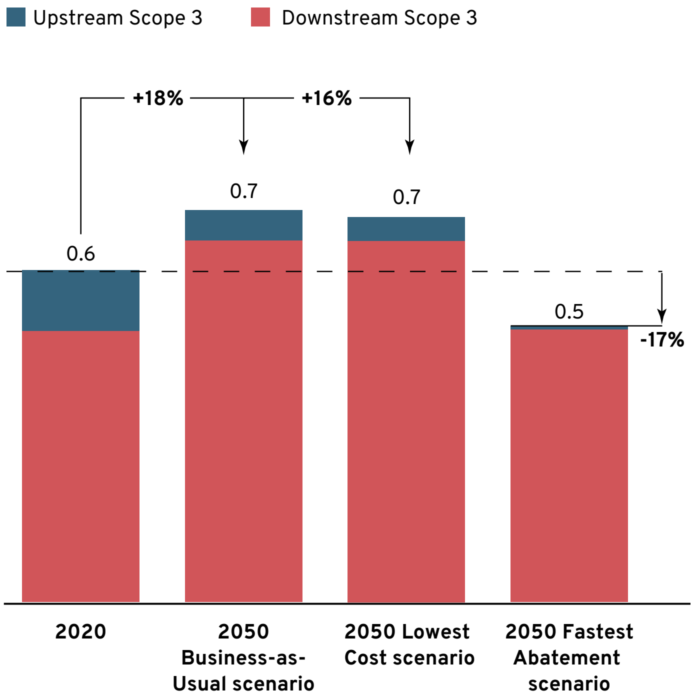
Measures to limit Scope 3 emissions are required across the full value chain to keep a 1.5°C-aligned emissions trajectory within reach:

- **Downstream Scope 3 N_2O emissions** from nitrification,[xiii] denitrification,[xiv] and urea hydrolysis[xv] and **CO_2 emissions from urea application** must be addressed. Left unmitigated, these downstream emissions could increase by 18% relative to 2020 to almost 670 Mt CO_2e annually (Exhibit C).[xvi]
- In the FA scenario, downstream Scope 3 emissions are reduced through the improvement of nutrient use efficiency and broader shifts to food systems that reduce demand for crops.
- In addition, **widespread application of nitrogen inhibitors** such as urease and nitrification inhibitors could lead to a 25% reduction in N_2O emissions intensity of nitrogen-based fertilisers. However, the long-term impacts of such products on the soil are not yet well understood. Further research is needed to improve their applicability and potential benefits.
- Continued fossil fuel–based ammonia production routes such as blue ammonia must be accompanied by measures to **reduce fugitive methane emissions and to end routine venting and flaring during coal and gas extraction. This should be done as soon as possible,** through the employment of leak detection, the improvement of technology standards, and policy enforcement to end non-emergency venting and flaring.[xvii]
- Even with these measures, **negative emissions solutions would be required** on the order of 0.5–0.8 Gt CO_2e annually by 2050 to neutralise residual emissions across the value chain.

EXHIBIT C

Upstream and downstream Scope 3 GHG emissions

Scope 3 GHG emissions, Gt CO_2e per year



Source: MPP analysis; IEA; IPCC; International Fertilizer Association

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[xiii] Two-step conversion of ammonia (NH_3) to nitrate (NO_3) by soil bacteria following application of ammonium-based fertiliser.

[xiv] Microbial process following nitrification to which nitrate (NO_3) is converted to nitrogen (N) gases that are lost to the atmosphere.

[xv] Cleavage process of chemical bonds in urea by urease enzymes occurring after contact with soil or plants in the presence of moisture, resulting in the release of CO_2 to the atmosphere.

[xvi] See "Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application", in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, IPCC, May 2019, **https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch11_Soils_N2O_CO2.pdf**.

[xvii] See International Energy Agency, *Methane Emissions from Oil and Gas*, November 2021, **https://www.iea.org/reports/methane-emissions-from-oil-and-gas**.

6.

Delivering 580–830 Mt of ammonia by 2050 would have major implications for the energy system, with total renewable energy requirements of around 3,700–7,100 terawatt-hours (TWh) per year by 2050.

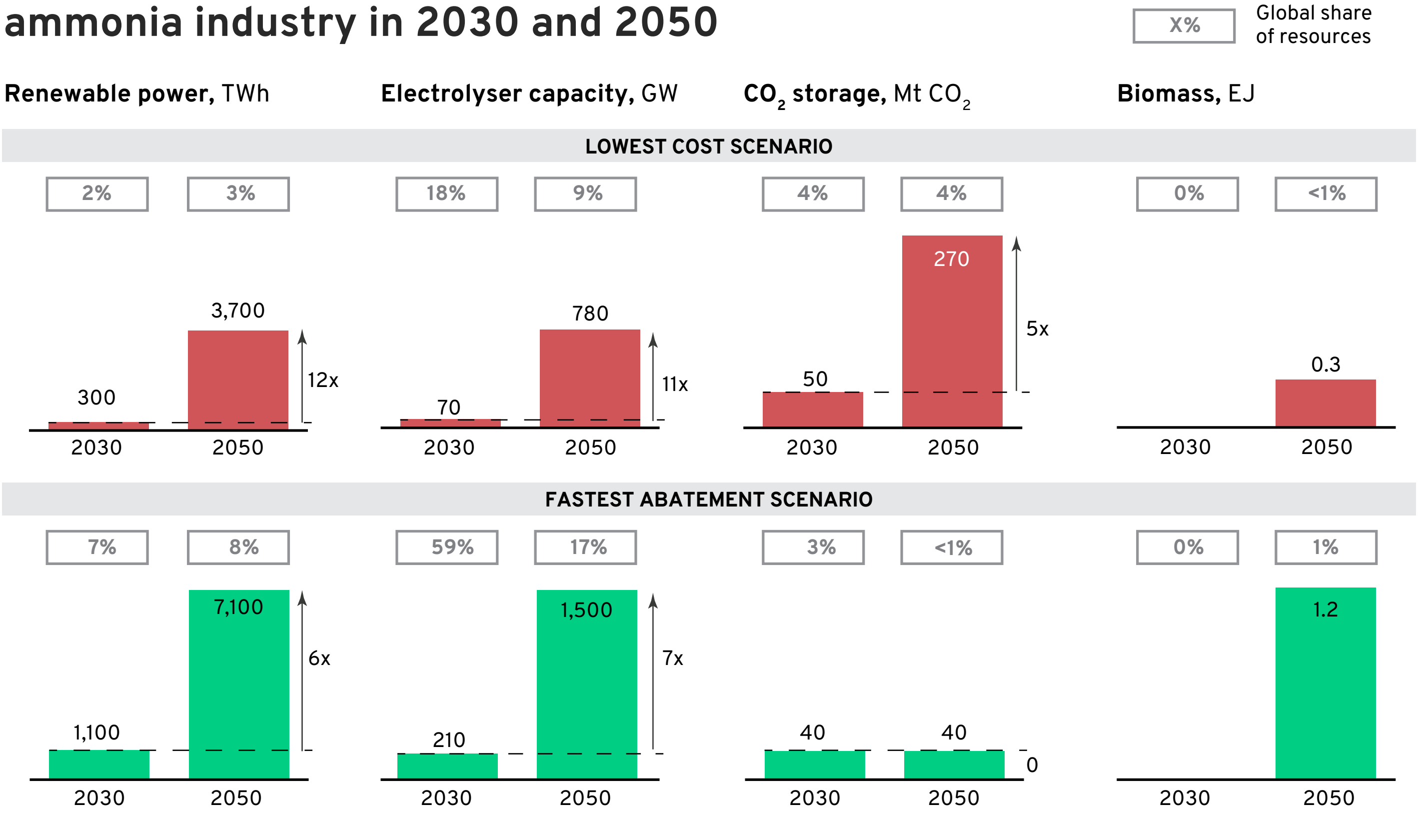
- Delivering ammonia production of 580–830 Mt will require 100–150 Mt of hydrogen.
- Green ammonia production will require an additional 780–1,500 GW of installed electrolyser capacity (around 9%–17% of global capacity in 2050[xviii]) and 3,700–7,100 TWh of renewable electricity (equivalent to 40%–80% of global wind and solar generation in 2022 and 3%–8% in 2050 as shown in Exhibit D).[xix]
- Blue ammonia production will require 20 billion–140 billion cubic metres (BCM) of natural gas (1%–4% of 2019 global demand for natural gas).

Pipelines and shipping infrastructure are required to enable a 13- to 20-fold increase in the amount of ammonia transported versus today.[xx]

- **Major synergies between the ammonia sector and the broader energy system can make the journey easier.** Large-scale electrification and the ramp-up of the hydrogen economy will benefit the ammonia economy, by driving economies of scale and reducing renewable electricity prices and electrolyser capital expenditures, the two major price components of green ammonia.

EXHIBIT D

Energy and feedstock resource demand of the global ammonia industry in 2030 and 2050



Source: MPP analysis; ETC

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xviii See Energy Transitions Commission, *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, April 2021, **https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf.**

xix See Energy Transitions Commission, *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*, April 2021.

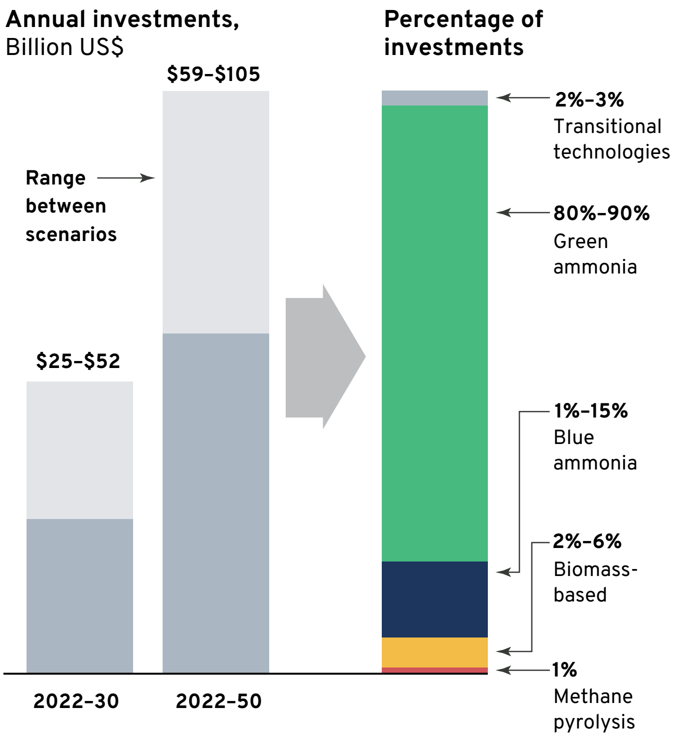
xx Approximately 10% of ammonia is transported today, according to the IEA *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertilizer Production*, 2021, **https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf**.

7. Decarbonising the hydrogen input for ammonia production will require a direct investment of $59 billion–$105 billion annually.

- **An average annual investment of approximately $59 billion–$105 billion in new ammonia production facilities is required between now and 2050, primarily dedicated to building ~560–1,120 new green ammonia plants and installing the dedicated renewables required (Exhibit E).**
- In addition to investment shown in Exhibit E, **an estimated additional annual investment of ~$20 billion to $30 billion is required outside of the ammonia industry:**
  - From 30%–50% of this investment is necessary in order to develop **CO_2 transport and storage infrastructure as well as hydrogen storage and to reduce upstream Scope 3 emissions from fossil fuel extraction.**
  - Another 30%–40% is required to **scale up renewable electricity infrastructure and supply.**
  - The remaining 20%–30% is required to **scale downstream uses of ammonia such as shipping and power generation.** For example, the shipping sector will need to retrofit and build ~40,000–80,000 ammonia-powered ships,[xxi] as well as bunkering and storage terminals to meet the increase in ammonia shipping fuel demand from 2030 to 2050. Retrofits to existing coal-fired thermal power plants in Japan and South Korea will enable first co-firing and eventually 100% ammonia use, and such technologies could be extended to other countries.
- **The cumulative investment of $1.7 trillion to $3.1 trillion is not distributed evenly across the decades.** Around 15% of the cumulative investment required should take place before 2030. After 2030, both scenarios require an average annual investment of $59 billion to $105 billion to achieve the required emissions reductions for ammonia as well as other sectors (such as shipping and power generation).

EXHIBIT E

Investments necessary to transition the ammonia industry to net zero



Source: MPP analysis

[xxi] See Tristan Smith et al., *A Strategy for the Transition to Zero-Emission Shipping: An Analysis of Transition Pathways, Scenarios, and Levers for Change*, UMAS, 2021, https://www3.weforum.org/docs/WEF_A%20Strategy_for_the_Transition_to_Zero_Emission_Shipping_2021.pdf; DNV-GL, *Maritime Forecast to 2050*, 2020; UMAS, *International Maritime Decarbonisation Transitions* (forthcoming), accessed April 2022, subject to change.

KEY MILESTONES AND ACTIONS TO 2030

8. Supply-side efforts to scale up near-zero-emissions ammonia production should start now: by 2030, 40–140 green ammonia plants and 15–25 blue ammonia plants must be operating.

The key supply-side milestones until 2025 and 2030 are the commercialisation and ramp-up of near-zero-emissions production capacity as well as energy system infrastructure (Exhibit F). By 2030, investment is needed to retrofit up to 35 of the existing ~500 ammonia plants, which exist today with transitional low-emissions technologies (capture of process emissions and small electrolysers to supply ~10% of the hydrogen feed). In addition, up to 15–25 new blue ammonia plants and 40–140 new green ammonia plants need to be built by 2030 to satisfy growing demand.

EXHIBIT F

Supply-side milestones until 2025 and 2030 to unlock the transition to a net-zero ammonia industry

	Key milestones until 2025	Key milestones until 2030
LOW-CARBON AMMONIA PRODUCTION RAMP-UP	10–30 Mt of ammonia production via transitional technologies ~15 SMR plants retrofitted with partial CO_2 capture, and up to 20 fitted with a small electrolyser to produce 10% of the hydrogen feed Around \$4 billion–\$12 billion of annual investments in transitional technologies	30–100 Mt of green ammonia production (40–140 plants) 10–20 Mt of blue ammonia production (15–25 plants) \$25 billion–\$52 billion of annual investments in near-zero-emissions ammonia production
WIDER ENERGY-SYSTEM INFRASTRUCTURE	Around 12 Mt of CO_2 storage required annually	70-210 GW of electrolyser capacity 300–1,100 TWh of renewable electricity demand annually 40–50 Mt of CO_2 captured and stored annually
TECHNOLOGY READINESS LEVEL	Green ammonia production reaches commercial scale Blue ammonia production comes online	Lower TRL technologies such as biomass-based routes and methane pyrolysis reach commercial scale

Source: MPP analysis

9. Scaling supply of near-zero-emissions ammonia by 2030 requires an unprecedented converging of efforts from policymakers, industry players, and financial institutions.

Policymakers should immediately mobilise resources and put incentives in place to increase the rate of electrolyser deployment and CO_2 capture capacity additions. Examples of this include:

- Enhancing and extending tax credit frameworks, such as the latest 45Q, 45X, and 45V in the United States, can reduce the cost of near-zero-emissions ammonia production.
- Direct investments in the form of funds, grants, and loans to de-risk capital expenditures required in the development of related flagship projects, as well as for the formation of industrial hubs/clusters in proximity to geological H_2 or CO_2 storage.

This early investment of public funds, which could be done efficiently through development banks such as such as European Investment Bank (EIB) in Europe, would lead to faster deployment of the technologies and hence a faster decline in their cost. This could create competitive advantages for countries that act fast and position themselves ahead of the curve.

Faced with the right incentives, and supported in its early stage, industry would be in a position to increase ammonia supply through the allocation of capital expenditure investments across the supply chain to **install and scale priority technologies and infrastructure. This includes:**

- Scaling installations of electrolysers; CCUS retrofits to existing SMR assets; and transportation and storage infrastructure
- R&D to improve performance and lower cost of electrolysers, flue gas CO_2 capture, and ammonia crackers
- Measures to bring down residual emissions across the supply chain (such as fugitive methane emissions from coal and gas extraction)

$25 billion to $52 billion of annual capital investment to 2030 would need to be directed through financial institutions to deploy and scale new ammonia production. Capital providers can contribute to mobilising capital by establishing clear investment principles (for example, the Poseidon Principles in shipping) to direct capital to infrastructure, companies, and financial institutions that contribute to scaling near-zero-emissions ammonia infrastructure. Financial institutions can work with regulators to design the kind of financial instruments that are fit-for-purpose to finance the investment needs of transforming the ammonia industry, in terms of the required time frame, risk-return profile, and other factors. The ability to quickly and efficiently securitise such instruments will be essential in order to scale up these efforts.

10. By 2030, the shipping sector alone has the potential to make or break the demand for near-zero-emissions ammonia. Targeted demand-side policy support is required to certify, adopt, and expand ammonia's new application as a marine fuel.

The International Maritime Organization (IMO) will be instrumental in delivering the following policy milestones across international shipping jurisdictions:

- **Certify ammonia as a shipping fuel, standardise handling and trading protocols** to facilitate its adoption, and establish safety regulations to mitigate perceived risks posed by the toxicity of ammonia.

- **Develop a comprehensive decarbonisation strategy, sending unambiguous signals of sector transformation.** The 50% emissions reduction ambition by 2050 should be increased to net zero by 2050, and an aggressive 2030 target of 5%–15% of deep-sea shipping to be powered by zero-emissions fuels should be set and these targets should be made enforceable.

- **Boost stringency on technical efficiency standards, for example EEDI**[xxii] (Energy Efficiency Design Index for new-build ships) and **EEXI**[xxiii]**/CII**[xxiv] (Energy Efficiency Existing Ship Index and Carbon Intensity Indicator for existing ships), in alignment with net-zero targets.

- **Implement market-based mechanisms (MBMs) to close the competitiveness gap between zero-emissions fuels and conventional fuels** through mechanisms like contracts for difference (CfDs) or subsidies. Closing the competitiveness gap through a carbon price to reach full decarbonisation for this sector is estimated at \$50–\$100/t CO_2 by 2030, increasing to \$191–\$400/t CO_2 by 2050.[xxv] Even more recent studies envision carbon prices up to \$650/t CO_2 by 2050.[xxvi]

The **implementation of voluntary mechanisms,** such as the establishment of green shipping corridors and information programmes disclosing environmentally related data, will be key in order to accelerate action amongst sector stakeholders.

[xxii] EEDI is a CO_2 intensity metric that considers the total emissions of a ship (at the design stage) relative to the transport work done by the ship resulting in grams of CO_2 per tonne of nautical mile.

[xxiii] EEXI is a future CO_2 intensity metric to be applied to existing fleets.

[xxiv] CII is a future annual operational carbon intensity indicator to be required for ships.

[xxv] See Domagoj Baresic et al., *Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping*, UMAS, January 2022, **https://www.globalmaritimeforum.org/content/2021/12/Closing-the-Gap_Getting-to-Zero-Coalition-report.pdf**; DNV-GL, *Maritime Forecast to 2050*, 2020.

[xxvi] UMAS, *International Maritime Decarbonisation Transitions* (forthcoming), accessed April 2022, subject to change.

11. Demand-side policy mechanisms for other ammonia use cases should improve cost-competitiveness in relevant markets and phase out highly emitting alternatives.

For the use of ammonia as **fertiliser**, policy mechanisms should encourage the use of near-zero-emissions ammonia, while seeking to optimise overall fertiliser use (Exhibit G).

- To encourage uptake of near-zero-emissions ammonia, **mandated content requirements** in fertiliser production should be established and increased over time. MBMs like **CfDs and cap-and-trade systems, in conjunction with border adjustment tariffs for carbon**, can create a level playing field against conventional fossil fuel-based alternatives.
- To drive improved nutrient use efficiency, policies should expand access to farmer extension services and subsidies. Incentives can be put in place to expand the **use of performance standards**. The current s**chemes of fertiliser subsidies driving intensification** should be reassessed and potentially removed from key jurisdictions like China and India.
- Voluntary mechanisms such as **training, evaluation programmes, and certifications**, including through the involvement of fertiliser producers/retailers, consumer packaged goods companies, and consumers, can encourage further adoption from farmers.

In geographies where ammonia's use in **power generation** is a low-emissions and cost-effective alternative, policies should initially **approve and regulate the use of ammonia for this new application**. Given the safety risks associated with ammonia due to its toxicity, its use as an energy carrier in new applications relies strongly on the establishment of safety standards and handling regulations to ensure a minimisation of these risks. Demand can then be accelerated by the drafting of **clean-energy roadmaps** integrating this alternative. Next policies should mobilise resources to **pilot and scale the ammonia co-firing technology** together with appropriate market conditions for expansion (such as low-carbon energy generation targets or feed-in tariffs [FITs]). These policies should be paired with the setting of rules to **phase out the current highly emitting fuel sources** in power generation systems (for example, coal in Japan's energy system). Finally, **information programmes** can be used to drive power purchase agreements (PPAs).

For ammonia as a **hydrogen carrier**, a supportive policy environment should be established to enable the **development of hydrogen markets**. Policy efforts should include integrating zero-emissions-ammonia into hydrogen roadmaps. Mobilising R&D resources to improve round-trip efficiencies (via ammonia cracking, for example) could make ammonia a lowest-cost technology for transporting hydrogen over long distances.

EXHIBIT G

Portfolio of policy instruments to unlock demand for net-zero-emissions ammonia

🟡 Initiate 2022–25 🔴 Initiate 2025–30

			Shipping	Power generation	Other energy carrier	Fertiliser
ENABLER	**Enabling regulation**	Certification, standards, and protocols	🟡 Certification as maritime fuel and handling regulation 🟡 Bunkering standards and protocols	🟡 Approval and safety standards for ammonia co-firing for power generation	🟡 Technical and safety standards for ammonia as energy carrier	
DEMAND	**Direct regulation**	Roadmaps	🟡 International maritime decarbonisation roadmap with net-zero target	🟡 Power sector decarbonisation roadmaps	🟡 Include ammonia as energy carrier in hydrogen roadmaps	🟡 Formal commitments to ambitious reductions on GHG and environmental impacts from agriculture sectors
		Mandates and quotas	🟡 Increase stringency of performance standards (EEDI, EEXI/CII)	🔴 Targets on power generation from ammonia co-firing		🟡 Mandates to uptake near-zero emissions ammonia as source for fertilisers 🟡 Performance standards to drive optimisation
		Moratoriums and bans		🔴 Phase-out rules for conventional fossil fuels		
	Market-based mechanisms	Carbon pricing and ETS	🔴 ETSs and carbon pricing schemes Up to \$50–\$100/t of CO_2 by 2030 and \$191–\$400/t of CO_2 by 2050 for full decarbonisation[1]			🔴 Emissions allowances below a benchmark in a cap-and-trade system and border adjustment tariffs
		Pricing and competitive mechanisms	🔴 CfDs and price subsidies	🔴 Feed-in tariffs and premiums; guaranteed access to grid and priority dispatch	🔴 CfDs in cases in which hydrogen has higher competitiveness	🔴 CfDs for fertiliser production 🟡 Extension services, subsidies, and incentives to promote efficiencies in fertiliser use
	Voluntary mechanisms and information programmes	Reporting, transparency, education	🟡 Information programs and performance data disclosure 🟡 Implementation of zero-emissions corridors	🟡 Information and awareness programmes to drive power purchase decisions by consumer, communities, and corporations	🟡 Information and awareness programmes to drive power purchase decisions by corporations	🟡 Training and evaluation programmes on fertiliser application efficiency 🟡 Certification schemes for sustainable food production
	Direct and indirect investments	Funds, loans, grants, and tax credits	🟡 Investments in bunkering infrastructure	🟡 Investments on co-firing technologies installation and expansion	🟡 Investments on R&D targeting efficiencies in ammonia cracking process	🔴 Investments in R&D to reduce Scope 3 emissions

[1] Even more recent studies envision carbon prices up to \$650/t CO_2 by 2050. UMAS, *International Maritime Decarbonisation Transitions* (forthcoming), accessed April 2022, subject to change.

Note: List is not mutually exclusive, nor collectively exhaustive; national policy packages should be tailored to the specific country and region.

Source: MPP analysis; IEA; UMAS; DNV-GL; IRENA

CONCLUSION

Transitioning the global ammonia industry to a 1.5˚C-aligned path to net zero and enabling the use of ammonia as a zero-emissions fuel in other sectors are feasible. However, this will require significant expansion of current production, substantial direct annual investment of $59 billion–$105 billion, and a massive increase in renewable energy infrastructure.

Collaboration among policymakers, financial institutions, and industry players along the value chain is critical to this transition. Early action this decade on both the supply and demand sides is required to kick off the transition and drive economies of scale to enable large-scale GHG reductions in the 2030s and 2040s.

Through a combined effort of all actors across the value chain, this mission can be made possible.

MAIN REPORT

MAKING NET-ZERO AMMONIA POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

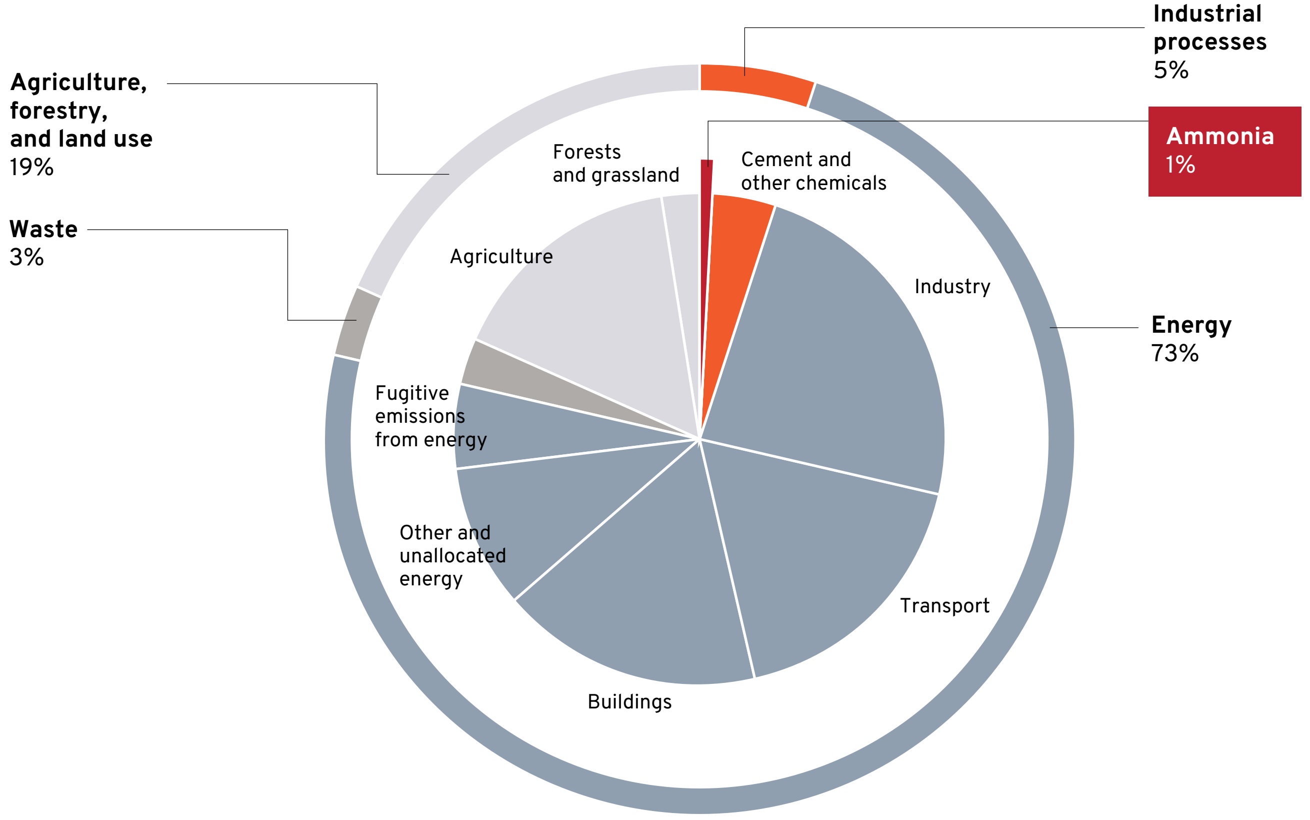
DECARBONISATION CHALLENGES AND SOLUTIONS

1.1 Decarbonising ammonia is critical to a net-zero future

With an annual production of ~185 Mt,[1] ammonia is one of the largest industrially produced chemicals globally. It is the single biggest carbon-emitting chemical production process, contributing ~1% of global CO_2 emissions[2] (Exhibit 1.1). Today, ammonia is used primarily for nitrogen-based fertilisers and is typically converted into products such as urea and ammonium nitrate; this represents ~70% of end usage.[3] These fertilisers are the most significant means of increasing the availability of nitrogen in agricultural systems and are thus essential for our food supply. The remainder is used in various industrial applications including explosives for mining and construction, plastics, cleaning products, and textiles.

EXHIBIT 1.1

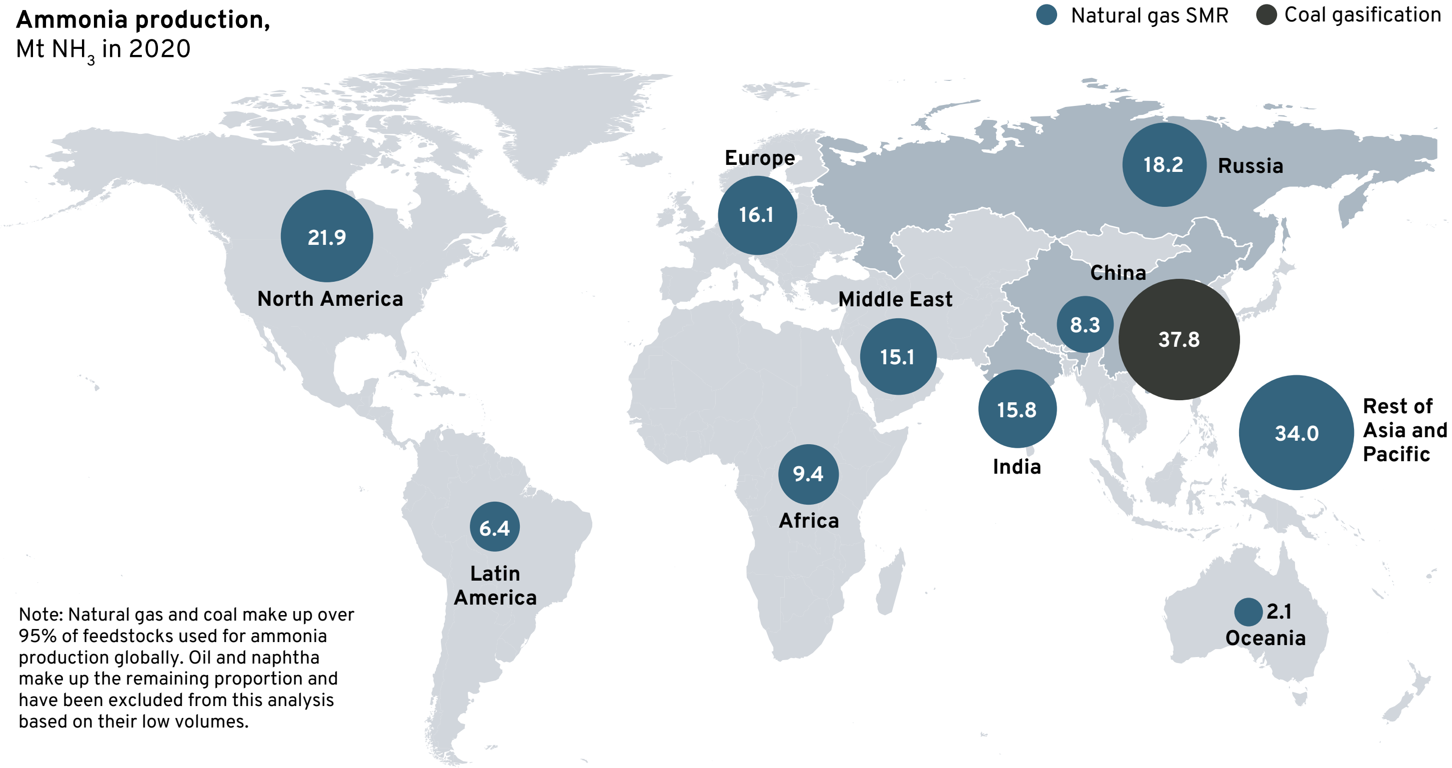
CO_2 emissions by sector in 2020



Source: MPP analysis; Our World in Data[4]

EXHIBIT 1.2

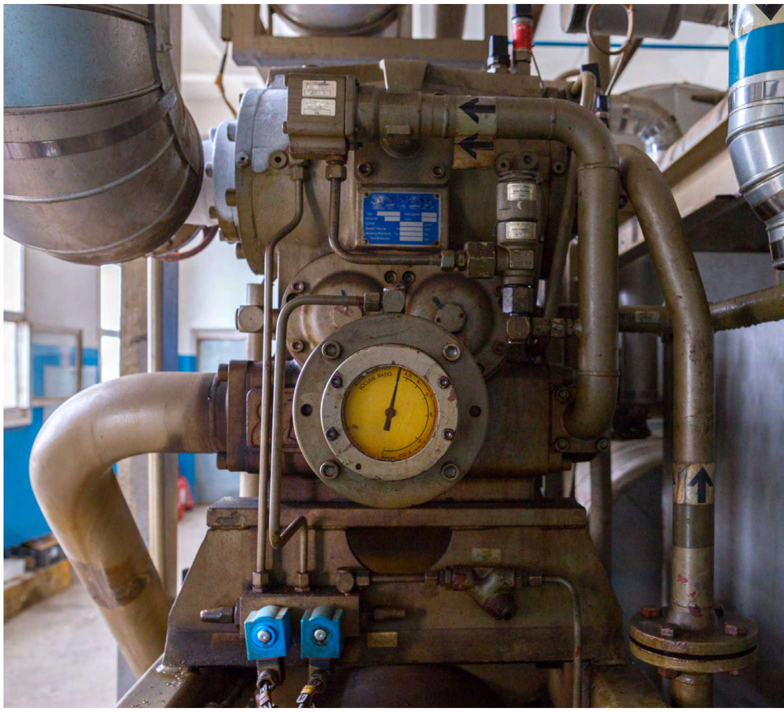
Ammonia production in 2020 by region of production and feedstock type



Note: Natural gas and coal make up over 95% of feedstocks used for ammonia production globally. Oil and naphtha make up the remaining proportion and have been excluded from this analysis based on their low volumes.

Source: International Fertilizer Association; Industrial Efficiency Technology Database; US Geological Survey[5]

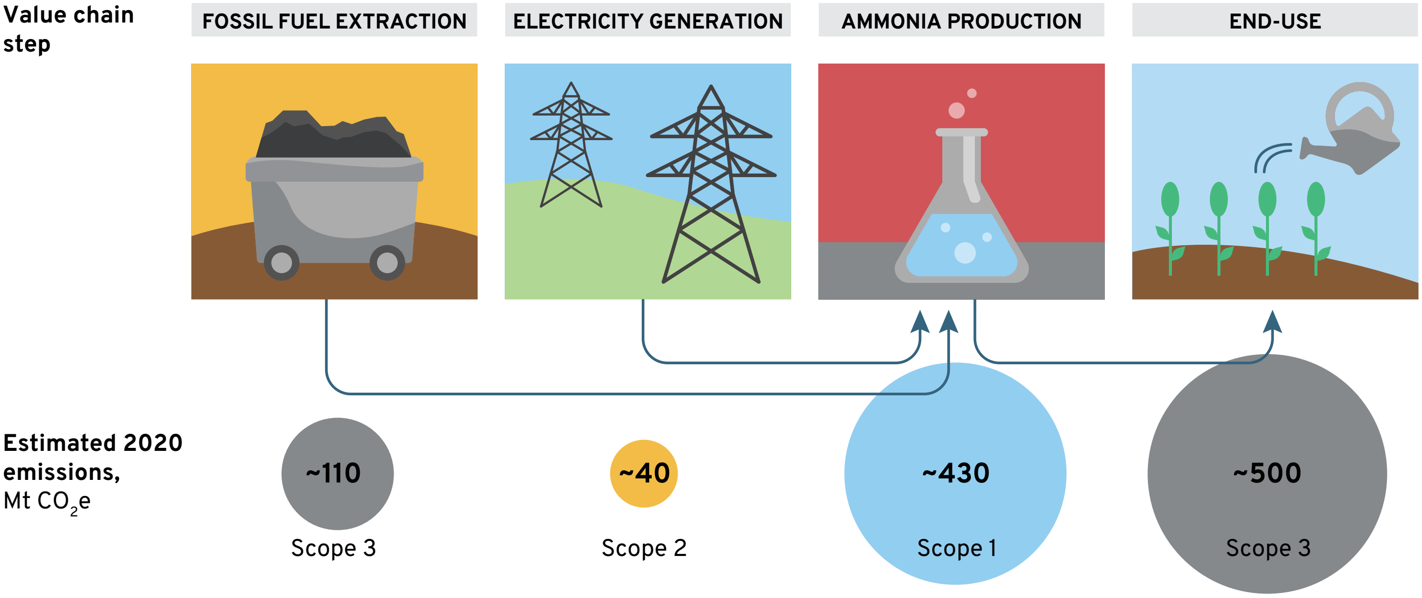
Current ammonia production is CO_2 intensive and relies heavily on fossil fuels. Ammonia production includes two stages: hydrogen production and the synthesis of ammonia from hydrogen and nitrogen (sourced directly from the air or via an electrically powered air separation unit). Currently, as shown in Exhibit 1.2, all hydrogen for ammonia production is derived from fossil fuels, predominantly natural gas (80%) and coal (20%). Along with hydrogen feedstocks, ammonia production also relies on fossil fuels to generate the required heat and pressure for the chemical process. Producing one tonne of ammonia requires ~0.18 tonne of hydrogen and ~0.82 tonne of nitrogen, and results in ~1.6–4.0 tonnes of Scope 1 CO_2 emissions, depending on the plant efficiency and whether natural gas or coal is used as the feedstock, amounting to 430 Mt CO_2 of Scope 1 emissions globally in 2020 (Exhibit 1.3). In addition to direct emissions, an estimated 40 Mt of Scope 2 CO_2 emissions were produced in electricity generation.



Ammonia production and usage also generate significant volumes of Scope 3 GHG emissions along its value chain. Upstream GHG emissions from flaring, venting, and fugitive methane during fossil fuel extraction for ammonia production were estimated to be around 112 Mt CO_2e in 2020.[6,xxvii] Similarly, as shown in Exhibit 1.3, large volumes of hard-to-abate GHG emissions are generated downstream in the use-phase of nitrogen-based fertilisers, which in 2020 amounted to an estimated 400 Mt CO_2e of nitrous oxide and an additional 105 Mt CO_2 from the use of urea-based fertilisers, given that CO_2 is a key input for urea production. Typically, this CO_2 input comes from captured process emissions during ammonia production, hence while the emissions are avoided during the production phase, they are ultimately released further downstream in the use-phase of urea-based fertilisers, transferring these emissions from Scope 1 to Scope 3.

EXHIBIT 1.3

GHG emissions along the ammonia supply chain by scope in 2020



Note: Due to their nature, upstream and downstream Scope 3 emissions are highly uncertain with many different estimates from different sources. These emissions have been calculated using estimated emissions factors for each region.

Source: MPP analysis; IEA; IPCC[7]

Given the right policy instruments and necessary scale-up of investment, the role of ammonia could change as the energy transition unfolds. Sustainably produced ammonia offers a carbon-free source of energy and is therefore being explored as a potential fuel for certain applications. For example, it is expected to become the main zero-emissions fuel for shipping,[8] as detailed in the Shipping Sector Transition Strategy,[9] as well as a fuel for power generation to replace coal. It could also become an attractive vector for transporting hydrogen over long distances, from regions with abundant and cheap renewable energy to resource-scarce geographies. However, initiating this transition requires strong policy support, the introduction of MBMs such as CfDs to bridge cost premiums, as well as large-scale investments in both supply-side and demand-side technologies to enable the use of ammonia as a fuel.

[xxvii] Variations between regions are accounted for and are based on the IEA's Global Methane Tracker.

While there are encouraging signs of progress with commitments and investments being made to develop both production of and demand for low-carbon ammonia, these alone are insufficient to kick off the transition.

Ammonia producers representing over a fifth of global production capacity have set climate neutrality commitments by 2050.[xxviii] Many major producers have also committed to shorter-term climate goals. For example, Yara and CF Industries, the two largest ammonia producers globally, have set 2030 production-related emissions reduction targets of 25%–30%.[10] There is also evidence of progress towards these targets: over 60 low-emissions ammonia projects have been announced in the past three years.[11]

Energy companies are also taking an interest in zero-emissions ammonia production to serve the rapidly growing new markets within the energy space. For example, Iberdrola launched a green ammonia project in Spain at the end of 2021 and is expected to produce around 57 kilotonnes (kt) of green ammonia by 2025.[12] Similarly, in March 2021, ACME Group launched a solar-powered green ammonia project in Oman, which is set to produce 1.2 Mt of ammonia per year at full capacity.[13]

Shipping decarbonisation is rapidly accelerating demand for net-zero-emissions ammonia. Mining giant Fortescue is planning to decarbonise its internal fleet of vessels, using ammonia as a fuel, with the aim of having its first net-zero emissions vessel hit water by the end of 2022.[14] In addition to industry movement, governments and ports have been taking steps. The Clydebank Declaration, signed by 24 countries at COP26, has catalysed the implementation of green shipping corridors.[15,xxix] Additional announcements have included movement towards the implementation of LA-Shanghai, Antwerp-Montreal, and Australia-East Asia green corridors.[16]

[xxviii] Including Yara, CF Industries, BASF, and Sinopec.

[xxix] These are specific maritime routes between major port hubs, which showcase low- to zero-emissions lifecycle marine fuels and technologies. See Mission Possible Partnership, *The Next Wave: Green Corridors*, 2021.

Key challenges

Why is ammonia hard to abate?

- **High costs and lack of level playing field:** The decarbonisation of ammonia is a contentious subject as existing applications of ammonia are supporting the most basic need of the global population: food. Hence, higher costs of near-zero-emissions ammonia could create a barrier to widespread adoption. Current green ammonia production costs of $550–$1,400 per tonne (t) and blue ammonia production costs of $350–$700/t are uncompetitive with conventional grey ammonia, which historically cost as low as $250/t but, in the current environment of high gas prices, has increased to $1,000–$1,500/t.[17] If fertiliser costs were directly transferred, the impact of increasing production costs on crop prices could be significant, particularly on vulnerable and resource-constrained communities. The transfer of costs will also impact industry as producers that are incurring the additional costs of decarbonisation and seek to pass on those costs will increasingly be less competitive compared to those that are not. Therefore, it is critical that the shift to lower-emissions production routes is accompanied with appropriate policy and financing mechanisms to ensure that price increases resulting from higher ammonia production costs are not excessive and do not disproportionately affect the most vulnerable communities.

Why is it particularly challenging to kick off the transition to net zero in this decade?

- **Low TRLs:** Near-zero-emissions production technologies are not yet at commercial scale. The technologies required to decarbonise the ammonia industry are at the start of their learning curves and require major process adaptations, making them expensive and uncertain to invest in. Large-scale green ammonia production using captive renewable energy sources is made challenging by the intermittency of variable renewable electricity. In addition, many technologies such as CCUS cannot operate economically at a small scale and thus require large capital investments to prove the concept and economics, which present a barrier to adoption.

- **Whole new value chains:** The application of ammonia as an energy carrier relies on the development of new global markets, value chains, and the deployment of new infrastructure. This requires significant collaboration among all players along the value chain. Policymakers must establish the needed regulation, certification, and an enabling policy environment, and financial institutions must support the development of these markets and deployment of infrastructure.

- **Limited market signals:** Kicking off the transition requires a massive scale-up in investment given the capital expenditure–intensive nature of ammonia production. Industry players require clear market signals, such as through offtaker agreements, in order to justify and de-risk these large-scale investments. Currently, these demand signals for low-carbon ammonia from both existing users and new applications, like shipping, are limited. Without clear mandates and market-based mechanisms such as CfDs to bridge the cost premiums, downstream players are unwilling to enter into long-term offtaker agreements, which in turn hinders supply-side investment decisions.

- **Large existing asset base:** Long lifetimes of existing assets of over 50 years with low marginal production costs favour retrofits and hinder technology switches. The average age of ammonia plants globally is around 24 years, but this varies regionally from around 12 years in China, where 25% of current production is based, to 40 years in Europe.[18] Production in China is also heavily dependent on coal, making its assets both young and emissions intensive. Given the capital-intensive nature of ammonia plants and their long lifetimes of over 50 years, there is resistance to technology switches, concern around stranding of assets, and hence a preference for retrofits of existing assets with CCUS over switching to new technologies. Furthermore, current assets are concentrated in regions with cheap coal and gas, while new assets, particularly for green ammonia, are likely to be based at sites with optimal renewable energy resources; the two do not always coincide, thus creating an additional barrier to technology switches.

1.2 Decarbonisation portfolio

1.2.1 Demand drivers and decarbonisation levers

Ammonia could play a significant role in the energy transition, driving massive demand growth to 2050. At a lower level, the evolution of ammonia demand could be driven by a combination of three trends: the growing demand for food and goods, the expected uptake of ammonia as a zero-carbon fuel, and the opposing trend of fertiliser-use optimisation. As shown in Exhibit 1.4, the uptake of ammonia as a zero-carbon fuel is the decisive trend, determining whether the massive demand growth to 2050 is realised.

- **Higher demand for food and goods:** Under a Business-as-Usual (BAU) scenario, demand for existing uses of ammonia is driven by the demand for food, fibre, and industrial products, which is strongly correlated with population growth and economic development. Thus, ammonia demand could grow around 1% per year, from 185 Mt in 2020 to around 250 Mt by 2050.

- **New applications as an energy carrier under a net-zero scenario:** Near-zero-emissions ammonia has the potential to play an important role as an energy carrier in a number of new applications. Its role as a clean shipping fuel, as well as in power generation and as a hydrogen vector for long-distance transport for resource-scarce regions, could increase demand by an additional 330–900 Mt by 2050. Capturing this opportunity requires the creation of new markets for ammonia supported by straightforward policy interventions. This includes approving the safe use of ammonia in energy systems, removing trading and handling barriers, and levelling the playing field to allow ammonia to compete with fossil fuel–based alternatives.

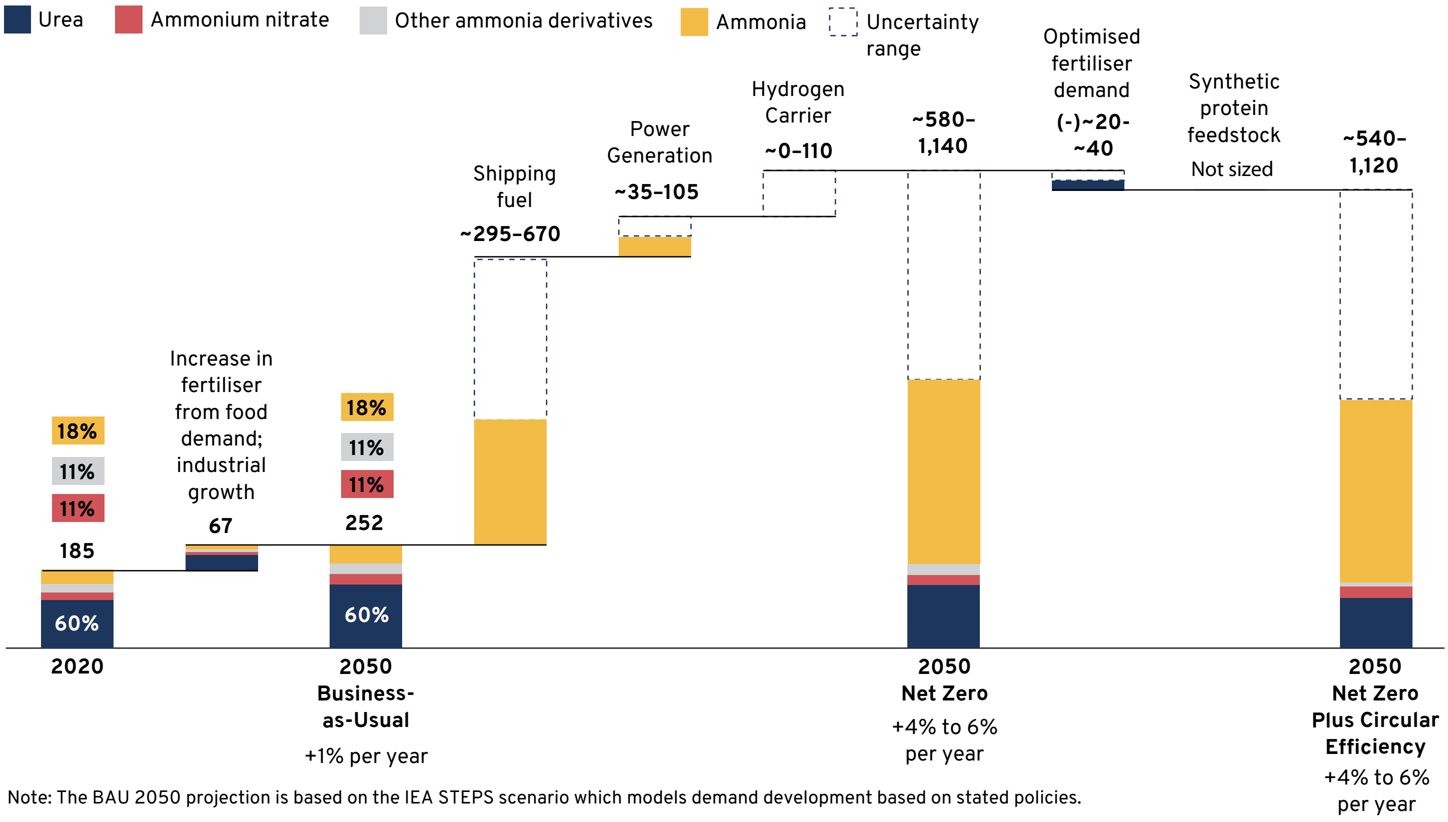
- **Fertiliser use optimisation:** The transformation of global food and land-use systems that target optimisation and reutilisation of nitrogen across the food system could moderate growth in ammonia demand. Optimisation would minimise nutrient losses via improved agricultural management practices and reduce pressure on demand for crops through reduced food waste and dietary shifts to less land-intensive diets while providing food security with improved nutritional intake for a growing global population. These levers are applied to the Fastest Abatement (FA) scenario, producing a slower growth in total ammonia demand for fertiliser applications of 0.6% per year, from 185 Mt in 2020 to 221 Mt in 2050. Because of inherent uncertainties and challenges to driving change in this critical industry, these levers should be considered potential opportunities in a net-zero world rather than a forecast or specific recommendation.

The size and growth rate of each of these demand trends are uncertain and will depend on myriad policy efforts, investments, and deep cost reductions in technologies across the value chain.

EXHIBIT 1.4

Ammonia demand could increase by 190%–520% by 2050

Ammonia demand drivers in different scenarios, Mt NH_3



Note: The BAU 2050 projection is based on the IEA STEPS scenario which models demand development based on stated policies.

Source: IEA; Food and Land Use Coalition; DNV-GL; UMAS; JERA; MOTIE; METI; AFRY[19]

1.2.1.1 Business-as-Usual: Higher demand for food and goods

Following current trajectories, demand for ammonia for conventional applications is projected to increase from 185 Mt in 2020 to 252 Mt by 2050 (Exhibit 1.4), growing by 1% per year relative to today.

The demand for ammonia for fertiliser is expected to maintain a historic (2010–20) growth rate at ~1% per year, tied to population and economic growth projections.[20] A growing population of over 9 billion in 2050 requires more food to sustain itself, and appropriately used fertiliser is critical to ensure strong soil yields and prevent deforestation. Economic development also leads to the continuation of shifts from low-intensity agriculture to large-scale industrial agriculture, as well as an increase in consumption of less nutrient-efficient animal food products, leading to higher fertiliser demand.

Globally, the growth in fertiliser demand per capita is expected to decelerate, rising only to 21 kilogrammes (kg) in 2050 (from 20 kg per capita in 2020). Complex regional dynamics underlie the relatively flat behaviour globally. Developing economies in Africa, Latin America, and Southeast Asia, as well as those that serve these markets like the Middle East, will be drivers for growth. Developed economies like Europe and North America may decrease their per capita use as they reach saturation and move towards greater nutrient-use efficiency (NUE). China, as the largest consumer, is not expected to see an increase in demand because of the implementation of the Action Plan on Zero Growth of Fertiliser Use by 2020, which already has met its initial targets.

The remaining non-fertiliser portion of demand, made up by a wide range of industrial applications such as plastics, explosives, and synthetic fibres, is expected grow at a higher rate of 1.3% per year. This growth trend represents a slowdown from historic trends (4% annual growth between 2010 and 2020), mostly driven by the slowdown in China's industrial expansion.[21] While there are potential demand reduction levers such as material efficiency measures and plastics recycling, which the IEA estimates could deliver a ~5 Mt reduction in ammonia demand,[22] these were not quantified in this analysis given the limited impact of these levers, particularly relative to the large and uncertain demand growth from energy applications.

1.2.1.2 Net zero: Ammonia as an energy carrier

In a net-zero future, ammonia could enable the long-distance transport of clean energy around the world: as well as being a carbon-free molecule, ammonia is also much easier to transport and store relative to both electricity and hydrogen, and much of the required handling expertise and infrastructure is already in place. Currently, given the globally traded volumes of 19 Mt of ammonia today and its widespread use in fertilisers, 192 ports worldwide have the infrastructure to handle, store, and transport ammonia.[23] However, considering the expected scale of demand from energy applications and the growth in traded volumes, a massive expansion in this infrastructure is needed, as well as a larger number of trained personnel, to ensure safe handling of ammonia.

In a net-zero future, ammonia could enable the long-distance transport of clean energy around the world: as well as being a carbon-free molecule, ammonia is also much easier to transport and store relative to both electricity and hydrogen, and much of the required handling expertise and infrastructure is already in place.

Demand as a shipping fuel could become the largest driver of ammonia demand, amounting to 295–670 Mt[xxx] by 2050 (Exhibit 1.4). This is contingent upon ammonia propulsion systems being available by 2025 and significant progress towards safety and fuel handling regulations, as well as certification.

Fossil fuels currently dominate the shipping fuel mix, but to achieve net zero by 2050, a shift to zero-emissions fuels will be needed. There is already momentum towards this shift with targets set to achieve 5% zero-emissions fuels as part of shipping's overall energy mix by 2030.[24] While there are several technically feasible zero-emissions fuel options to decarbonise shipping, ammonia is likely to be the most scalable and economically viable option for long-distance international shipping. Alternative zero-emissions fuels such as biofuels will likely play only a limited transitional role because of the scarce amount of sustainable biomass production,[25] which will likely be prioritised for biomaterials (plastics, wood products, pulp and paper, etc.), and the aviation sector, which has fewer viable alternative decarbonisation options. Lastly, carbon-feedstock-based fuels (such as methanol) rely on the availability of sustainable carbon feedstock, either from scarce bio-resources or from direct air capture (DAC), a technology that is likely to remain expensive in the medium term. Green methanol and green ammonia as shipping fuels are compared in more detail in Exhibit 1.5.

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xxx Shipping demand projections for ammonia are based on DNV GL and forthcoming UMAS analysis. Further details can be found in the *Technical Appendix.*

EXHIBIT 1.5

A comparison between the use of green methanol and green ammonia as shipping fuels

+ Advantage   ! Challenge or need

SCENARIOS		GREEN METHANOL	GREEN AMMONIA
Readiness of technology and infrastructure		! **Scalability challenges** due to lack of sources of sustainable CO$_2$ + **Container vessels ordered** (e.g., 8 vessels by Maersk), showing commitment in the fuel by operators	+ **Strong long-term scalability** potential in the late 2020s leveraged through increasing demand from Asia + **Natural hydrogen storage** and **ammonia terminals at some ports available** (e.g., Australia production for bunkering in Asia) ! **Nitrogen oxides (NO$_x$) emissions** produced by ammonia combustion have global warming potential; however, **99% mitigation rate** can be achieved through use of selective catalyst reactors[1]
Regulation		+ **Interim guidelines** for the use of e-methanol on ships **available** + **ISO specification** of methanol as a marine fuel **under development** + **Strong government support** for green hydrogen (and vectors) from EU	! Robust **safety guidelines** and **fuel handling guidelines needed** for the safe handling of ammonia on board ships + **Strong government support** for green hydrogen (and vectors) from EU
Cost of ownership	**Fuel cost**	! **High costs of green methanol** from both DAC and carbon capture from sustainable feedstock	+ **Lower production costs for hydrogen and ammonia** than maethanol from DAC
	Vessel capital expenditure	+ **Cheaper storage cost on board** due to atmospheric temperature and pressure, also can be stored in smaller tanks in natural voids throughout the ship	! **More expensive due to pressurised/ refrigerated storage** and spherical/ cylindrical tank shapes, also internal combustion engine requires aftertreatment to remove N$_2$O

[1] Selective catalyst reactors (SCR) are emissions control systems that capture NO$_x$ emissions from combustion and reduce it down to near-zero levels by converting NO$_x$ to nitrogen and water, using ammonia as the reductant.

Source: Lloyds Register and UMAS; ETC for GMF; Maersk Mc-Kinney Møller Center for Zero Carbon Shipping NavigaTE model[26]

The demand for ammonia for shipping is expected to be in the range of 295–670 Mt by 2050. The wide range of the estimate reflects the uncertainty of ammonia uptake compared with other zero-emissions shipping fuels such as methanol. For ammonia to be adopted as the primary shipping fuel of the future, three major tipping points need to be reached:

- The availability of engine and on-vessel storage technologies. Major marine engine manufacturers such as Wartsila and MAN Engine are working towards making ammonia propulsion systems available by 2024.[27]
- The regulatory approval of ammonia as a marine fuel, as well as implementation of safety and handling regulations. Due to its toxicity, ammonia has concerns associated with its use on-board vessels. This will hamper uptake until proper procedures, such as how refuelling should be conducted and how the ammonia should be stored, are put in place.
- The deployment of a policy framework targeting the creation and expansion of this new market. Policies consist of direct regulation to mandate the adoption of these new applications, increased stringency on environmental controls and limitations on the use of conventional fossil fuels, and promotion of a level playing field by reducing price impacts due to higher ammonia production costs compared with conventional alternatives. A detailed description of this framework is described in Box 1.

Demand for ammonia as a vector for transporting hydrogen over long distances where hydrogen pipelines are not feasible could represent up to 110 Mt of additional ammonia demand by 2050. Countries with severe constraints on renewable resources and/or land may be unable to meet their low-carbon energy needs locally and thus will rely more heavily on energy imports, most likely in the form of ammonia or hydrogen. For long-distance transport of energy in a net-zero world,[xxxi] ammonia presents the most viable option given the challenges associated with transporting hydrogen via ship and the lower relative cost of shipping ammonia compared with liquefied hydrogen.[28] It is estimated that up to 10% of hydrogen produced in 2050 could be shipped over large distances, potentially representing up to 110 Mt of ammonia demand annually by 2050.[29,xxxii]

In addition, the use of imported near-zero-emissions ammonia to generate electricity in regions with severe resource constraints could represent an additional 35–105 Mt of ammonia demand by 2050. Similar to the case for ammonia as a hydrogen vector, countries facing severe constraints on renewable resources and/or land may be unable to meet their domestic electricity demands through local renewable electricity generation in a net-zero world, and are therefore likely to rely more heavily on zero-carbon energy imports.

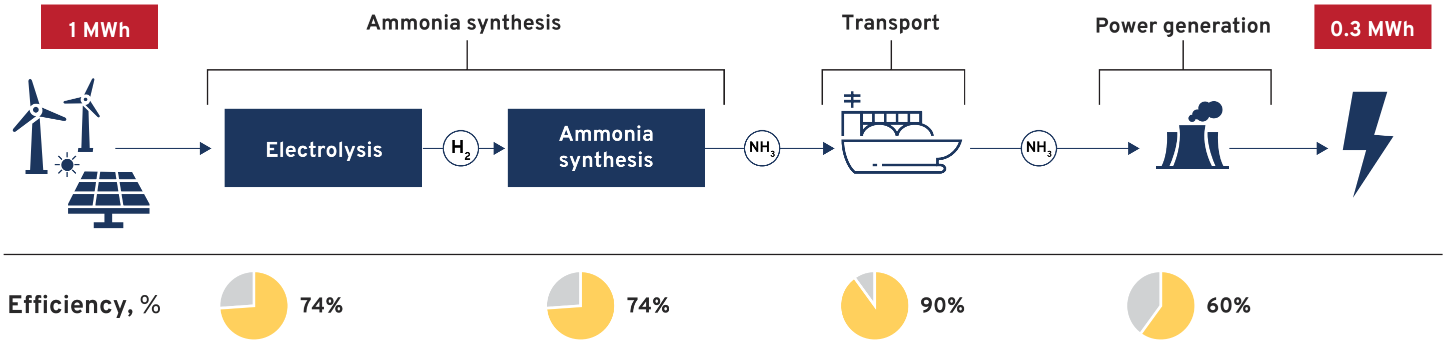
Where it is feasible to import hydrogen via pipeline for direct use in power generation, this is preferable to ammonia given the higher round-trip efficiency and more favourable economics. However, for imports over longer distances where hydrogen pipelines are not feasible, the direct use of near-zero-emissions ammonia presents the next best option, with countries such as Japan and South Korea already making commitments to replace existing coal demand with ammonia for use in thermal power plants, initially through co-firing, increasing to 100% ammonia-fired power generation plants.[30] In 2020, Japan received its first shipment of blue ammonia from Saudi Arabia to test this concept.[31]

However, using ammonia for power generation entails efficiency losses from the transformation processes involved. The round-trip efficiency is currently 25%,[xxxiii] and while it is expected to increase to around 30% by 2050 (Exhibit 1.6), it still remains lower than the 33%–60% average efficiency of power generation with fossil fuels. These efficiency losses reduce the economic viability of ammonia in energy applications and thus increase the green premium. For ammonia to begin to compete with and replace fossil fuel–based incumbents in these applications, R&D investment is required, particularly in ammonia-fired turbines and ammonia crackers, to improve round-trip efficiency and thus economic competitiveness of ammonia.

EXHIBIT 1.6

Expected 2050 efficiencies at each stage of ammonia production, transport, and combustion for power generation

Efficiency at each stage of power-to-ammonia to power conversion, based on lower heating value



Source: MPP analysis; IEA; ETC; Chatterjee et al.[32]

[xxxi] Long-distance transport refers to distances at which pipelines can no longer be used.

[xxxii] Global demand for H_2 in 2050 is taken from ETC analysis and regional split from the AFRY Global Hydrogen Trade Model. The proportion of imported H_2 that is likely to be via pipeline and the proportion that would need to be shipped are based on approximate distances between regional flows. Assuming all long-distance shipped H_2 is in the form of ammonia, this would translate to an additional 110 Mt of demand by 2050. Because of the high degree of uncertainty and possibility that round-trip efficiency of hydrogen could improve, the range of 0–110 Mt of ammonia of demand is taken.

[xxxiii] Refers to the conversion of power to ammonia, followed by ammonia to power. Based on the lower heating value.

The combustion of ammonia in shipping and for power generation, if complete, produces only nitrogen and water as by-products. However, in practice, combustion is incomplete, generating large volumes of NO_X emissions, which leads to air pollution and the formation of ozone, and thus further climate impact. While 99% of these emissions can be mitigated through the use of SCRs, the remaining 1% of emissions released could still lead to unacceptable levels of NO_X, and thus further improvement of the mitigation rate of SCRs is required to ensure that adverse climate impacts are avoided.

In addition to these applications, there are other use cases of ammonia as an energy carrier, particularly in resource-constrained regions, which may materialise but are not quantified in this analysis as they are at earlier stages of development and remain relatively uncertain. Examples include its use in residential fuel cells for combined heat and power, as is being explored in Japan using solid oxide fuel cells,[33] as well as its use in industry to generate high-temperature process heat.

BOX 1

The determining role of public policy to trigger and scale new markets

Initial demand for new energy applications of ammonia, as well as the pace and scale of growth, will require significant interventions beyond technological innovation. Public support must incentivise end-user markets to adopt new ammonia applications. Policy instruments needed will include direct regulation to guarantee ammonia uptake in new applications, MBMs to incorporate environmental costs and level the playing field, and voluntary mechanisms to exert influence and drive sector collaboration. Part 3.2 of this report details public policy recommendations to make this happen, together with actions required for industry and financial stakeholders. A summary of the necessary policy instruments and their sequencing is presented to outline the critical role they play to catalyse demand growth to 2050.

Ammonia as shipping fuel

Policy to decarbonise the shipping sector at the lowest total cost will create a market for ammonia as shipping fuel, yet much intervention is necessary to set the right conditions for an accelerated uptake. The implementation of these policies will need to be largely driven by the International Maritime Organization, which has international jurisdiction over shipping matters. Amongst its most relevant short-term policy interventions are the approval of ammonia as a new maritime fuel, increasing ambition from current emissions reduction targets to a net-zero goal for 2050, and boosting technical efficiency standards, including EEDI (emission efficiency indicator for new-build ships) and EEXI/CII (emission efficiency and carbon intensity indicators for existing ships) in the same path towards net zero. The IMO should also collaborate with all stakeholders in the sector to drive voluntary action and commitment to the deployment of Green Corridors. Midterm policies should establish market-based mechanisms including emissions trading schemes (ETS), to pave way for an international carbon pricing scheme on shipping emissions towards the next decade. CfDs and subsidies for zero-emissions fuels are additional economic instruments to be applied while differences in price between ammonia and fossil fuel–based alternatives remain high. Once ammonia as a shipping fuel reaches a tipping point of economic competitiveness, fuel mandates and quotas to prescribe uptake should be rolled out together with the phasing out and eventual banning of fossil fuel usage on ships.

Ammonia for power generation in renewable resource–constrained markets

For power generation, short-term policy also starts with the definition of national roadmaps committing to long-term incorporation of near-zero-emissions ammonia into energy systems. Tailored support for flagship co-firing projects should be put in place in the form of grants, loans, and tax breaks in order to test, scale, and increase process efficiencies. As scale grows, targets on percentages of power generation from low-carbon sources (including ammonia) should be established, along with preferential market conditions that include FITs, guaranteed access to power grids, and priority dispatch. These policies must be paired with efforts to reduce the role of conventional fossil fuels in power generation, such as the establishment of phase-out rules. Cross-cutting carbon emissions pricing schemes can also be used to level the playing field in energy markets where ammonia alternatives remain uncompetitive.

Ammonia as a hydrogen carrier over long distances

For the case of ammonia as a hydrogen carrier, policies should be directed to increase the role of hydrogen in the energy system and recognise the potential role of ammonia in hydrogen strategies and roadmaps. Policies to mobilise resources for R&D will be necessary to drive technology advancements that ensure long-term competitiveness of ammonia as a hydrogen vector for long-distance transport versus liquefied hydrogen, such as ammonia cracking, making this application cost competitive. By 2030, economic instruments including CfDs will be necessary to create incentives to displace fossil fuel alternatives. The establishment of cross-cutting carbon emissions pricing schemes for the end-use applications of hydrogen will enable wider market adoption.

1.2.1.3 Optimisation of fertiliser use

In a net-zero future, greater efficiencies in nutrient management and food production systems could moderate growth in ammonia demand, enabling supply to be channelled to energy uses where it can deliver emissions reductions, while simultaneously reducing polluting nutrient losses to the environment, all while meeting the nutrient demands of a growing global population. These levers are applied to the FA scenario, producing a slower growth in total ammonia demand of 0.6% per year from 185 Mt in 2020 to 221 Mt in 2050. The slower demand growth results from two types of interventions:

A. **Improvements in NUE across food production systems via readily available nutrient management practices**

Uptake of innovative agronomic practices and improvements in nutrient management techniques could enhance NUE, reducing demand for mineral nitrogen while meeting the same nutrient requirements. The fertiliser industry has developed guidance to improve the utilisation of crop nutrients, known as the 4R Nutrient Stewardship: *applying the right nutrient source, at the right rate, at the right time, in the right place.*[34] By following these principles in accordance with local agronomic conditions, farmers can maximise the proportion of mineral nitrogen uptake by crops, which in turns allows for a reduction in fertiliser input or an increase in crop yields for the same input. Related management practices include the utilisation of precision agriculture, regenerative farming, and variable-rate technologies, as well as timing and selection of fertiliser according to soil and weather conditions. Further detail is given in Box 2.

Furthermore, increasing the use of organic fertilisers could have a positive impact on NUE by maximising the reuse of waste nitrogen from a diverse set of sources (for example, crop residues, livestock excreta, and food waste) thus reducing demand for ammonia. The application of crop rotation techniques also delivers improvements by including more biological nitrogen fixation through natural sources. Cover crops provide further support through additional protection that avoids nitrogen losses and improves soil structure and water retention.[35] The application and combination of these measures require careful analysis and testing of materials, soil, and crop conditions in order to ensure that the net result of these levers has the desired outcome and consistently delivers NUE improvements.

The implementation of these practices could help improve NUE at the crop level from current levels of 45%–60% towards recommended levels of 50%–90%,[36] while reducing environmental and societal costs in the form of nutrient pollution.

BOX 2

Selection of the right nutrient source and impacts on downstream Scope 3 emissions

Selecting the type of mineral fertiliser in accordance with soil type and conditions, humidity, and other weather conditions can help reduce CO_2 and N_2O emissions from fertiliser use. Emissions generated during the use phase vary per type of fertiliser depending on these conditions.[37] Applying nitrate-based fertilisers to arable soils, under dry conditions, can result in lower total emissions compared with urea. The case is the same for applying urea to grasslands, peat soils, and clay soils under wet conditions.

However, while urea is the most widely used mineral N fertiliser, with a high nitrogen content (46%) and greater convenience for storage, transport, and application, it is also the only fertiliser associated with CO_2 emissions during its use phase. Manufacturing urea requires CO_2 that is later released during hydrolysis after application to the soil. This moves the CO_2 from where it can be managed in the production phase to where it is difficult to mitigate in the use phase. These emissions could be reduced through greater uptake of nitrate alternatives such as ammonium nitrate and calcium ammonium nitrate, which do not release CO_2 during their use. Seizing these opportunities, however, requires adaptation and mitigation measures to reduce impacts to food production systems and food security. Greater uptake of nitrate-based fertilisers would require higher rates of application due to their lower concentrations of nitrogen. In addition, there are significant safety risks around handling and transport of ammonium nitrate that must be carefully managed as it is classified as an oxidiser under the United Nations Recommendation on the Transport of Dangerous Goods Model Regulations,[38] requiring special handling and storage conditions.

Optimising the selection of fertiliser type to reduce GHG emissions during the use phase, in cases where infrastructure for safe handling is available, could lead to a reduced demand for urea ranging from a 9% increase to a 28% reduction by 2050 compared with 2020.[39]

B. **Broader shifts to and optimisation of food systems that reduce fertiliser demand by reducing demand for crops**

Streamlining food supply chains to minimise waste could reduce overall demand for nutrients. Approximately one-third (by weight) of all food produced is lost across all stages of the food value chain. Reducing food waste could mean that nutrient requirements of the growing population could be met without increasing land under cultivation or crop yields. Currently there is widespread global commitment to reduce food waste, including the Sustainable Development Goals target for a 50% waste reduction at the retail and consumer level by 2030.[40] Meeting waste reduction goals requires an end-to-end transformation across the value chain, high innovation, and investments that deliver improvements in distribution and storage infrastructure. Technological innovation will be needed in the form of packaging materials that extend product shelf life. Additionally, shifts towards more local and closed-loop food economies that capture and recycle food by-products and waste will also be necessary.

A shift to healthier diets with higher caloric and protein intake from plant-based food products could significantly improve food system NUE. Lowering consumption of animal food products increases nutrient efficiencies by reducing crop land requirements as well as nitrogen nutrient demand to feed the global population. Achieving this depends on inherently unpredictable consumer behaviour, as current trends show rising income leads to an increased intake of animal food products. Countries and regions will experience different changes in dietary patterns depending on their starting point: developing countries may increase protein intake to the levels seen in developed countries through plant-based sources (sub-Saharan Africa) while developed countries may reduce their protein and caloric intake from animal sources, particularly from red meat (North America and Europe).

While the described technologies and management practices (together with other abatement measures) contribute to reducing Scope 3 emissions from the fertiliser use phase, no method is currently available to completely eliminate these emissions without also eliminating mineral fertiliser use. Hence, in a net-zero world, any remaining emissions from fertiliser application would require CDRs.

BOX 3

Additional upside from added chemical land treatments (for example, N inhibitors/urease inhibitors)

Application of chemical additives and enhancers in the form of inhibitors and controlled-release fertilisers can continue to optimise nutrient intake by crops and further reduce losses by lowering nitrous oxide emissions.

These additives and enhancers have the potential to hold mineral nitrogen in the soil for longer or reduce direct and indirect nitrous oxide losses, increasing the chance that plants can make use of nitrogen before nitrification or denitrification occurs.

Utilisation of chemical land treatments like nitrogen and urease inhibitors also reduces Scope 3 N_2O emissions that stem from microbial processes occurring in the soil after fertiliser application. Urease and nitrification inhibitors slow the conversion of nitrogen fertiliser to other nitrogen compounds in the soil. Controlled-release fertilisers help match nutrient release with crop requirements through use of coatings to control the availability of nutrients.

Application of these technologies on a significant share of global acreage could reduce the fraction of nitrogen from urea that is volatilised or directly lost as nitrous oxide emissions through the nitrification process and lead to a net 25% reduction in emissions intensity.[41] These measures are already being used, particularly for the slowdown of ammonia volatilisation from urea (something that urea has a higher potential than other mineral fertilisers[42]). In India, since 2015 all subsidised urea is coated in neem oil, which has nitrification inhibitor properties.[43] Similarly, Germany has required that all urea is either incorporated into the soil or combined with urease inhibitors since 2020.[44]

However, the long-term impacts of such products on the soil are still not well understood. Further research is needed in order to improve their applicability, for example, to address concerns about the long-term impact of releasing the polymer coatings into the soil (such as by developing biodegradable coatings). Additional research is also needed to better understand the extent to which the impact of nitrification inhibitors on direct nitrous oxide emissions may be offset by increased ammonia volatilisation and indirect nitrous oxide emissions.[45] The long-term impacts on the soil microbiome of nitrification and urease inhibitors also require further research.[46]

BOX 4

Ammonia for use as feedstock in alternative protein production

In a net-zero future, the role of alternative proteins as a substitute for conventionally cultivated animal protein is expected to grow to 65 Mt per year or 8% of protein by 2030.[47] Though there remains significant uncertainty as to when price, taste, and texture parity may be achieved with animal proteins, plant-, microbial-, and animal cell-based alternatives are most likely to play a role. Microbial-based protein sources, which include algae, fungi, yeast, and bacteria, rely on nitrogen as a feedstock in many production processes. These technologies are high TRL despite limited current scale of production. The size of ammonia production to meet feedstock requirements for microbial proteins represents a small potential upside but is outside the scope of this report.

Demand-side measures to curb the growth in ammonia demand and reduce downstream GHG emissions from fertiliser use are essential. However, given the scale of demand growth expected, particularly from energy applications for use as a zero-emissions fuel, demand-side measures alone are insufficient: supply-side action is therefore critical.

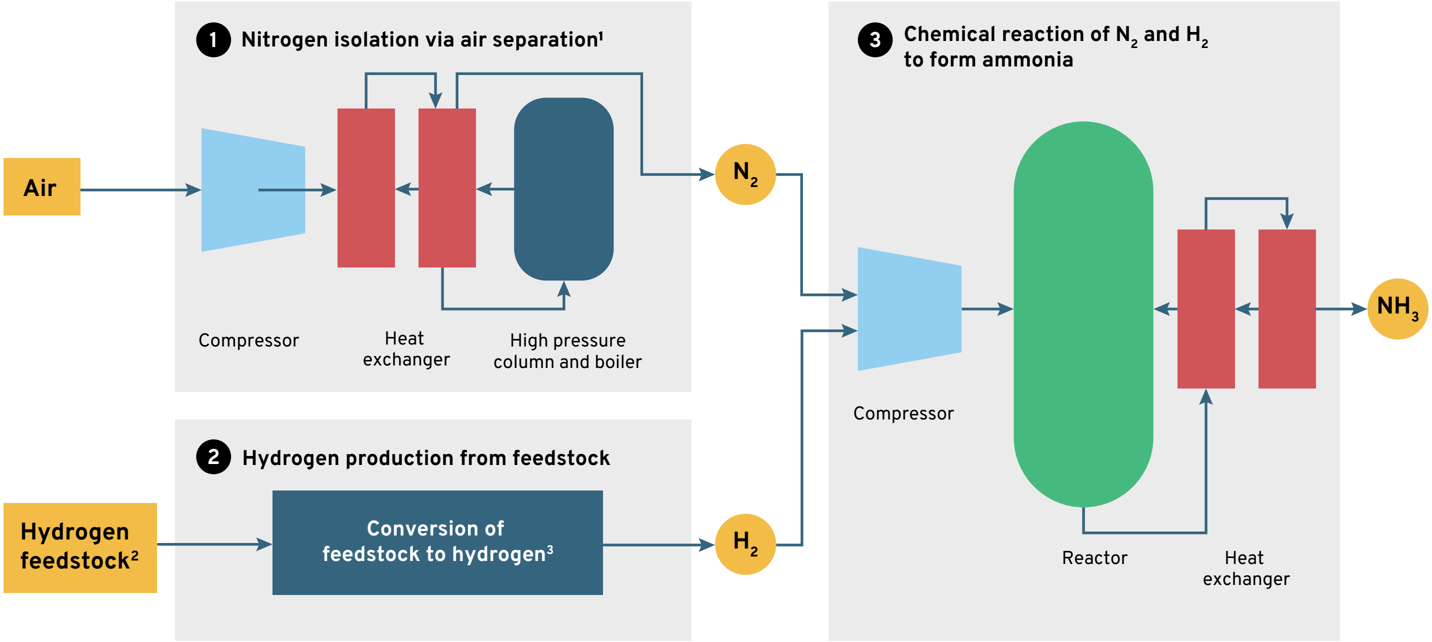
1.2.2 Supply-side decarbonisation levers

The H-B process, in which atmospheric nitrogen and hydrogen are chemically reacted, has been used to produce ammonia on an industrial scale since the early 20th century. Today, all ammonia is produced via this process, which involves three stages, as shown in Exhibit 1.7: (1) the separation of nitrogen from the air, (2) the production of hydrogen from a feedstock, and (3) the chemical reaction of hydrogen and nitrogen at high temperatures (typically 400°C –500°C) and pressures (typically 100–300 bar) in the presence of a catalyst to enable a rate of reaction that is economical for industrial production.

EXHIBIT 1.7

Three stages of ammonia production

Simplified schematic of stages of ammonia production



[1] Air separation is not necessary in SMR-based production.
[2] Hydrogen feedstock may be coal, natural gas, water, or biomass.
[3] Conversion may be SMR, ATR, coal gasification, electrolysis, methane pyrolysis.

Source: MPP analysis

Step 1, the separation of nitrogen from the air, is straightforward to decarbonise. In the case of SMR-based ammonia production, oxygen from the air reacts with natural gas, leaving behind the stoichiometric volumes of nitrogen required for ammonia synthesis at no additional expense, while alternative production routes require an electrically powered air separation unit to isolate the nitrogen from air. Powering the air separation unit with renewable electricity, for example via a renewable PPA, enables full decarbonisation of this process; hence, all supply-side decarbonisation levers, summarised in Exhibit 1.8, consider the use of renewable electricity to decarbonise this phase of ammonia production.

Step 2, the production of hydrogen, is responsible for the vast majority of production-related CO_2 emissions and has a number of potential decarbonisation levers. To date, almost all hydrogen for ammonia production has been derived from fossil fuel feedstocks, generating large volumes of Scope 1 and 2 CO_2 emissions, in the form of both process emissions from the chemical reaction of natural gas to form syngas, as well as flue gas emissions from combustion. Over 98% of production-related emissions from ammonia synthesis are generated in this phase, hence the supply-side decarbonisation solutions, summarised in Exhibit 1.8, focus almost entirely on this stage. There are six major supply-side levers to decarbonise this phase of ammonia production, each of which can be categorised as either a transitional technology or a near-zero-emissions technology (Box 5).

Step 3, the chemical reaction of hydrogen and nitrogen, requires very little additional energy input and is straightforward to decarbonise. As this reaction is exothermic, most of the energy needed for the process is generated by the reaction itself, requiring only a small amount of additional electricity input to power the compressors, motors, and the pressure and temperature control equipment. Similar to the isolation of nitrogen for air, if renewable electricity is used to meet these power demands, this phase can be fully decarbonised. Hence, all supply-side decarbonisation levers, summarised in Exhibit 1.8, consider the use of renewable electricity to decarbonise this phase of ammonia production. There are currently no viable or technologically mature alternatives that can compete with or replace the H-B process. While novel processes such as direct electroreduction of N_2 to ammonia are being actively researched and explored as alternatives to the H-B process, these technologies are at early prototype stages and still face a number of major technical challenges regarding yield rates and efficiencies.[48]

BOX 5

Supply-side technology categories

The six major supply-side decarbonisation levers are categorized in the following ways:

- **Transitional technologies** are supply-side technologies that are available today and reduce the Scope 1 and 2 emissions intensity of ammonia production below that of conventional routes but do not bring emissions sufficiently close to net zero. These include partial carbon capture and storage as well as the installation of revamp electrolysers.[xxxiv]
- **Near-zero-emissions technologies** include technologies that reduce the Scope 1 and 2 emissions intensity of ammonia production close to net zero. This includes all blue ammonia production technologies with capture rates of 90% and above. In addition, this includes zero-emissions ammonia production technologies such as green ammonia production, biomass-based ammonia production, and methane pyrolysis.

[xxxiv] This includes the installation of a small electrolyser at existing production sites to supply ~10% of the hydrogen feeding the ammonia synthesis unit.

EXHIBIT 1.8

Supply-side decarbonisation technologies

Near-zero-emissions technologies

Supply-side emissions reduction lever	Green ammonia	Blue ammonia	Biomass-based production	Methane pyrolysis
Technologies	Electrolysis and ammonia synthesis, powered by: • Renewable PPA • Renewable PPA plua dedicated renewables • Dedicated renewables plus geological H_2 storage • Dedicated renewables plus pipeline H_2 storage	Steam methane reformer with CCUS Gas-heated reformer with CCUS Autothermal reformer with CCUS Oversized autothermal reformer with CCUS (burns H_2) Electrified steam methane reformer with CCUS Coal gasification with CCUS	Biomass digestion plus ammonia synthesis Biomass gasification plus ammonia synthesis	Methane pyrolysis plus ammonia synthesis
Feedstock	Water	Natural gas or coal	Biomass	Natural gas
2020 levelised cost, \$/t NH_3 ⬚ Range between regions	**550–1,400**	**350–770**	**770–1,350**	**480–840**
2050 levelised cost, \$/t NH_3 ⬚ Range between regions	**290–770**	**370–680**	**740–1,230**	**460–750**
Scope 1 CO_2 abatement potential	**100%**	**96%**	**100%**	**100%**
Current TRL/ year available	TRL 7-8 2025	TRL 7-9 2025 / 2030	TRL 3-7 2030	TRL 6-7 2030
Main barriers	Fluctuations in renewable electricity supply Cheapest where there is access to geological storage for green H_2 Constrained by land availability for dedicated VRE	Large upstream emissions from natural gas extraction CO_2 storage is not available in all regions CO_2 capture is incomplete	Limited supply of sustainable biomass Much higher cost compared to other solutions	Large upstream emissions from natural gas extraction Limited uses/value of solid carbon by-product and risk of emissions if sold for other uses

Note: These costs do not include a carbon price.

Source: MPP analysis

EXHIBIT 1.8

Supply-side decarbonisation technologies, continued

Transitional technologies

Supply-side emissions reduction lever	**Revamp electrolyser**	**Partial carbon capture and storage**
Technologies	Steam methane reforming plus revamp electrolyser to supply ~10% of hydrogen feeding synthesis unit Coal gasification plus revamp electrolyser to supply ~10% of hydrogen synthesis unit	Capture of process emissions from natural gas SMR production followed by permanent storage
Feedstock	Natural gas or coal	Natural gas
2020 levelised cost, \$/t NH_3 ⬚ Range between regions	**300–670** 	**300–560** 
2050 levelised cost, \$/t NH_3 ⬚ Range between regions	**320–670** 	**320–480** 
Scope 1 CO_2 abatement potential	 **10%**	 **67%**
Current TRL/ year available	TRL 9 Today	TRL 9 Today
Main barriers	Higher cost relative to grey ammonia Large cost for small emissions reduction	CO_2 storage is not available in all regions Infrastructure for transport and storage not ready in most regions

Note: These costs do not include a carbon price.

Source: MPP analysis; ETC; IEA; Fasihi et al.; Topsoe; Sanchez et al.; BEIS[49]

What is the contribution of each lever to decarbonising ammonia production?

The endgame is green ammonia. By decoupling ammonia from fossil feedstocks, electrolysis provides a pathway to fully decarbonised ammonia production and is the only zero-emissions technology that is projected to be both economically viable and technologically mature within the next decade.[xxxv] At a levelised cost of \$350–\$380/t NH_3 (\$1.2–\$1.5/kg H_2), green ammonia becomes more cost competitive compared with blue ammonia by 2030 in the lowest-cost power regions, driven by the continued decline of wind, solar photovoltaic (PV), and electrolyser costs. By 2040, green ammonia is projected to be cost competitive in most regions, driving a widespread adoption of green ammonia across the world; this relies strongly on large declines in electrolyser capital expenditures and renewable electricity costs driven by economies of scale.

Blue ammonia is a cost-effective route to reducing emissions in the short term, offering both a transitional abatement option for existing assets and, to a lesser extent, a long-term solution for regions with low-cost natural gas and availability of geological CO_2 storage. In early years, retrofitting existing assets with CO_2 capture is a low-cost, capital expenditure-efficient abatement solution, particularly in current production locations that typically have access to cheap fossil feedstocks, such as North America and the Middle East. In these regions, blue ammonia is produced at a levelised

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[xxxv] The point at which a technology is considered to reach maturity is the year in which it is estimated to reach TRL 9 and thus commercial scale, which is 2025 for electrolysis-based ammonia production.

cost of \$350–\$400/t NH_3 (\$1.4–\$1.7/kg H_2[xxxvi]) by 2030 and reduces Scope 1 emissions intensity by 90%–96%.[xxxvii] However, higher CO_2 capture rates are technically achievable and certain ATR-based plants have the ambition of achieving over 99% CO_2 capture. Therefore, while emissions are reduced significantly through the addition of CCUS, this technology alone does not meet the ambition of getting to net zero and thus must be accompanied with CDR to neutralise residual emissions.

Other near-zero-emissions production technologies such as methane pyrolysis and biomass-based production are likely to play a limited role. Based on the current project pipeline, electrolysis and fossil fuel–based ammonia production with CCUS are emerging as the primary production routes for near-zero-emissions ammonia, collectively accounting for the vast majority of the more than 30 Mt of lower-emissions ammonia production capacity expected by 2030.[50] However, given the large volumes of demand that may need to be met by 2050, relying entirely on blue and green ammonia production may be a high-risk strategy as this would require rapid and prolonged ramp-ups of electrolyser capacity for green ammonia as well as the materialisation of large electrolyser cost reductions. Similarly, in the case of blue ammonia, the uptake is contingent on the achievement of high capture rates and the development of large-scale permanent CO_2 storage. Therefore, in order to de-risk the transition, additional production routes including biomass-based ammonia production technologies and methane pyrolysis should also be explored despite their higher costs. There is a particular use-case for biomass-based urea production given that the use of biogenic CO_2 produced during ammonia production eliminates the issue of downstream Scope 3 CO_2 emissions from fertiliser use. These routes, however, face a number of scalability challenges and hence are unlikely to take up large volumes of production.

Transitional technologies deliver emissions reductions cost-effectively this decade as near-zero-emissions production technologies are not yet available at a commercial scale. While near-zero-emissions technologies are not yet available, there are transitional technologies that enable early emissions reductions. These technologies are available today and allow current assets to be retrofitted to produce lower emissions ammonia at costs as low as \$300/t NH_3. Transitional abatement options include the partial capture of emissions from SMR-based production, as is routinely done today, followed by permanent storage, and the installation of small electrolysers in existing production plants to produce a portion of the hydrogen (~10%) feeding the ammonia synthesis unit, thus reducing the required fossil inputs and resulting emissions.

Lastly, residual emissions from incomplete carbon capture in blue ammonia production and Scope 3 emissions from upstream fossil fuel extraction and downstream fertiliser use must be offset by CDR. CDR solutions ranging from natural climate solutions to hybrid and engineered solutions must be employed in the ammonia sector to complement but not replace in-sector decarbonisation, in order to close the emissions gap to net zero and remain within the allocated carbon budget.[51] In fossil fuel–based ammonia production with CCUS, carbon capture rates are less than 100% and thus residual emissions from blue ammonia production must be neutralised via CDR to reach net-zero emissions. In addition, it is likely that even after all levers are applied to reduce Scope 3 emissions from fertiliser use, there will be a need for CDR to offset any residual emissions.

1.2.2.1 Green ammonia: Electrolysis-based ammonia production

Electrolysis provides a pathway to fully electrified ammonia production, decoupling ammonia from fossil feedstocks and reducing CO_2 emissions to zero. Green ammonia production relies on the use of an electric current, generated by renewable energy sources such as wind, solar, and hydropower, to split water molecules into their constituent elements: hydrogen and oxygen. In addition, electricity is used to power all other stages in the process, including extracting nitrogen from the air via an air separation unit and ammonia synthesis. Therefore, this production pathway decouples ammonia production from fossil feedstocks, thus reducing upstream Scope 3 emissions from fossil fuel extraction, which are otherwise hard to abate, and eliminating all Scope 1 and 2 emissions, given that renewable electricity is used throughout the process. However, this does not tackle the issue of downstream Scope 3 emissions from fertiliser use.

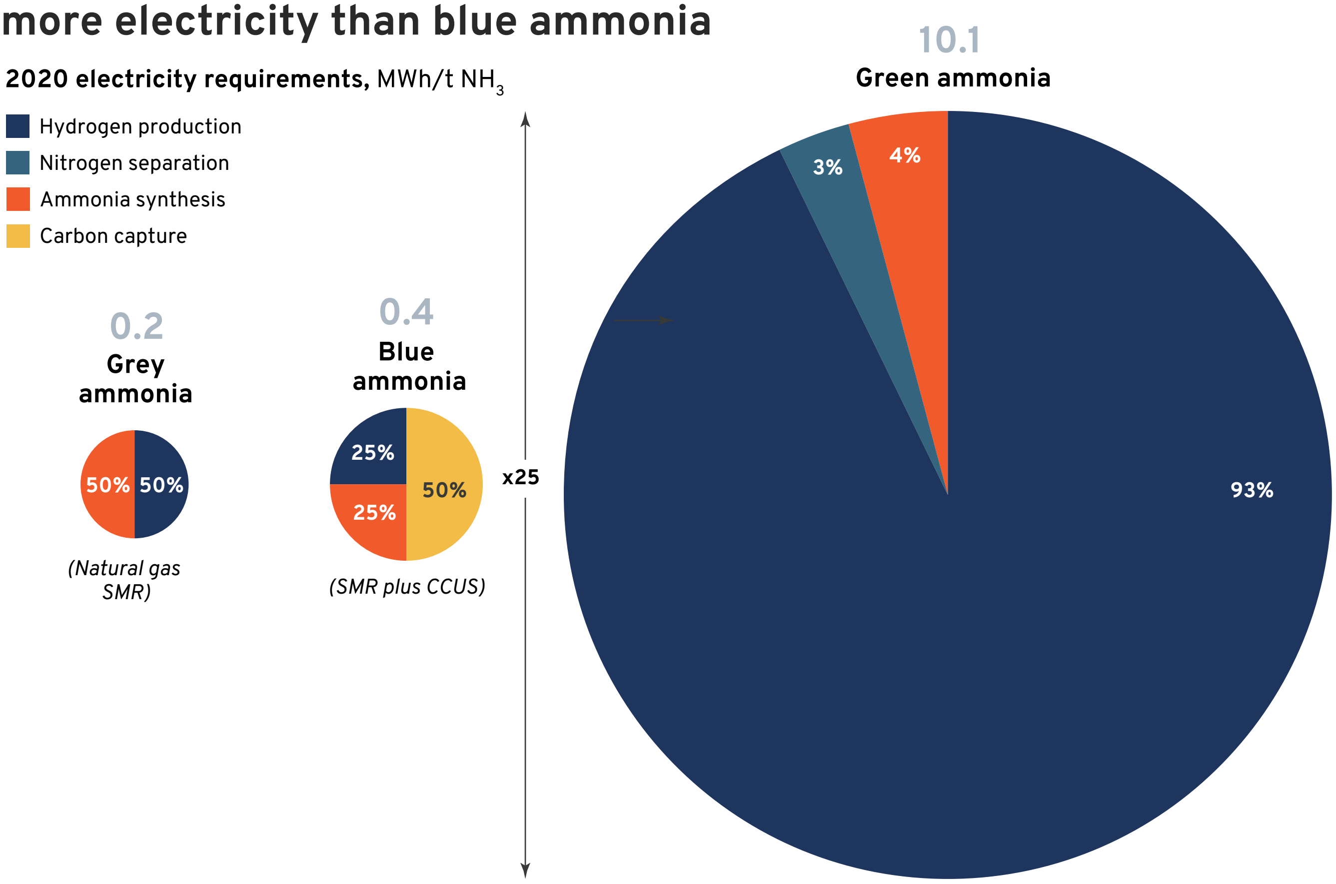
However, a major technical challenge faced by this production route is the integration of large volumes of intermittent renewable electricity sources, particularly given the inflexibility of the ammonia synthesis loop and low capital expenditure efficiency this would yield. Large amounts of renewable electricity are required for green ammonia production compared with other production routes (Exhibit 1.9), the vast majority (93%) of which is used to power the electrolyser for hydrogen production. The H-B process for ammonia synthesis typically requires a constant, stable supply of hydrogen to the ammonia synthesis loop, which operates with very high-capacity factors of around 95% to ensure a high capital expenditure efficiency. This is ultimately incompatible with the load factors of variable renewable electricity sources, which are typically around 20%–55% and thus produce a fluctuating supply of hydrogen. A number of different plant setups are explored (Box 6) to overcome this challenge posed by intermittent renewable electricity sources.

[xxxvi] The hydrogen prices for blue ammonia produced via SMR are greater than for green ammonia for the same levelised cost of ammonia, as green ammonia prices include the additional operating expenditures and capital expenditures associated with the air separation unit for ammonia production, but these are not included in the hydrogen prices.

[xxxvii] The range corresponds to different technologies with ATR-based routes at the upper end and SMR at the lower end.

EXHIBIT 1.9

Green ammonia production requires 25 times more electricity than blue ammonia



Source: MPP analysis; ETC; Worell et al.; IEAGHG; Fasihi et al.[52]

BOX 6

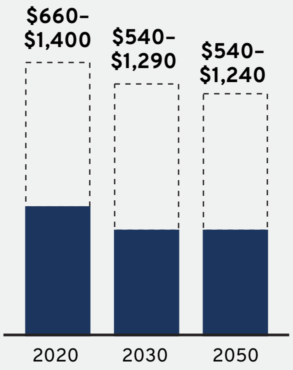
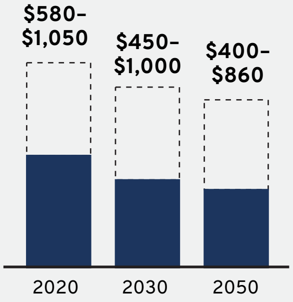
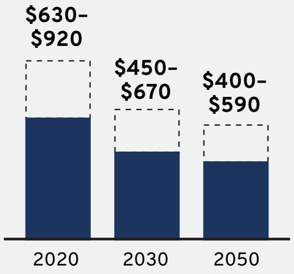
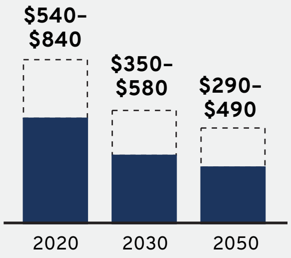
Four different setups of electrolysis-based production were explored, varying the source of green power and the means of compensating for the intermittency of variable renewable energy sources (VREs)

There are two main options for obtaining zero-emissions electricity:

1. Installing on-site dedicated variable renewable energy sources such as solar PV and wind
2. Purchasing renewable electricity via a PPA to guarantee a stable supply of green electricity

The former is typically cheaper, as it avoids additional costs such as those for transmission and distribution, and it satisfies the additionality criteria required to produce certified green hydrogen. However, it requires a greater area of land and, to guarantee a stable supply of hydrogen for the H-B process, the use of either a backup supply of power to cope with intermittency, or hydrogen storage. Hydrogen storage, for example in caverns and pipelines, allows variable hydrogen production to be decoupled from inflexible hydrogen demand. The following exhibit summarises the trade-offs of the different configurations.

Green ammonia can be produced either via a renewable grid PPA or via dedicated on-site renewable resources

Ammonia production route	**Electrolysis with renewable PPA plus ammonia synthesis**	**Electrolysis with dedicated VREs supplemented by PPA plus ammonia synthesis**	**Electrolysis with dedicated VREs and pipeline H_2 storage plus ammonia synthesis**	**Electrolysis with dedicated VREs and geological H_2 storage plus ammonia synthesis**
Description	The hydrogen feeding the ammonia synthesis unit is produced via electrolysis powered by renewable electricity purchased through a PPA.	The hydrogen feeding the ammonia synthesis unit is produced via electrolysis powered by dedicated renewables and supplemented by a renewable PPA to balance the intermittency.	The hydrogen feeding the ammonia synthesis unit is produced via electrolysis powered by dedicated renewables. The surplus of H_2 produced when the wind is blowing and sun is shining is stored in pipeline storage and used during times of deficit to ensure a steady supply of H_2.	The hydrogen feeding the ammonia synthesis unit is produced via electrolysis powered by dedicated renewables. The surplus of H_2 produced when the wind is blowing and sun is shining is stored in geological storage and used during times of deficit to ensure a steady supply of H_2.
Levelised cost, $/t NH_3 ⬚ Range between regions				
Pros	• High electrolyser load factor ~95% • Small plant footprint	• High electrolyser load factor ~95%	• Satisfies additionality criteria for certified green hydrogen production	• Satisfies additionality criteria for certified green hydrogen production • Lowest cost option in long-term
Cons	• Does not satisfy additionality criteria for certified green hydrogen production • Most expensive option in the long run	• Only a proportion of production satisfies additionality criteria for certified green hydrogen production • Larger plant footprint	• Requires more electrolyser capacity for same volume of ammonia produced • Larger plant footprint	• Limited by availability and accessibility of geological H_2 storage • Requires more electrolyser capacity for same volume of ammonia produced • Larger plant footprint

Note: The range in levelised costs reflects the variation between different regions. The costs apply to an alkaline electrolyser. See *Technical Appendix* for the underlying cost and efficiency assumptions.

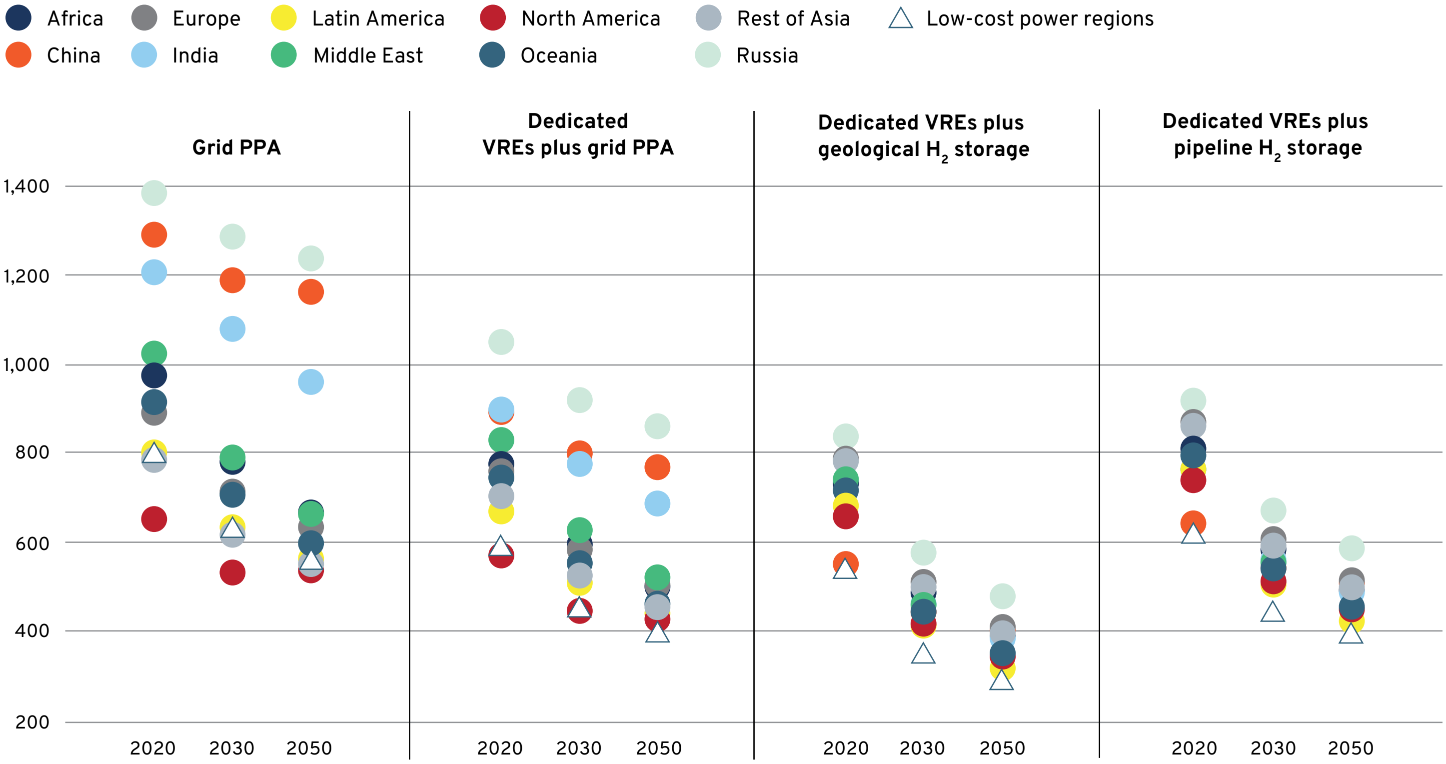
Source: MPP analysis; ETC[53]

The production location is an important determinant of the cost of green ammonia given its sensitivity to renewable electricity prices, which make up 50%–75% of the levelised cost. Locations with a combination of both high solar and high wind potentials, or access to cheap hydroelectric power, are deemed to be optimal for green ammonia production, reducing the need for H_2 storage or firm-up power to cope with intermittency. While there are opportunities to generate low-cost power in a number of regions, including in Asia, Europe, and North America, due to high solar and wind potentials at certain sites with optimal conditions, for the purpose of the modelling, four locations within Africa, Latin America, Middle East, and Australia were used to represent low-cost power locations across the globe. In these regions, prices of dedicated renewable electricity, particularly solar, are as low as $25–$30/MWh today and are expected to decrease to less than $10–$20/MWh by 2050.[54] As shown by the example in Exhibit 1.10, in low-cost power regions the levelised cost of green ammonia falls to $350–$380/t NH_3 by 2030, becoming cost competitive with blue ammonia production. This milestone is reached by 2040 in all other regions.

EXHIBIT 1.10

Levelised costs of green ammonia

By green power source, $/t NH_3



Note: The costs apply to an alkaline electrolyser. See *Technical Appendix* for the underlying cost and efficiency assumptions.

Source: MPP analysis; ETC[55]

Therefore, with the uptake of electrolysis-based ammonia production, it is economically favourable for new capacity to be positioned in low-cost power regions, thus increasing the importance of global trade and the need to carefully manage energy security risks. In most cases, existing production sites, which are currently positioned in demand centres and regions with low-cost coal and gas feedstocks, are typically not in optimal locations for low-cost renewable power. While existing production is likely to remain in these locations, mainly to serve existing markets, new capacity to supply emerging applications is likely to be positioned in low-cost power regions to produce green ammonia at a competitive cost. Therefore, with a growing demand from energy applications and an increasing share of green ammonia in the supply mix, a larger proportion of production is likely to be positioned in these locations, thus increasing the importance of trade. However, recent events in Europe have exposed the risks of globally traded commodities, and thus decoupling production and consumption of ammonia in this way may pose similar energy and national security risks, which must be managed carefully to enable open trade. Due to ammonia's toxicity, transporting it also carries safety risks, which are currently well managed. With increasing trade, it is critical that these safe practices are widely adopted across all parts of the distributed supply chain, particularly in the transport, storage, and use of ammonia in densely populated areas.

1.2.2.2 Blue ammonia: Fossil fuel–based ammonia production with CCUS

To decarbonise conventional fossil fuel–based ammonia production, both the process emissions, from extracting hydrogen from fossil feedstocks, and the energy emissions, from the combustion of fossil fuels, should be captured and either used or permanently stored.[xxxviii] In existing production, process CO_2 emissions, which constitute approximately two-thirds of total Scope 1 emissions, are routinely separated from hydrogen. Hence, the technology for capturing these emissions, typically amine-based scrubbing, is well-established. Today, a proportion of this high-purity CO_2 stream is utilised in industrial processes, for example within the same production facility to produce urea-based fertilisers, or in the food and beverage industry. Increasingly, however, captured CO_2 emissions are also being used in enhanced oil recovery or, less commonly, being stored permanently in geological formations. The remaining third of Scope 1 emissions, generated from the combustion of fossil fuels, are diluted in a flue gas mixture. Capturing these emissions in so-called post-combustion capture is rarely done today in ammonia production and requires additional capture equipment as well as an additional 0.6 gigajoule (GJ) of electricity per tonne of ammonia. For blue ammonia production to be aligned with a net-zero future, both streams of CO_2 emissions must be captured, with an overall capture rate of at least 90%, and permanently stored without risk of release to the atmosphere.

Although not currently used in ammonia production, ATR is commonly used in large scale methanol production and may be pursued for new-build blue ammonia capacity given the higher capture rates that can be achieved for the same cost. In ATR-based ammonia production, heat is generated internally, combining both the heating stage and the hydrogen production in a single reactor, with only a small proportion (around 10%) of the natural gas required for pre-heating. Therefore, over 90% of emissions generated in ATR are highly concentrated and hence can be captured at relatively low costs and high capture rates without the need for an additional capture unit. More nascent ATR-based technologies, such as an ATR installation with a gas-heated reformer in parallel (ATR + GHR), are expected to come online in 2030. This particular configuration would allow for the recovery of waste heat, thus improving efficiency and reducing the overall gas consumption. In addition, compared with SMR plants, which have capacities of around 2,000–3,000 tonnes of NH_3 per day, novel ATR-based technology may allow for much larger-scale plants with double the production capacity of conventional plants.[56]

In most regions, blue ammonia production is projected to remain cheaper than electrolysis-based production to 2030, delivering ammonia at levelised costs of as low as of \$300/t NH_3. Blue ammonia production allows retrofits of current assets. This, together with initially high electrolyser and renewable electricity costs, means that in most locations blue ammonia production will be cheaper than green ammonia until at least 2030. This is particularly the case for regions with abundant cheap fossil fuels such as Russia, the Middle East, North Africa, and North America. As shown in Exhibit 1.11, the lowest-cost abatement option in all regions is initially the retrofitting of SMR-based production with CCUS. However, after 2030, the cheapest route in most regions becomes the ATR + GHR route with CCUS,[xxxix] which improves the overall process efficiency by recovering waste heat, resulting in a natural gas savings of 8% per tonne of ammonia compared with conventional production.[57] In China, as new gas-based production is prohibited and existing production is likely to be phased out, retrofitting coal-based assets with CCUS is the most attractive decarbonisation option for existing assets in the short term. However, in the long term, large volumes of residual emissions (0.3–0.4 t CO_2/t NH_3) from incomplete CO_2 capture and high upstream emissions from coal mining bring into question whether coal-based production with CCUS is compatible with a net-zero world.

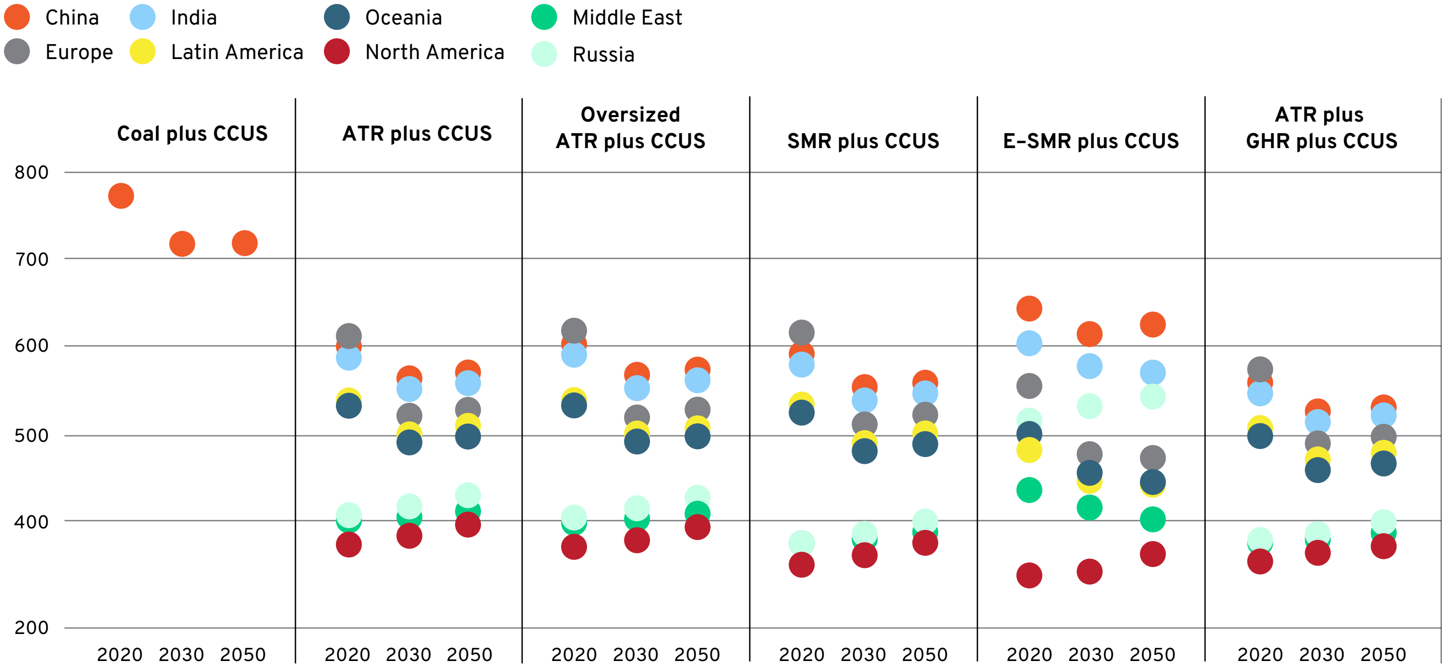
[xxxviii] Usage of CO_2 considers applications where CO_2 is stored for very long periods (such as in building materials) or where CO_2 is captured at end of life (for example, incineration of plastics).

[xxxix] Electrified SMR (e-SMR)+ CCUS could be a cheaper production route than ATR + GHR + CCUS in some locations, but its cost depends substantially on PPA prices for electricity supply, which have large variation across regions and uncertainty to their future evolution.

EXHIBIT 1.11

Levelised costs of blue ammonia

By production route, $\$/t\ NH_3$



Note: See *Technical Appendix* for the underlying cost and efficiency assumptions.

Source: MPP analysis; BEIS; IEA[58]

While CO_2 capture of process emissions in SMR production is well established, blue ammonia routes are not yet commercially ready as extending capture to flue gas emissions is economically challenging. In addition, the development and scaling of commercial CO_2 transport and storage infrastructure faces several obstacles. While analysis shows that the world has ample CO_2 storage capacity, in the form of saline formations and depleted oil and gas fields, few sites have been developed for commercial use with only around 10 Mt of CO_2 currently being stored annually in dedicated geological storage capacity, and an additional 30 Mt being used for enhanced oil recovery or in industry.[59] The main barrier to further development in this space is permitting of geological storage sites and the high risks associated with large upfront investments required for reservoir exploration and CO_2 transport infrastructure.[60] Storage capacity also varies considerably by region, with most capacity concentrated in China, Europe, North Africa, North America, and Russia, which largely coincides with where current ammonia production capacity is concentrated. The potential of CCUS retrofits to existing plants will therefore depend on the availability of CO_2 storage capacity and/or transportation and utilisation.

The continued dependence on fossil fuel extraction poses the risk of high Scope 3 emissions and residual emissions from incomplete capture. While increasing capture rates to 99% is technically achievable, it is likely to be uneconomical to do so, and thus typically 5%–10% of emissions generated are left uncaptured and released into the atmosphere. Depending on the technology, this equates to 0.1–0.3 t CO_2 per tonne of ammonia. With large volumes of blue ammonia in the production mix, this could result in significant levels of residual CO_2 emissions being generated by the ammonia industry even by 2050, thus locking the industry into a dependence on CDR. Capturing CO_2 is also energy intensive and thus comes at an additional cost. Therefore, there may be an incentive, particularly during times when gas prices are higher, to switch off the capture equipment in order to reduce operating costs.

Blue ammonia production also means relying on the continued extraction of fossil fuels, thus posing a risk of continued high upstream methane emissions. Therefore, the uptake of blue ammonia must be accompanied by measures to ensure that capture equipment is always operating, as well as to reduce fugitive methane emissions and to end routine flaring during coal and gas extraction, through the employment of leak detection, the improvement of technology standards, and the enforcement of bans on venting and flaring.

1.2.2.3 Other near-zero-emissions ammonia production technologies: Biomass-based production and methane pyrolysis

While green and blue ammonia are expected to emerge as the primary production, other near-zero-emissions production technologies such as methane pyrolysis and biomass-based may also be viable under specific conditions and should be explored to de-risk the net-zero transition of the ammonia sector.

As the technology for methane pyrolysis is still under development, its role in the future of near-zero-emissions ammonia production is highly uncertain and subject to the production costs versus blue and green ammonia, and the status of ongoing technical challenges such as the low purity of hydrogen and low efficiency. The technology is expected to come online towards the end of the decade, but its scalability may be limited by ongoing technical challenges, and its economic viability depends on the fate of the solid carbon by-product produced in the process. While there is potential for this by-product to be valorised and sold as carbon black – for example for use in tires and as a pigment, making the business case potentially economically viable – the market for this is likely to remain small. There is also a risk that excessive production of solid carbon from methane pyrolysis could result in further emissions downstream if the carbon is sold for use in other applications. There is, however, potential for the carbon to be stored underground (similar to CO_2 storage in CCUS applications but significantly less challenging and cheaper) to ensure that emissions are not produced downstream. However, the economics of this are less convincing and thus may not be a viable option today. Nevertheless, exploring and advancing this production route is a valuable effort in order to de-risk the net-zero transition of the ammonia sector.

Similarly, given the high costs and limited availability of sustainable biomass feedstocks, the role of biomass digestion and gasification in the future of ammonia production is likely to be limited. The maximum amount of globally available sustainable biomass is constrained, and therefore its allocation to sectors must be considered carefully. The exact limits are uncertain, and different sources provide a wide range of estimates: a prudent scenario estimates a global constraint of about 50 EJ of sustainable biomass while the maximum potential could be about 110 EJ but is tied to very ambitious assumptions.[61] Although for some sectors, such as aviation, biomass is the most attractive decarbonisation solution, particularly in the short term, this is not the case for ammonia production. Biomass-based ammonia production is more expensive than blue and green ammonia production routes, at two to four times the cost in 2050, and faces scalability challenges due to the scarcity and distributed nature of the feedstock. Ammonia production is therefore unlikely to be a priority sector for biomass feedstock allocation. However, given the large volumes of downstream Scope 3 CO_2 emissions from the application of urea-based fertilisers to soils, biomass-based urea production could provide a viable emissions reduction lever given that it is the only zero- emissions production route that provides an on-site carbon-neutral source of CO_2 (Box 7).

BOX 7

Urea production in a net-zero world

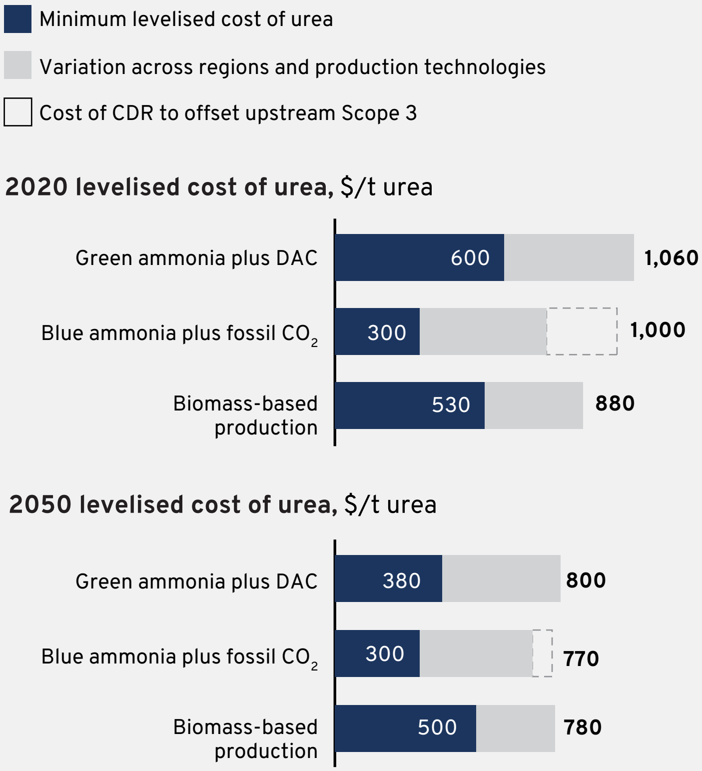
CO_2 is a key input for urea production: 0.73 tonne of CO_2 is required for every tonne of urea produced. Conventionally, ammonia production is integrated in the urea plant, and the required CO_2 is obtained from the concentrated stream of process emissions generated during the production of hydrogen from fossil fuel feedstocks. Hence, these emissions are avoided during the production phase but are ultimately released further downstream in the use phase of urea-based fertilisers, transferring these emissions from Scope 1 to Scope 3.

In a net-zero world, this CO_2 input to urea production would ideally be sourced from carbon-neutral, non-fossil sources in order to avoid these large downstream Scope 3 CO_2 emissions from the application of urea fertilisers to soil and, in turn, avoid the CDR that would be required to offset those emissions. There are two potential ways to obtain carbon neutral CO_2 – via direct air capture (DAC) or by capturing biogenic CO_2.

This exhibit compares the levelised cost of urea production via three different production routes: green urea production with CO_2 sourced via DAC, biomass-based urea production with biogenic CO_2 produced on-site, and urea production with fossil fuel–based CO_2 and CO_2 capture on all remaining emissions i.e., blue urea production; however, note that this is not very different to urea production today as it simply shifts CO_2 emissions from Scope 1 to Scope 3. The large range in costs for each production route is due to the variation across regions and across production technologies.

Without considering the additional CDR cost to offset the downstream Scope 3 CO_2 emissions, so-called blue urea production emerges as the most cost-competitive option given its lower cost of production relative to biomass-based production, and while green ammonia production is expected to become cheaper than blue ammonia by 2050 in most regions, blue urea production avoids the additional cost of DAC. Given that DAC is a considerably expensive source of carbon-neutral CO_2, with current estimates ranging from \$300–\$500/t CO_2 in 2020 to \$50–\$200/t CO_2 in 2050, urea produced from CO_2 obtained via DAC is unlikely to be cost competitive. However, including the cost of CDR to offset Scope 3 fossil fuel–based CO_2 emissions from so-called blue urea minimises its cost advantage relative to green urea production.

Biomass feedstocks may be an economically viable option for urea production in regions with access to large volumes of cheap, sustainable biomass



Source: MPP analysis; BEIS; IEA; Sanchez et al.[62]

Alternatively, in certain regions with access to large volumes of cheap biomass, biomass-based urea could emerge as a cost-competitive option, as shown by the lower end of its cost range in the exhibit, as it benefits from the on-site generation of biogenic CO_2, thus avoiding the high additional cost of DAC as well as the additional CDR costs that may eventually be priced into blue urea production. This is particularly true in the transition to 2050 before DAC and CDR costs are expected to come down considerably.

Therefore, while biomass is generally not expected to play a major role in ammonia production given its high production costs and the expected competition over limited sustainable biomass resources, there may be specific opportunities for biomass-based urea production where location-specific conditions make this route economically viable. For example, in regions of concentrated agricultural activity, there is potential for farmers and urea producers to form symbiotic relationships in which the generation of large, concentrated volumes of agricultural waste could be used locally for biomass-based urea production, in turn giving the farmers access to a net-zero-aligned source of urea.

1.2.2.4 Transitional technologies allow emissions reductions in this decade

Until near-zero-emissions technologies become commercially available towards the second half of this decade, the adoption of transitional technologies is the best option to deliver early emissions reductions. These technologies, which are already being deployed by some of the world's largest ammonia producers, involve small-scale retrofits to existing assets to reduce the emissions intensity of current production capacity. There are two major options for transitional technologies:

1. **Installing a small electrolyser to produce a proportion of the hydrogen feeding the ammonia synthesis unit.** An alternative transitional emissions reduction lever involves installing a small electrolyser to the existing front-end process (SMR or coal gasification) to feed a small proportion (~10%) of hydrogen feeding the ammonia synthesis unit, thus reducing the emissions intensity of ammonia produced. Introducing ~10% green hydrogen to the input feed of the ammonia synthesis does not cause significant fluctuations in the ammonia synthesis loop and thus does not face the same technical challenges as a green ammonia plant. Both CF Industries and Yara, the two largest ammonia producers in the world, have announced plans to blend green and grey hydrogen in existing ammonia production plants.[63]

2. **Partial capture and storage or usage of emissions from SMR.** In existing production, process emissions, which make up two-thirds of Scope 1 CO_2 emissions, are separated out from the hydrogen, typically via amine-based scrubbing prior to ammonia synthesis. By directing these emissions to usage or permanent storage, the emissions intensity of ammonia production may be reduced by 67% to 0.6–0.9 t CO_2/t NH_3. This is a capital expenditure–light means of reducing emissions from ammonia production, requiring only an additional CO_2 compressor for transport, and results in an approximately 10% higher levelised cost of production versus conventional SMR.

While opportunities to reduce emissions through efficiency improvements and the adoption of best available technology (BAT) should also be pursued, it should be noted that significant progress on this front has been made in the last century, and efficiency gains have started to slow down as energy intensity has come increasingly close to the theoretical minimum.[64]

1.2.3 Carbon dioxide removals

CDR solutions are needed *in addition to, not instead of,* deep and rapid in-sector decarbonisation. For ammonia, CDR solutions are necessary in order to offset large downstream Scope 3 emissions from fertiliser use even under scenarios that consider the adoption of ambitious efficiency measures and of nitrogen inhibitors, and to neutralise the residual emissions from blue ammonia production as only 90%–96% of Scope 1 emissions are captured. Hence, CDR solutions will be needed by 2050 even under ambitious sectoral decarbonisation scenarios to close the emissions gap to a net-zero ammonia industry. These solutions include:[65]

- **Natural climate solutions (NCS):** Restoring natural ecosystems (such as forests and peatlands) and better managing current use of land
- **Hybrid solutions:** Biochar (burning biomass in the absence of oxygen to slow decomposition) and bioenergy with carbon capture and storage (BECCS, to produce energy from biomass and then capturing and storing the CO_2 produced)
- **Engineered solutions:** Direct air carbon capture and storage (DACCS)

The overview in this section draws on a recent in-depth analysis from the ETC on the role of CDR to complement deep decarbonisation in order to keep 1.5°C alive.[66] Today NCS comes at a cost of up to \$100/t CO_2 while hybrid and engineered solutions cost \$300–\$600/t CO_2. However, these costs are projected to decrease with increasing cumulative capacity deployed to around \$100–\$300/t CO_2 by 2050.[67]

ACHIEVING NET ZERO: POSSIBLE TRAJECTORIES

There is a range of different pathways to achieving net-zero GHG emissions in the ammonia sector. Different combinations of decarbonisation measures can lead to the same emissions outcomes but with different cost profiles and cumulative emissions along the way. Two trajectories to net zero by 2050 are presented to illustrate the pace of change under different demand assumptions, investment decision logics, and constraints: the Lowest Cost (LC) scenario and the Fastest Abatement (FA) scenario. Both scenarios highlight the different requirements to kick off and drive the net-zero transition of the ammonia industry in terms of investments, resource demand, and early milestones.

The two scenarios are not projections of the future, but instead present two potential transition pathways towards net zero by mid-century; the reality may lie somewhere in between. The scenarios enable a discussion around concrete actions that should be taken regardless of the decarbonisation measures chosen, for example the large investment in renewable electricity infrastructure, which is essential either way, as well as around the key trade-offs between different decarbonisation technologies. These trade-offs deliver insights into the circumstances under which certain decarbonisation solutions would have greater market penetration.

2.1 Scenario definition

The two trajectories to net zero by 2050 are the **LC** and **FA** scenarios, which illustrate the efforts required to achieve net-zero emissions by 2050, compared with a **Business-as-Usual (BAU)** scenario, that is, a scenario that assumes a general prolongation of current supply and demand trends. The key model features for each scenario are summarised in Exhibit 2.1.

The LC scenario illustrates an ambitious but realistic trajectory to achieve net-zero emissions in 2050 at the lowest cost to industry within a 1.5°C-aligned carbon budget (see section 2.3.2), while employing ammonia to decarbonise the shipping and other sectors to a large extent. In this scenario, cost is the primary driver for choosing technologies and production locations. Existing production capacity can be retrofitted or rebuilt to transitional and near-zero-emissions supply technologies only if such a transition decreases the levelised cost of production. Furthermore, the modelling assumes that new demand coming from net-zero drivers can be met only by transitional and near-zero-emissions technologies. The LC scenario provides insights on the carbon price required to ensure a cost-effective transition on a 1.5°C-aligned emissions reduction pathway. This scenario assumes no circularity/fertiliser efficiencies; the net-zero demand scenario is employed with the lower end of the demand for shipping and power generation. A sensitivity analysis is also conducted around key assumptions in the LC scenario, including the carbon price and the gas price, as the evolution of these prices is highly uncertain but is a key determinant of the future production landscape of ammonia.

The FA scenario illustrates an ambitious net-zero scenario for decarbonising the ammonia, shipping, and other sectors as quickly as possible employing all policy and investment levers. In this scenario, the technologies for transforming existing assets and building new production capacity are chosen according to the largest reduction in CO_2 emissions (Scope 1, 2, and 3 upstream). If two technologies have the same reduction in emissions, the technology with lower cost is selected. The FA scenario uses the demand scenario in which demand-side circularity/fertiliser efficiency levers are employed and takes the midpoint of the demand range for shipping, for power generation, and for ammonia as a hydrogen vector.

In contrast to the two net-zero scenarios, the BAU scenario illustrates how the ammonia industry could develop until 2050 in the absence of any pressure to reduce GHG emissions, allowing new-build capacity to use conventional technologies. Because the scenario does not model a trajectory compatible with a 1.5°C world, the uptake of near-zero-emissions ammonia for decarbonising other sectors is not included in the demand assumptions.

It is important to note that the scenarios presented are not forecasts but instead illustrate potential trajectories for the ammonia industry under different assumptions.

EXHIBIT 2.1

The model logic and key assumptions underlying each scenario

	Business-as-Usual scenario	Lowest Cost scenario	Fastest Abatement scenario
Scenario logic	Pathway in the **absence of any emission reduction** pressure	Pathway to net zero within a 1.5°C- aligned carbon budget at **lowest cost to the industry**	Pathway to net zero within a 1.5°C-aligned carbon budget with the fastest possible emissions reduction
Demand scenario used	BAU	Net zero with low demand for ammonia as an energy carrier	Net zero with medium demand for ammonia as an energy carrier plus circularity/efficiency measures
Technology switches	**Driven by lowest cost:** existing plants switch if levelised cost of X product (LCOX) can be reduced by at least 5%, new plants choose the available technology with lowest LCOX		**Driven by largest emissions reduction,** with the technology with lower LCOX preferred if emissions are identical
Carbon price	None	• Applied to **Scope 1, Scope 2, and Scope 3 upstream CO_2 emissions** • Set at $**100 USD/t CO_2 from 2035** on with linear ramp-up starting in 2026 to ensure that initial technologies switch to net-zero compatible technologies	None
Retrofit and rebuild of existing plants	• Maximum **5% of the entire plant stack can be revamped annually** • Retrofit transitions start in 2025, rebuild transitions in 2027		
New capacity to supply growing demand	No constraint	Growing demand apart from fertiliser usage can be supplied by **transition and end-state technologies only**	
Regional production	• Each region can **supply maximum 30% of new global demand** • **Minimum 40% of demand in each region** needs to be met by production in that region		
Transport costs	None (approximated through regional production constraints)		
Constraint on geological CO_2 storage availability	None	• **Uptake of CCUS technologies** constrained by globally available CO_2 storage • **10% of ETC projections** for global annual CO_2 storage additions are allocated to the ammonia industry	
Constraint on annual electrolysis capacity additions	None	Constrained to maximum 20% of ETC projections for global electrolyser manufacturing capacity ramp-up	None
Regional technology restrictions	• **No electrolysis with geological H_2 storage in India** because of lacking salt cavern availability • **No new capacity in China with natural gas** due to mandated phase-out		

Source: MPP analysis, see technical appendix for more details.

2.2 What it will take to achieve net-zero ammonia

2.2.1 Limited decrease in CO_2 emissions to 2030, halving emissions before 2040, and net zero by 2050

By 2030, production emissions decline by 3% in the LC scenario and by 25% in the FA scenario relative to 2020, despite a 30% and 50% increase in demand, respectively (Exhibit 2.2). Initially, production-related emissions increase towards the middle of this decade as demand growth continues, requiring higher volumes of production. However, after 2025 the adoption of near-zero-emissions technologies begins to scale, such that the emissions intensity of production declines faster than demand increases: Emissions intensity is reduced by 25%–50% until 2030, while demand increases by 30%–50% in the same period. Therefore, the combined effect is a modest reduction in production emissions in the FA scenario and a slight reduction in the LC scenario. The LC scenario relies on low-emissions transitional technologies for a longer period, given the lower cost of retrofitting versus new build; hence, the decline in emissions is slower. In the BAU scenario, however, emissions remain flat through to 2030, as the change in supply technology mixed with announced green and blue ammonia projects coming online only just compensates for the steady demand growth from existing applications.

By 2040, production emissions could reduce by over 70% relative to 2020, as shown in Exhibit 2.2, despite a 150%–250% increase in ammonia demand. The milestone of reaching 90% emissions reductions in the net-zero scenarios, implying an over ~98% reduction in the emissions intensity of production, is achieved around 2037 in the FA scenario and eight years later in the LC scenario. In both scenarios, steep emissions reductions are driven primarily by the adoption of green, and to a certain extent blue, ammonia production technologies, which enter the market in the mid-2020s.

By 2050, production-related emissions could be reduced by 92%–99% relative to 2020, with all unabated Scope 1 emissions resulting from incomplete carbon capture in blue ammonia production. Compared with the BAU scenario, the LC and FA scenarios reduce the 2020–50 cumulative Scope 1 and 2 emissions by 37% and 56%, respectively. In 2050, the FA scenario has a lower share of CCUS-based production technologies and thus lower residual emissions. However, both scenarios require carbon dioxide removals of the order of 3–40 Mt CO_2 annually to offset production-related residual emissions. Note that this does not include GHG emissions from fossil fuel extraction or from downstream use of ammonia and its derivatives.

However, with the inclusion of Scope 3 GHG emissions, the decline is less pronounced, with total emissions decreasing by 31%–53% by 2050 (Exhibit 2.3).

BOX 8

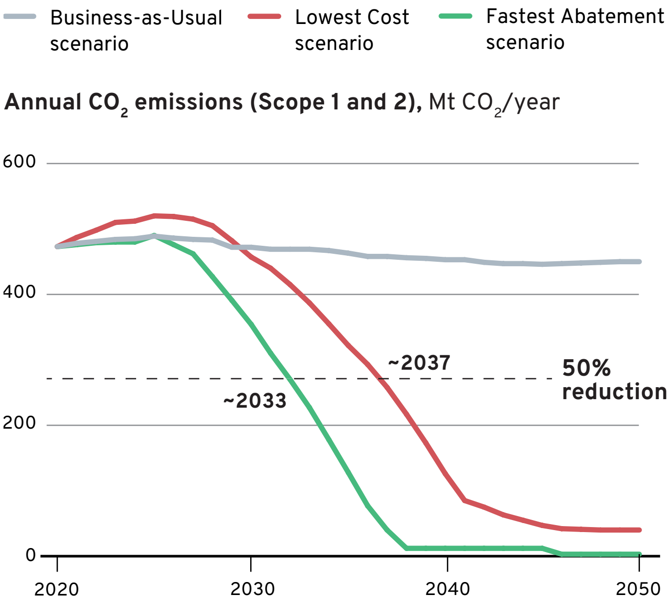
What is "net zero"?

The world needs to get to net-zero GHG emissions by 2050 to avoid the most harmful effects of climate change. Thereby, "net zero" means priority in-sector decarbonisation, complemented by CDR.

- **About 90%–95% of current emissions in each sector need to be reduced by in-sector measures.** This is in line with the Science Based Targets initiative (SBTi). For the chemicals sector, SBTi prescribes long-term deep decarbonisation of 90%–95% for Scope 1 and 2 before 2050 as well as reductions in Scope 3 emissions as the single most important target for a net-zero world. SBTi is currently developing its standard for the chemicals sector to set expectations for Scope 3 target setting.
- The remaining 5%–10% of residual emissions that cannot be reduced by in-sector decarbonisation need to be neutralised by CDR,[xl] the potential of which is described in a recent report from the ETC. [68]

EXHIBIT 2.2

By mid-century, annual Scope 1 and 2 emissions from ammonia production are reduced by 92%–99% relative to 2020 in the net-zero scenarios



Source: MPP analysis

[xl] Details on CDR can be found in *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*, a recent report of the ETC.

By 2050, upstream Scope 3 emissions in the net-zero scenarios are reduced by 61%–95% relative to 2020. Although production-related emissions are decreasing, increased fossil fuel extraction due to higher demand for fossil feedstocks results in a risk of higher upstream methane emissions from fossil fuel extraction. Therefore, the role of fossil feedstocks in a net-zero world relies strongly on deep reductions of upstream Scope 3 emissions, going above and beyond what is committed to in the Global Methane Pledge.[69] A rapid and sustained reduction in upstream Scope 3 emissions to close to zero is considered to be achievable through the ambitious application of policy measures such as banning all non-emergency flaring and venting, strict enforcement of better technology standards, mandatory leak detection and repair, and the installation of emissions control devices.[70] It is estimated that, along the current trajectory, through a combination of both demand reduction and the listed policy measures, upstream Scope 3 emissions relative to 2020 could be reduced to 40 Mt CO_2e/y by 2050 in the LC scenario, in which gas-based production continues to play a significant role, and to about 6 Mt CO_2e/y in the FA scenario.

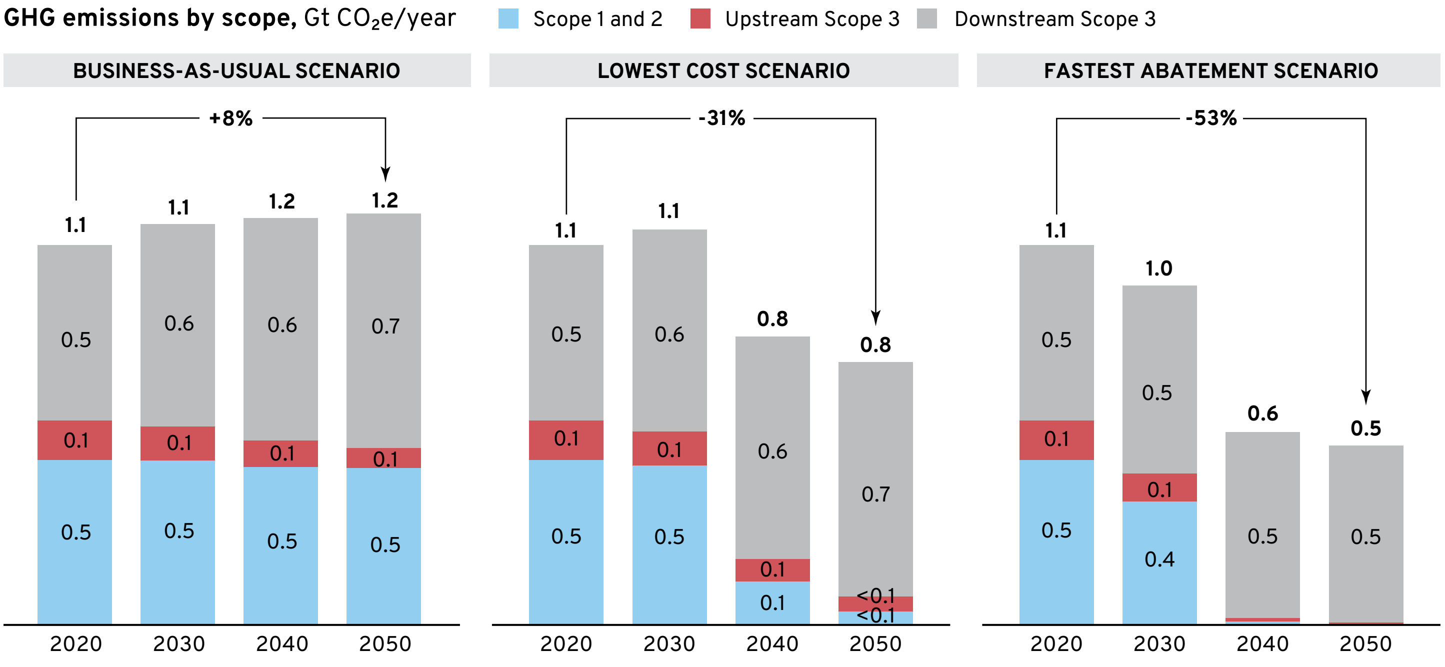
By 2050, downstream Scope 3 GHG emissions from fertiliser use increase by 33% in the BAU and LC scenarios, compared with only a 0.6% increase in the FA scenario. As discussed in Part 1, global population growth to 2050 drives a 36% increase in nitrogen-based fertiliser demand in the BAU and LC scenarios, resulting in a 33% increase in downstream emissions of N_2O and CO_2 from fertiliser application to 670 Mt CO_2e/year. The FA scenario, however, considers the ambitious application of demand-side circularity measures, such as improving NUE, substitution of urea with other nitrogen-based fertilisers, and shifting to less land-intensive diets, as well as the widespread adoption of nitrogen inhibitors, limiting the growth in downstream Scope 3 GHG emissions to 510 Mt CO_2e/y by 2050. Of the remaining emissions, 15% are CO_2 emissions from urea application, which are avoided at the production stage and instead shifted from Scope 1 to 3. By using a carbon-neutral CO_2 source in urea production instead of fossil CO_2, as is currently used, these emissions may be mitigated even further and potentially brought to zero. As discussed in Box 7, this presents a special-use case for biomass-based ammonia production as it enables the use of biogenic CO_2 in urea production.

When all scopes of GHG emissions are considered, the reduction in GHG emissions relative to 2020 is 53% in the FA scenario and 31% in the LC scenario, requiring 0.5–0.8 Gt of carbon dioxide removals annually by 2050. At an average cost of about \$50–\$100/t CO_2 in 2050, CDR solutions will incur additional annual costs of about \$25 billion to \$80 billion by 2050.

EXHIBIT 2.3

Total GHG emissions in each scenario

GHG emissions by scope, Gt CO_2e/year



Note: Totals shown above bars may not equal sums of numbers within bars due to rounding.

Source: MPP analysis; IEA; IPCC; IFA[71]

BOX 9

What is the 1.5°C carbon budget for ammonia?

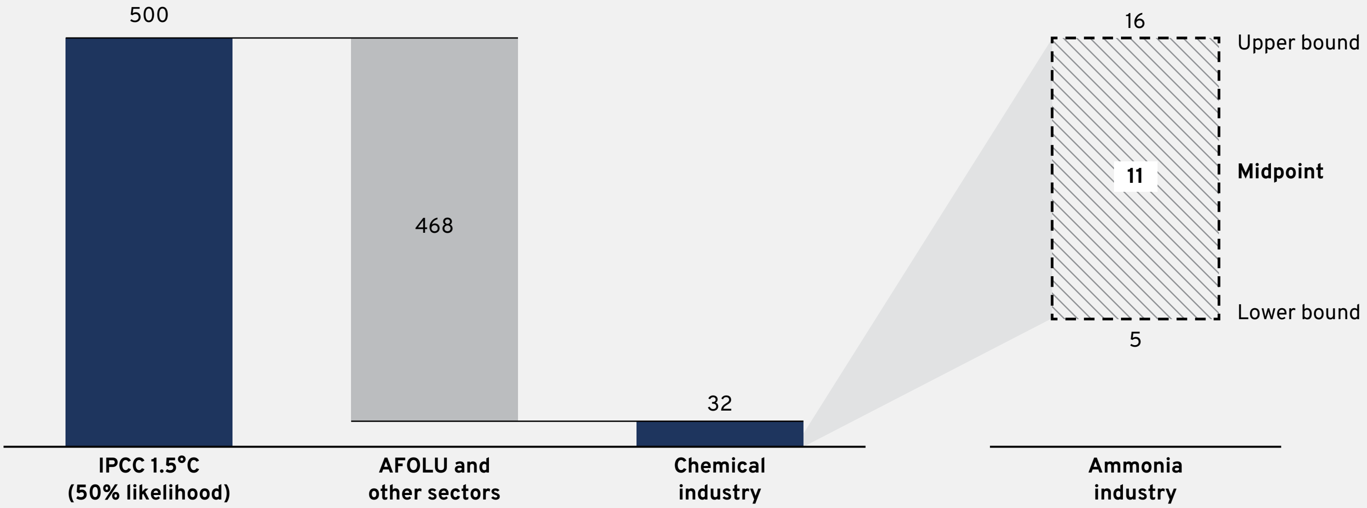
The Intergovernmental Panel on Climate Change (IPCC) estimated that in order to have a 50% chance of limiting global warming to 1.5°C above preindustrial levels, the global carbon budget from the beginning of 2020 was around 500 Gt CO_2. From this, around 50 Gt CO_2 of net anthropogenic emissions from agriculture, forestry, and other land use (AFOLU) are subtracted. That leaves roughly 450 Gt CO_2 for all energy sectors that needs to be allocated to individual sectors according to their decarbonisation complexity. Hard-to-abate sectors are limited in their decarbonisation speed, whereas other sectors like the power or automotive sector could switch to low-carbon technologies more quickly.

In a preliminary assessment by the MPP, roughly 50% of the 450 Gt CO_2 has been allocated to the seven MPP sectors (aluminium, chemicals such as ammonia and petrochemicals, concrete/cement, steel, aviation, shipping, and trucking). The sectoral allocation is based on the cumulative sectoral emissions from the IEA's *Net Zero by 2050* report and the BloombergNEF *New Energy Outlook 2021* report (and for some sectors the *One Earth Climate Model* [OECM]) between 2020 and 2050, which serve as a proxy of how hard to abate each individual sector is.

Following this methodology, global chemicals production is estimated to have a 1.5°C carbon budget of ~32 Gt CO_2, of which the ammonia sector is allocated 20%–50% **(5–16 Gt CO_2, midpoint 11 Gt CO_2, as shown in the exhibit below)** based on its share of total chemical industry emissions in 2020 and an assumed 50% variability to account for the large uncertainty in this sectoral allocation. Given the variety of other potential sectoral allocation methods, the allocated budget share of 11 Gt CO_2 should not be taken as the absolute truth but rather as an indicative figure for a 1.5°C-aligned carbon budget for the ammonia sector. This figure can serve as a guardrail to ensure that emissions reductions on the way to a net-zero ammonia industry are fast enough to not overshoot the 1.5 °C target.

The ammonia sector has an allocated budget of 5–16 Gt CO_2

1.5°C pathway: carbon budgets, 2020–50, Gt CO_2



Note: The IPCC's carbon budget from the beginning of 2018 has been updated to the beginning of 2020. AFOLU emissions are based on Roe et al., EAT-Lancet Commission, and ETC analysis.

Source: IEA Net-Zero Emissions scenario; OECM; BloombergNEF NEO 2021; ETC analysis[72]

2.2.2 Compatibility with a 1.5°C carbon budget

Both net-zero scenarios remain well within this 11 Gt carbon budget (Exhibit 2.4), with the FA scenario using only 57% of the carbon budget, emitting 6.3 Gt CO_2 by 2050, around 1% of the remaining global carbon budget. The LC scenario also offers a saving on the 11 Gt CO_2 carbon budget allocated to ammonia, emitting 9.0 Gt CO_2 by 2050, around 2% of the remaining carbon budget. In contrast, under the BAU scenario the carbon budget allocated to the ammonia industry is overshot by 31% with 14.4 Gt CO_2 emitted by 2050. Note that this applies only to CO_2 produced as Scope 1 or 2 emissions during the production phase. Therefore, the carbon budget comparison excludes all Scope 3 and non-CO_2 emissions.

2.2.3 Green ammonia production contributes the largest share of CO_2 emissions intensity reduction

Exhibit 2.5 shows that in all three scenarios, the uptake of green ammonia is responsible for the vast majority of emissions reductions by 2050.

- **Business-as-Usual:** By 2050, the average emissions intensity of production is reduced by around 30% relative to 2020. The uptake of electrolysis-based green ammonia production in optimal locations with the lowest-cost renewable power reduces emissions intensity by 17%, with an additional 2% reduced by the retrofitting of existing gas-based production with transitional technologies and less than 1% reduced by the uptake of blue ammonia. An additional 12% of emissions intensity reduction comes from switching from coal-based to gas-based grey ammonia production.

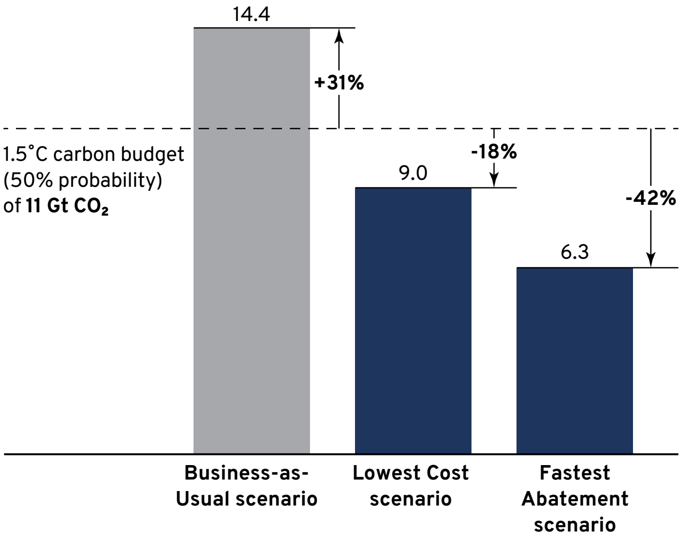
  Lowest Cost: By 2050, only 3% of the Scope 1 and 2 emissions per tonne of ammonia production remain unabated. Around two-thirds of the reduction in emissions intensity is from the uptake of green ammonia, while 26% stems from the use of CCUS on fossil fuel–based production routes, with only around 3% of the reduction by 2050 coming from the adoption of transitional and other zero-emissions technologies. The remaining 1% of reduction comes from the slight uptake of methane pyrolysis and biomass-based production.

- **Fastest Abatement:** The average emissions intensity of production is reduced by close to 100% by 2050, of which 91% comes from the large uptake of green ammonia. The adoption of blue ammonia accounts for 3% of the reduction while 4% is reduced through the optimisation of nitrogen-based fertiliser use in this scenario, which reduces total demand for ammonia by around 30 Mt by 2050. Other technologies such as methane pyrolysis and biomass-based production play a limited role because of much lower uptake, collectively delivering an emissions intensity reduction of around 1% by 2050.

EXHIBIT 2.4

Cumulative emissions in the net-zero scenarios remain well within allocated 1.5°C carbon budget

1.5°C carbon budget for global ammonia, from beginning of 2020 in Gt CO_2 vs. cumulative CO_2 emissions of net-zero scenarios between 2020 and 2050



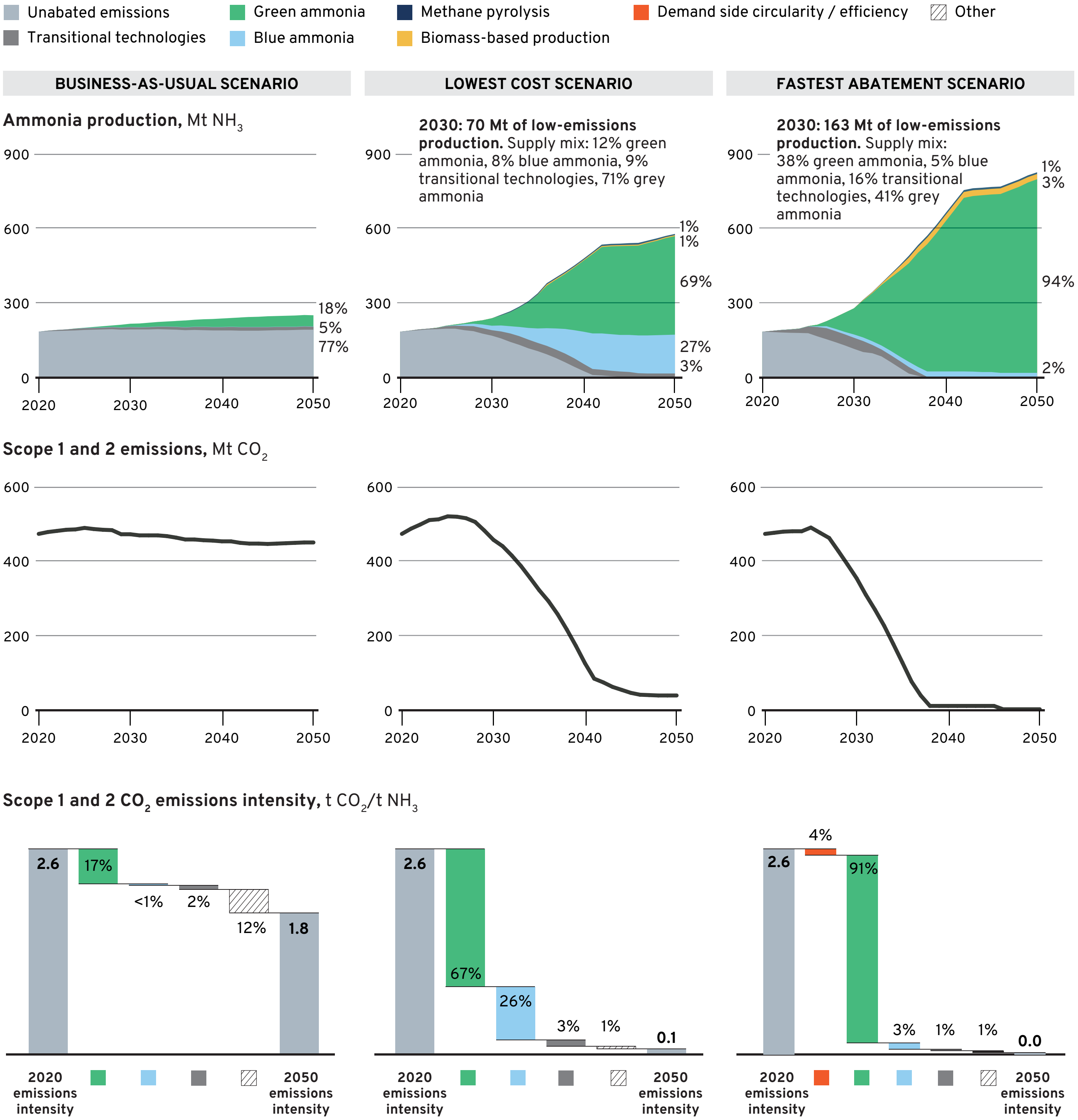
Note: Since the carbon budget figure is based on Scope 1 and Scope 2 CO_2 emissions (excluding non-CO_2 and Scope 3 emissions), it is compared with the sum of the cumulative Scope 1 production emissions and Scope 2 emissions from grid electricity generation. The carbon budget should not be understood as a precise value; it rather provides an indicative figure, and therefore we have accepted slight over- and undershoots.

Source: MPP analysis; IPCC[73]

The main difference between the two net-zero scenarios is the relative shares of blue and green ammonia by 2050. The LC scenario relies on a higher share of blue ammonia (27% by 2050) given its cost advantage in early years relative to green ammonia, particularly as it enables continued operation of existing assets, thus offering a cheap, capital expenditure-efficient, and rapid route to emissions reduction. However, this locks the LC scenario into higher upstream Scope 3 emissions from fossil fuel extraction and a larger volume of unabated emissions from incomplete capture. These factors limit the uptake of blue ammonia in the FA scenario (2% by 2050), in which green ammonia technologies are preferred because of their mitigation of all Scope 1 and 2 emissions and the avoidance of upstream Scope 3 emissions.

EXHIBIT 2.5

Green ammonia delivers the largest reduction in emissions intensity across all scenarios



BUSINESS-AS-USUAL SCENARIO

LOWEST COST SCENARIO

FASTEST ABATEMENT SCENARIO

Ammonia production, Mt NH_3

2030: 70 Mt of low-emissions production. Supply mix: 12% green ammonia, 8% blue ammonia, 9% transitional technologies, 71% grey ammonia

2030: 163 Mt of low-emissions production. Supply mix: 38% green ammonia, 5% blue ammonia, 16% transitional technologies, 41% grey ammonia

Scope 1 and 2 emissions, Mt CO_2

Scope 1 and 2 CO_2 emissions intensity, t CO_2/t NH_3

Note: Numbers may not sum to 100% because of rounding. "Other" includes methane pyrolysis and biomass-based production, as well as the emissions reduction from switching from coal to gas-based grey ammonia production in the BAU scenario. Transitional technologies are supply-side technologies which reduce emissions from ammonia production below conventional production but do not bring emissions sufficiently close to net zero.

Source: MPP analysis

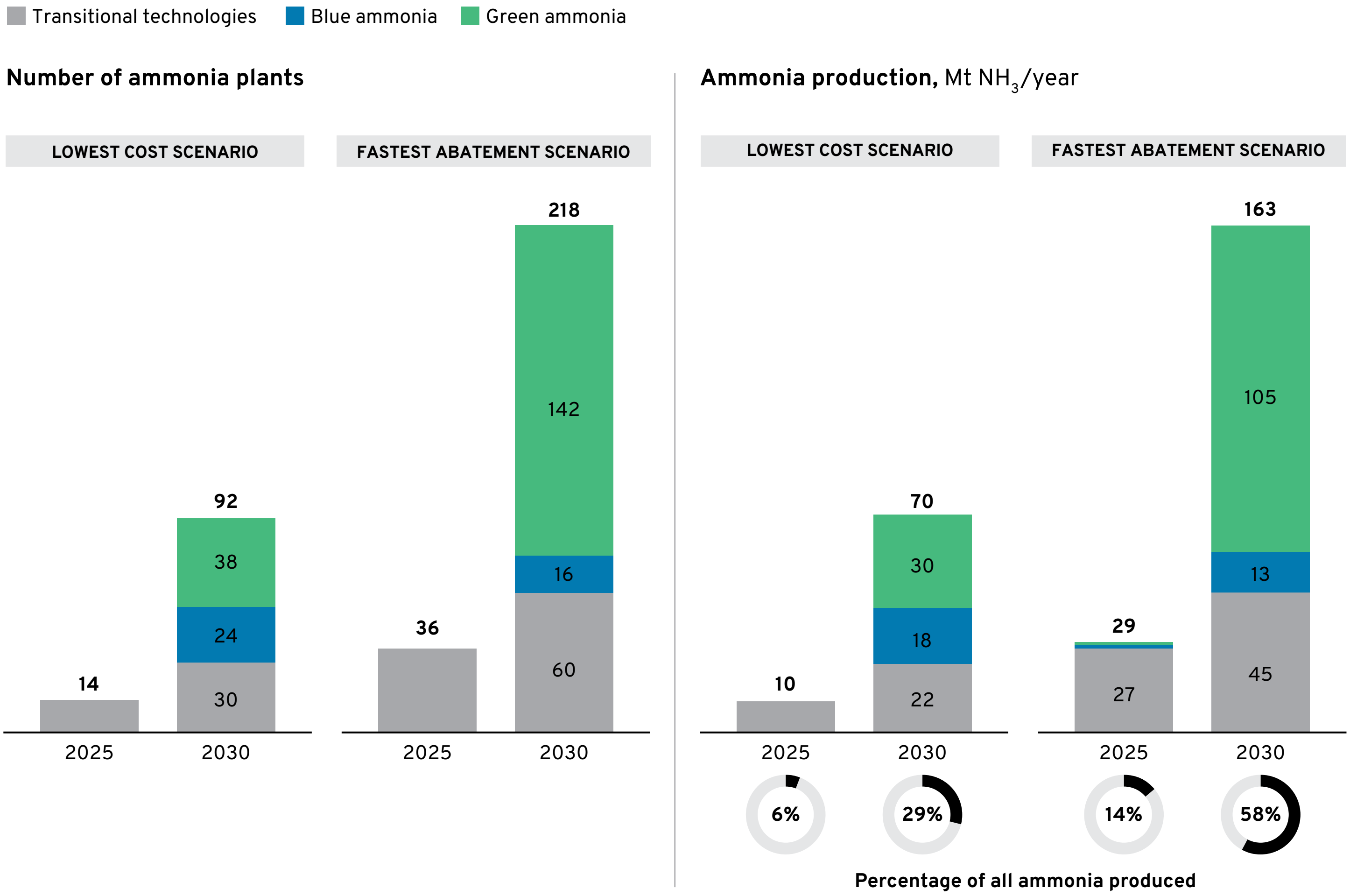
2.2.4 2020s milestones to kick off the transition to net-zero ammonia production

By 2030, low-emissions ammonia production supplies 29%–58% of demand in the two net-zero scenarios,[xli] amounting to around 70–163 Mt of ammonia (Exhibit 2.6).

This requires near-zero-emissions production of ammonia to increase by a factor of two to four from currently planned capacity, which is around 30 Mt, by 2030[74] (Exhibit 2.7).

EXHIBIT 2.6

Production of low-emissions and near-zero-emissions ammonia in 2025 and 2030



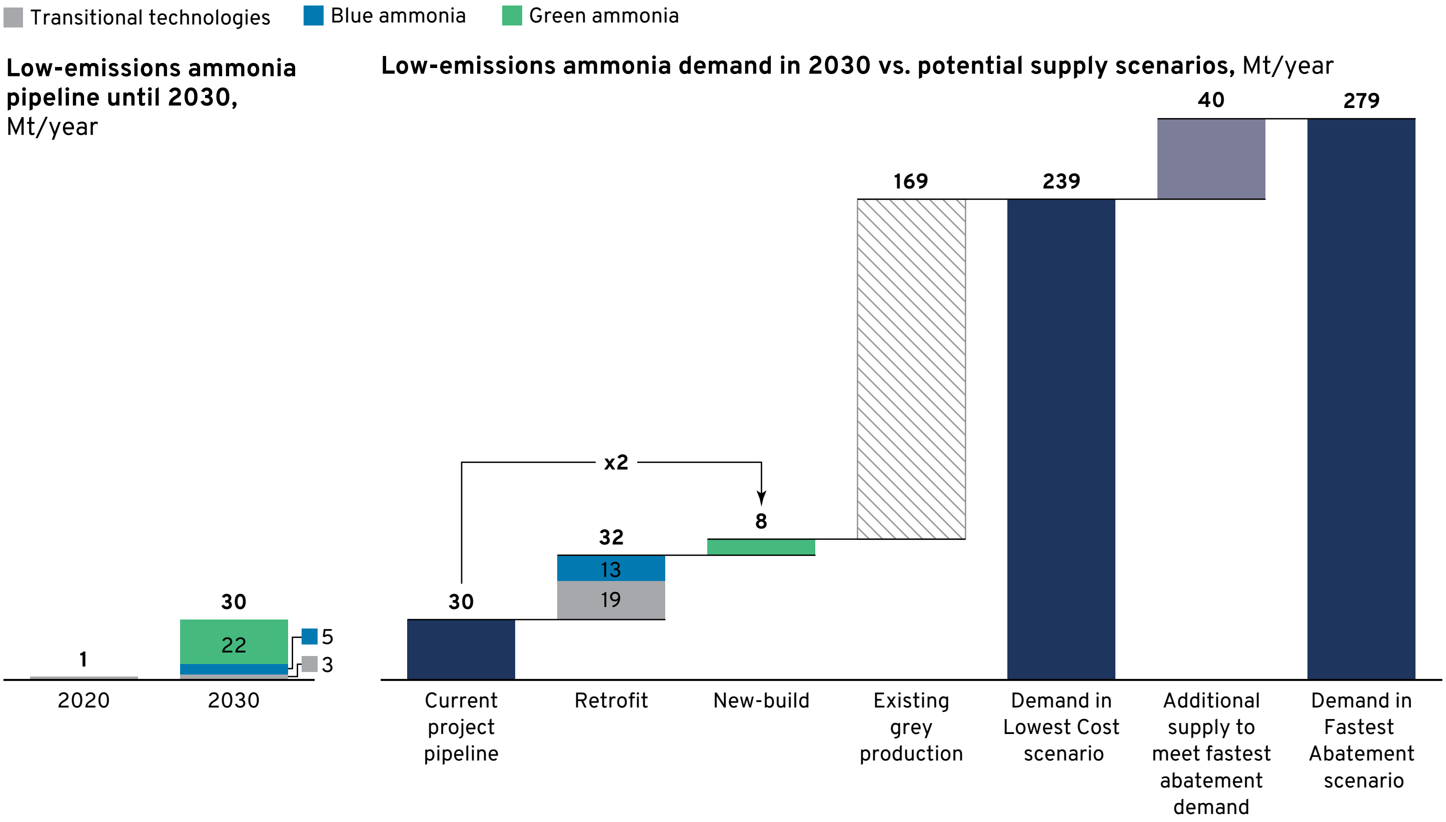
Note: Assumed plant sizes are 2,000 tonnes per day of ammonia with a standard capacity utilisation factor (CUF) of 95% and includes the plants for production of ammonia for ammonium nitrate and urea. Note that in reality CUF varies widely by region and year based on projected demand and plant economics.

Source: MPP analysis

[xli] Low-emissions ammonia production technologies include transitional technologies as well as green ammonia, blue ammonia, biomass-based routes, and methane pyrolysis.

EXHIBIT 2.7

The current pipeline of near-zero-emissions ammonia projects must increase by a factor of 2 by 2030



Source: MPP analysis; IRENA[75]

Given the project lead times of over five years, project planning for the 92–218 lower-emissions ammonia plants required by 2030 in these net-zero scenarios needs to start now, with a particular focus on:

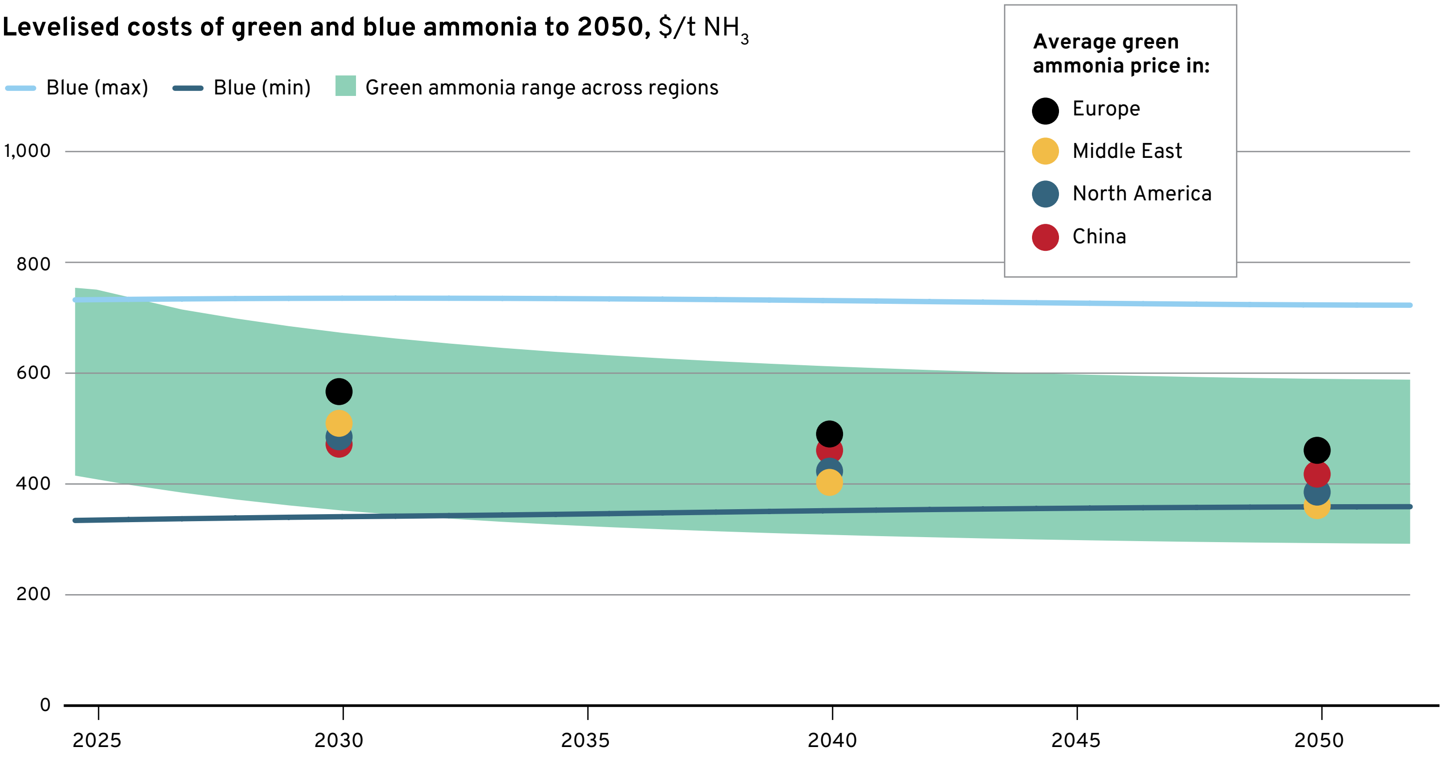
1. **Retrofitting existing gas-based production with CCUS where geological storage or opportunities for usage are available and developing the necessary infrastructure for CO_2 transport and storage.** Currently, there is less than 3 Mt of fossil fuel–based ammonia production capacity with CCUS,[76] the entirety of which has a capture rate of around ~67%, capturing only process emissions. From this capacity, all captured CO_2 emissions are being used for methanol production, for other industrial applications, or in enhanced oil recovery. While all existing plants could be retrofitted with carbon capture to eliminate at least ~90% of production emissions at a modest additional cost, the lack of supporting infrastructure for transport and storage of CO_2, particularly the lack of Class VI wells due to the challenges and time required for permitting, is a major barrier. Therefore, the industry requires government support to mobilise resources and accelerate the process of gaining permits. In addition, financial support in the form of loans, grants, and tax breaks should be used to incentivise such retrofits.

2. **Forming green ammonia production hubs with access to geological H_2 storage and building out renewable power infrastructure in locations with low-cost renewables to meet growing demand.** The levelised cost of green ammonia is highly sensitive to the price of renewable electricity, which accounts for over 50% of this cost. By shifting production to low-cost renewable power regions such as the Middle East, Australia, and optimal power locations in North America and Latin America, which have LCOEs up to 50% lower than other regions, green ammonia becomes more cost competitive than blue, at a levelised cost of ammonia of as low as $350/t NH_3 by 2030 (Exhibit 2.8). Encouraging signs are emerging with the announcement of a number of green ammonia pilots in these regions, the majority of which are to be based in Australia. However, this also relies strongly on a rapid build-out of renewable electricity infrastructure in these locations.

EXHIBIT 2.8

Green and blue ammonia price range, 2025–50

Levelised costs of green and blue ammonia to 2050, $/t NH_3



Source: MPP analysis; ETC; BNEF[77]

While transitional technologies are important in the short term, the long-term focus should be on near-zero-emissions technologies,[xlii] which could supply 20%–42% of total demand by 2030. Early adoption of these technologies, with strong support from governments in this decade, is key in order to unlock economies of scale and drive the ramp-up of near-zero-emissions production to meet the full net-zero demand by 2050 of 580–830 Mt of ammonia. After 2030, greater experience in developing CCUS projects and in electrolysis-based ammonia production gained this decade as well as demonstration of their competitiveness and viability are expected to lower the associated risk of these projects and increase the TRL of these production routes. In turn, this could accelerate the adoption of these technologies and thus drive rapid and deep emissions reductions in the ammonia sector in the 2030s.

Green ammonia production requires adequate kick-off support this decade to drive early emissions reduction, unlock economies of scale to enable cost competitiveness, and thus avoid lock-in to a fossil-dependent system.

As shown in Exhibit 2.9, there is a large uptake of blue ammonia in the LC scenario relative to the FA scenario, which could risk locking the industry in to a fossil fuel-dependent system. While CCUS enables early, rapid emissions reductions and supports early demand markets for near-zero-emissions ammonia, this also carries two risks.

The first is the high upstream Scope 3 emissions from continued fossil fuel extraction and residual emissions from incomplete carbon capture, as only the concentrated CO_2 stream, constituting two-thirds of total emissions from SMR, is captured today. While it is technically possible to capture more than 90% of total emissions, additional capture capacity and energy are required. The combination of these two factors means a greater need for CDRs and a higher risk of exhausting the carbon budget.

The second risk is that without early investment in electrolysis, both within and outside of the ammonia industry, and given the long lifetimes and capital expenditure-intensive nature of ammonia plants, green ammonia production, the only promising

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[xlii] Near-zero-emissions technologies do not include transitional technologies. Only technologies which reduce emissions by 90% or more are considered near-zero emissions.

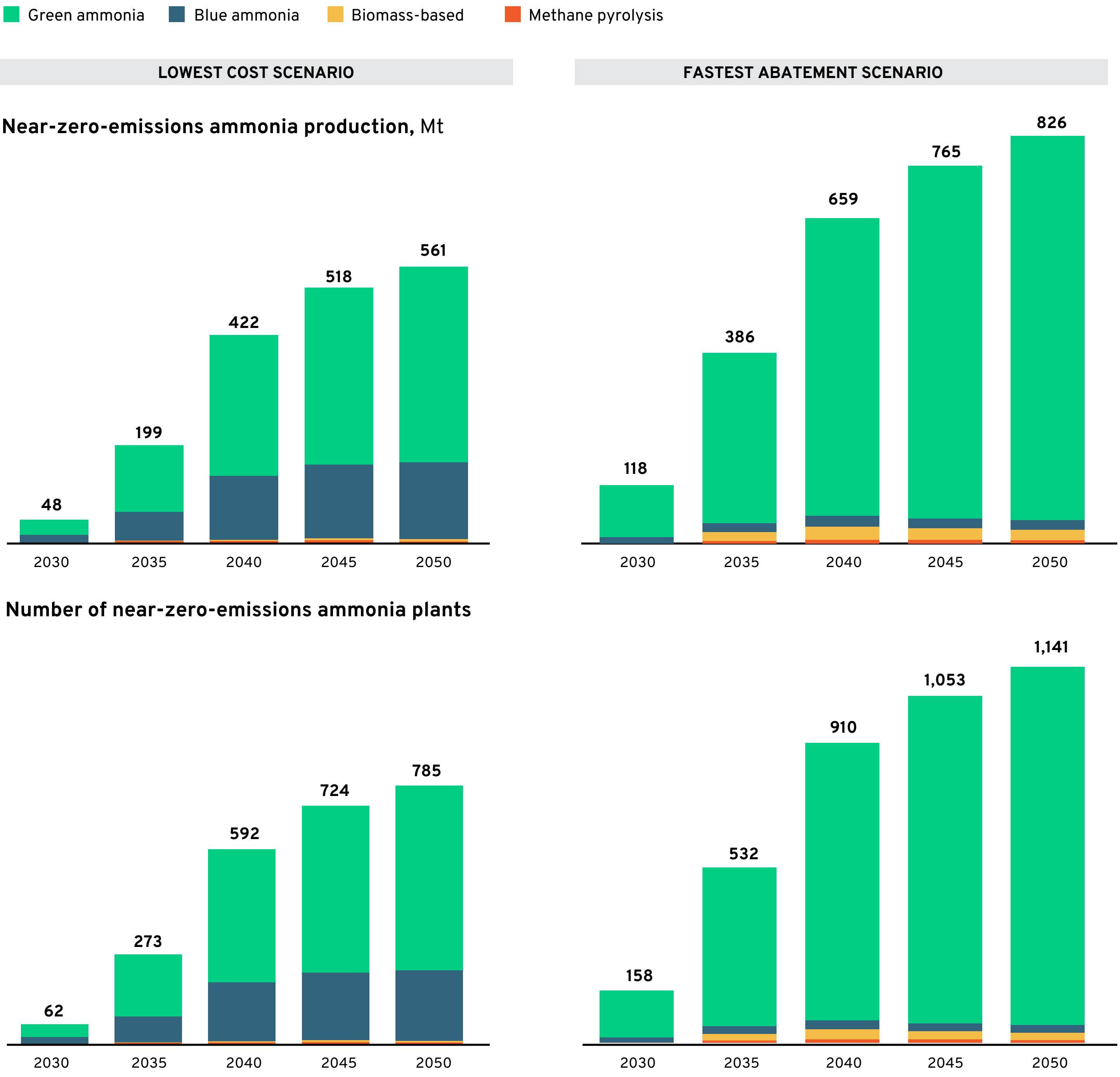
scalable zero-emissions production technology, does not become competitive with blue ammonia and is thus unable to scale.

The FA scenario, on the other hand, almost exclusively relies on green ammonia to drive emissions reductions, limiting the need for carbon dioxide removals by 2050 and the risk of high upstream emissions from continued fossil fuel extraction. The deployment of increasing volumes of green ammonia production, in addition to the large volumes of green hydrogen production outside of the ammonia industry, will drive the necessary cost declines of electrolysers from economies of scale. Electrolysers are projected to have learning rates of around 13%–18%, that is, a cost decline of 13%–18%[78] per doubling of cumulative installed capacity, with the potential to increase to rates similar to that of solar PV, which has experienced learning rates of about 30%.[79]

This learning-by-doing is based on **technology-related learnings** like the standardisation of processes, increased operational efficiencies, greater specialisation in manufacturing, and lower prices due to the purchase of larger quantities of resources.[80] Additionally, it can be based on **financial learnings:** (1) As a growing number of projects come online, elements of the project that were perceived as high risk by financing parties due to their nascence will become better understood by financing parties and thus perceived as lower risk when considering the next project of that kind. (2) In addition, early projects could have “project on project” risk, where new value chains being built rely on multiple stages being established and the supporting infrastructure built (for example, renewable electricity generation, hydrogen production, ammonia synthesis, transport to ports, and storage at ports). As the industry matures, more and more projects will be able to plug into existing infrastructure and thus will not be reliant on other new projects being completed at the same time. Both learnings serve to reduce the risk perceived by financing parties, and thus projects will be able to attract lower-cost capital.

EXHIBIT 2.9

Near-zero-emissions ammonia production and number of plants



Note: Assumed plant sizes are 2,000 tonnes per day of ammonia with a CUF of 95% and includes ammonia for urea and ammonium nitrate production.

Source: MPP analysis

2.2.5 Cost of the switch to zero-emissions solutions

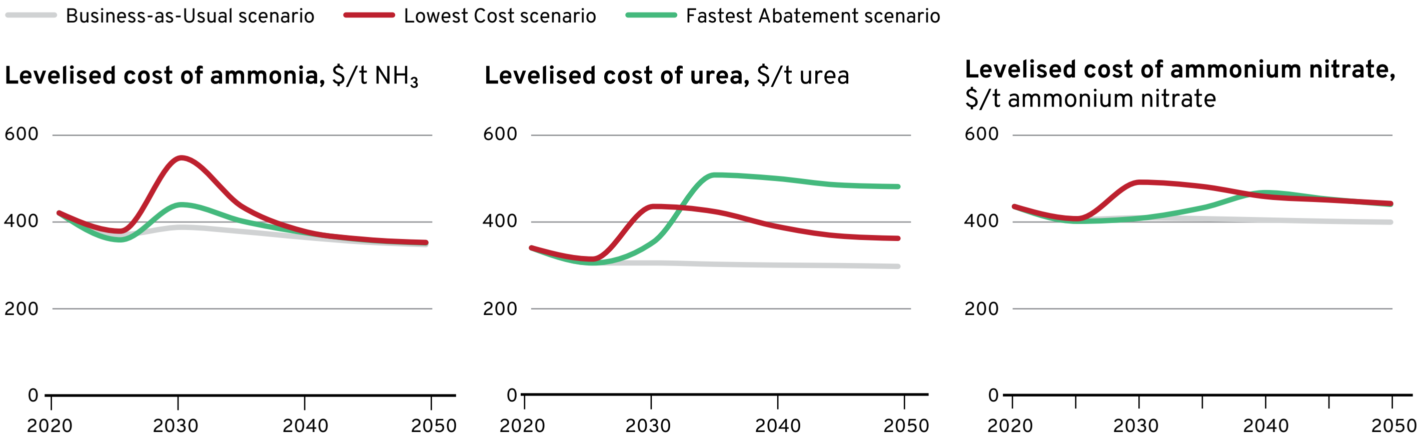
Switching to lower-emissions ammonia production increases the weighted average levelised cost of ammonia production by 13%–41% in 2030 relative to BAU, but by the late 2040s, the price premium of ammonia in the net-zero scenarios above that of the BAU scenario is reduced to almost zero. In the net-zero scenarios, up to 2030, the levelised cost of ammonia increases with an increasing share of near-zero-emissions production, before decreasing to 2050 to the BAU cost of ~$350/t. The reversal of the cost trajectory after 2030 is a result of the declining price premiums of blue and green ammonia production and is particularly pronounced in the FA scenario due to higher uptake of green ammonia production, which faces both higher initial costs as well as steeper cost declines compared with blue ammonia production.

However, in the case of ammonia derivates used for fertiliser, urea, and ammonium nitrate, price premiums of $70–$190/t urea and ~$40/t ammonium nitrate above BAU prices remain in 2050. The levelised cost of urea and ammonium nitrate in the net-zero scenarios remains above the BAU prices to 2050, at a cost of $360–$480/t urea, due to the cost of CO_2 from DAC and $440/t ammonium nitrate. While the levelised cost of ammonium nitrate in the net-zero scenarios remains above the BAU cost, in both scenarios by 2050 there is only a 2% increase in costs relative to 2020, suggesting that the risk of higher crop prices by 2050 as a result of decarbonising ammonium nitrate production is low. However, in the case of urea production, switching to lower-emissions production routes in the net-zero scenarios results in increasing levelised costs of production, which then plateau to 2050, settling at a cost that is 7% and 42% higher relative to 2020 in the LC and FA scenarios, respectively. The greater uptake of electrolysis-based production in the FA scenario means a greater dependence on DAC for a carbon-neutral CO_2 source (see Box 7) and thus a higher average levelised cost of urea compared with the LC scenario, in which urea demand is met mostly by blue ammonia.

The increasing costs of ammonia and its derivatives over the next 30 years carry the risk of higher crop and shipping prices; however, this is expected to be well below recent price increases. As we are seeing today with the effects of the gas crisis, fertiliser prices can be highly volatile, feeding through to farm costs. Fertiliser costs historically represent 15%–40% of crop production costs (according to figures from North America).[81] In 2030, crops with higher fertiliser application rates, such as maize and wheat, with fertiliser cost shares around 35%, could see crop prices increase by 8%–9%, if fertiliser costs impact were directly transferred. Cost impacts could be minimized in part through optimizations in fertiliser application or savings through other efficiencies in farm management. This is a challenge to be addressed, as without appropriate policy and financing mechanisms the transition to near-zero to zero-emissions ammonia production could carry the risk of a new normal of higher crop prices, affecting the most vulnerable populations disproportionally who spend upward of 60% of their income on food. The estimated impact of zero-emissions shipping fuel on shipping freight costs could be significant, though well below historically high freight increases seen today. While these intermediate services could see a larger impact (for example, up to 60% increase in freight costs for consumer goods), due to the small proportion that freight represents for end product costs, the consumer impact would be significantly lower, 0.5%–1% on final goods.[82]

EXHIBIT 2.10

The transition to net zero results in an increase in the levelised cost of ammonia and its derivatives



Note: The LC scenario includes a carbon price that increases to $100/t CO_2 by 2035 while the BAU and FA scenarios do not include a carbon price. Prices shown are for five-year intervals only with interpolation between the five-year intervals.

Source: MPP analysis

BOX 10

Sensitivity analysis

Ammonia decarbonisation is highly sensitive to a number of parameters, two of which are the price of natural gas and the carbon price.

A. The cost of fossil fuel–based ammonia production is very sensitive to gas prices.

Gas consumption in grey ammonia production accounts for 30%–75% of the levelised cost of production. Therefore, gas price volatility has a significant impact on the cost of ammonia production. Green ammonia prices are expected to fall over time, while the future of fossil fuel prices is highly uncertain. As shown in the exhibit below, by 2050 green ammonia produced in the most optimal lowest-cost power locations is cost competitive with grey ammonia above a gas price of ~$4/MMBtu; below this gas price, a carbon price is required to switch from grey to green production. To be cost competitive with the cheapest blue ammonia by 2050, a gas price of above $2/MMBtu is required. Therefore, as shown on the next page, the relative share of green to blue ammonia increases at higher gas prices.

By 2050, green ammonia is cost competitive with blue ammonia in all regions with a gas price above $2/MMBtu

Levelised cost of ammonia production pathways at different gas prices

Note: For grey ammonia, natural gas steam methane reforming is assumed, and for blue ammonia, autothermal reforming with CCUS is assumed. Green ammonia price assumes an LCOE of $20–$53/MWh in 2020, $16–$35/MWh in 2030, $12–$30/MWh in 2040, and $10–$25/MWh in 2050.

Source: MPP analysis

Under higher natural gas prices, green ammonia becomes economically competitive earlier, taking a larger share of total production by 2050. Under low natural gas prices, green ammonia becomes competitive later and only in optimal, low-cost power locations (such as Australia, Latin America, and the Middle East), accounting for around 50% of total production by 2050.

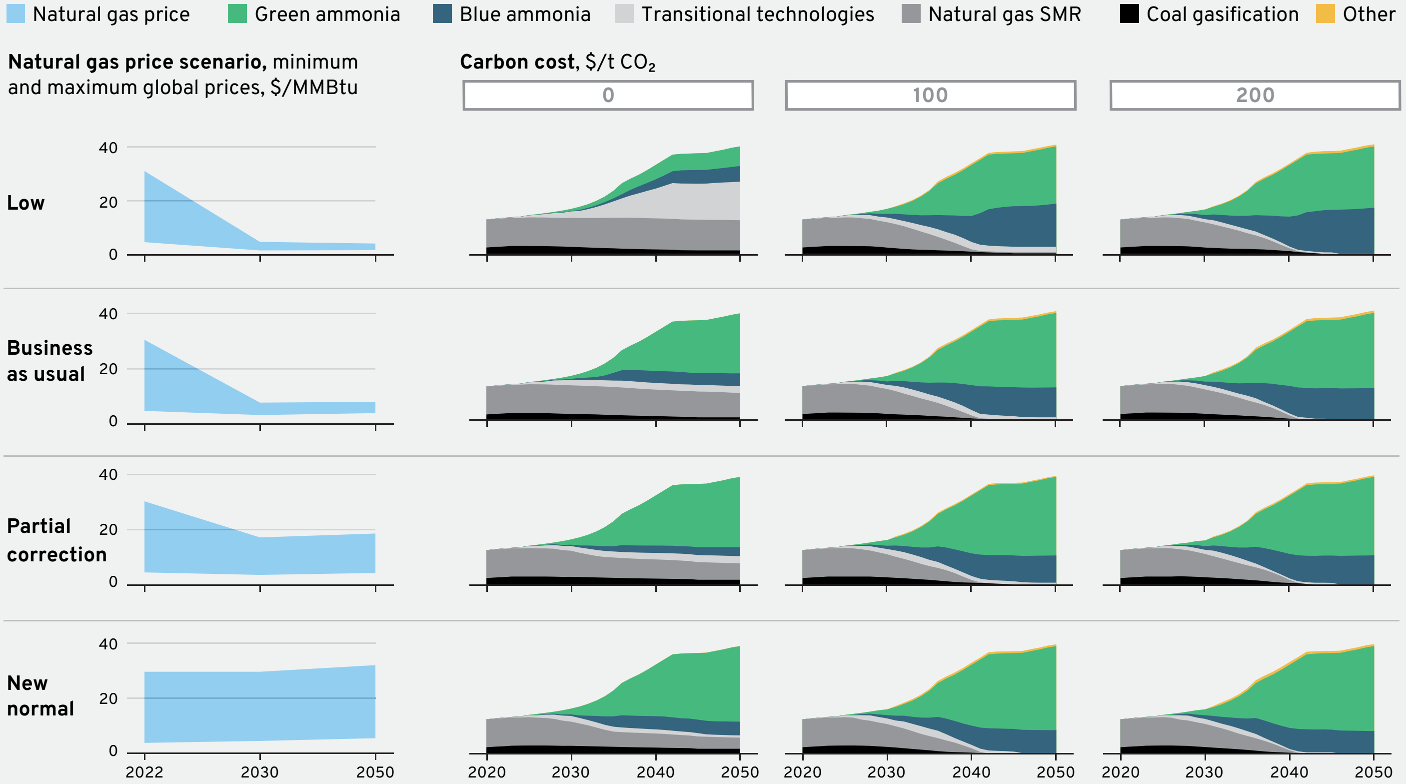
While historical natural gas prices from 2000 to 2020 were on average \$3–\$10/MMBtu, the 2020–21 European gas crisis, recently exacerbated by the war in Ukraine, has led to an unprecedented spike in prices and a call for a renewed policy environment favouring national energy security over cost. The future development of fossil fuel prices is highly uncertain. A sensitivity analysis considers three additional gas prices scenarios in addition to the BAU scenario prices: a new normal in which there is a continuation of the 2022 regional peak prices, a partial correction representing a 50% reduction towards the BAU, and a low gas price scenario in which prices return to pre-crisis levels and decrease over time.[xliii]

The results of the sensitivity analysis, given in the exhibit on the previous page, show that at natural gas prices above \$16/MMBtu, green ammonia becomes cost competitive with blue ammonia in all regions by 2030. However, in low-cost power regions, where renewable electricity prices are as low as \$18–\$25/MWh, the price at which cost competitiveness between blue and green ammonia is reached in 2030 is as low as \$7/MMBtu, which is in line with pre-crisis gas prices across most regions.

Under the low-cost gas scenario natural gas price of \$1.7–\$4.8/MMBtu, green ammonia becomes cost competitive with blue ammonia in all regions only by the late 2040s, delaying the adoption of electrolysis. The 2050 share of green ammonia is therefore much lower than in the higher gas price scenarios at 49% compared with 77%, while the blue ammonia share is 42% compared with 21% (for a carbon cost of \$100/t CO_2).

Carbon price impacts decarbonisation while natural gas price impacts the ratio of green to blue ammonia production

2020–50 shares of blue, green and grey ammonia production in the Lowest Cost scenario



Note: The range of gas prices corresponds to the variation across regions. BAU prices correspond to IEA STEPS prices, and the low gas price scenario corresponds to the IEA Net Zero emissions scenario. The partial correction scenario assumes that gas prices partially return to pre-gas crisis prices and follow the BAU trajectory, and the new-normal gas price scenario assumes a continuation of the current high gas prices. The default gas price scenario used across the BAU, LC, and FA scenarios is the BAU scenario.

Source: MPP analysis; IEA[83]

[xliii] All prices scenarios are region specific. See the *Technical Appendix* for more detail.

B. As ammonia plants are extremely capital intensive, a carbon price is needed in order to trigger technology switches from grey ammonia production to lower-emissions production routes.

Without a carbon price and the introduction of carbon border adjustment mechanisms (CBAM),[xliv] it is more economical to continue operating existing unabated fossil fuel–based assets rather than to retrofit with CCUS or rebuild and switch to a different production route. This inertia hinders a complete transition to near-zero-emissions technologies by 2050, with a significant proportion of existing grey production still operating by 2050, as illustrated by the BAU scenario, in which 77% of production by 2050 remains grey, producing 450 Mt CO_2 annually in Scope 1 and 2. Applying different levels of carbon price affects the pace and technology choices for ammonia decarbonisation:

- **The carbon price mostly affects the pace and level of decarbonisation. In the LC scenario without a carbon price and under BAU gas prices, 25% of existing production, equivalent to 150 Mt, remains grey to 2050.** At \$50/t CO_2e, the pace of decarbonisation accelerates but insufficiently to decarbonise the sector by 2050, leaving 5% of unabated fossil fuel–based production by 2050.
- **A moderate carbon price is sufficient to decarbonise ammonia production technologies.** Under a BAU gas price scenario, at a carbon price of ~\$100/t CO_2e (growing in \$10 increments from 2026 to 2035),[xlv] 97% of existing grey ammonia capacity transitions to near-zero-emissions production technologies by 2050.
- **However, demand sectors (e.g., shipping) require higher carbon prices to trigger technology switches.** Higher carbon prices of up to \$191–\$400/t CO_2e would enable downstream sectors such as shipping to shift away from the currently used fossil fuel–based fuels towards net-zero aligned alternatives such as near-zero-emissions ammonia.[84,xlvi] A number of policy instruments, such as the establishment of ETS, carbon tax requirements per sector, and subsidies, are discussed in more detail in Part 3 that could be used to implement these measures.

There are additional factors beyond carbon price and gas price that are outside of the scope of this sensitivity analysis but may potentially bring forward the year in which green ammonia becomes more cost competitive than blue ammonia, for example by including the revenue from oxygen produced in electrolysis in the business case for green ammonia production and applying more stringent constraints on the allocated share of CO_2 storage. These are additional sensitivities that are not explored here but could affect the share of green versus blue ammonia by 2050.

2.2.6 Investment needs for the transition to net zero

Achieving the net-zero scenarios requires an average investment of \$81 billion–\$138 billion per year from 2022 to 2050 across the full value chain, of which \$59 billion–\$105 billion is required directly in the ammonia industry to transition the production landscape (Exhibit 2.11). These figures do not include the cost of CDR solutions that would be required by 2050 to offset residual emissions from incomplete capture and unabated Scope 3 emissions; these incur additional annual costs of about \$25 billion–\$80 billion by 2050.

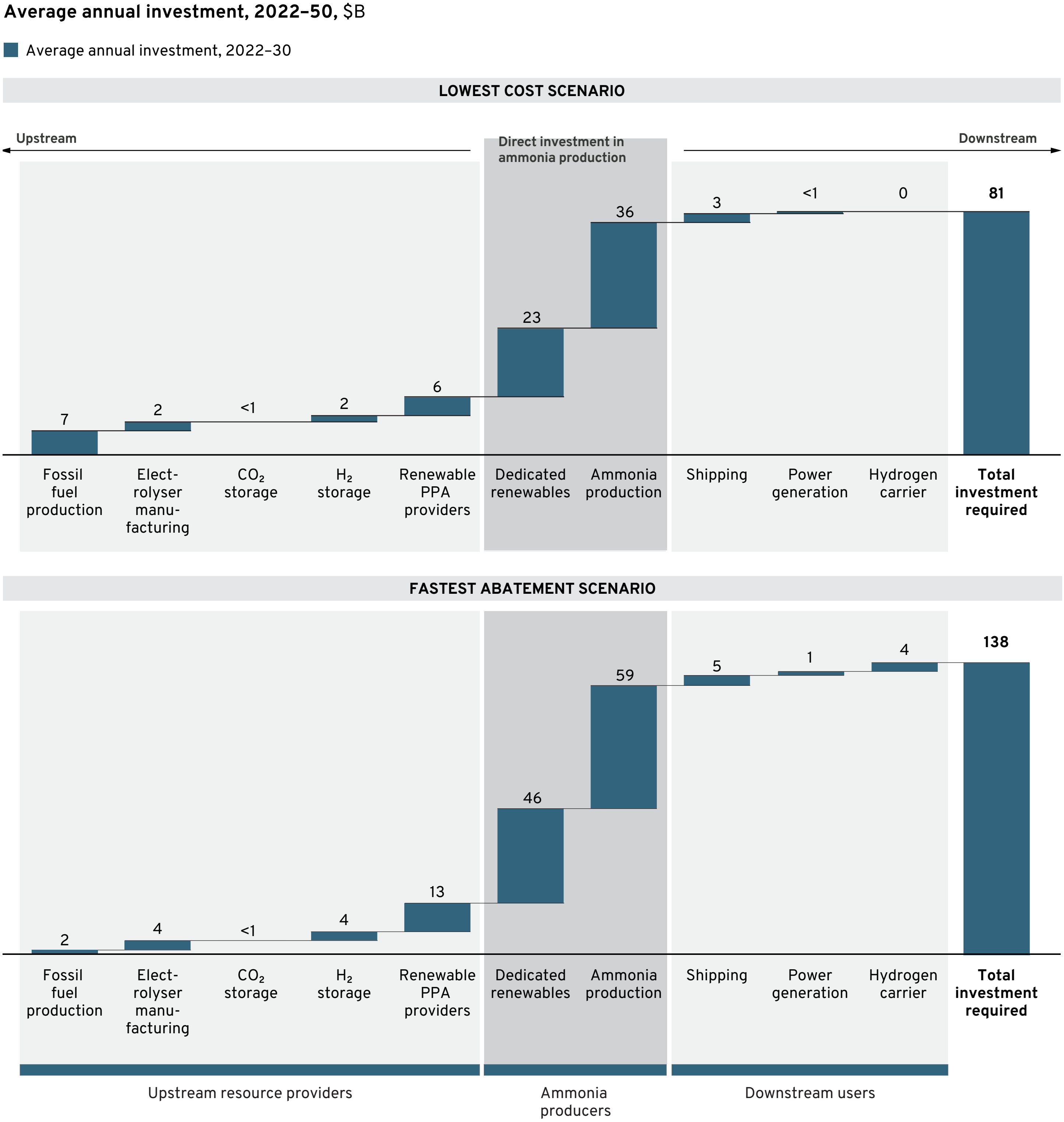
[xliv] The CBAM is needed so that imports not exposed to carbon pricing don't outcompete domestic production.

[xlv] In the LC scenario, the carbon price is ramped up from \$10/t CO_2 in 2026 to \$100/t CO_2 by 2035, then stays stable until 2050.

[xlvi] Even more recent studies envision carbon prices up to \$650/t CO_2 by 2050. UMAS, *International Maritime Decarbonisation Transitions* (forthcoming), accessed April 2022, subject to changes.

EXHIBIT 2.11

Average annual investments required along the ammonia supply chain to enable the transition in the net-zero scenarios



Note: investments for CDR are not included here.

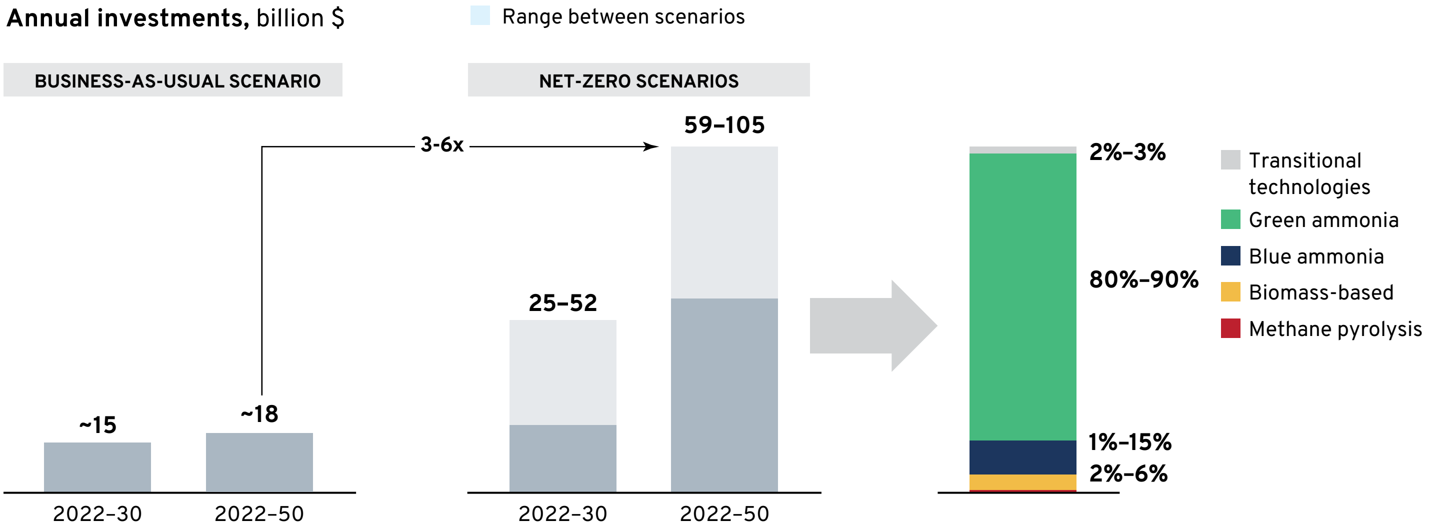
Source: MPP analysis, IEA; ZEP; BNEF; Fasihi et al.; UMAS[85]

Bringing ammonia production to net zero by 2050 will require direct investment of about $59 billion–$105 billion on average in upfront capital annually over the next three decades, compared with ~$18 billion annually in a BAU scenario (Exhibit 2.12). Of these investments:

- 2% to 3% of this investment is required, predominantly this decade, for the **deployment of transitional technologies**. This is primarily for the retrofitting of existing SMR capacity with carbon capture and storage of process emissions, with a smaller proportion of investment going towards the installation of small electrolysers in existing facilities to produce ~10% of the required hydrogen and thus reduce the consumption of fossil fuels.
- The vast majority of investment, 80%–90%, is needed for **green ammonia production**, predominantly in the renewable electricity capacity to power the electrolysers, air separation units, motors, compressors, and pressure and temperature control equipment, as well as in the electrolysers themselves.
- Up to 15% is necessary for **retrofitting existing assets with CCUS and building new blue ammonia plants.**
- 2% to 6% is in other technologies, predominantly **biomass-based production routes** with smaller investments in **methane pyrolysis**.

EXHIBIT 2.12

Investments required to transition the ammonia industry to net zero



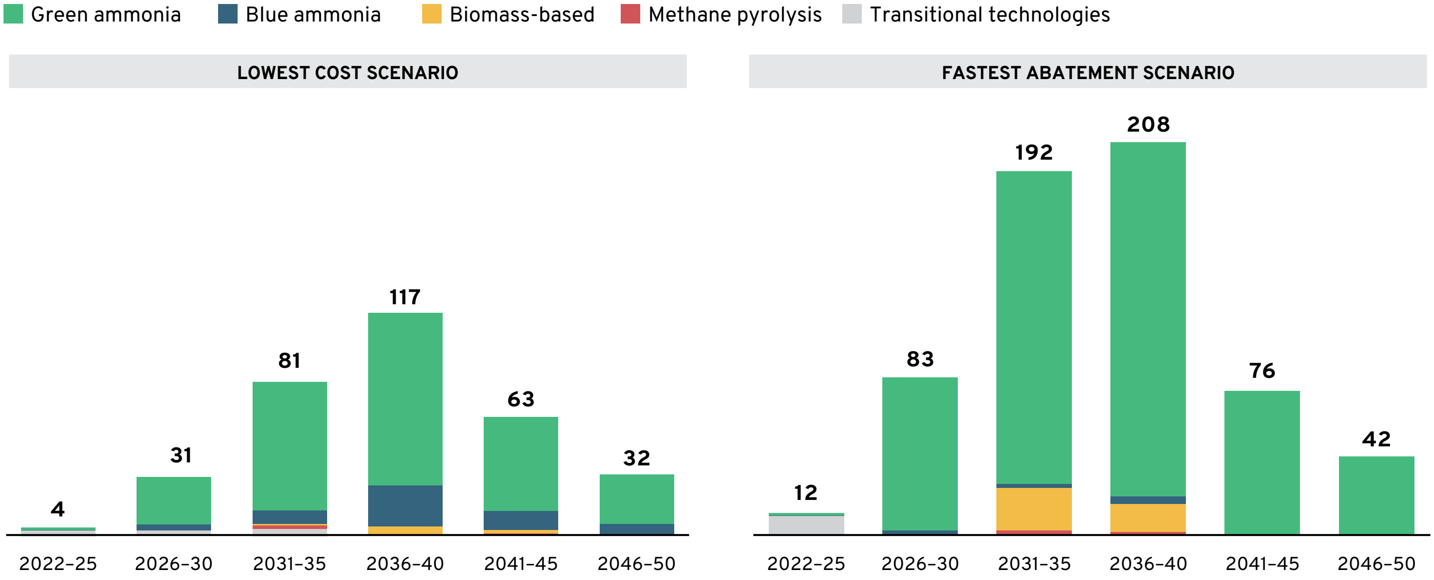
Source: MPP analysis

The cumulative direct investment in ammonia production needed to 2050 ($1.7 trillion–$3.1 trillion) is not distributed evenly across the decades to come, as shown in Exhibit 2.13. In the 2020s, about 15% of the cumulative investments necessary between 2022 and 2050 need to happen. These $25 billion–$52 billion of average annual investments, particularly in green ammonia production and dedicated renewable electricity infrastructure, are critical to kicking off the transition. The 2030s are also a critical period, requiring a large ramp-up of investment, accounting for two-thirds of the cumulative investment between 2022 and 2050. These $100 billion–$200 billion of average annual investments in the 2030s are needed to accelerate the transition, meeting rapidly growing near-zero-emissions ammonia demand while simultaneously delivering steep emissions reduction.

EXHIBIT 2.13

The cumulative investment of $1.7 trillion–$3.1 trillion would not be distributed evenly across the decades, with most of the investment taking place in the 2030s

Average annual investment, billion $



Source: MPP analysis

- In the LC scenario, an average $59 billion per year ($1.7 trillion cumulatively between 2022 and 2050) would be required to transition the ammonia industry to net zero by 2050. Of this cumulative investment, 15% is needed for blue ammonia production, 80% is required for green ammonia production, and only 3% is necessary for retrofitting existing assets with transitional technologies.

- Similarly, in the FA scenario, an average $105 billion per year ($3.1 trillion cumulatively between 2022 and 2050) would be needed for this transition. Given that 94% of ammonia is produced via electrolysis in 2050, it is also responsible for the largest share of investments, at around 90%, while CCUS uptake is relatively limited, accounting for around 1% of total cumulative investment to 2050. The demand-side efficiency in this scenario also reduces the required cumulative investment in new capacity, which could otherwise be much greater.

In addition to the direct investment required in the low-carbon production technologies, the net-zero scenarios also rely on significant additional capital investment of the order of $20 billion–$30 billion annually in wider energy-system infrastructure including for CO_2 transport and storage, geological hydrogen storage, and renewable electricity infrastructure (Exhibit 2.11).

These capital investments are critical to the net-zero transition of the ammonia sector and is absorbed in the operational expenditure paid by the sector to service providers through long-term contracts.

Of this additional capital investment, around \$4 billion–\$10 billion is needed annually from 2022 to 2050 in downstream sectors across shipping, energy, and hydrogen carrier uses, to enable the use of ammonia as a zero-carbon energy carrier.

- Downstream ammonia off-takers across the shipping sector will need to retrofit existing ships and build new ammonia-powered ships, amounting to around ~40,000–80,000 ammonia-powered ships,[86] and bunkering and storage terminals to meet the 700%–900% increase in ammonia shipping fuel demand from 2030 to 2050. This will require approximately \$3 billion–\$5 billion in annual investment from 2022 to 2050.
- Similarly, retrofitting existing coal-fired thermal power plants across Japan and South Korea[87] to enable first co-firing and eventually 100% ammonia use will require around \$1 billion of investment annually to 2050.
- The use of ammonia as a hydrogen vector enables global trade of hydrogen, allowing it to be transported via ship over long distances. However, this could require an average annual investment of up to \$4 billion in ammonia crackers as well as additional infrastructure including storage, additional export terminals, and transport vessels.

Beyond what is quantified here, there is significant additional investment that is outside of the scope of this analysis but is nevertheless essential to support the large uptake in ammonia demand. This includes the build-out of grid infrastructure (e.g., transmission lines) to support the large increase in renewable electricity demand via PPAs, as well as the construction of desalination plants to meet the large water requirements and supporting infrastructure to enable storage and distribution within each region, such as ammonia pipelines where industrial use would not be located near production or ports.

2.2.7 Energy prerequisites and requirements

2.2.7.1 Energy requirements of the ammonia sector

By 2050, the ammonia sector could require 3%–8% of global wind and solar electricity generation, 9%–17% of global electrolyser capacity, and up to 4% of developed geological CO_2 storage capacity (Exhibit 2.14).

Fulfilling the low-carbon energy demand of the ammonia sector needs to be planned in the context of all other sectors decarbonising their own activities. The ammonia industry will be a major competitor for renewable power, electrolyser capacity, and geological CO_2 storage, but it is unlikely to be a priority sector for the constrained biomass supply. There are trade-offs with regards to these resources: the more renewable electricity and electrolyser capacity the industry can access, the less CO_2 storage is required and vice versa. However, as the supply of these resources and the rate of infrastructure build-out are constrained, no single resource will be sufficient to meet the required demand in 2050 in both net-zero scenarios. A combination of all will be necessary.

EXHIBIT 2.14

Resource use of the ammonia sectors

Wind and solar power consumption in the ammonia sector, TWh/year

Installed electrolyser capacity in the ammonia sector, GW

Annual geological CO_2 storage capacity required by the ammonia sector, Mt CO_2/year

Source: MPP analysis; ETC[88]

A. Renewable electricity is a prerequisite: 3%–8% of the projected global demand for wind and solar power in 2050, that is, 3,700–7,100 TWh, is needed to decarbonise ammonia production, requiring 0.02%–0.03% of global land area by 2050.[xlvii]

- Driven largely by the rapid scaling of green ammonia production, but also by increased power demand for nitrogen isolation from the air, CO_2 capture, and for the motors, compressors, and pressure and temperature control equipment required for ammonia synthesis, total electricity demand in the sector is expected to increase by a factor of 40–70 from around 100 TWh in 2020 to 3,700–7,100 TWh in 2050, at which point all of the electricity is to be generated by renewable sources.

- Dominated by green ammonia production, which makes up 94% of production in 2050, the FA scenario relies on a 12-fold increase in renewable electricity between 2030 and 2050, while in the same period the LC scenario, which instead relies on greater uptake of CCUS, relies on a sixfold increase in renewable electricity generation.

- The uptake of green ammonia at the scale given in the FA scenario requires a large share of greenfield production to be located in regions with abundant low-cost renewable electricity such as the Middle East, Latin America, North Africa, and Australia.[xlviii] Other sectors with similarly high demands for low-cost renewable electricity such as steel, aluminium, and aviation (for producing Sustainable Aviation Fuel), could similarly see a shift in production to these regions. Therefore, given land constraints in these regions and the potential limits on human capital and rate of infrastructure build-out, there may be significant competition over low-cost green power between these sectors. Alternatively, large demands for renewable electricity from multiple players may drive greater ambition and investment in these regions, enabling an unprecedented rapid scale-up of supply, exceeding these limits.

- If the demand for renewable electricity from the ammonia sector were to be met entirely by solar and onshore wind capacity, it would require an additional installed capacity of around 1.5–3.0 TW of solar PV and onshore wind, around 3%–6% of the projected global installed capacity in 2050.[89] This is estimated to require 0.02%–0.03% of global land area by 2050,[90] equivalent to the size of Belgium, at the lower end of the range, and Costa Rica at the upper end.

B. A rapid scale-up of electrolyser capacity underpins the net-zero transition of the ammonia sector: 9%–17% of global electrolyser capacity in 2050 is concentrated in the ammonia sector.

- In the net-zero scenarios, the ammonia sector requires 70–140 Mt of green hydrogen by 2050, around 9%–28% of projected global production.[91] This relies on a rapid ramping-up of installed electrolyser capacity to 780–1,500 GW for ammonia production by 2050.

- In line with renewable electricity demand, the FA scenario is at the top end of this range, with a greater share of electrolysis-based production compared with the LC scenario.

- Uptake of electrolysis-based production at the scale suggested in both net-zero scenarios relies on early market entry of green ammonia this decade to drive economies of scale and unlock the required cost reductions of electrolysers.

[xlvii] This depends on the mix of solar and wind assumed as solar PV technologies directly affect 90% of dedicated land area (taking up around 12–17 km^2 per TWh/year; see Megan Day, *Land-Use Planning for Large-Scale Solar*, National Renewable Energy Laboratory, 2018, **https://www.nrel.gov/docs/fy19osti/72470.pdf**) while wind farms can coexist with grazing, farming, and other land uses, thus affecting only 1% of the total dedicated land area. In addition, this assumes that all land area globally is suitable for renewable power generation for ammonia production; in reality, only a proportion of this land is likely to be suitable.

[xlviii] This list is not exhaustive. Similar levelised costs of green ammonia production could realistically be achieved in optimal locations within regions that are not listed here. However, to simplify the modelling, optimal locations within these four listed regions were used to represent all low-cost power regions around the world.

BOX 11

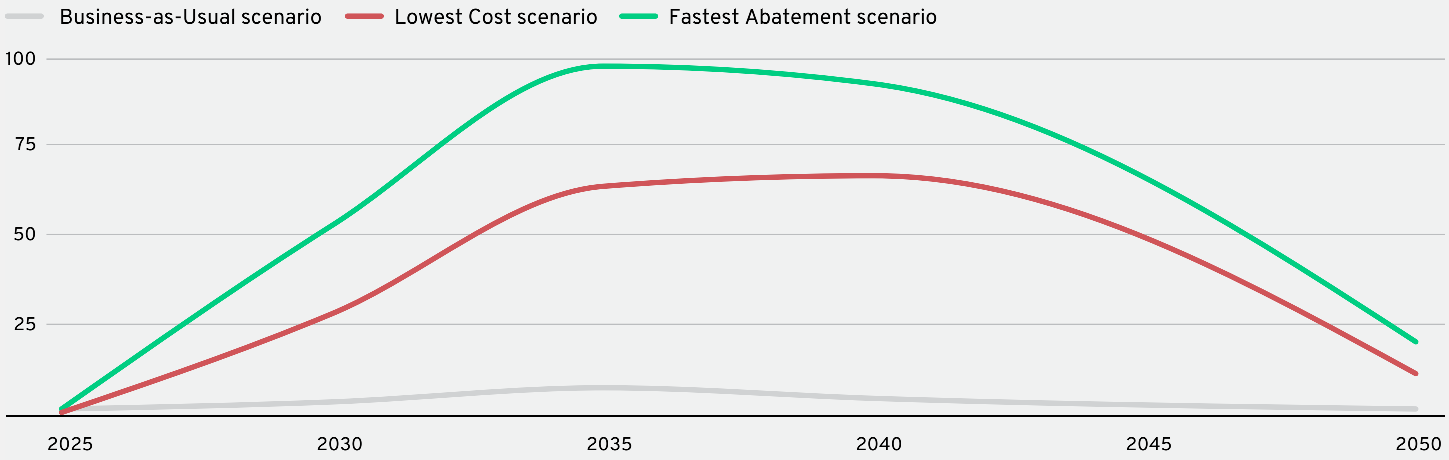
What is required to scale up electrolysers to the necessary capacity?

Current global electrolyser manufacturing capacity is around 1.3 GW/year.[92] In the LC scenario, electrolyser capacity additions by 2030 reach 28 GW/year. Assuming that the ammonia sector could account for around 15%–20% of electrolyser capacity, this implies a 100-fold increase in global electrolyser manufacturing capacity required by 2030 relative to today (see exhibit below). This is based on a net-zero scenario presented by the ETC in which hydrogen demand by 2050 reaches 700–1,000 Mt, of which 15%–20% is for ammonia production while the remaining 80%–85% is estimated to be used in steel production, cement production, other chemicals, Sustainable Aviation Fuel production, heating, and power storage. The FA scenario, on the other hand, implies a much more aggressive 200-fold increase in global electrolyser manufacturing capacity required by 2030 relative to today.

By 2030, it is estimated that a total of 135 GW/year of electrolyser manufacturing capacity is required globally for total hydrogen production, of which 20% (28 GW) in the LC scenario is assumed to be used for ammonia production, increasing to 67 GW for the ammonia sector by 2040. This is broadly in line with market outlooks from other sources.[93] The FA scenario, on the other hand, relies on a much more rapid build-out of electrolyser capacity to satisfy the larger ammonia demand from energy applications, requiring average annual additions of 95–100 GW/year in the 2030s. This is an extremely optimistic scenario that relies on all levers being pulled immediately and ambitiously by all actors to support such a rapid and unprecedented scale-up of manufacturing capacity.

Annual electrolyser capacity additions in the net-zero scenarios

Electrolyser additions per year, GW



Average annual capacity additions, GW

Scenario	2026–30	2031–35	2036–40	2041–45	2046–50
Lowest Cost	13	44	60	27	12
Fastest Abatement	42	95	100	41	20

Source: MPP analysis; ETC[94]

Although less aggressive than the FA scenario, the rate of manufacturing capacity ramp-up implied in the LC scenario, requiring an average 13 GW/year of annual electrolyser capacity additions between 2026 and 2030, and 44 GW/year between 2036 and 2040, is also relatively ambitious given the current 1.3 GW/year of electrolyser manufacturing capacity that exists today,[95] and thus relies on the following enablers:

- **Large economies of scale through automating stack production in GW-scale manufacturing facilities.** It is estimated that scaling up manufacturing from MW-scale to GW-scale could result in a 60%–70% cost reduction in the stack,[96] thus enabling further build-out of lower-cost manufacturing capacity and in turn enabling the electrolyser capital expenditure decline required for the uptake of green ammonia shown in the net-zero scenarios.
- **Significant regulatory and financial support.** An example of the policy support needed is the recent announcement in Europe, where a joint declaration was signed between the EU commissioner for internal market and 20 industry CEOs in which industry committed to a tenfold increase of its electrolyser manufacturing capabilities by 2025.[97] Governments should also work closely with industry, setting manufacturing tax benefits as well as grants and loans for capacity expansion since it is extremely capital intensive, requiring an estimated investment of ~$54 million–$83 million per GW of manufacturing capacity.
- **Adequate mineral supply**, particularly for proton-exchange membrane (PEM) electrolysers. Analysis of future demands for key minerals required in alkaline electrolyser production suggests that there will be no long-term constraints.[xlix] If the green ammonia in the net-zero scenarios was produced entirely by alkaline electrolysers built using primarily nickel, the cumulative capacity would consume 3%–5% of known reserves by 2050[98] However, for the less mature PEM electrolysers, the material constraints are more significant. IRENA suggests that current production of iridium and platinum would only support 3–7 GW of annual production,[99] thus alternative materials and reductions in material intensity will be essential for the PEM technology to scale, as is being explored via the development of anionic exchange membrane (AEM) electrolysers, which have lower critical material requirements. Electrolyser recycling and "designed-in" circularity can significantly reduce new minerals required. However, it is important to anticipate the timing of mineral demand growth, which will be driven both by hydrogen developments and by direct electrification.[100]

C. **Blue ammonia production requires up to 4% of the developed global CO_2 storage capacity by 2050.**

  - The greater the dependence on blue ammonia, the higher the requirement for geological CO_2 storage capacity. Therefore, while the LC scenario has lower renewable electricity and electrolyser capacity requirements relative to the FA scenario, it requires around 50 Mt of CO_2 storage annually by 2030 and 270 Mt by 2050. The FA scenario, on the other hand, relies almost entirely on green ammonia production, requiring only 40 Mt of CO_2 storage annually from 2030 to 2050.
  - In both net-zero scenarios, the demand for CO_2 storage is concentrated in regions with cheap fossil fuels, access to geological storage sites, and, in most cases, higher-cost renewable resources.
  - For ammonia, carbon capture followed by permanent storage provides a capital expenditure–efficient route to significantly reducing emissions by over 90% at existing production assets and can therefore play an important transitional role. However, the current pace of development of CO_2 transport and storage infrastructure is far slower than what is required to meet these targets. This is a result of past confusion about where CCUS is required the most, inadequate investment, and controversies that have generated public opposition, particularly around the safety, permanence, and appropriate role in the transition. Therefore, while the theoretical limit of global geological storage available for CO_2 does not present a meaningful constraint, the current rate of supporting infrastructure development does, and hence this limits the adoption of blue ammonia, particularly in this decade.

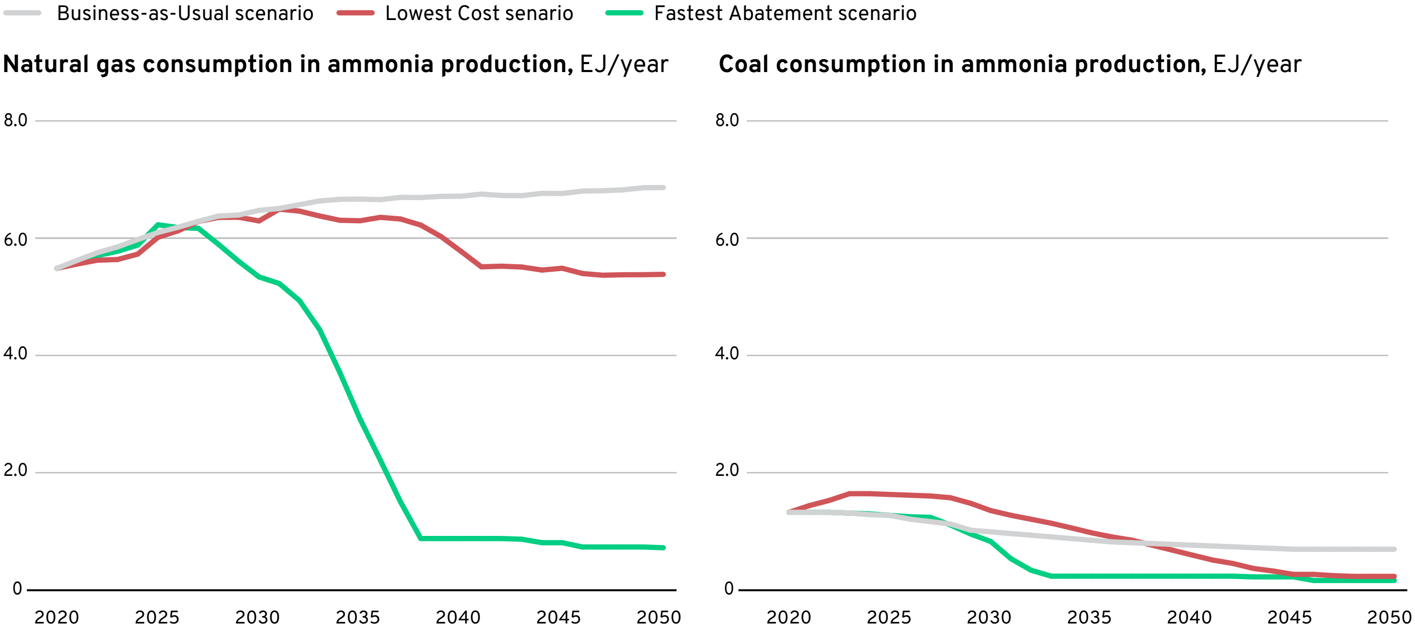
[xlix] Electrolysers rely on specific metals to realise high efficiencies and long-term stability (today: nickel for alkaline electrolysers, platinum and iridium for PEM electrolysers).

D. **Demand for biomass feedstocks is projected to be low at around 0.3–1.3 EJ by 2050 because of the higher costs of biomass-based ammonia production compared with other near-zero-emissions alternatives.**

- Given that the ammonia industry has more economical and scalable alternatives to biomass-based decarbonisation routes, it is unlikely to be a priority sector for biomass feedstock allocation.
- However, biomass-based routes provide an on-site source of carbon neutral CO_2, making it a viable production route for urea under certain conditions as discussed in Box 7.
- The uptake of biomass-based technologies is, therefore, low and limited mainly to integrated ammonia and urea production. In the LC scenario, 1% of total ammonia is produced from biomass feedstocks, using around 0.3 EJ of biomass, less than 1% of the global sustainable supply. Similarly, the FA scenario relies on biomass feedstocks for 3% of its ammonia production by 2050, using 1.3 EJ of biomass, around 2% of the global sustainable supply.[101,I]

EXHIBIT 2.15

Annual fossil fuel demand from ammonia production



Source: MPP analysis

E. **Coal demand declines by 82%–88% by 2050 relative to 2020 in both net-zero scenarios while the consumption of natural gas declines by only 2% in the LC scenario because of a greater reliance on natural gas–based ammonia production with CCUS (Exhibit 2.15).**

- Coal-based ammonia production, found almost exclusively in China, is substantially reduced by 2050 because of the high levels of residual emissions from incomplete CO_2 capture and its higher cost relative to new-build green ammonia production in China by 2050.
- The greater the dependence on blue ammonia production, the higher the demand for natural gas. Therefore, in the LC scenario, given the large uptake of CCUS also as a transitional technology, natural gas demand increases initially by 15% until 2030. As green ammonia technologies scale, capacity growth after 2035 comes mainly from green ammonia, so after this point, natural gas demand decreases and falls slightly below 2020 levels until 2050.
- On the other hand, in the FA scenario, electrolysis is pursued early on to reduce emissions with almost zero dependence on CCUS technologies. In consequence, fossil fuel–based production is reduced substantially, and hence the growth in ammonia production is immediately decoupled from natural gas demand, resulting in a 90% decline in gas consumption until 2050.
- In both net-zero scenarios, methane pyrolysis has limited impact on natural gas demand as this technology only comes online by 2030 and its uptake is limited.

[I] Estimates for the global supply of sustainable biomass vary widely. For the purpose of this study, a range of 50–110 EJ is taken from ETC analysis. See Energy Transitions Commission, *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible*, July 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf.**

2.2.8 A new ammonia value chain

The new net-zero system model will reshape ammonia value chains, the location of global production infrastructure, and trade patterns.

The landscape of ammonia production will drastically change as new capacity, predominantly made up of green ammonia, shifts from demand centres to regions with abundant low-cost renewable power, increasing the importance of trade. Currently, the majority of ammonia production is located in demand centres and in regions with access to cheap fossil fuels, such as China, North America, and Russia. However, with a growing demand for low-carbon ammonia from energy applications, and the corresponding uptake of electrolysis-based production, a large share of greenfield production capacity will most likely be concentrated in regions with favourable renewable resources such as Australia, Latin America, the Middle East, and North Africa, while blue ammonia production is likely to remain in existing demand centres. As a result, new trade patterns are likely to emerge with global trade increasing 13- to 20-fold by 2050 relative to today. However, as seen from recent events in Europe, with this level of trade and energy dependence, national security risks must be considered and managed in order to enable this new system model.

Supporting infrastructure must be scaled up to enable the formation of new value chains and trade patterns. To enable the increase in long-distance interregional traded volumes by 2050, the existing infrastructure would need to be retooled as only a small proportion of ammonia production is transported as liquid ammonia, the majority being processed and traded as prilled or granular fertilisers such as urea or ammonium nitrate. This calls for large-scale investment from ammonia producers, consumers, and industry associations in the required transport vessels, storage containers, and distribution networks. Forming ammonia production hubs in the new production locations also enables the development of shared supporting infrastructure. Given the lead times on developing this infrastructure, decisive action must be taken this decade to enable the formation of these value chains and to set up ammonia for success as a near-zero-emissions energy carrier.

As the scale of global ammonia trade increases and new players enter the ammonia space, careful attention must be paid to safety risks given the toxicity of ammonia. Transporting ammonia carries safety risks that must be carefully managed, particularly in the transport, storage, and use of ammonia in densely populated urban areas. Governments, ports, and the chemical, shipping, and agricultural industries all have ample experience in safely storing, handling, and transporting ammonia across the globe. Therefore, existing players that hold much of this expertise will be essential to this transition and the scaling-up of global trade in a safe manner. On the other hand, new players from the energy sectors lack experience in handling toxic chemicals but have significant experience in developing and managing global value chains. Existing and new players are therefore complementary, and thus both are required to form new value chains, develop the appropriate infrastructure, and manage the safety risks of handling ammonia appropriately.

CONCLUSION: HIGH-LEVEL ACTIONS TO DECARBONISE THE AMMONIA SECTOR

The 2020s have been labelled the Decisive Decade for the climate. In 2021, with the adoption of the Glasgow Climate Pact, nations recognised that “limiting global warming to 1.5°C requires rapid, deep, and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 per cent by 2030 relative to the 2010 level”.[102] This will require accelerated and coordinated action this decade on the basis of the best available scientific knowledge.

This decade is likewise a critical window for the ammonia industry as decisions taken in the next few years will determine the landscape of future production, its ability to meet future low-carbon energy demands, and ultimately its long-term success in meeting net zero by 2050. Given the scale of transformation called for in the net-zero scenarios as well as the levels of investment required, the next decade requires strong and coordinated action from all actors in order to deliver the rapid and sustained emissions reductions required to meet our climate targets.

3.1 Priority supply-side actions this decade to unlock long-term progress

The key supply side milestones until 2025 and 2030 are summarised in Exhibit 3.1.

Until 2030, the commercialisation of green ammonia production is the critical supply-side milestone to meet the rapidly rising demand for zero-emissions ammonia from energy applications and kick off the industry's transition to net zero by 2050. Green ammonia production volumes need to increase by up to a factor of five compared with the current project pipeline until 2030 of ~22 Mt/year. Given the lead times of more than five years for projects, investment decisions for these projects must be taken now.

From 2025, all new-build fossil fuel–based production should be fitted with CO_2 capture and, by 2030, a fifth of existing ammonia production plants should be retrofitted with transitional technologies or CCUS. Older, inefficient assets should be decommissioned and replaced with either green ammonia production or, to a lesser extent and only where local conditions are favourable, blue ammonia production, while younger plants with BAT should be retrofitted with transitional technologies or CCUS to avoid the stranding of these assets, particularly in regions with a scarcity of renewable resources.

Up to 2030, an average of \$25 billion–\$52 billion of annual investments in near-zero-emissions ammonia production plants is necessary. Of these investments, around 13%–16% is required in transitional technologies, up to 10% in blue ammonia production, and the vast majority, 75%–85%, in electrolysis-based production. A further \$10 billion–\$20 billion of annual investment is also required in the wider energy-system infrastructure, particularly to expand renewable power generation, to develop geological storage sites for CO_2 and hydrogen, as well as to scale electrolyser manufacturing capacity and downstream users of ammonia as an energy carrier. Although demand for green and blue ammonia accelerates only after 2030, policymakers need to anticipate this by setting ambitious targets for renewables, CO_2 storage, and electrolyser manufacturing capacity now to meet demand in the 2030s and 2040s.

EXHIBIT 3.1

Supply-side milestones until 2025 and 2030 to unlock the transition to a net-zero ammonia industry

	Key milestones until 2025	Key milestones until 2030
LOW-CARBON AMMONIA PRODUCTION RAMP-UP	10–30 Mt of ammonia production via transitional technologies ~15 SMR plants retrofitted with partial CO_2 capture, and up to 20 fitted with a small electrolyser to produce 10% of the hydrogen feed Around \$4 billion–\$12 billion of annual investments in transitional technologies	30–100 Mt of green ammonia production (40–140 plants) 10–20 Mt of blue ammonia production (15–25 plants) \$25 billion–\$52 billion of annual investments in near-zero-emissions ammonia production
WIDER ENERGY-SYSTEM INFRASTRUCTURE	Around 12 Mt of CO_2 storage required annually	70–210 GW of electrolyser capacity 300–1,100 TWh of renewable electricity demand annually 40–50 Mt of CO_2 captured and stored annually
TECHNOLOGY READINESS LEVEL	Green ammonia production reaches commercial scale Blue ammonia production comes online	Lower TRL technologies such as biomass-based routes and methane pyrolysis reach commercial scale

Source: MPP analysis

3.2 Policy, industry, and finance action to achieve 2030 milestones

Policymakers, industry leaders, and financial institutions can drive the change towards a sustainable future by enabling the transition to a net-zero-emissions ammonia economy. Doing so requires close and immediate collaboration to trigger the transformation of the conventional ammonia value chain by addressing three main barriers:

1. **The absence of a regulatory regime** to permit the safe use of ammonia as an energy carrier
2. A **lack of demand** due to uncompetitive prices resulting from higher production costs of zero-emissions ammonia and the absence of markets for new applications in energy systems
3. The missing capacity to meet the expanding new ammonia economy with **sufficient supply**

The following analysis details the policy, investment, and industry actions required to overcome these challenges and enable a competitive market for ammonia.

3.2.1 Key policy actions in this decade

A bold, long-term, and consistent policy framework is necessary to transform the ammonia value chain to reach net zero by 2050. Both demand and supply measures, together with enabling regulation, are needed to approve the use of ammonia for new applications.

- Enabling regulation is a priority in the short term (2022–25) to remove barriers to adoption of ammonia in energy systems. This regulation should create standards and protocols for appropriate handling in relation to health and safety, public security, distribution, and environmental protection. Certification is also necessary to distinguish ammonia by source of production and carbon intensity, facilitating its adoption in both new and conventional applications.
- Policies must **stimulate demand** for conventional and new applications. **Direct regulatory mechanisms** prescribe action among sector stakeholders, initially with the development of clean energy roadmaps in the short term (up to 2025), incorporating ammonia as a core component. These are followed (2025–30) by mandates and quotas instructing uptakes of near-zero-emissions ammonia or specific conditions aimed at levelling the playing field (for example, performance indicators, standards, and preferential market conditions). As the supply of near-zero-emissions ammonia ramps up and becomes cost competitive (beyond 2030), moratoriums and bans can be established to phase out conventional fossil fuels. **Market-based mechanisms (MBMs)** must be used to incorporate environmental costs into market dynamics. Due to higher complexities in their implementation, conditions for these mechanisms should be set over the second half of this decade (2025–30), although their full operation will most likely be seen throughout the next decade. **Voluntary initiatives and information programmes** can be implemented in parallel to drive sectorwide collaboration.
- Policies to secure **a sufficient supply** should immediately be put in place and scaled to mobilise resources in the form of loans, grants, and tax credits to build production assets, infrastructure, and manufacturing capacity. Policy support should be targeted to increase ammonia production capacity, as well as to expand the availability of critical resources and sustainable feedstocks. Funding for R&D is also required to accelerate the commercialisation and cost competitiveness of related technologies.

Exhibit 3.2 describes the tailored and robust policy framework necessary to support the market entry of near-zero to zero-emissions ammonia.

EXHIBIT 3.2

Portfolio of policy instruments to unlock a net-zero-emissions ammonia economy

🟨 Initiate 2022–25 🟥 Initiate 2025–30 🟩 Initiate after 2030

			A SHIPPING	B POWER GENERATION	C OTHER ENERGY CARRIER	D FERTILISER
ENABLER	**Enabling regulation**	**Certification, standards and protocols**	🟨 Certification as maritime fuel and handling regulation 🟨 Bunkering standards and protocols	🟨 Approval and safety standards for ammonia co-firing for power generation	🟨 Technical and safety standards for ammonia as energy carrier	
DEMAND	**Direct regulation**	**Roadmaps**	🟨 International maritime decarbonisation roadmap with net-zero target	🟨 Power sector decarbonisation roadmaps	🟨 Include ammonia as carrier in hydrogen roadmaps	🟨 Formal commitments to ambitious reductions on GHG and environmental impacts from agriculture sectors
		Mandates and quotas	🟨 Increase stringency of performance standards (EEDI, EEXI/CII) 🟩 Ammonia fuel mandates	🟥 Targets on power generation from ammonia co-firing		🟨 Mandates to uptake near-zero emissions ammonia as source for fertilisers 🟨 Performance standards to drive optimization
		Moratoriums and bans	🟩 Bans on new heavy fuel oil ships	🟥 Phase-out rules for conventional fossil fuels in power generation	🟩 Bans on fossil fuels for industrial applications	🟩 Bans and phase-out rules for emission-intensive fertiliser production
	Market-based mechanisms	**Carbon pricing and ETS**	🟥 ETSs and carbon pricing schemes Up to \$50–\$100/t CO_2 by 2030 and \$191-\$400/t CO_2 by 2050 for full decarbonisation[1]	🟥 Up to \$120/t CO_2 with 60% co-firing share in 2050 (Japan context)	🟥 Carbon price dependent on end-use application (ranging between \$50–\$145/t CO_2)	🟥 Emissions allowances below a benchmark in a cap-and-trade system and border adjustment tariffs 🟩 International carbon markets
		Pricing and competitive mechanisms	🟥 CfDs and price subsidies	🟥 Feed-in tariffs & premiums; guaranteed access to grid and priority dispatch	🟥 CfDs in cases in which hydrogen has higher competitiveness	🟥 CfDs for fertiliser production 🟨 Extension services, subsidies, and incentives to promote efficiencies in fertiliser use
	Voluntary mechanisms and information programmes	**Reporting, transparency, and education**	🟨 Information programs and performance data disclosure 🟨 Implementation of zero-emissions corridors	🟨 Information and awareness programmes to drive power purchase decisions by consumers, communities, and corporations	🟨 Information and awareness programmes to drive power purchase decisions by corporations	🟨 Training and evaluation programmes on fertiliser application efficiency 🟨 Certification schemes for sustainable food production
	Direct and indirect investments	**Funds, loans, grants, and tax breaks**	🟨 Investments in bunkering infrastructure	🟨 Investments on co-firing technologies installation and expansion	🟨 Investments on R&D targeting efficiencies in ammonia cracking process	🟥 Investments in R&D to reduce Scope 3 emissions
E SUPPLY			🟨 Expansion of tax breaks and credits frameworks 🟨 Loans, grants, and funds to spur ammonia & hydrogen infrastructure and production, together with manufacturing of associated technologies 🟨 Fund safe and secure CCUS infrastructure and retrofitting infrastructure 🟨 Mobilise funding for R&D on manufacturing process improvements (ammonia crackers and electrolyzer performance)			

[1] Even more recent studies envision carbon prices up to \$650/t CO_2 by 2050. UMAS, *International Maritime Decarbonisation Transitions* (forthcoming), accessed April 2022, subject to change.

Source: IEA; UMAS; DNV-GL; IRENA[103]

Based on the policy framework described, the most relevant policy milestones to be reached are detailed by sector:

A. **Shipping: The shipping sector targets the approval of ammonia as a maritime fuel and sets a regulatory framework to accelerate uptake. The IMO plays a key role to advance the needed policies to accelerate shipping decarbonisation.** This will require an expanded mandate and capacity to reach broad consensus and trigger uniform action.

   The critical milestones for the IMO include:

   - **Before 2025, approve the use of ammonia as shipping fuel and establish safety and handling regulations.** Because of its toxicity, there are concerns with ammonia's use aboard vessels. This will hamper uptake until procedures for refuelling and storage are in place.
   - **Launch a comprehensive and ambitious decarbonisation roadmap.** IMO should deepen its current ambition of 50% emissions reduction by 2050 by adopting a net-zero target by 2050 and an ambitious 2030 milestone.[104] Mandating the shared recommendation by the First Movers Coalition, Getting to Zero Coalition, and UN Climate Champions of at least 5% of shipping to be powered by zero-emissions fuels by 2030 could unlock sufficient demand within the Lowest Cost (LC) scenario;[105] however, a 10%–15% target would be required to enable the demand ramp-up in the Fastest Abatement (FA) scenario.
   - **Enforcement mechanisms on technical efficiency standards**; for example, EEDI and EEXI/CII should be implemented and boosted towards a net-zero target.
   - **By 2030,** as ammonia supply and the new fleet of ammonia-powered vessels begin to scale, **MBMs must start taking effect to reduce price differences** caused by the gap in production cost between near-zero-emissions ammonia and fossil fuel alternatives. Policy instruments include CfDs, price subsidies, and/or carbon pricing schemes. As domestic and regional ETS are put in place (for example, incorporation of shipping sector to the EU ETS from 2023[106]), these efforts could be used to pilot an expansion towards an international carbon price for international shipping. Estimations state that to reach full decarbonisation of the shipping industry, a carbon price should reach \$50–\$100/t CO_2 by 2030 and up to \$191–\$400/t CO_2 by 2050.[107] Even more recent studies envision carbon prices up to \$650/t CO_2 by 2050.[108]
   - **Beyond 2030,** policy instruments should expand to include a gradual phase-out of bunkers using fossil fuel and new fossil fuel–powered ships – similar to bans in the automotive sector on new sales of internal combustion engines, which are expected to come into force in the 2030s and early 2040s.

Additionally, immediate collaboration amongst all sector stakeholders to establish Green Corridors in the short term (as has been announced for LA-Shanghai, Antwerp-Montreal, and Australia-East Asia), will play an important role to drive voluntary action within the sector and ramp up demand.[109]

MOL Group photo

B. **Power generation: Policies for the use of ammonia in power generation in renewable resource-constrained markets follow a twofold approach: drive demand by demonstrating and expanding the potential of ammonia in energy systems, while setting the rules to phase out highly emitting alternatives.**

Policies to demonstrate and expand the use of ammonia for power generation include:

- **Towards 2025, approve ammonia for new applications in power generation,** together with operational health and safety regulation.
- **Define roadmaps committing to long-term incorporation** of near-zero-emissions ammonia into energy systems (for example, Japan recently launched its Roadmap for Ammonia in Power Generation, estimating annual consumption of 30 Mt of ammonia by 2050[110]).
- **Mobilise resources for flagship projects** in the form of grants, loans, and tax breaks to demonstrate ammonia's potential for power generation at scale, with a focus on improving co-firing process conditions and efficiencies.
- **By 2030,** as integration into large-scale power generation systems is scaled, **set targets on percentages of power generated from low-carbon sources,** including ammonia. Feed-in tariffs (FITs) from ammonia-generated power would provide further support for growth.

As ammonia establishes a relevant and competitive role in future energy systems, policies to phase out high-emitting alternatives should be established:

- Draft and implement **phase-out rules for emissions-intensive energy feedstocks** (coal for Japan's power generation system).
- To consolidate a level playing field, implement a **carbon penalty system** to position ammonia as a cost-competitive alternative to coal within Japan's power generation context, which should reach $120/t CO2e by 2050 considering 60% co-firing share.[111]

Lastly, **voluntary instruments and information programmes could catalyse demand** by creating awareness from community or corporate power buyers on the benefits of low-carbon energy.

C. **Hydrogen carrier: Policies for the use of ammonia as a hydrogen carrier should be incorporated to broader policy frameworks aiming to grow momentum for the hydrogen industry.**

For the case of ammonia as a hydrogen carrier, policies should be directed to increasing the role of hydrogen in energy systems. Policies targeting this objective include:

- **By 2025,** recognition of the potential role of ammonia for this application and **incorporation into hydrogen strategies and roadmaps.**
- Mobilise resources for **R&D to deliver technology advancements that enable long-term competitiveness** of ammonia as a hydrogen vector for long-distance transport, such as for ammonia cracking.
- **By 2030, economic instruments including CfDs** will be necessary to create incentives to displace fossil fuels with hydrogen in certain applications (such as CfDs included in the German government's plan to help the industry transition to low-carbon technologies[112]).
- **Carbon pricing will depend on the end-use application of hydrogen,** ranging from \$50 to \$60/t CO_2 for most competitive applications like cement or steel, and up to \$139–\$145/t CO_2 for applications like methanol in 2050.[113] Adequate pricing should be carefully determined as it will vary according to sectoral and regional contexts.
- **Voluntary instruments and information programmes could drive demand** by creating awareness from corporate power buyers on the benefits of integration of hydrogen as feedstock into their industrial processes.

D. **Current applications: Policies seek to mandate uptake for near-zero-emissions ammonia in nitrogen-based fertilisers, while modifying existing policy frameworks seeking to optimise the use of fertilisers.**

Policies to accelerate the uptake of near-zero-emissions ammonia as a source of production for fertilisers include:

- **Towards 2025,** demand for near-zero-emissions ammonia can be initially triggered by the fertiliser sector through the introduction of **mandates prescribing stable and increasing content requirements.** For example, India's draft hydrogen strategy requires 5% minimum green ammonia production for the domestic fertiliser sector by 2023–24 and 20% by 2027–28.[114] Mandates can also be extended to the inclusion of additives and performance enhancers (such as nitrogen inhibitor coatings) to further improve NUE.

- **By 2030, MBMs can increase the competitiveness of these type of fertilisers,** which could also include the use of CfDs to subsidise differences in price. Carbon pricing for this sector should be implemented through extensive international collaboration, to prevent incentivisation of production in markets with the lowest environmental ambitions. Preliminary policies to set the path in that direction include the establishment of free allowances for emissions below a benchmark in a cap-and-trade system or the adoption of carbon border tariffs and efforts by the G-7 to establish a carbon club to ensure a level playing field.[115]

- **Beyond 2030,** as supply of competitive near-zero-emissions ammonia fertiliser increases, **bans and phase-out rules** can be established to force out emissions-intensive fertiliser production.

Policies to drive optimisation of fertiliser use should focus on **improvements in nutrient management practices**. Some of these policies are already implemented in many countries, with the objective to reduce nitrogen pollution.[116] They should be expanded over the course of the decade, to regions with higher agricultural yields and over usage of nitrogen.

Some of the recommended policy instruments include:

- **Rollout of nutrient management best practices through extension services**

- **Subsidies** to overcome initial transition costs (such as developing a nitrogen management plan or buying appropriate equipment) or where the best practices create ongoing net costs

- **Incentives for the** increased use of enhanced-efficiency fertilisers

- **Reduction and gradual removal of nitrogen fertiliser subsidies in key jurisdictions** like China and India

Voluntary instruments can further contribute to achieving these objectives. Such mechanisms include training and evaluation programmes for farmers, agriculture retailers, and crop advisers on fertiliser application efficiency, paired with certification schemes focused on sustainable food production (for example, the Farm Sustainability Assessment of the Sustainable Agriculture Initiative Platform and the GLOBALG.A.P. certification for good agricultural practices). **Information programmes** also enable data sharing on environmental footprint-setting benchmarks and references for action.

As mentioned in Part 1, even with the application of efficiency and circularity levers in the FA scenario, large volumes of downstream Scope 3 emissions remain unabated. This means that in addition to policy efforts targeting emissions reductions, action will also be required to enable CDR of these remaining hard-to-abate residual emissions. A portfolio of policy mechanisms including previously listed instruments, such as incentives, resource mobilisation, and carbon pricing schemes, must be targeted towards expanding technically feasible CDR solutions. These include the use of NCS, such as the restoration of forests and other ecosystems that can sequester carbon, as well as the expansion of engineered approaches such as DACCS to remove carbon dioxide from the atmosphere and store it in geographical reservoirs or in other long-lasting forms. Hybrid approaches should also be explored and incentivized, such as the development of BECCS.

E. **Cross-sector supply-side actions: Supply-side policy actions will be needed to accelerate the scale-up of infrastructure to provide sufficient supply for growing demand.**

   A series of policy instruments should be **immediately** adopted to increase hydrogen and CCUS productive capacities and be maintained over the course of this transition. These policies include:

   - **Incentives in the forms of grants, investments, loans, and expansion to tax credit frameworks** (for example, enhancements and extensions of the latest 45Q, 45X and 45V tax credits for green hydrogen production and CCUS from the United States[117]) should be put in place immediately to de-risk the capital expenditures required for a substantial scale-up of electrolyser capacities and hydrogen pipelines and storage. These policy interventions can enable increased use of available resources for manufacturing and installation of renewables and electrolysers, as well as development of geological H_2 storage sites.

   - The **same type of instruments should also target the transition of existing fossil fuel–based assets** through the installation of CCUS retrofits, while streamlining the processes for any necessary government approvals or permits, particularly for developing CO_2 storage sites, which has been a key bottleneck. Policies will need to mobilise the resources required for developing infrastructure to transport and store CO_2, targeting, when possible, the formation of industrial hubs with proximity to geological CO_2 storage sites or usage opportunities. A clear regulatory framework on the operation of CCUS should also be developed.

   - **Resources should also be mobilised towards R&D,** pilot and demonstration projects, and other initiatives intended to improve performance and cost competitiveness with focus on electrolyser performance.

3.2.2 Key industry actions in this decade

Faced with the right incentives, and supported in its early stage, industry would be in a position to increase ammonia supply and **scale priority technologies and infrastructure.** Markets for the rapidly expanding new applications of ammonia represent an enormous growth opportunity across the value chain.

Key actions to be taken by industry include:

- **Investments should be put in place by energy and feedstock providers to deliver necessary inputs.** Upstream oil and gas companies must invest to reduce fugitive emissions in their natural gas operations (for example, the Commitment from Oil & Gas Climate Initiative to reduce methane emissions by 2030[118]). Renewable energy providers should allocate investments to supply 300–1,100 TWh of renewable power capacity by 2030, and electrolyser manufacturers should direct investment towards scaling up manufacturing capacity to meet the 70–210 GW of installed electrolyser capacity in the ammonia sector by 2030.

Faced with the right incentives, and supported in its early stage, industry would be in a position to increase ammonia supply and scale priority technologies and infrastructure. Markets for the rapidly expanding new applications of ammonia represent an enormous growth opportunity across the value chain.

- **Ammonia producers should concentrate investments on increasing production capacity.** R&D efforts need to shift from the development of new production technologies to testing the performance of technologies in combination, at scale, and under relevant conditions (for example, improving the performance and reducing the cost of electrolysis).

- **Investments must be put in place to grow ammonia distribution and storage infrastructure** to support up to a threefold increase in traded volumes by 2030.

- **Stakeholders need to work in collaboration to bring down residual emissions across the supply chain** through actions that include the improvement of CO_2 capture rates, the sending of clear signals for purchase of CDR to spur investment in DAC needed to remove residual emissions, and investments in nitrogen inhibitors to reduce N_2O emissions from fertiliser in use.

Off-takers can accelerate a ramp-up in demand by committing right away to the utilisation of near-zero to zero-emissions ammonia and making necessary capital expenditure investments to enable its uptake.

Shipping sector off-takers should enter into multiyear offtake agreements for green ammonia to provide market signals and de-risk green ammonia production. Collaboration will also be necessary with customers and stakeholders to begin with first-mover commercial-scale projects such as green shipping corridors.[119] Additionally, shipping players can explore the implementation of a book-and-claim system for shipping that allows for increased flexibility in the use of ammonia as a shipping fuel.

Other users of ammonia as an energy carrier should allocate capital expenditure investments to enable the use of ammonia as a long-term energy source, including ammonia and hydrogen storage tanks and co-firing technology in thermal power plants.

Fertiliser producers should set ambitious emissions reduction targets for 2030 (for instance, Yara, Nutrien, and CF Industries have set targets to reduce emissions by 25%–30% by 2030). Industry should work towards product certification and labelling to identify fertilisers produced from low-emissions sources, driving transparency of carbon accounting for buyers across the value chain (such as food processors, retailers, and final consumers). Other measures include the establishment of long-term purchase agreements by distributors and farmers, as well as the exploration of a book-and-claim system[li] for this sector.[120]

Industry associations will also play a valuable role in driving down emissions from members. These organisations can provide comparative metrics and tools, as well as facilitate and accelerate knowledge exchange.

3.2.3 Key finance actions in this decade

Financial institutions can accelerate the transition to near-zero-emissions ammonia by directing capital to deploy and scale new technologies throughout this decade. Banks and financial institutions must contribute with urgent and unprecedented capital mobilisation to achieve the annual investment levels of $25 billion–$52 billion required between 2022 and 2030 to decarbonise the sector. **The key individual actions for financial institutions over the next decade include:**

- **Establishing climate-aligned investment principles for near-zero-emissions ammonia production (Exhibit 3.3):** Investment principles are necessary to clearly and appropriately identify ammonia-related infrastructure assets, companies, and financial institutions that contribute to decarbonisation of the sector. This will allow for a faster channelling of the required capital flows.
- **Establishing public–private partnerships to accelerate and de-risk investments in new near-zero-emissions ammonia production plants,** especially in regions with access to low-cost renewable energy (such as Latin America, North Africa, and the Middle East[lii]).
    - **Public–private partnerships at the scale of the necessary investments are starting to appear.** However, they must be multiplied across geographies to meet the required demand for investments. Three relevant examples are the US government's Infrastructure Investment and Jobs Act, which has allocated $8 billion for hydrogen hubs; the US Department of Energy's Hydrogen Shot $1/KG by 2030; and the Japanese government's funding for critical ammonia energy projects with a budget of $500 million by 2030. This early investment of public funds, which could be done efficiently through development banks such as EIB in Europe, would lead to faster deployment of the technologies and hence a faster decline in their cost. This could create competitive advantages to countries and regions that act fast and position themselves ahead of the curve.
    - **The sector must receive additional investments from programmes seeking to establish public–private partnerships.** Examples of these investments include the High Impact Programme for the Corporate Sector from The Green Climate Fund, the Clean Technology Fund, the Global Environment Facility, and the European Fund for Sustainable Development. These funds, which currently range in value from $1.5 billion to $5 billion with diverse replenishment time frames, apply to a broad and competing set of decarbonisation and sustainability projects. Project developers and investors in near-zero-emissions ammonia should seek to access these funds and use them to unlock more private capital to meet the annual $25 billion–$52 billion of investments required between 2022 and 2030. New funding mechanisms will be required leading up to 2030 and beyond as annual value chain investments across every hard-to-abate sector will grow significantly.

[li] Chain of custody mechanisms, also known as "certificate trading" or "credit trading", allow for sustainability targets and claims to be decoupled from certified products and materials. Sustainability certificates are issued at the beginning of the supply and can be bought by market participants, usually via a certificate-trading platform, intended to reward responsible production where the physical supply chains make sourcing the actual product difficult.

[lii] This list is not exhaustive.

EXHIBIT 3.3

Essential elements of climate-aligned investment principles

Climate-aligned investment principles for near-zero to zero-emissions ammonia should:

Establish a deadline to end investments in the sector that are not climate aligned: By 2030, banks, institututional investors, and public sector banks commit that 100% of their investments into infrastructure and companies comply with 1.5°C targets

Mandate beneficiaries of climate-aligned finance to disclose performance indicators and progress towards decarbonisation targets

Encourage engagement of investors to:

- Develop best practices of new financing instruments tailormade to make near-zero to zero-emissions ammonia production plants investable (e.g., green bonds)
- Standardise due diligence and analytics process to assess and de-risk projects for financial institutions

Establish specific investment criteria:

- Build upon current criteria (EU Green Taxonomy and Japan criteria as examples)
- **Exclusion criteria:** Ammonia is produced from hydrogen that complies with greenhouse gas emissions 60%–73% lower than unabated fossil fuels
- **Exclusion criteria:** Emissions are within or lower than the emission levels associated with the best available techniques ranges published in Best Available Techniques Reference (BREF)
- Explore inclusion of transitional criteria for blue ammonia (currently not included)

Source: MPP analysis; European ICC Bureau, Best Available Techniques Reference Documents, **https://eippcb.jrc.ec.europa.eu/reference/**

The financial models to mobilise the necessary capital to projects and companies that deliver the ammonia economy transition will need to be tailored in alignment with sectoral and regional contexts. Some considerations in the development of financing strategies should include:

- **The capital providers.** The balance of investment from public and private sources will vary according to the relative importance of different industrial sectors to a given nation. National governments will be more likely to allocate public funding according to national interests (for example, power generation and food production with higher investment priority than shipping). Capital that is more dependent on private investments could require additional efforts to mobilise as it is dependent on a larger set of factors, such as appropriate regulatory frameworks, infrastructure planning, standardised and scalable contractual frameworks, appropriate market design, and fiscal incentives.[121]

- **The capital requirements.** Financing strategies must be designed for the full value chain. Although the biggest need for investment will be upstream in energy and near-zero-emissions ammonia production, capital requirements can vary according to specific downstream conditions per sector. This is the case of the shipping sector, which will require investments in ammonia-powered vessels including engines, on-board storage, and ship-based energy efficiency technologies.[122] The applications of ammonia in power generation and as an energy vector will also require significant amounts of capital to be directed to the development of enabling infrastructure (such as network infrastructure for storage and distribution).

- **The risk profiles and mitigating mechanisms.** Capital project risks vary according to the sectoral business models (business cycles, sources of revenue, cash flows, etc). This affects the necessary de-risking mechanisms. One such example is the type of offtake agreements needed per sector: PPAs for power generation in which the government acts as off-taker to buy electricity and long-term contracts for shipping in which buying commitments are made for longer periods at prevailing market rates.

THE WAY FORWARD

The ammonia sector has a highly ambitious but also viable pathway to decarbonise by 2050, remaining within a 1.5°C-aligned carbon budget while forging a new role as a key energy feedstock in the net-zero economy. There is increasing momentum behind this pathway, due to the volatility brought on by the recent European gas crisis. However, there remains a large gap to close between our current trajectory and what is required to achieve net zero. Now, the onus is on policymakers and industry decision makers to accelerate this transition.

The global scenarios presented in this report need to be broken down by region and tailored to ammonia's role in fertiliser applications, in industry, and as an energy carrier, particularly in the maritime industry. Transition strategies that are tailor-made to sectoral and national policies need to be drafted and brought to action.

Long-term, consistent, and ambitious national energy strategies, with clear demand signals and ample financing for new projects, are some of the many solutions to ensure an economically, ecologically, and socially viable, just, and successful transition to climate neutrality by 2050. MPP can play a role through its convening power across the whole ammonia value chain, including policymakers and financial institutions. Building upon the 2030 milestones in the last section of this report, MPP will connect the dots among industry, policy, and finance via workshops, quantitative analyses, and other formats.

The first-mover risk needs to be transformed into a first-mover advantage so that success stories can empower hesitant actors to follow pioneers. Critical ingredients of a successful take-off will be de-risking investments in large-scale, near-zero-emissions technologies creating real-world proof points that production costs can be reduced rapidly in only a few years. Subsidies and incentives to bridge this cost gap are necessary in the interim. Coordinated action among policy, industry, and financial stakeholders is imperative. By working closely with stakeholders across the value chain, MPP can develop practical resources and toolkits to help organisations operationalise commitments (for example, through ammonia emissions certifications, developing scale-up financing initiatives in priority technologies, and by quantifying the impact of individual policies on reducing the cost of zero-emissions ammonia technologies).

Our Sector Transition Strategy scenarios demonstrate that both cost parity and rapid demand take-up are achievable this decade if a highly ambitious suite of incentives, policy support, and investment are put in place now. If not, the ammonia as well as maritime and power generation sectors risk a continued reliance on fossil fuels and unsustainable rise in emissions. The new ammonia economy will offer new market opportunities. For example, zero-emissions shipping fuel will enable further adoption of shipping as a net-zero-aligned transportation mechanism. By working together across the value chain, the ammonia industry can lead this transition. Already, the sector plays a leading role in feeding a growing global population. The development of mineral nitrogen fertilisers through ammonia synthesis was one of the great technological achievements of the 20th century. The industry has technical resources and vision to create a new role for zero-emissions ammonia in this century. To get there, it needs decisive leadership from governments, companies, and financial institutions, and dedication to delivering a sustainable future for people and planet.

GLOSSARY

AEM	Anionic exchange membrane
AFOLU	Agriculture, forestry, and other land use
ATR	Autothermal reforming
BAU scenario	Business-as-Usual scenario
BCM	Billion cubic metres
BECCS	Bioenergy with carbon capture and storage
CBAM	Carbon border adjustment mechanism
CCS	Carbon capture and storage
CCUS	Carbon capture and utilisation or storage
CDR	Carbon dioxide removal
CfD	Contract for difference
CII	Carbon Intensity Indicator for existing ships
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
EEDI	Energy Efficiency Design Index for new-build ships
EEXI	Energy Efficiency Existing Ship Index
EIB	European Investment Bank
EJ	Exajoule
ETC	Energy Transitions Commission
ETS	Emissions trading scheme
FA scenario	Fastest Abatement scenario
FIT	Feed-in tariff
GHG	Greenhouse gas
GHR	Gas-heated reformer
GJ	Gigajoule
GMF	Global Maritime Forum
Gt	Gigatonne (billion tonnes)
GW	Gigawatt
H_2	Hydrogen
H-B	Haber-Bosch
IEA	International Energy Agency
IEA STEPS	International Energy Agency Stated Policies scenario
IEA NZE	International Energy Agency Net-Zero Emissions scenario
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kg	Kilogramme
kt	Kilotonne
LC scenario	Lowest Cost scenario
LCET	Low-Carbon Emitting Technologies initiative
LCOA	Levelised cost of ammonia
LCOE	Levelised cost of electricity/energy
LCOX	Levelised cost of X product, e.g., levelised cost of ammonia
MBM	Market-based mechanism
MMBtu	Metric million British thermal unit
MPP	Mission Possible Partnership
Mt	Megatonne (million tonnes)
MW	Megawatt
MWh	Megawatt-hours
N_2O	Nitrous oxide
N	Nitrogen
NCS	Natural climate solutions
NH_3	Ammonia
NO_x	Nitrogen oxides
NUE	Nutrient use efficiency
OECM	One Earth Climate Model
PEM	Proton-exchange membrane
PPA	Power purchase agreement
PV	Photovoltaic
RES	Renewable energy systems
SBTi	Science Based Targets initiative
SMR	Steam methane reforming
t	Tonne
TRL	Technology readiness level
TWh	Terawatt-hours
VRE	Variable renewable energy

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The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonise some of the world's highest-emitting industries in the next 10 years.