MAKING NET-ZERO AMMONIA POSSIBLE

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

EXECUTIVE SUMMARY / SEPTEMBER 2022

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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**.

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.

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.**

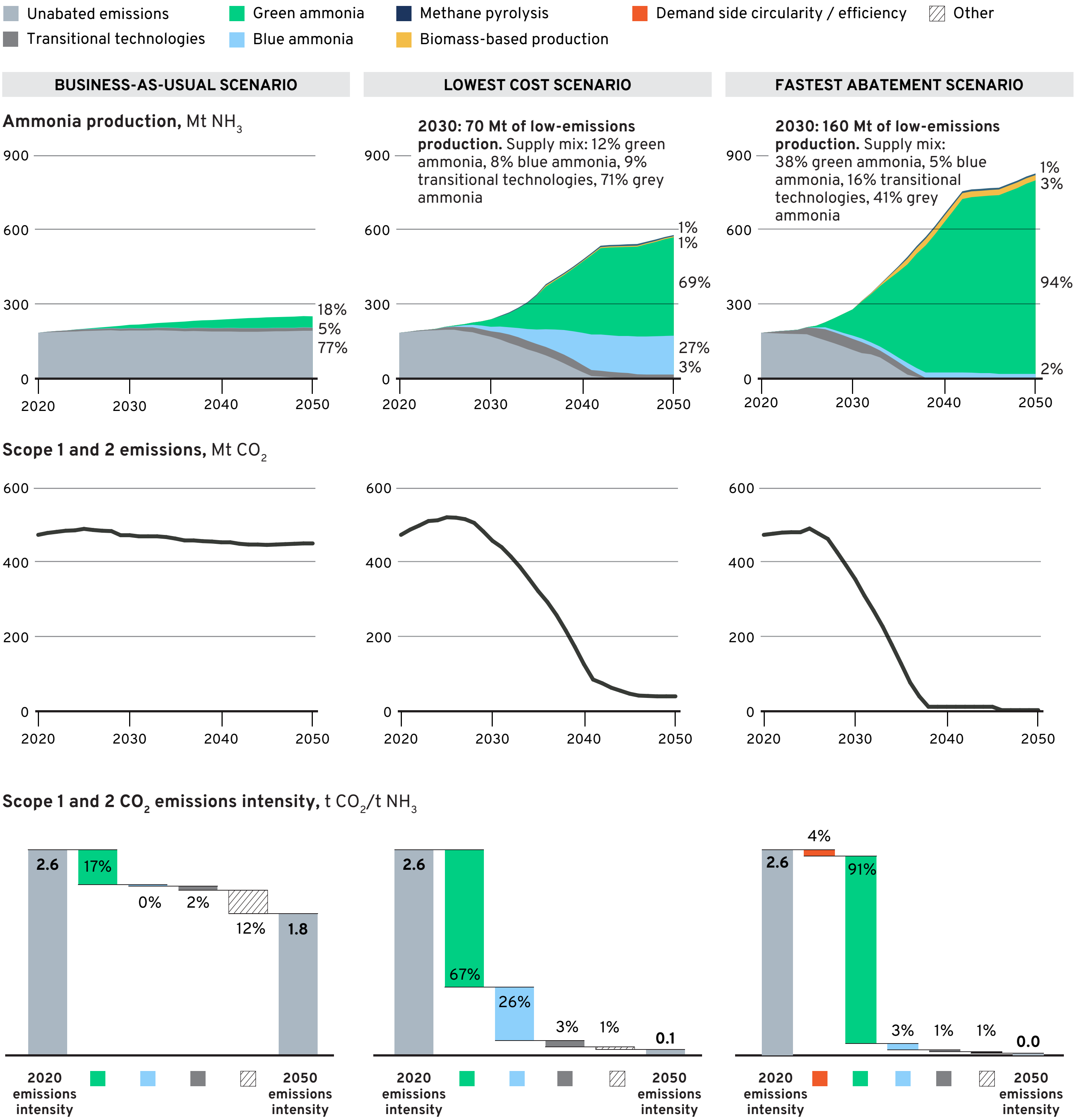
The Business-as-Usual (BAU) scenario, on the other hand, relies on stated polices and the continuation of historical trends which may drive ammonia production emissions down by only 5% between 2020 and 2050.

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



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.

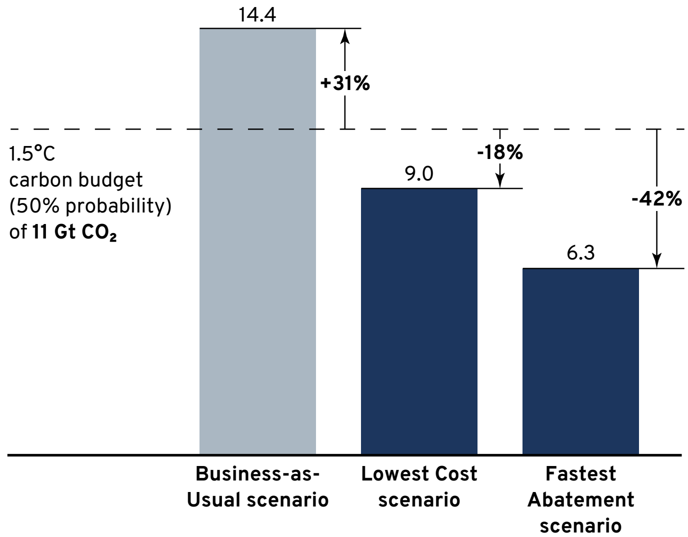
Blue ammonia costs and thus its share of total production by 2050 depend strongly on the **evolution of natural gas prices**. Gas prices in some regions are currently multiple times their long-run average, at over \$30/MMBtu. A persistent environment of high natural gas prices could drive the relative 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*

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.

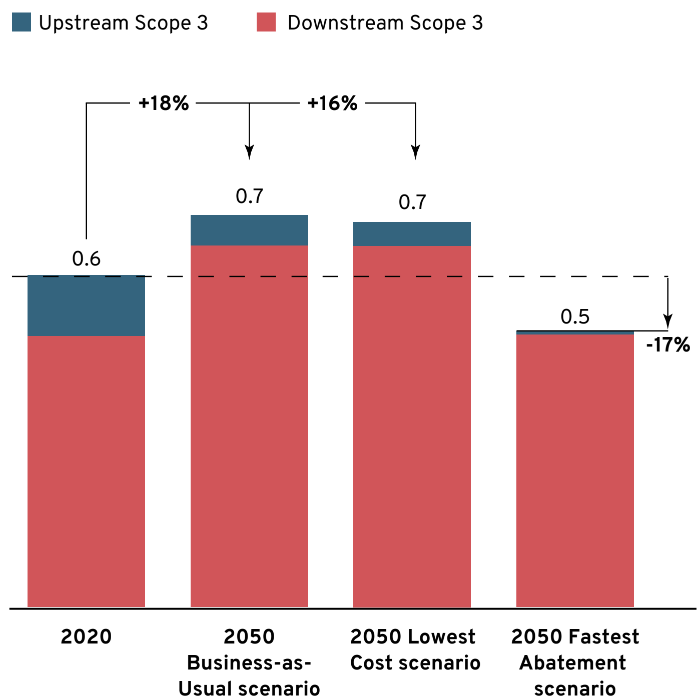
- Continued fossil fuel–based ammonia production routes such as blue ammonia must be accompanied by measures to **reduce fugitive methane emissions and to end routine venting and flaring during coal and gas extraction. This should be done as soon as possible,** through the employment of leak detection, 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[1]

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]

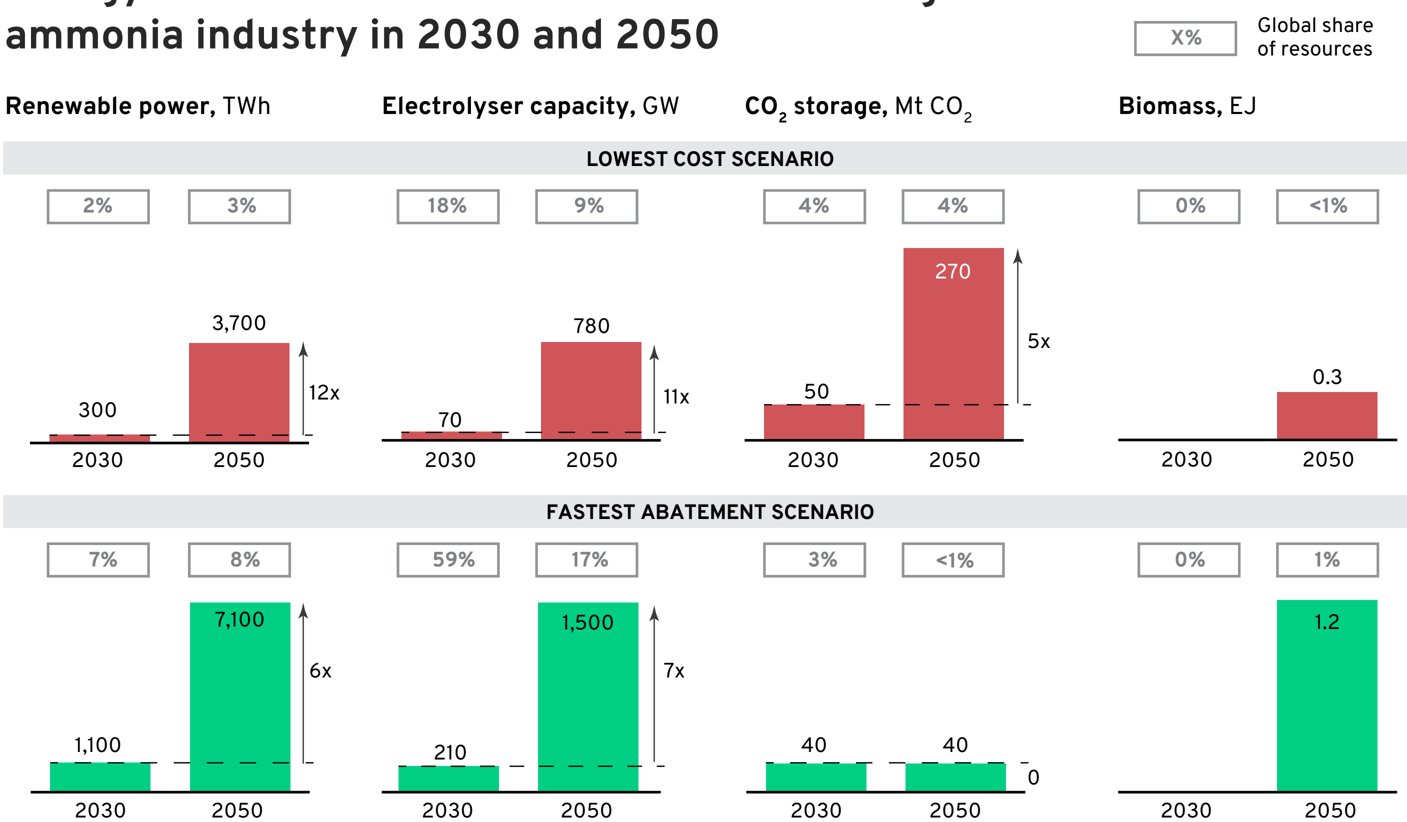
- Blue ammonia production will require 20 billion–140 billion cubic metres (BCM) of natural gas (1%–4% of 2019 global demand for natural gas).

  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[2]

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.

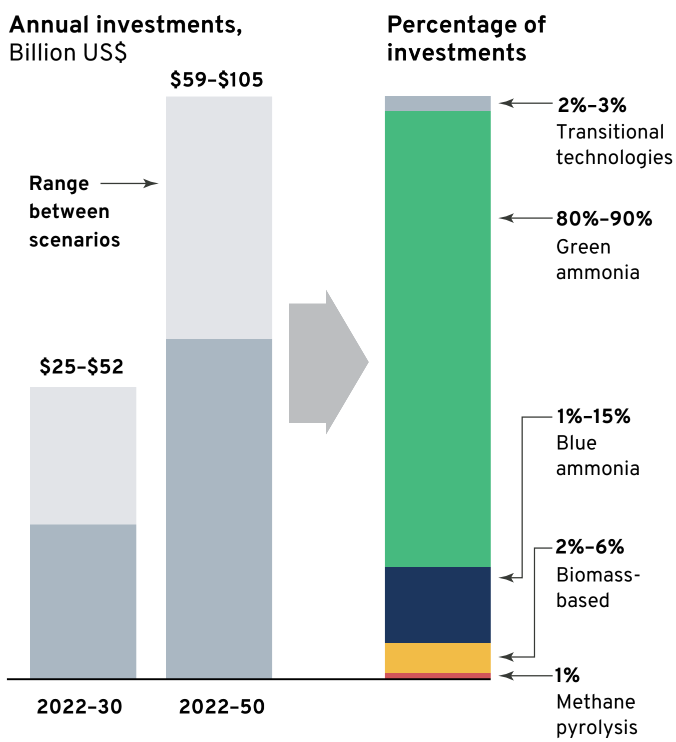
xx Approximately 10% of ammonia is transported today, according to the IEA *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertilizer Production*, 2021, **https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf**.

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
DEMAND	Direct regulation	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
DEMAND	Direct regulation	Moratoriums and bans		🔴 Phase-out rules for conventional fossil fuels		
DEMAND	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
DEMAND	Market-based mechanisms	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
DEMAND	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
DEMAND	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[3]

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.

EXHIBIT ENDNOTES

1 International Energy Agency, *Global Methane Tracker 2022*, February 2022, **https://www.iea.org/reports/global-methane-tracker-2022**; Kristell Hergoualc'h et al., "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*, Intergovernmental Panel on Climate Change, May 2019, **https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch11_Soils_N2O_CO2.pdf**; and International Fertilizer Association, *Reducing Emissions from Fertiliser In-Use* (forthcoming, TBC).

2 Energy Transitions Commission (ETC), *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.**; ETC, *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*, April 2021, **https://www.energy-transitions.org/publications/making-clean-electricity-possible/**; ETC, *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; and ETC, *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, July 2022, **https://www.energy-transitions.org/wp-content/uploads/2022/08/ETC-CCUS-Report-V1.9.pdf**.

3 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**; IEA, *Global Hydrogen Review 2021*, 2021, **https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf**; 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**; 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**; IRENA, *Innovation Outlook: Renewable Ammonia*, 2022, **https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf**; and IRENA, *Renewable Energy Policies in a Time of Transition*, 2018, **https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_IEA_REN21_Policies_2018.pdf**; and DNV-GL, *Maritime Forecast to 2050*, 2020.

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