TECHNICAL APPENDIX

MISSION POSSIBLE PARTNERSHIP

MAKING NET-ZERO, 1.5°C-ALIGNED AMMONIA POSSIBLE

This technical appendix accompanies the Mission Possible Partnership's Ammonia Sector Transition Strategy. It provides background information on:

- The benefits and climate impact of the ammonia industry
- Demand development
- Supply-side decarbonisation technologies
- Methodology for sectoral allocation of 1.5°C carbon budget
- Overview of the model (i.e., a discussion of the model setup and its limitations)
- The cost of inaction

1 The benefits and climate impact of the ammonia industry

Ammonia production is critical to sustaining the global agricultural system and feeding the world's growing population. It is the starting point for all mineral nitrogen-based fertilisers used globally and has enabled the shift towards more intensive farming**,** enabling less land to be used to produce the same tonnage of food. Without it, the vital nutrients in soils could not be replenished at the rates required to feed our global population, leading to much lower agricultural yields. The global market size of ammonia in 2020 was around $67 billion and is projected to growth to over $100 billion by 2028 at a CAGR of 6.4%. [1]

In the transition to net-zero, ammonia is also being looked to as a potential zero-carbon fuel for certain sectors such as shipping, and in some cases, power generation. Therefore, ammonia has the opportunity to play a key role in the decarbonisation of other sectors.

However, whether or not the sector is able to seize this growth opportunity depends on the sector's ability to decarbonise production rapidly and soon. Currently, ammonia is a major contributor to climate change, accounting for ~1% of global CO_2 emissions in 2020. It relies entirely on fossil fuels both for feedstock, to produce hydrogen, and for energy. Given increased momentum around the globe in the battle against climate change, delaying decarbonisation activities could risk the sector's future role in serving energy applications. Therefore, there is growing urgency to act now, scale up near-zero emissions production and set the industry on track to achieving net-zero by mid-century.

2 Demand development

All modelling assumptions on demand are informed by industry expertise across the value chain (from the industry community of the Low Carbon Emitting Technologies Initiative (LCET) and the Mission Possible Partnership as well as recent academic insights and reports from organisations such as the IEA, ETC, IRENA, DNV and UMAS.

The demand evolution of ammonia is a key determinant of the scenario results. For each end-use sector, the demand for ammonia is modelled by region. However, given the large uncertainties in the demand development for ammonia, particularly for new markets such as shipping, power generation and as a hydrogen carrier, as well as in the potential for demand reduction through fertiliser optimisation, a high and low range is modelled for each driver. The low end of the demand range is used in the lowest cost scenario to remain within constraints on e.g. electrolyser manufacturing capacity build-out, while the fastest abatement (FA) scenario uses the middle of the low and high demands. The following sections discuss the modelling approach and various data sources used to inform the demand projection for each sector.

2.1 BAU demand

The BAU demand is driven by growth in existing applications: fertilisers and industrial applications such as explosives for mining and construction, plastics, cleaning products, and textiles. The BAU demand projection was based off the IEA's Stated Policies (STEPS)[2] scenario in which ammonia demand grows 1.1% per year and is driven by the following trends:

- Increasing food, feed, and fibre demand in developing economies as population increases by 0.8% and GDP by 3% per year up to 2050
- Economic development leads to increasing shift away from small-scale farming towards more fertiliser-intensive industrial farming.
- Increasing wealth drives higher consumption of animal products. This requires more crop production per calorie and thus is more fertiliser-intensive overall.
- As economies reach maturity, per-capita demand tends to saturate, and fertiliser demand decouples from economic growth. These economies often pursue higher nutrient use efficiency.
- Non-fertiliser demand growth slows down from an annual rate of 4% per year to 1.3% per year.

Scenarios from other sources also show a ~1% growth in ammonia demand per year. For example, the UN FAO[3] scenario projects a moderate growth in global wealth, a continuation of historical agricultural innovation and yield improvement, and assume food waste and hunger remain unaddressed. This leads to a demand growth of 0.9% per year.

In the BAU scenario, the demand split between different nitrogen-based fertilisers is assumed to remain constant to 2050 with urea making up the largest share of fertiliser demand, accounting for 60% of nitrogen applied to soils via fertiliser. Exhibit 1 shows the BAU demand projection by end-use and end-product.

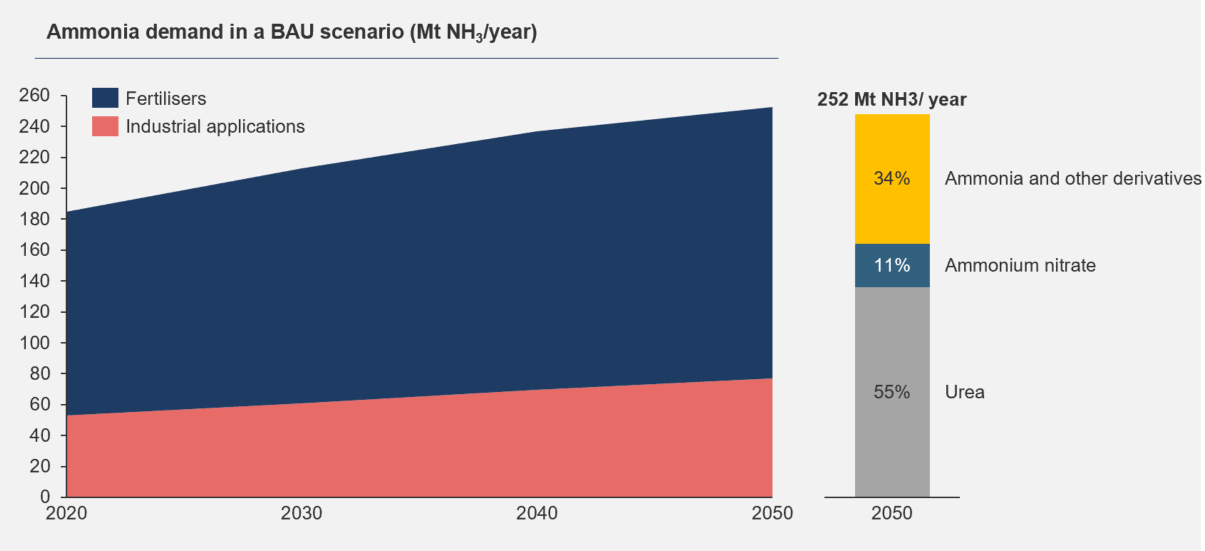


Exhibit 1: BAU demand growth to 2050 by sector and end-product

Source: MPP analysis, IEA[2]

2.2 Shipping

The shipping sector is expected to become the largest driver of near-zero emissions ammonia demand by 2050, accounting for 295 Mt – 670 Mt NH3 demand. The demand projection to 2050 is based on analysis conducted by UMAS[4,5] and DNV-GL[6]. The low end of the range corresponds to the DNV-GL scenario 14 projection and the high end corresponds to the UMAS projection. These estimates sit within the range of projections from other sources as shown in Exhibit 2. The scenarios assumes carbon prices of \$50-100/tCO$_2$ by 2030 increasing up to \$191-400/tCO$_2$ -by 2050. More recent iterations of this UMAS work show possible carbon prices up to \$650/t CO$_2$ by 2050. [5]

The UMAS Scenario A shows models decarbonisation in the international shipping sector by 2050. It models a significant transitional role for LNG starting from 2022 through the early 2040s. Demand for ammonia begins in 2025 and grows significantly through the 2030's reaching ~90% of shipping fuel consumption by 2050.

The DNV-GL scenario 14 forecasts full decarbonisation of the shipping sector by 2050. It assumes a significant uptake of sustainable fuels in the late 2030s and mid-2040s depending on policy, fuel price and seaborne trade demand growth factors. By 2050 Zero emissions ammonia takes up a share of ~55% with the remainder met by 30-35% e-MGO and 10-15% e-LNG. Ammonia is used in new builds and retrofits, while e-MGO is used as a drop in fuel for existing ships. As the annual ramp up from DNV-GL Scenario 14 is not published, the ramp up rate was derived according to an S curve comparable with that of the UMAS scenario.

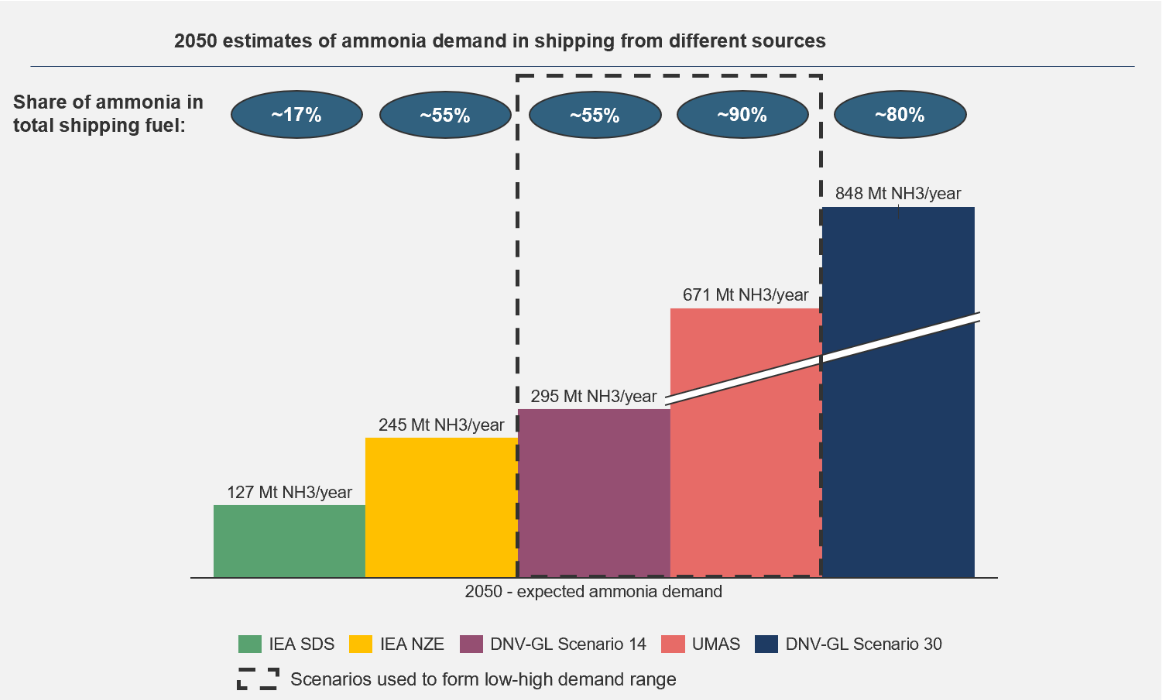
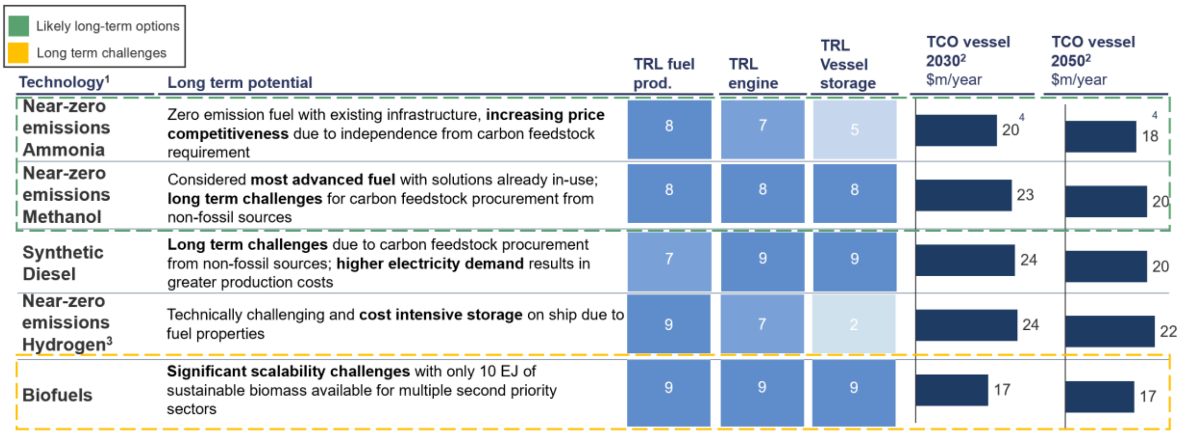


Exhibit 2: 2050 projections of ammonia demand from shipping from various sources

Source: IEA[7], DNV[6], UMAS[4,5]

The wide range of the projected demand reflects the uncertainty of ammonia take-up compared to other zero emissions shipping fuels as there are multiple zero-emissions fuel pathways for shipping. However, as shown in Exhibit 3 which compares the TRL and TCO of each fuel, only two of the pathways present viable long-term options: ammonia or methanol. However, near-zero emissions methanol presents a much higher cost compared to ammonia both in 2030 and 2050 due to the high cost of carbon-neutral CO_2 from DAC.



🟩 Likely long-term options
🟨 Long term challenges

Technology[1]	Long term potential	TRL fuel prod.	TRL engine	TRL Vessel storage	TCO vessel 2030[2] $m/year	TCO vessel 2050[2] $m/year
Near-zero emissions Ammonia	Zero emission fuel with existing infrastructure, **increasing price competitiveness** due to independence from carbon feedstock requirement	8	7	5	20[4]	18[4]
Near-zero emissions Methanol	Considered **most advanced fuel** with solutions already in-use; **long term challenges** for carbon feedstock procurement from non-fossil sources	8	8	8	23	20
Synthetic Diesel	**Long term challenges** due to carbon feedstock procurement from non-fossil sources; **higher electricity demand** results in greater production costs	7	9	9	24	20
Near-zero emissions Hydrogen[3]	Technically challenging and **cost intensive storage** on ship due to fuel properties	9	7	2	24	22
Biofuels	**Significant scalability challenges** with only 10 EJ of sustainable biomass available for multiple second priority sectors	9	9	9	17	17

Exhibit 3: The potential zero-emission fuel pathways for shipping and the TRLs and TCOs associated with them.

Note: 1) Numbers based on direct air capture technology (DAC) in this overview for green methanol, synthetic diesel 2) Based on 15,000 TEU container vessel with bunkering in Middle East; Typical speed of 18 knots and 8 annual canal transits;

Green Ammonia with 95% Ammonia and 5% LSFO; Green Methanol with 97% Methanol and 3% LSFO 3) Assumes liquid hydrogen 4) Does not include additional cost of $75,000 per year for NOx SCR Reaction

Source:Getting to Zero Coalition [8], TRL: Lloyd's Register and UMAS[9], TCO: Maersk Mc-Kinney Moller Center for Zero Carbon Shipping NavigaTE model[10]

2.3 Power generation

Power generation is estimated to account for 35Mt-105Mt of ammonia demand by 2050. In a net-zero future, countries with severe constraints on land and/or renewable resources will likely rely on importing energy from low-cost production regions. Given the challenges associated with transporting renewable electricity over large distances, these imports are likely to be in the form of hydrogen or ammonia.

The economics of importing both hydrogen and ammonia were considered in 2 scenarios:

1) A scenario in which the importing region is in close enough proximity to a low-cost renewables region for hydrogen pipelines to be built – for example, Europe importing energy from North Africa.
2) A scenario in which the importing region is far from a low-cost renewables region and thus building a hydrogen pipeline is not feasible – for example, Japan importing energy from the Middle East.

Exhibit 4 shows the results of this analysis based on cost projections for 2050. In scenario 1, the lowest cost option is to import hydrogen via a transmission pipeline for direct use in power generation while in the second scenario, given the high costs of hydrogen liquefaction or reconversion from ammonia, the lowest cost option is to import ammonia for direct use.

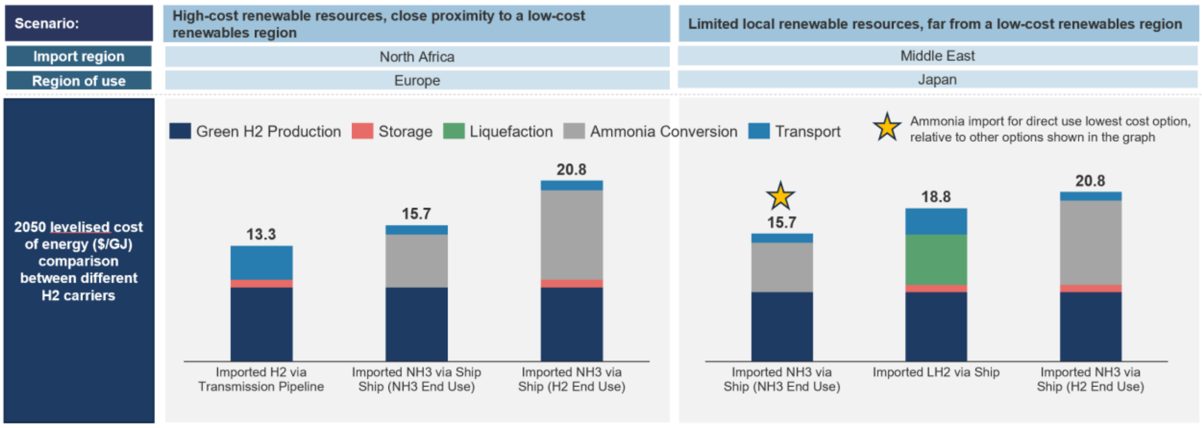


Exhibit 4: Levelised cost of energy of different energy carriers in 2050

Source: MPP analysis, Al-Breiki et al[11]., Hank et al[12]., Chatterjee et al.[13]

Countries which fall into the second category such as Japan and South Korea have already made plans to co-fire ammonia in coal power plants with potential expansion of ammonia usage to mixed combustion in CCGTs, with the following commitments announced:

- Japan expects to start importing ammonia for co-firing in coal power plants by 2027, reaching 3 Mt ammonia by 2030 and growing to 30 Mt by 2050[14]
- JERA, Japan's largest power generating company, plans to achieve 20% co-firing in all its coal power plants by 2040, and shift to 100%-ammonia plants by 2050[15]

- South Korea committed to 20% co-firing in half of its coal power plants by 2030 (estimated ~3-4 Mt)[16]

Based on these commitments, we estimate that power generation could account for 35Mt-105Mt of ammonia demand by 2050, as shown in Exhibit 5. For Japan, the projection is based on stated government commitments and for South Korea, the 2050 demand of around ~5 Mt is projected by assuming the same trajectory as for Japan, adjusted for the relative size of South Korea's current coal-fired electricity generation. The low end of the demand range for Japan is 30 Mt while the high end of the range is 100 Mt; both estimates come from the Japanese Ministry for Economy, Trade, and Industry (METI)[17] and assume fully fired ammonia plants by 2050. However, the 100 Mt is based on the existing coal fleet and additional firing in ACCGTs while the 30 Mt assumes decommissioning of a number of inefficient coal plants, and co-firing only in coal power plants.

This analysis is limited to these geographies based on the announcements made and clear signals indicating the consideration of ammonia in power generation. However, the analysis is not exhaustive and the potential demand for ammonia in power generation could be even greater when additional markets such as India and Taiwan are considered.

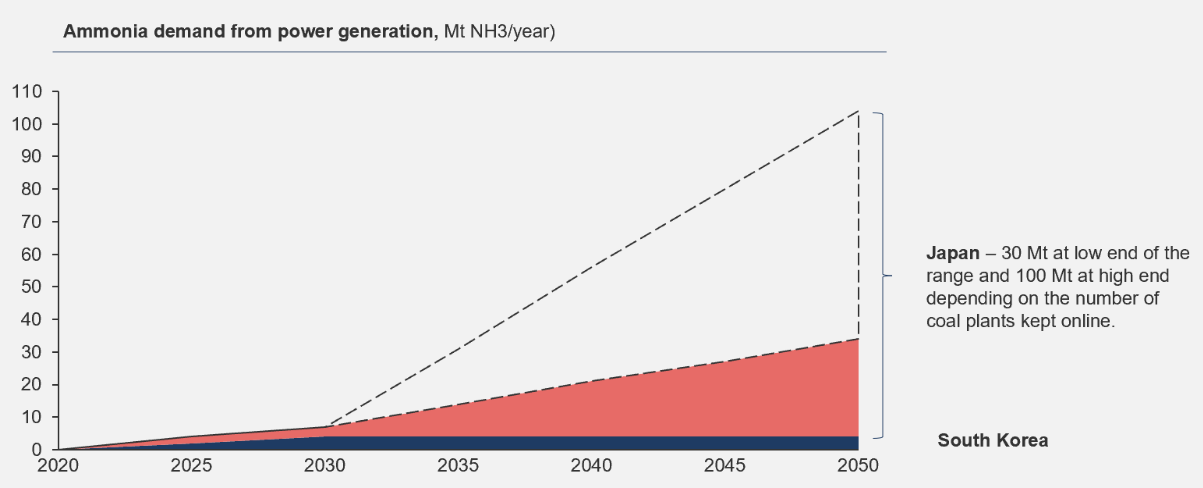


Exhibit 5: Ammonia demand from power generation 2020-2050

2.4 Hydrogen carrier

Similar to power generation, in a net-zero future, countries with severe constraints on land and/or costrenewable resources are likely to rely heavily on energy imports, most likely in the form of hydrogen or ammonia. While the direct use of ammonia is technically feasible and economically viable in power generation, there are certain applications such as iron ore reduction in steel production, and fuel for heavy duty transport, in which the direct use of ammonia may not be suitable. Therefore, in these cases, and where hydrogen pipelines are not feasible, it may be necessary to ship hydrogen in the form of a hydrogen carrier to meet demand.

The results of AFRY's Global Hydrogen Trade Model[18] were used to estimate the volumes of hydrogen that may need to be shipped over long distances by 2050. The trade model solves for the least cost method of meeting global demand for hydrogen given potential supply costs in different regions and the cost of transporting hydrogen between regions. Based on this approach, AFRY[18] estimates that around ~30% of hydrogen produced by 2050 would be traded, of which roughly a third would need to be shipped over long distances. Based on the AFRY hydrogen trade model[18] as well as the ETC'S estimated demand for hydrogen by 2050[19], and adjusting for cases where it is more economical to ship the end-product, e.g., sustainable aviation fuels, rather than hydrogen, this leaves a demand of around 10 - 20 t H_2 that would need to be shipped using a hydrogen carrier.

While there are a number of potential hydrogen carriers which have been explored in depth in a recent IRENA report[20], the two most economically viable and technologically mature options are considered in this analysis are: liquified hydrogen and ammonia. Exhibit 6 compares the attractiveness of each carrier across three different criteria: cost, roundtrip efficiency and TRL.

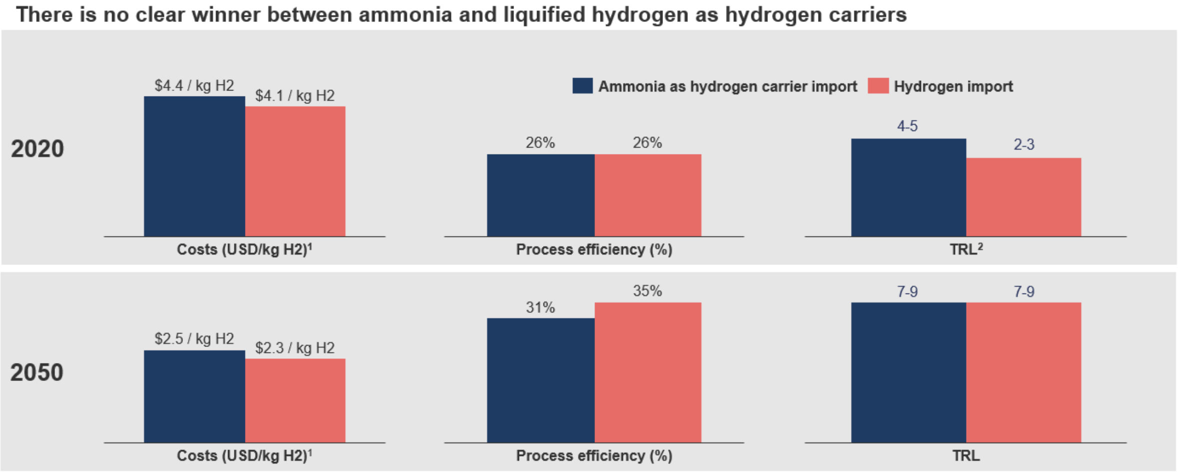


Exhibit 6: A comparison of liquified hydrogen and ammonia as a hydrogen carrier for long distance transport or hydrogen across costs, efficiency and TRL in 2020 and 2050.

Source: MPP analysis, Al-Breiki et al[11]., Hank et al[12]., Chatterjee et al.[13]

As shown in Exhibit 6, there is no clear winner on a cost or efficiency basis. Both technologies have low roundtrip efficiencies of around 26% currently, expected to increase to around 31%-35% by 2050, due to the losses and energy-intensive nature of conversion, transport, and reconversion. In addition, both hydrogen carriers currently have high costs of around $4.1-$4.4/kg but these are expected to improve significantly as the technologies mature, driving learning curves for ammonia crackers and liquefaction technologies. While both technologies currently have a low TRL, primarily due to the low maturity of ammonia cracking and large-scale hydrogen liquification as well as shipping LH_2, by 2050 both technologies are expected to reach TRL 7-9. As there is no clear winner between these two hydrogen carriers, the future of ammonia as an energy carrier is highly uncertain. To reflect this uncertainty, the low end of the demand range assumes that all demand for shipped hydrogen by 2050 is met by liquefied hydrogen thus yielding a demand of 0 Mt of ammonia while the upper end of the range assumes all demand for shipped hydrogen by 2050 is met by ammonia. This results in a maximum estimated demand of 110 Mt of ammonia, which accounts for the losses during conversion, shipping, and reconversion.

2.5 Fertiliser efficiency and circularity

Fertiliser reduction

In 2019 the Food and Land Use Coalition[21] modelled a net-zero scenario for all food and land use, using the extensive GLOBIOM model[22]. The "Better Futures" scenario results in a reduction in nitrogen fertiliser use of 25% in 2050 relative to the BAU scenario, assuming 0% growth in demand from 2020, as shown in Exhibit 7, and is based on the following key assumptions:

- Global population **diet follows recommendations of the human and planetary health diet** delivering universal food security through better mix of nutrient-efficient foods
- A global average growth in crop yield of **1.1%** per year through **less nutrient-intensive farming practices & technologies**
- A **reduction in food loss and waste to 25% by 2050**, compared to current trends (**33%**) which **allows food production to peak in 2030**.
- **Reduction in loss and waste coming from across the food value chain**. Regional priorities vary. Developed economies to reduce biggest loss at consumption level (disposal & overconsumption). Developing regions to reduce in handling & storage (transportation & international trading)

This scenario considers the maximum potential fertiliser demand reduction through efficiency measures and is based on relatively aggressive assumptions. In this analysis, the FA scenario considers a more conservative fertiliser efficiency scenario, taking the midpoint between the BAU fertiliser demand and the "Better Futures" scenario, thus assuming a demand growth with an average CAGR of ~0.5% to 2050. The LC scenario does not consider the adoption of any efficiency measures and thus takes the full BAU demand.

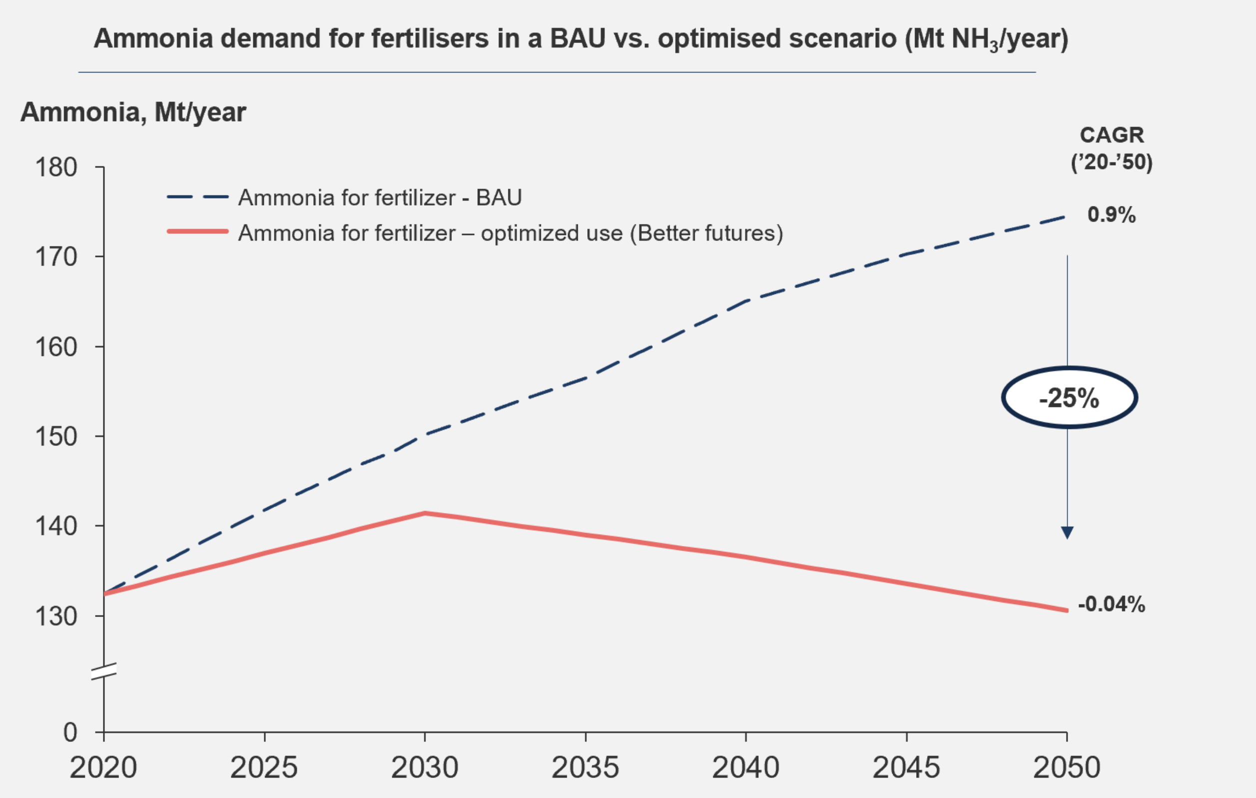


Exhibit 7: Ammonia demand for use in fertilisers in a BAU scenario vs. an optimised scenario

Source: FOLU[23], IIASA[22]

Fertiliser substitution

According to the IEA[2], 29% of urea can be substituted with alternative nitrogen-based fertilisers by 2050 to enable a reduction in downstream scope 3 CO_2 emissions. This is the assumption that we used in our analysis. When substituting urea with other fertilisers, the tonnage of nitrogen used must be equivalent. There are a number of potential substitutes for urea, but ammonium nitrate presents the most promising in terms of scalability and existing infrastructure. There are limitations to scaling CAN supply as the production is restricted by geo-morphological conditions to regions such as Russia and Belarus. Ammonium nitrate, however, has a number of safety risks given that it is highly explosive. Therefore, stringent safety requirements must be enforced when scaling up supply, particularly around handling, transport, and storage.

3 Techno-economic assumptions of supply-side technologies

All modelling assumptions on supply are informed by industry expertise across the value chain (from the industry community of the Low Carbon Emitting Technologies Initiative (LCET) and the Mission Possible Partnership as well as recent academic insights and reports from organisations such as the IEA, ETC, and IRENA.

3.1 Description of ammonia production technologies

Since the early 20th century, the Haber-Bosch process has been used to produce ammonia on an industrial scale. This involves converting nitrogen, sourced directly from the air, and hydrogen, from fossil feedstocks, into ammonia using high temperatures (typically 400-650°C) and pressures (typically 100-400 bar) in the presence of a catalyst. There are currently no viable or technologically mature alternatives which can compete with or replace the H-B process.

Over 98% of scope 1 and 2 emissions from ammonia production are generated in the production of hydrogen from fossil fuel feedstocks while the other 2% is generated in the nitrogen separation and ammonia synthesis stages. These stages are straightforward to decarbonise by using renewable electricity to power the various components required including the air separation unit for nitrogen separation, as well as the motors, compressors and temperature and pressure control equipment for ammonia synthesis. The hydrogen production stage, however, is more challenging to decarbonise and has a number of viable production routes which vary the hydrogen feedstock and process in which hydrogen is generated. Hence, all supply-side levers focus on this stage of ammonia production but include the decarbonisation of nitrogen separation and ammonia synthesis via the use of renewable electricity.

Exhibit 8 below provides a comprehensive list of the supply-side technologies included in the analysis as well as the current technology readiness level (TRL) of each technology and the year in which the technology is expected to come online.

		Supply side technology	**Description**	**Current TRL**	**Year available**

Initial	Carbon-based	**Natural Gas SMR (steam methane reforming) + ammonia synthesis**	Natural gas is heated in the presence of steam to produce syngas which undergoes a water-gas shift reaction to then produce hydrogen. The hydrogen is reacted with nitrogen from the air at pressures above 10 MPa and temperatures between 400-500 °C via the Haber-Bosch process.	9	today
		Coal Gasification + ammonia synthesis	Coal is heated in the presence of oxygen and steam to generate a syngas which undergoes a water-gas shift reaction to then produce hydrogen. The hydrogen is reacted with nitrogen from the air at pressures above 10 MPa and temperatures between 400-500 °C via the Haber-Bosch process.	9	today
Transitional	Carbon-based	**Natural gas SMR + CCUS (process emissions only) + ammonia synthesis**	Equivalent to **Natural Gas SMR + ammonia synthesis** but process CO_2 emissions generated during steam methane reforming reaction and water-gas shift are compressed and transported to either a geological CO_2 storage site for permanent sequestration, or to be used in applications which offer permanent storage.	9	today
		Electrolyser + SMR + ammonia synthesis	The **Natural Gas SMR + ammonia synthesis** plant is kept unchanged, but a small electrolyser is installed to supply 10% of the hydrogen feed. The existing synthesis gas frontend operation is optimised to this new operating point.	8	today
		Electrolyser + Coal Gasification + ammonia synthesis	The **Coal Gasification + ammonia synthesis** plant is kept unchanged, but a small electrolyser is installed to supply 10% of the hydrogen feed. The existing synthesis gas frontend operation is optimised to this new operating point.	8	today
Nea-zero emissions	Carbon-based	**Natural gas SMR + CCUS + ammonia synthesis**	Equivalent to **Natural gas SMR + CCUS (process emissions only) + ammonia synthesis** but a capture unit is added to the diluted flue gas CO_2 emissions from fossil fuel combustion; both the process and flue gas CO_2 emissions are compressed and transported to either a geological CO_2 storage site for permanent sequestration, or to be used in applications which offer permanent storage.	8	2025
		Coal Gasification + CCUS + ammonia synthesis	Equivalent to **Coal Gasification + ammonia synthesis** but a capture unit is added to capture the diluted flue gas CO_2 emissions from fossil fuel combustion and both the process and flue gas CO_2 emissions are compressed and transported to either a geological CO_2 storage site for permanent sequestration, or to be used in applications which offer permanent storage.	8	2025
		Natural gas ATR (autothermal reforming) + CCUS + ammonia synthesis	Similar to **Natural gas SMR + CCUS + ammonia synthesis but** the natural gas is reacted with pure oxygen from an air separation unit and the heating takes place internally so minimal external energy inputs are required for pre-heating.	8	2025
		Oversized natural gas ATR + CCUS + ammonia synthesis	Equivalent to **Natural gas ATR + CCUS + ammonia synthesis** but the small energy input required for pre-heating is supplied by hydrogen produced in the ATR which is combusted to provide the required heat inputs.	8	2025
		ATR + GHR (gas heated reformer) + CCUS + ammonia synthesis	Equivalent to **Natural gas ATR + CCUS + ammonia synthesis** but a gas-heated reformer (or heat exchange reformer) is added to recover waste heat from the syngas mixture produced in the upstream ATR to provide heat for the endothermic reforming reaction and thus produce additional syngas from which the hydrogen and thus the ammonia is produced.	6-7	2025
		e-SMR Gas + CCUS + ammonia synthesis	Equivalent to **Natural gas SMR + CCUS (process emissions only) + ammonia synthesis** but the heat inputs required are generated via electricity (renewable electricity purchased via a PPA) instead of via the combustion of natural gas. Therefore, the flue gas CO_2 emissions are eliminated.	4	2030
		Methane Pyrolysis + ammonia synthesis	Methane is split into hydrogen and solid carbon by using high temperature heat provided by electric plasma in the absence of oxygen. No CO_2 emissions are generated in the process.	6-7	2030

	Direct carbon avoidance	**Electrolyser + ammonia synthesis - grid PPA**	An electric current is passed through water to split the molecules into hydrogen and oxygen. The electricity source is renewable electricity generated off-site and purchased through a PPA. N_2 is 'provided' via an air separation unit. Nitrogen and hydrogen are used to produce ammonia via the Haber-Bosch process.	8	2025
		Electrolyser + ammonia synthesis - grid PPA + dedicated renewables	Equivalent to **Electrolyser + ammonia synthesis - grid PPA** but the electricity source is dedicated on site renewables with a PPA to balance intermittency and ensure a stable supply of H_2 to the Haber-Bosch process.	8	2025
		Electrolyser + ammonia synthesis - dedicated renewables + H2 storage (geological)	Equivalent to **Electrolyser + ammonia synthesis - grid PPA** but the electricity source is dedicated on site renewables with geological H_2 storage is used to balance intermittency and ensure a stable supply of H_2 to the Haber-Bosch process.	7	2025
		Electrolyser + ammonia synthesis - dedicated renewables + H2 storage (pipeline)	Equivalent to **Electrolyser + ammonia synthesis - grid PPA** but the electricity source is dedicated on site renewables with pipeline H_2 storage is used to balance intermittency and ensure a stable supply of H_2 to the Haber-Bosch process.	7	2025
		Biomass Gasification + ammonia synthesis	Similar to **Coal Gasification + ammonia synthesis** but the feedstock used to produce hydrogen is dry biomass.	5	2030
		Biomass Digestion + ammonia synthesis	Similar to **Natural Gas SMR + ammonia synthesis** but using biomethane feedstock instead of natural gas which is produced from digestion of wet biomass.	1-3	2030

Exhibit 8: A description of all supply-side technologies for ammonia production

Source: MPP analysis, IEA[2]

Exhibit 9 below is a flow diagram which illustrates the stages of ammonia production via each of these technologies from feedstock production all the way to end use and highlights the processes in which greenhouse gas emissions are produced. As shown, the production routes differ primarily by the hydrogen feedstock and hydrogen production technology but regardless of the source of hydrogen, each technology uses the same process for ammonia synthesis and for the production of derivatives.

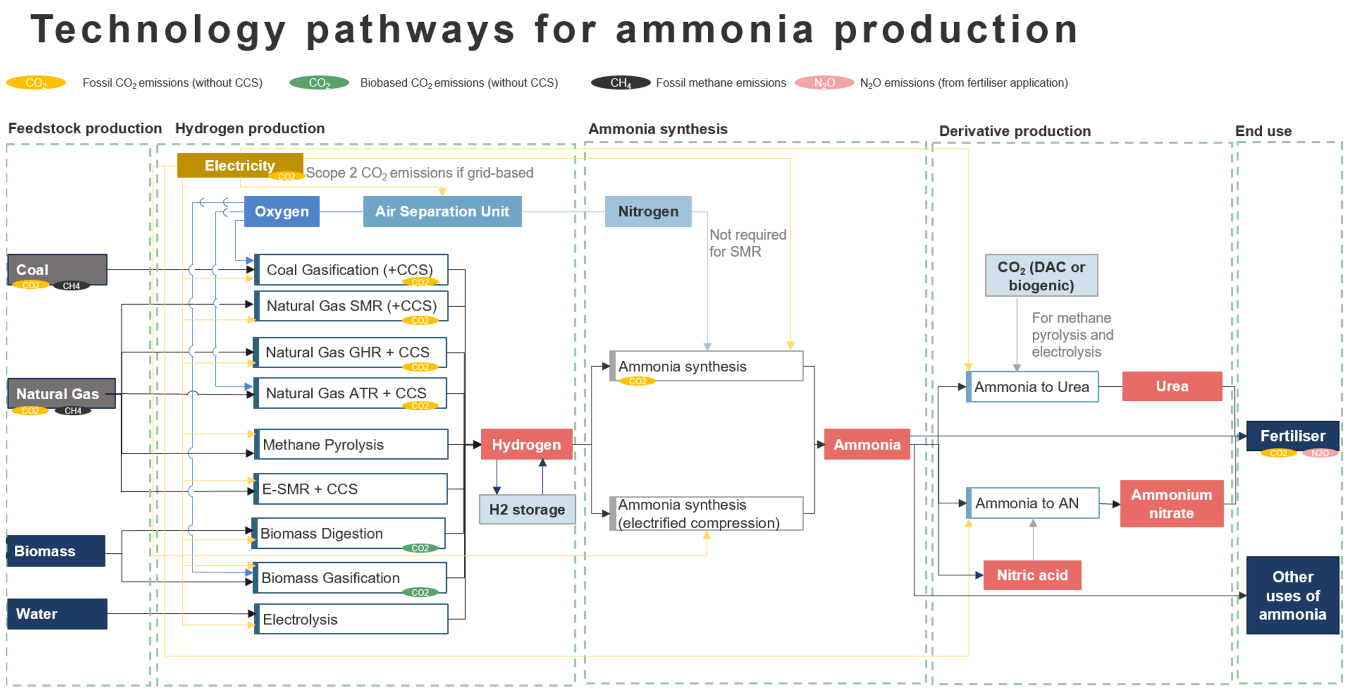


Exhibit 9: Flow diagram of ammonia production from feedstock to end use via each production route

3.2 Technology cost assumptions

The ammonia production routes listed in Exhibit 8 can be grouped by technology into the following categories: (1) steam reforming, (2) gasification, (3) electrolysis and (4) methane pyrolysis.

3) **Steam reforming** is the process in which in which methane, or bio-methane in the case of biomass digestion, is used to produce syngas by reacting the hydrocarbons with steam. A water-gas shift reaction then converts the syngas into a mixture of H_2 and CO_2 and the resulting hydrogen is purified before entering the ammonia synthesis loop where it is reacted with nitrogen at high pressures and temperatures in the presence of a catalyst to produce ammonia. The nitrogen is sourced from the air via an air separation unit.

4) **Gasification** is the process in which coal or biomass is converted into a syngas mixture by reacting the feedstock material at high temperatures (>700 °C) with steam in the presence of pure oxygen. The syngas mixture is then converted into into a mixture of H_2 and CO_2 via a water-gas shift reaction and the process proceeds in the same way as described above for steam reforming.

5) **Electrolysis**-based ammonia production uses a direct electric current to split water molecules into its constituent elements: hydrogen and oxygen. The hydrogen generated is then compressed and enters the ammonia synthesis unit and the process proceeds in the same way as described above for steam reforming.

6) **Methane pyrolysis** is a novel process in which methane gas or biomethane is thermally decomposed into its constituent components: solid carbon and hydrogen. The hydrogen is then purified, and the rest of the process proceeds in the same way as described for steam reforming.

Each production route requires a different set of feedstock and energy inputs to produce one tonne of ammonia which are listed in the tables below. In addition, where relevant, the CO_2 capture rate assumed for each technology is listed. These inputs ultimately determine the variable OPEX component of the LCOX and GHG emissions produced by each technology.

	Steam reforming technologies							
	Natural Gas SMR + ammonia synthesis	**Natural Gas SMR (process emissions only) + CCS + ammonia synthesis**	**Natural gas ATR + CCS + ammonia synthesis**	**Oversized natural gas ATR + CCS + ammonia synthesis**	**Natural gas SMR + CCS + ammonia synthesis**	**ATR+ GHR + CCS + ammonia synthesis**	**Biomass Digestion + ammonia synthesis**	**ESMR Gas + CCS + ammonia synthesis**
Electricity (kWh/t NH_3)	138.9[24]	209.0[24–26]	444.4[2,26]	463.9[2,26]	301.4[24–26]	301.4[2,26,27]	1866.9[28]	2343.1[24–26]
Natural gas (GJ/t NH_3)	35.7[2,24]	34.5[24–26]	30.5[2,26]	31.5[2,26]	34.5[24–26]	28.4[2,26,27]	-	21.0[24–26]
Coal (GJ/ t NH_3)	-	-	-	-	-	-	-	-
Biomass (GJ/t NH_3)	-	-	-	-	-	-	78.9[28]	-
CO2 capture rate (%)	-	65%[24–26]	94%[2,26]	95%[2,26]	90%[24–26]	96%[2,26,27]	-	95%[24–26]

Exhibit 10: Energy and feedstock inputs for steam reforming technologies.

	Gasification			**Electrolysis**			**Methane pyrolysis**
	Coal Gasification + ammonia synthesis	**Coal Gasification+ CCS + ammonia synthesis**	**Biomass Gasification + ammonia synthesis**	**Electrolyser + SMR + ammonia synthesis**	**Electrolyser + Coal Gasification + ammonia synthesis**	**Electrolyser - grid PPA + ammonia synthesis**	**Methane Pyrolysis + ammonia synthesis**
Electricity (kWh/t NH_3)	1027.8[2,29]	1472.2[2,29]	1672.4[28]	1068.6[24,30]	1963.1[2,29,30]	10330.9[19,31,32]	2333.3[2]
Natural gas (GJ/t NH_3)	-	-	-	30.3[24,30]	-	-	40.5[2]
Coal (GJ/ t NH_3)	38.0[2,29]	33.7[2,29]	-	-	32.3[2,29,30]	-	-
Biomass (GJ/t NH_3)	-	-	29.9[28]	-	-	-	-

CO2 capture rate (%)	-	90%[2]	-	-	-	-	-

Exhibit 11: Energy and feedstock inputs for gasification technologies, electrolysis, and methane pyrolysis.

The assumptions listed for ammonium nitrate and urea production in Exhibit 12 are incremental values which only include the additional energy and feedstock required to produce ammonium nitrate or urea from ammonia. The production of ammonium nitrate requires both ammonia and nitric acid; nitric acid itself is also produced by reacting ammonia and oxygen. The ammonia input therefore also includes the ammonia required for nitric acid production.

Nitric acid production generates N_2O at a rate of 6-9 kg N_2O/ t HNO_3. However, with the adoption of abatement technologies, emission rates are reduced by at least 98%; this abatement rate is assumed in the model. [2]

	Incremental ammonia to ammonium nitrate	**Incremental ammonia to urea**
Ammonia (t NH_3/ t product)	0.43	0.57
Electricity (kWh/t product)	30.1[33,34]	83.3[35]
CO_2 (t CO_2/ t product)	-	0.7

Exhibit 12: Incremental energy and feedstock inputs for ammonium nitrate and urea production.

The emissions intensity of production via each of these technologies, shown in Exhibit X, is determined by the various energy and feedstock inputs as well as the rate of CO2 capture.

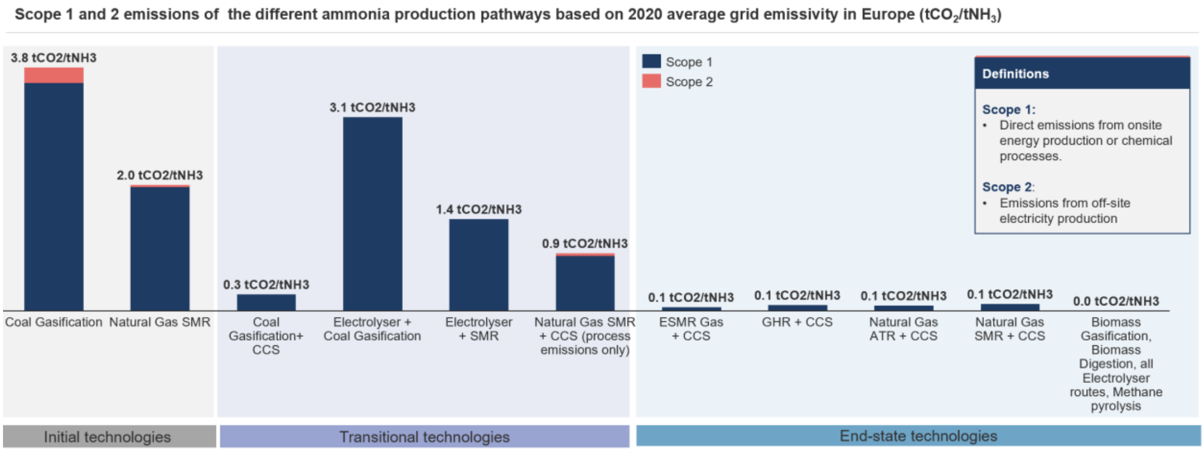


Exhibit 13: Scope 1 and 2 emissions intensity of production via each production route.

Note: scope 2 emissions are based on the average grid emissivity in Europe in 2020.

Source: MPP analysis, IEA[2]

In addition to the variable OPEX components listed in the tables above, the LCOX depends on the CAPEX, WACC and fixed OPEX, which are given in the tables below for 2020. The CAPEX is assumed to be the same for both greenfield and brownfield plants and the renovation CAPEX is the incremental CAPEX required to retrofit an existing plant with either CO_2 capture or a small electrolyser to switch from a conventional production route to a transitional or end state production route.

Note that the CAPEX, fixed OPEX and WACC assumptions for each technology are consistent across regions, with the exception of the CAPEX for electrolysis-based production as the electrolyser CAPEX is different for China versus other regions as shown in Exhibit 16. However, the variable OPEX varies by region depending on the energy and feedstock prices as discussed in section 3.3. The values for variable and total OPEX presented in the table below are therefore specific to North America and will vary by region while the other assumptions are consistent across regions. For each production route a lifetime of 30 years was assumed, and the capacity utilisation factor was determined by the model. Further information on this is provided in section 5.

🟩 **Varies by region depending on commodity prices**

	Steam reforming technologies							
2020	**Natural Gas SMR + ammonia synthesis**	**Natural Gas SMR (process emissions only) + CCS + ammonia synthesis**	**Natural gas ATR + CCS + ammonia synthesis**	**Oversized natural gas ATR + CCS + ammonia synthesis**	**Natural gas SMR + CCS + ammonia synthesis**	**ATR+ GHR + CCS + ammonia synthesis**	**Biomass Digestion + ammonia synthesis**	**ESMR Gas + CCS + ammonia synthesis**
CAPEX (USD/ t NH_3)	1105[26]	1196[26]	1651[26]	1619[26]	1501[26]	1612[26]	3176[28]	1196[26]
Retrofit CAPEX **(USD/ t NH_3)**	-	91[26]	-	-	396[26]	-	-	-
Fixed OPEX (USD/ t NH_3)	55[36]	60[36]	87[36]	81[36]	80[36]	85[36]	159[28]	60[36]
Variable OPEX (USD/ t NH_3)	50	68	82	85	73	72	312	128
Total OPEX (USD/ t NH_3)	105	127	169	166	153	157	470	188
WACC (%)	8%[37]	8%[37]	8%[37]	8%[37]	8%[37]	8%[37]	8%[37]	8%[37]
Plant capacity	2,000[36]	2,000[36]	2,000[36]	2,000[36]	2,000[36]	2,000[36]	150[28]	2,000[36]

(tonnes per day)								

Exhibit 14: 2020 CAPEX and OPEX assumptions for all steam reforming technologies.

🟩 **Varies by region depending on commodity prices**

	Gasification			**Electrolysis**			**Methane pyrolysis**
2020	**Coal Gasification + ammonia synthesis**	**Coal Gasification+ CCS + ammonia synthesis**	**Biomass Gasification + ammonia synthesis**	**Electrolyser + SMR + ammonia synthesis**	**Electrolyser + Coal Gasification + ammonia synthesis**	**Electrolyser - grid PPA + ammonia synthesis**	**Methane Pyrolysis + ammonia synthesis**
CAPEX (USD/ t NH_3)	2175[37]	2810[37]	5629[28]	1235[26,30]	2305[30,37]	1794[19,38,39]	1320[40]
Retrofit CAPEX (USD/ t NH_3)	-	635[37]	-	130[30]	130[30]	-	-
Fixed OPEX (USD/ t NH_3)	109[37]	149[37]	281[28]	62[26]	115[30]	59[19,38,39]	66[40]
Variable OPEX (USD/ t NH_3)	115	144	252	80	125	442	161
Total OPEX (USD/ t NH_3)	224	293	533	142	241	501	227
WACC (%)	8%[37]	8%[37]	8%[37]	8%[37]	8%[37]	8%[37]	8%[37]
Plant capacity (tonnes per day)	2,000[36]	2,000[36]	780[28]	2,000[36]	2,000[36]	1,100[31]	2,000[36]

Exhibit 15: 2020 CAPEX and OPEX assumptions for gasification, electrolysis and methane pyrolysis technologies.

Note: Variable and total OPEX vary by region as they depend on commodity prices. Values shown here are for North America in 2020.

The plant capacities assumed for each technology are also given in Exhibit 14 and Exhibit 15; these plant capacities are the underlying capacities assumed for the CAPEX figures quoted. However, note that when calculating a approximate number of plants, the capacities were all standardised to 2000 tonnes per day. The CAPEX for all technologies is assumed to remain constant over time with the exception of electrolysis-based technologies which assume a progressive decline in the electrolyser CAPEX to 2050. The 2020 electrolyser CAPEX assumptions are based on analysis conducted by the Energy Transitions Commission and BloombergNEF data. The evolution of the CAPEX, shown in Exhibit 16, assumes a learning rate of 13%-18% and is based on a global electrolyser capacity projection which is tied to an ambitious scenario presented by the Energy Transitions Commission[19].

The electrolyser efficiency projection (Exhibit 16) is also sourced from the Energy Transitions Commission[19].

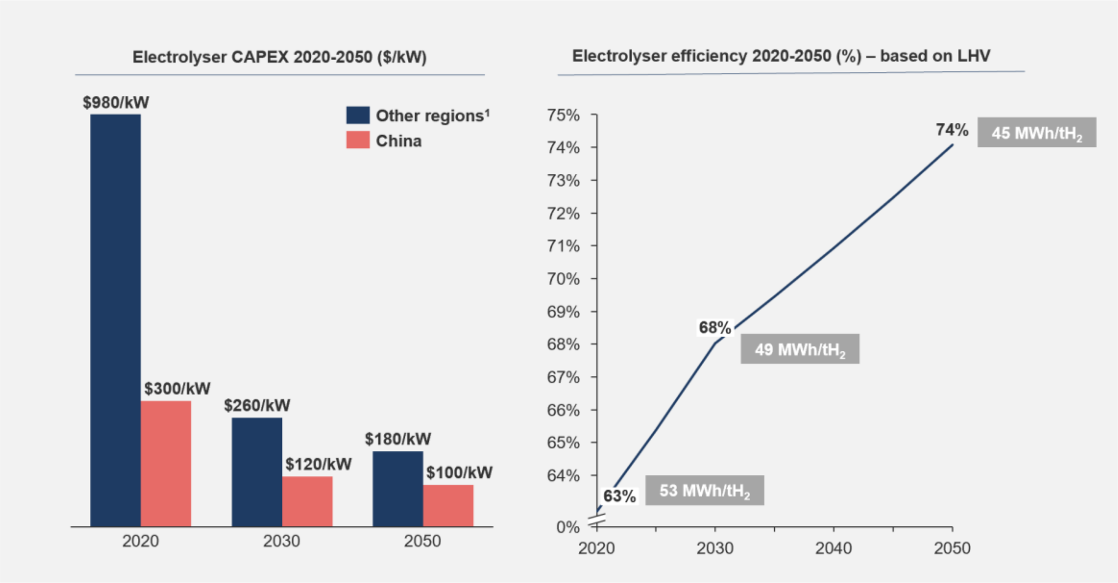


Exhibit 16: Electrolyser CAPEX and efficiency 2020-2050

Source: BNEF[38,39], Energy Transitions Commission[19]

Based on the above assumptions, and the energy prices given in section 3.3, the levelised cost of ammonia for each technology is calculated for each region and in each year. Exhibit 17 shows the LCOAs for all region in 2020, 2030 and 2050.

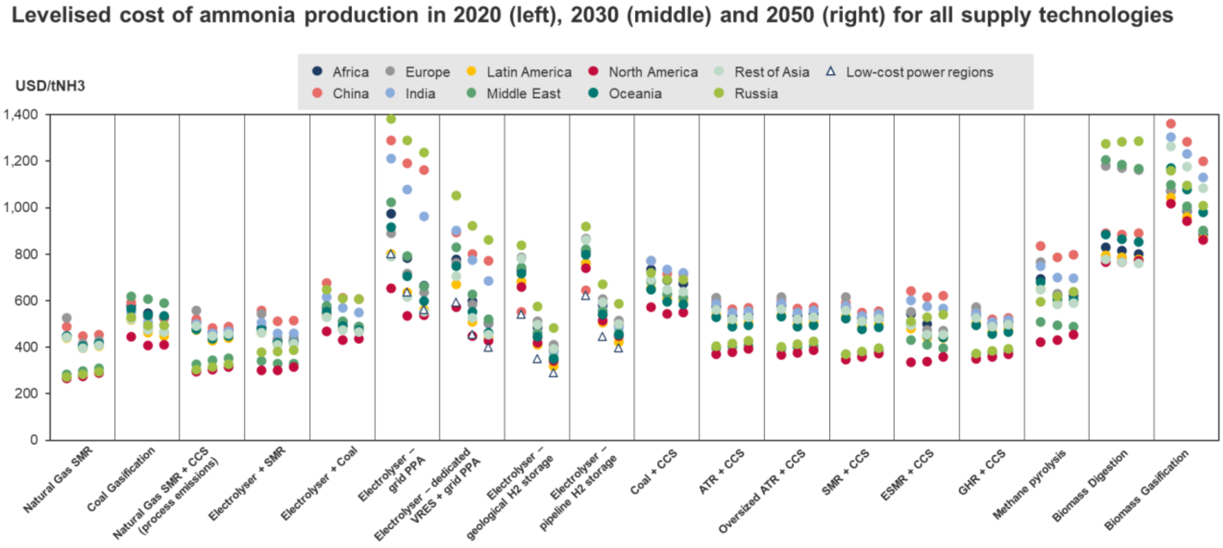


Exhibit 17: Levelised cost of ammonia production in all regions for each supply technology in 2020 (left), 2030 (middle), and 2050 (right).

3.3 Energy prices

Fossil fuel prices

The 2020 prices for natural gas and coal are taken from regional spot market indices. Price projections until 2050 are calculated based on the IEA's World Energy Outlook. These projections are made for two scenarios: a BAU scenario based on the IEA's Stated Policies scenario, and a decarbonised scenario based on the IEA's NZE scenario. In our modelling, the IEA's Stated Policies scenario prices underpin all scenarios given that there is a continued reliance on fossil fuels in ammonia production thus using the IEA's NZE prices, which assumes declining use of fossil fuels would be contradictory and lead to greater uptake of fossil fuel-based production. However, the IEA's NZE prices are used in the sensitivity analysis to assess the impact of lower fossil fuel prices on the production mix. We also test two additional gas price scenarios in the sensitivity analysis: a partial correction to the current high gas prices, and a new normal or current high gas prices.

To account for near term spikes in fossil fuel prices, pricing for 2021 and 2022 is based on the World Bank's Commodity Markets Outlook[41] as of March 2022. Following 2022, prices are assumed to decline back to original IEA estimates by 2025 in the BAU and low gas price scenarios. Price projections until 2050 are calculated by applying implied growth rates from the IEA scenarios to 2025 regional estimates. Exhibit 18 shows the fossil fuel prices in each scenario for four regions.

		China			North America			Europe			India		
		2022	2030	2050	2022	2030	2050	2022	2030	2050	2022	2030	2050
Natural gas prices (USD/ MMbtu)	**Low (IEA NZE after 2025)**	18.4	5.3	4.7	5.2	1.9	2.0	34.0	3.9	3.6	19.1	3.9	3.7
	BAU (IEA STEPS after 2025)	18.4	8.6	8.9	5.2	3.6	4.3	34.0	7.7	8.3	19.1	7.1	7.7
	Partial correction	18.4	13.5	13.5	5.2	4.4	4.4	34.0	20.8	20.8	19.1	13.1	13.1
	New normal	18.4	18.4	18.4	5.2	5.2	5.2	34.0	34.0	34.0	19.1	19.1	19.1
Coal prices (USD/t)	**Low (IEA NZE)**	342	61	51	176	24	22	207	52	54	258	49	42
	BAU (IEA STEPS)	342	83	74	176	39	38	207	67	63	258	67	62

Exhibit 18: Fossil fuel prices in 2020, 2030 and 2050 across 4 regions in 2 different scenarios

Source: MPP analysis, IEA[42]

Power prices

Grid and PPA prices are sourced from the MPP's Power Pricing Model. Levelized costs of energy (LCOEs) are calculated for each power supply technology based on their respective CAPEX, OPEX, fuel costs, capacity factors, and WACC. All input assumptions are taken from open-source data, which is mainly obtained from the IEA[42], Bloomberg New Energy Finance (BNEF)[43], and the European Commission's Joint Research Centre (JRC)[44,45].

Grid prices are calculated by:

(1) Weighing the LCOE of each technology by its share in the regional grid mix.

(2) Adding transmission and distribution costs as well as taxes, which are both region specific where possible.

PPA prices are calculated by:

(1) Taking starting point PPA prices for 2020 from LevelTen Energy's PPA Price Index[46] and from Pexapark's Pexa Euro Composite Index[47].

(2) Indexing these starting points in line with the growth in grid prices.

In addition, the LCOEs of dedicated onshore wind and solar are also sourced from the MPP's Power Pricing Model and are largely based on projections from Bloomberg New Energy Finance (BNEF)[43].

The grid price and PPA price outputs are modelled deeply across four different key regions: US, EU, China, and India. Outputs for other regions are proxied based on these key regions. For dedicated solar and wind, prices are modelled deeply across all regions. Exhibit 19 shows the grid prices, PPA prices and dedicated renewables prices for each of these regions.

	China			North America			Europe			India		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Grid power prices (USD/MWh)	111	113	100	69	54	66	114	108	86	93	107	87
PPA power prices (USD/MWh)	105	106	97	46	40	50	69	67	61	83	91	80
Dedicated solar (USD/MWh)	27	20	13	32	19	12	53	34	21	21	20	13
Dedicated wind (USD/MWh)	36	35	19	29	26	20	52	36	26	27	22	17

Exhibit 19: Grid power prices, PPA prices and dedicated onshore wind and solar power prices in four regions in 2020, 2030 and 2050.

Low-cost power regions

In addition to the 10 main regions which were modelled, a group of "low-cost power regions" were included to represent optimal locations for renewable energy resources across the globe. Four archetypal locations were used to represent such locations: Saudi Arabia, Australia, Brazil, and Namibia. For each of these regions, LCOEs were calculated for optimal locations within these regions based on more favourable solar and wind capacity factors (Exhibit 20). While only four regions were explicitly modelled, these regions represent optimal locations for low-cost renewable electricity which could potentially be found across all of the 10 main regions.

LCOEs of dedicated wind and solar ($/MWh)	2025	2030	2050
Brazil	19.0	15.0	11.0
Saudi Arabia	24.5	23.3	18.8
Namibia	27.5	25.2	19.5
Australia	20.7	18.2	13.5

Exhibit 20: LCOEs of combined wind and solar in low cost power regions.

4 The 1.5°C carbon budget

The estimation of the remaining carbon budget for the ammonia sector seeks to ensure that the net-zero pathways developed in this Sector Transition Strategy do not only reach net-zero emissions, but also limit cumulative emissions until 2050 to an amount that is compatible with a reasonable likelihood of limiting global warming to 1.5°C. In this section, the methodology for allocating the 1.5 °C carbon budget to the ammonia sector is explained in detail.

4.1 Breakdown of carbon budget to energy- and non-energy sectors

Exhibit 21 shows how the carbon budget to limit global warming to 1.5°C with a probability of 50% has been derived for all MPP sectors. The IPCC's carbon budget of 580 Gt CO2[48] from the beginning of 2018 has been updated to about 500 Gt CO2 from the beginning of 2020.

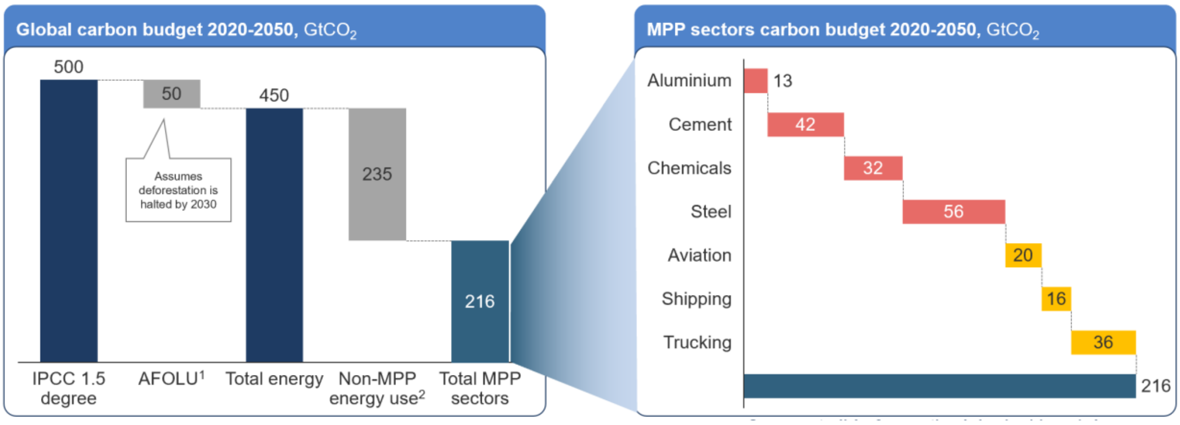


Exhibit 21: Allocation of global carbon budget to limit global warming to 1.5°C to MPP and non-MPP sectors.

Based on Roe et al. (2019)[49] and ETC analysis, 50 Gt CO2 have been subtracted to account for the cumulative net anthropogenic emissions between 2020 and 2050 from Agriculture, Forestry, and Other Land Use (AFOLU). This scenario assumes a rapid and steep end to deforestation with 90% reduction in emissions from deforestation by 2030 and 95% by 2050. In addition, it assumes a 65% reduction in process emissions from agriculture by 2030 and a 50% shift towards plant-dominant diets by 2050, in line with the recommendations of the EAT-Lancet Review (2019)[50]. Emissions figures include net human-driven land use change but do not include the terrestrial sink or CDR through restoration efforts. After the subtraction of AFOLU, a total of 450 $GtCO_2$ of cumulative emissions from 2020 to 2050 remain for allocation to energy use.

4.2 Sectoral allocation of energy-related carbon budget

Exhibit 22 documents how the remaining carbon budget for energy-related sectors has been allocated to individual MPP sectors (and hence also how the carbon budget for the non-MPP energy sectors has been defined). Non-MPP energy sectors include the energy use in buildings, other industry (tobacco, pulp and paper, food, textile and leather, non-ferrous metals other than aluminium, non-metallic minerals other than cement) and other transport (rail, road transport apart from trucking).

The sectoral allocation is defined by the average of the cumulative emissions of each MPP sector three existing models: the IEA's *Net Zero by 2050* report, the BloombergNEF *New Energy Outlook 2021* report, and for some sectors the *One Earth Climate Model*[51–53]. These existing models serve as a proxy of how hard to abate each individual sector is. The following assumptions have been made:

- For NEO and OECM, trucking emissions were estimated by the emission share of trucking in total road transport in 2019 (30%, from IEA NZE).
- For IEA NZE, scope 2 emissions were estimated by each subsector's share in total industry or transport scope 1 emissions.
- For NEO, scope 2 emissions were estimated from final electricity consumption multiplied by carbon intensity of grid electricity.
- For OECM, scope 3 emissions were assigned as scope 1 emissions in the three transport sectors because OECM defines scope 3 emissions as direct emissions incurred during vehicle operation.
- For IEA NZE and OECM, emissions data was interpolated linearly between the given years.

The allocation to MPP sectors is based on three existing models

Models evaluated

		IEA NZE	NEO'21 Green Scenario	OECM
Conceptual approach		Carbon budget allocation is a result of model assumptions on technology cost, demand and policies	Assignment of sectoral carbon budgets based on availability and cost-competitiveness of abatement technologies	Energy system model used to develop technical bottom-up scenarios for a desired future, i.e. net-zero in 2050; accounting model: no cost optimisation
Technical summary	**Carbon budget**	500 Gt CO_2	500 Gt CO_2	400 Gt CO_2 equiv.
	<1.5 °C likelihood	50%	50%	67%
	AFOLU assumptions	Allocated 40 Gt of carbon budget	Not considered	Assumes 86 Gt CO_2 cumulative sequestration through natural sinks
	CDR assumptions	CCUS with fossil fuel combustion	No CCS	No CCS
	Non-CO_2 emissions	Not reported, but methane emissions reduced by 91% from 2020 to 2050	Not reported	Accounted for, uses CO_2 equivalent
	Breakdown by MPP sectors	• Scope 1: sub-sectors apart from Aluminium* • Scope 2: only industry and transport	• Scope 1: all subsectors • Scope 2: only industry and transport	• Scope 1 and 2: subsectors

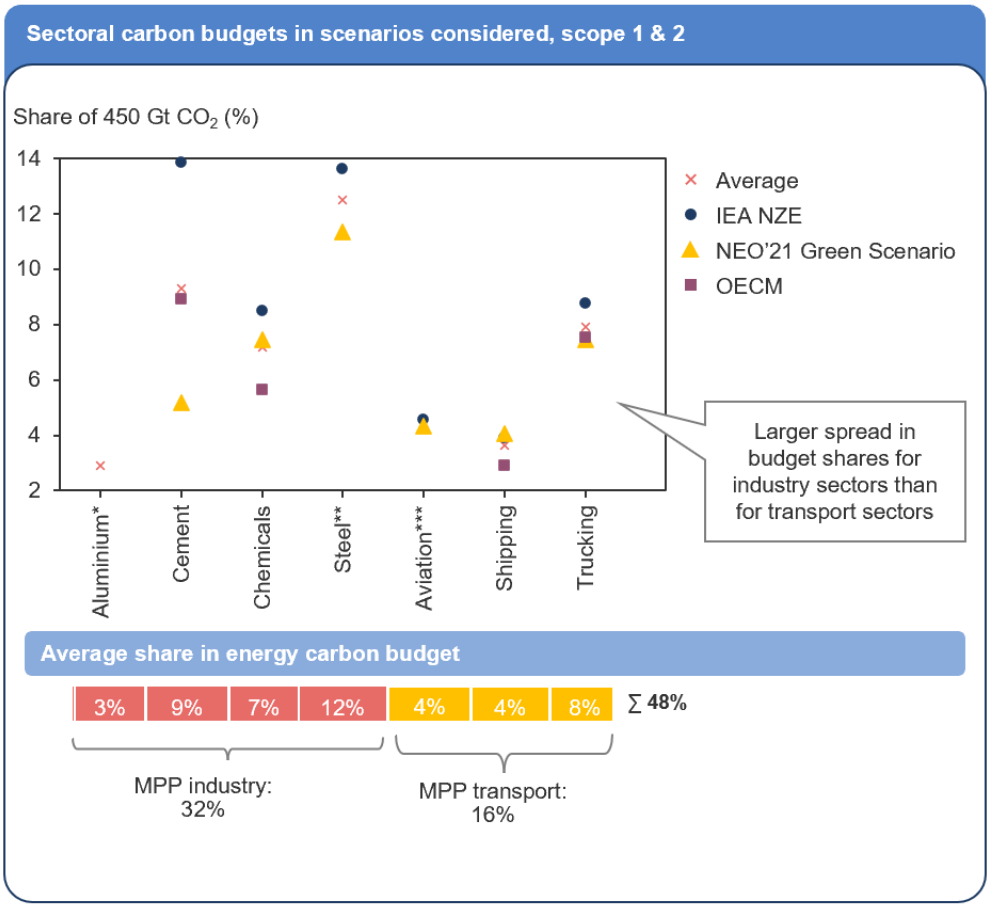

Sectoral carbon budgets in scenarios considered, scope 1 & 2

*Exhibit 22: Methodology for sectoral allocation of carbon budget, based on IEA NZE[52], OECM[53], BloombergNEF NEO 2021[51], ETC analysis. *Not broken out as a sub-sector in IEA NZE; **OECM Steel value not included in average because of significant deviation to the other scenarios.*

Based on this methodology, the 1.5°C carbon budget for the chemical industry from the beginning of 2020 amounted to about 32 Gt CO_2. Based on its 33% share in total chemical industry emissions in 2020[i], the ammonia industry is allocated 20%-50% (**5-16 Gt CO_2, midpoint 11 Gt CO_2**). For this allocation, a 50% variability is assumed to account for the large uncertainty in breaking down the carbon budget to different sectors. Finally, subtracting the CO_2 emissions from the global ammonia sector in 2020 and 2021 leaves a remaining carbon budget from the beginning of 2022 of about 10 Gt CO_2.

10 Gt CO_2 is the estimated carbon budget for the ammonia sector from the beginning of 2022

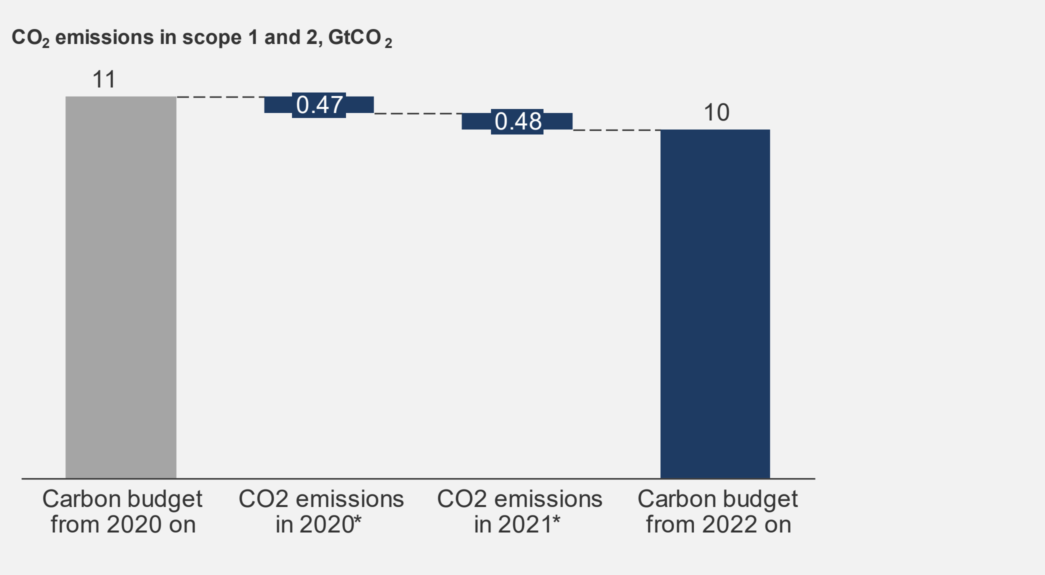


*Exhibit 23: 1.5°C carbon budget for the global ammonia sector from the beginning of 2020 and 2022, respectively. *2020 and 2021 emissions are as projected by the Sector Transition Strategy Model for the BAU scenario.*

5 Sector Transition Strategy Model

The Ammonia Sector Transition Strategy Model simulates pathways to net-zero emissions by 2050 for the ammonia sector by using a bottom-up approach in which investment decisions are optimised on the plant level under a set of constraints. The model is implemented in Python, a widely used programming language for data science and optimisation modelling.

The model design, inputs and key formulas were checked with various industry stakeholders, including ammonia producers, to ensure a robust model design that simulates real-world design making in the ammonia industry.

As shown in Exhibit 24, the model first takes the set of calculation inputs to calculate cost and emission metrics for every possible switch from one supply technology to another, including the construction of a new plant at a greenfield side. In the next step, these cost and emission metrics are employed in the year-by-year optimisation of plant investment decisions, during which plants can undergo different types of technology switches. These technology switches are chosen dependent on the scenario logic and optimised under a set of constraints. The aggregation of the annual plant-level simulation then leads to a transformation pathway for the ammonia supply technology mix to net-zero in 2050. The model employs a yearly granularity between 2020 and 2050 for 10 regions and 4

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[i] CO_2 in scope 1 and 2

exemplary low-cost power regions. In the following, each step shown in Exhibit 24 is explained in detail.

The model uses a bottom-up approach to simulate net-zero pathways for the ammonia industry

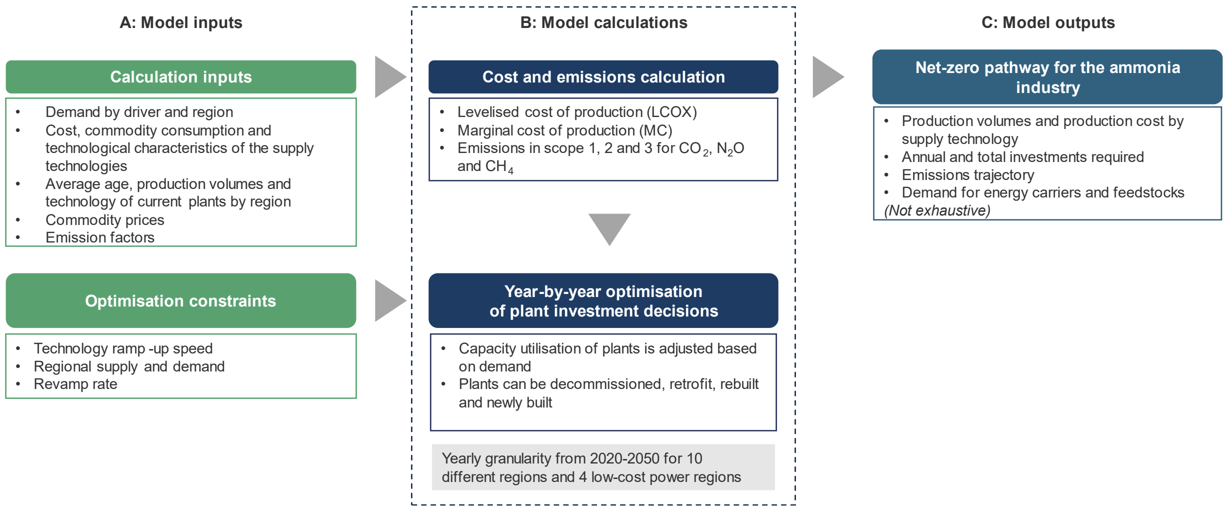


Exhibit 24: Modelling approach underpinning the Sector Transition Strategy.

5.1 Calculation inputs

The model is designed to simulate the evolution of the supply technology mix of the ammonia industry in a scenario-dependent logic for optimising plant investment decisions. The demand for ammonia, ammonium nitrate and urea in every region and year is taken as an exogeneous assumption that does not interact with the supply part of the model (see section 2 of the Technical Appendix for the demand drivers and scenarios).

The calculation inputs for each supply technology (see section 3 of the Technical Appendix) are listed in Exhibit 25.

Input parameter	Unit	Symbol
Initial CAPEX investment (differentiated into newbuild and retrofit) per ton of annual production capacity	USD/tpa	$CAPEX_0$
Fixed OPEX per ton annual production capacity	USD/tpa	$OPEX_t$
Fuel, feedstock or hydrogen storage input per ton produced	GJ/t	E_{input}
Capture rate for CO_2 and N_2O emissions	%	ξ
Technology lifetime	Years	T
Weighted average cost of capital	%	$WACC$
Standard capacity utilisation factor	%	CUF

Exhibit 25: Calculation inputs to the model for each supply technology.

Because of the difficulty of accurately depicting variation across business cases and regions, the WACC is set at a standard value of 8% for all supply technologies and all regions. This is aligned with the WACC used by the IEA in their report “The Future of Hydrogen”[37]. The standard Capacity Utilisation

Factor (CUF) is set at 0.95, which might be adjusted for a specific plant during the year-by-year optimisation.

In addition to the calculation inputs specific to each technology, the model also uses emission factors for CO_2, N_2O and CH_4 for every input in scope 1, scope 2 and scope 3 upstream, and for the application of ammonia, ammonium nitrate and urea as fertiliser (scope 3 downstream emissions). These are listed in Exhibit 26**Error! Reference source not found.**.

Emission factors of inputs	tCO2/GJ	ef_{input}
Emission factors of outputs	tCO2/t of product	ef_{output}
Cost of an input	USD/GJ	c_{input}
Cost of CCUS (split into transport and storage)	USD/CO_2	c_{CCS}

Exhibit 26: Emission factor and cost inputs to the model.

The last set of calculation inputs describes the initial state of the ammonia industry in 2020, for which the International Fertilizer Association provided data that was aggregated into the 10 model regions. The initial industry state is described for each of the 10 regions in the form of archetype plants with an average duration since the last revamp of the plant (Exhibit 30). The annual production capacity in each region along with the 2020 demand determines how many archetype plants are initialised in each region and for each product when the annual optimisation logic starts in 2020.

This plant archetype approach does not seek to accurately depict the state of the ammonia industry on the level of existing plants, since the goal of the model is not to show the optimum transformation pathway for a specific plant that exists today in a certain location, but rather for the ammonia industry as a whole. Therefore, using archetype plants is sufficient for simulating the transformation pathway of the entire industry with the described bottom-up approach of optimising investment decisions at the plant level.

Product	**Region**[ii]	**Plant technology**	**Annual production capacity (Mtpa)**	**Average duration since last plant revamp (years)**
Ammonia	North America	Natural Gas SMR	8.7	12
	Latin America	Natural Gas SMR	5.9	13
	Africa	Natural Gas SMR	2.2	9
	Middle East	Natural Gas SMR	5.4	13
	Russia	Natural Gas SMR	9.9	9
	Europe	Natural Gas SMR	4.1	20
	China	Coal Gasification	18.6	9
		Natural Gas SMR	3.4	9
	India	Natural Gas SMR	1.0	12
	Rest of Asia	Natural Gas SMR	5.9	18
	Oceania	Natural Gas SMR	0.2	6

[ii] Low-cost power regions are not included here because they are mapped to their corresponding regions (e.g. Brazil to Latin America) and are only considered for newbuild production capacity.

Ammonium nitrate	North America	Natural Gas SMR	10.8	14
	Latin America	Natural Gas SMR	2.9	10
	Africa	Natural Gas SMR	5.2	9
	Middle East	Natural Gas SMR	2.1	21
	Russia	Natural Gas SMR	12.9	10
	Europe	Natural Gas SMR	25.5	23
	China	Coal Gasification	15.6	12
		Natural Gas SMR	2.9	12
	India	Natural Gas SMR	1.4	11
	Rest of Asia	Natural Gas SMR	5.5	19
	Oceania	Natural Gas SMR	2.7	10
Urea	North America	Natural Gas SMR	16.4	10
	Latin America	Natural Gas SMR	6.6	6
	Africa	Natural Gas SMR	12.9	12
	Middle East	Natural Gas SMR	25.0	13
	Russia	Natural Gas SMR	9.8	8
	Europe	Natural Gas SMR	16.5	13
	China	Coal Gasification	54.6	8
		Natural Gas SMR	10.0	8
	India	Natural Gas SMR	25.7	9
	Rest of Asia	Natural Gas SMR	28.0	14
	Oceania	Natural Gas SMR	1.7	7

Exhibit 27: Regional archetype plants used to describe the 2020 state of the ammonia industry (aggregated from data provided by the International Fertilizer Association).

As part of the described approach of using archetype plants, a standard production capacity of 2000 tNH_3/day is assumed for every ammonia plant, and translated into the according production capacity for ammonium nitrate and urea plants, respectively (Exhibit 28).

Product	Standard plant production capacity (t/day)
Ammonia	2,000
Ammonium nitrate	4,700
Urea	3,540

Exhibit 28: Standard production capacities assumed for all ammonia, ammonium nitrate and urea archetype plants in the model.

In all scenarios, the model also integrates the pipeline of announced projects, which reach until 2040. The pipeline is based on IRENA's 2022 report "Innovation Outlook: Renewable Ammonia"[54]. In this case, the actual announced capacity is used instead of the standard production capacities for archetype plants. The project pipeline has been aggregated from company announcements and is summarised in Exhibit 29.

		Cumulative installed production capacity (tNH_3/year)								
Supply technology	**Region**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2030**	**2035**	**2040**

Natural Gas SMR + CCUS (process emissions only)	Middle East	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	North America	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Natural Gas SMR + CCUS	Australia	0	0	0	0	0	0.8	0.8	0.8	0.8
	Europe	0	0	0	0	0	1.2	2.1	2.1	2.1
	Middle East	0	0	0	0	0	1.0	1.0	1.0	1.0
	North America	0	0.4	0.4	0.4	0.6	0.6	0.6	0.6	0.6
	Rest of Asia	0	0	0	0	0	0	0.7	0.7	0.7
Electrolyser - dedicated VRES + H2 storage - geological + ammonia synthesis	Africa	0	0	0	0	0	0	0.2	0.2	0.2
	Australia	0	0	0.4	0.5	0.7	3.3	9.5	15.5	15.5
	Europe	0	0	0	0.3	0.6	0.9	1.6	1.6	1.6
	Latin America	0	0	0	0	0	0.1	1.6	0.9	0.9
	Middle East	0	0	0	0	0	1.3	9.0	11.6	13.1
	North America	0	0	0	0.0	0.0	0.2	0.2	0.2	0.2

Exhibit 29: Announced project pipeline (based on [54]) integrated into the model in terms of cumulative installed production capacity split by supply technology and region.

Source: IRENA[55]

5.2 Cost and emissions calculation

Emissions calculation

Emissions of CO_2, CH_4 and N_2O are calculated for all scopes by multiplying the emission factors ef with the quantity of input required for producing one ton of ammonia, ammonium nitrate or urea. In scope 1, direct emissions from fuel and feedstock inputs occur for CO_2 and, only in the case of ammonium nitrate, N_2O. For supply technologies with CCUS and a nitrous oxide scrubbing (all ammonium nitrate supply technologies), a capture rate is applied to total scope 1 emissions.

$$m_{CO_2\ or\ N_2O, scope\ 1} = \xi_{capture} * \left(\sum_{all\ feedstock\ inputs} E_{feedstock\ input} * ef_{feedstock\ input, scope\ 1} + \sum_{all\ energy\ inputs} E_{energy\ input} * ef_{energy\ input, scope\ 1} \right)]$$

GHG emissions in scope 2, i.e. indirect emissions from the generation of electricity that is used as an input for the supply technology, are calculated analogously without a capture rate. Scope 3 upstream emissions pertain to upstream supply chain-chain emissions from fossil fuel production, also use the same approach. For scope 3 downstream emissions, which stem from the application of ammonia, ammonium nitrate and urea as fertiliser, are calculated by multiplying the quantity of the product used as fertiliser with the respective emissions factor.

Cost calculation

The model employs two cost metrics: the Levelised Cost of Product X (LCOX) and the Marginal Cost of Producing X (MCX).

The LCOX describes the annual cost of investment per unit of production. Its definition stems from a discounted cash flow analysis and thus corresponds to the price of product X for which the Net Present Value (NPV) of the investment is zero. Hence, LCOX allows to directly compare the cost of an investment to market prices (and assess its profitability), and compare the profitability of different investment options among each other. This is why the model uses LCOX as the cost metric to compare the cost of technology switches among each other and identify the lowest-cost technology switch.

The LCOX for a specific supply technology for ammonia, ammonium nitrate or urea is calculated by dividing the NPV of investing in that supply technology by the total discounted production over the technology lifetime T. The NPV is the sum of the initial investment and the total discounted OPEX over the lifetime.

$$LCOX = \frac{CAPEX_0 + \sum_{t=0}^{T} \frac{OPEX_{fixed,t} + CUF * OPEX_{variable,t}}{(1 + WACC)^t}}{CUF * \sum_{t=0}^{T} \frac{1\ tpa}{(1 + WACC)^t}}$$

The application of the carbon cost in the LC scenario is effected by adding the carbon cost component to the LCOX. For this, total CO_2 emissions in scope 1, scope 2 and scope 3 upstream are summed for the supply technology in a given region for each year. The multiplication with the carbon cost in each year then gives an additional variable OPEX that increases the total discounted OPEX and thus the LCOX accordingly.

The MCX describes the cost of producing an additional unit of product X in a specific year t, and is hence identical to the total OPEX in that year. This metric is used by the model to construct a merit order for adjusting the capacity utilisation of plants, which is explained in the next section.

$$MCX_t = OPEX_{fixed,t} + CUF * OPEX_{variable,t}$$

The multiplication of variable OPEX with the Capacity Utilisation Factor (CUF) in both formulas is necessary in order to express both OPEX components relative the installed production capacity when they are summed.

Carbon cost trajectories in the LC scenario

In the LC scenario, several carbon cost trajectories were tested to find a net-zero pathway (Exhibit 30). In each trajectory, the carbon cost starts increasing linearly from 2026 on by 10 USD/tCO$_2$ each year until it reaches its final value. For a final carbon cost of 100 USD/tCO$_2$, this is the year 2035, for 200 USD/tCO$_2$ the increase stops 10 years later in 2045. From this, the carbon cost trajectory with a final cost of 100 USD/tCO$_2$ reached in 2035 was chosen, as the modelling showed this to be the minimum carbon cost required to drive technology switches such that the supply technology mix becomes net-zero until 2050.

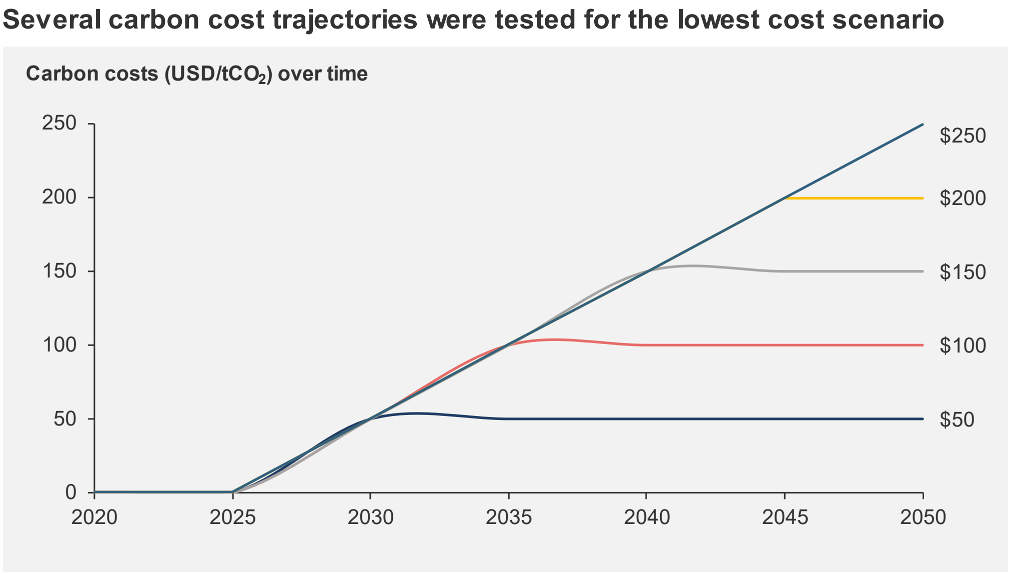


Exhibit 30: Carbon cost trajectories with different final values that were tested in the lowest cost scenario.

5.3 Year-by-year optimisation of plant investment decisions

After calculating the emissions and cost metrics for all technology switches, the model enters into the year-by-year optimisation of technology investment decisions on a plant level. The optimisation logic is shown in Exhibit 31 and consists of two steps in every year between 2020 and 2050: first, adjust capacity utilisation of each plant; second, find the optimum technology switch for each plant.

In the first step, adjusting capacity utilisation, the model first calculates the global demand balance. If there is a production deficit, i.e. demand exceeds supply, the CUFs of plants are increased in the order from lowest to highest MCX to an upper CUF threshold of 0.95 until either the demand is met or all plants operate at the maximum CUF. If there is a production surplus, i.e. supply exceeds demand, the CUFs of plants are decreased in the order from highest to lowest MCX to a lower CUF threshold of 0.5 until either supply meets demand or all plants operate at the minimum CUF. This adjustment mimics a merit order approach in which those plants are ramped up that can supply the market at the lowest cost.

In the second step, the model searches for the optimum technology switch for each plant. Every year, a plant can undergo four types of technology switches or remain unchanged:

1. Newbuild: construction of a new plant on a greenfield site.
2. Rebuild: construction of a new plant on a brownfield site, i.e. complete replacement of an existing plant.
3. Retrofit: addition of either a CCUS unit or a revamp electrolyser to an existing plant employing Natural Gas SMR or Coal Gasification.
4. Decommission: demolishing of an existing plant.

For a plant to be eligible for either of these four technology switches, certain conditions need to be fulfilled. For a plant to be decommissioned, it needs to operate at the minimum CUF of 0.5 and be older than 20 years. Plants are decommissioned until supply is low enough to no longer exceed demand.

Regardless of whether there is a production surplus or deficit, plants can undergo renovation (i.e. rebuild or retrofit): a plant can be rebuild if it operates at above the minimum CUF threshold and is older than 20 years. This duration was chosen as a reasonable approximation to ensure that the initial investment in the plant is written off when it is rebuilt. In contrast, a retrofit of a plant can happen at any time, but only once, during its lifetime. To take into account that the real-world capacity for renovating existing plants is limited, e.g. by the availability of engineering capability and construction lead times, the model has a revamp constraint such that maximum 5% of all existing plants can be rebuilt or retrofit in each year. If a plant is eligible for renovation, the choice of destination technology depends on the scenario logic: in the LC scenario, the destination technology with the lowest LCOX of all possible destination technologies is chosen in order to simulate a net-zero pathway with the lowest total cost to industry. However, the switch only happens if the destination technology has an LCOX that is at least 5% lower than the LCOX of the current technology. This features seeks to simulate real-world investment decision making, where a plant would only be switched to a new technology if production cost is decreased substantially. In contrast, in the FA scenario the destination technology for a retrofit or renovation is chosen according to the highest reduction in emissions (scope 1 and 2 CO_2), with a small weight given to LCOX to avoid an unrealistic uptake of particularly expensive zero emissions supply technologies. In this way, the FA scenario simulates a pathway that reduces emissions to net-zero as fast as possible. Due to the constraints on the renovation technology switches, in a given year many plants will not be renovated, such that they remain unchanged and are thus eligible for a retrofit or rebuild in subsequent years.

After eligible plants have been renovated under the set of constraints, the model builds new plants until global production and demand for each of the three products are balanced. The choice of newbuild region and technology again depends on the scenario logic: in the LC scenario, the regions and supply technologies with the lowest LCOX are chosen, while satisfying the constraints that will be explained in the next section. In the FA scenario, the regions and supply technologies with the lowest emissions are selected. Again, a small weight is given to the LCOX of supply technologies in the FA scenario, such that the technology with lower LCOX is selected if two technologies have the same emissions.

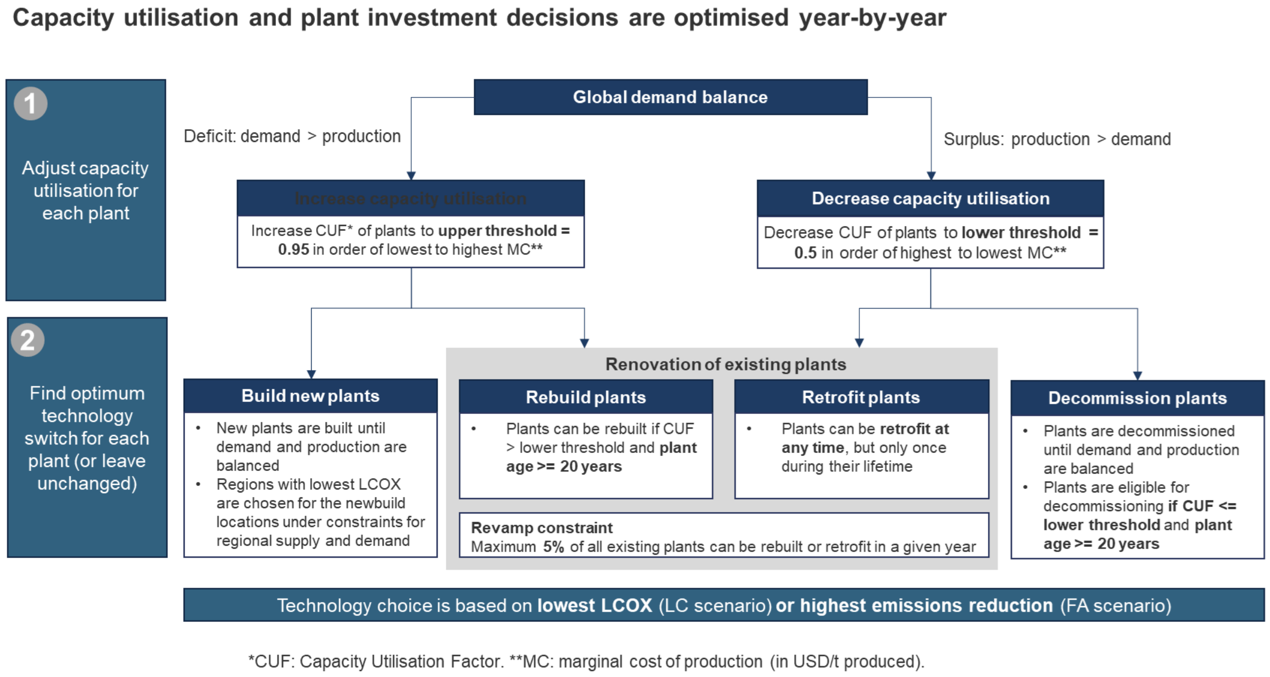


Exhibit 31: Design of the annual optimisation of plant investment decisions.

Consideration of trade

As explained above, the adjustment of plants' capacity utilisation and construction of new plants is based on a global demand balance. The assumption underlying this modelling approach is that ammonia, ammonium nitrate and urea are globally traded commodities with new global demand, in particular for ammonia, being supplied by those locations where the production cost is lowest. The model does not include any transport costs or consideration of trade flows, because this would substantially increase model complexity without providing significant new insights on the global level of transitioning the ammonia sector to net-zero. In the absence of modelling trade, the constraints on regional supply and demand (see next section) prevent that one region would supply unrealistically large shares of demand in other regions, which amounts to a similar effect as including transport costs between regions.

Consideration of uncertainty

The model is designed fully deterministic, with one exception: in choosing the technology switch with lowest LCOX, a ranking methodology is employed where technology switches with very similar LCOX are assigned the same rank score. This serves to avoid that one technology completely wins out over another if the difference in LCOX between the two technologies is very small, and likely smaller than the uncertainty in the various cost components contributing to LCOX. The histogram-based algorithm for assigning the same rank score uses a relative uncertainty of 10% for creating bins for LCOX values that each correspond to an identical rank scores. The model then chooses randomly from technology switches with the same rank score.

5.4 Constraints

The yearly optimisation of plant investment decision takes place under a set of constraints. When the model selects a plant to undergo a technology switch, all the below constraints are checked. The technology switch is only executed when none of the constraints is hurt. For example, when the model selects a plant with Natural Gas SMR to be retrofit with a CCUS unit, this technology switch might not be executed if the constraint on available CO_2 storage is hurt.

Constraints on regional supply and demand

In the absence of modelling transport costs for shipping ammonia, ammonium nitrate and urea between different regions, the model uses constraints on regional supply and demand to ensure that no unrealistic shifts of substantial parts of existing and/or new production capacity to a single region take place. In every year, each region can supply a maximum share of 30% of new global demand, and minimum 40% of demand in each region needs to be me by production in that region. In the constraints application, the four low-cost power regions are mapped to the corresponding larger regions, i.e. Brazil is included in Latin America, Namibia in Africa, Saudi Arabia in the Middle East and Australia in Oceania.

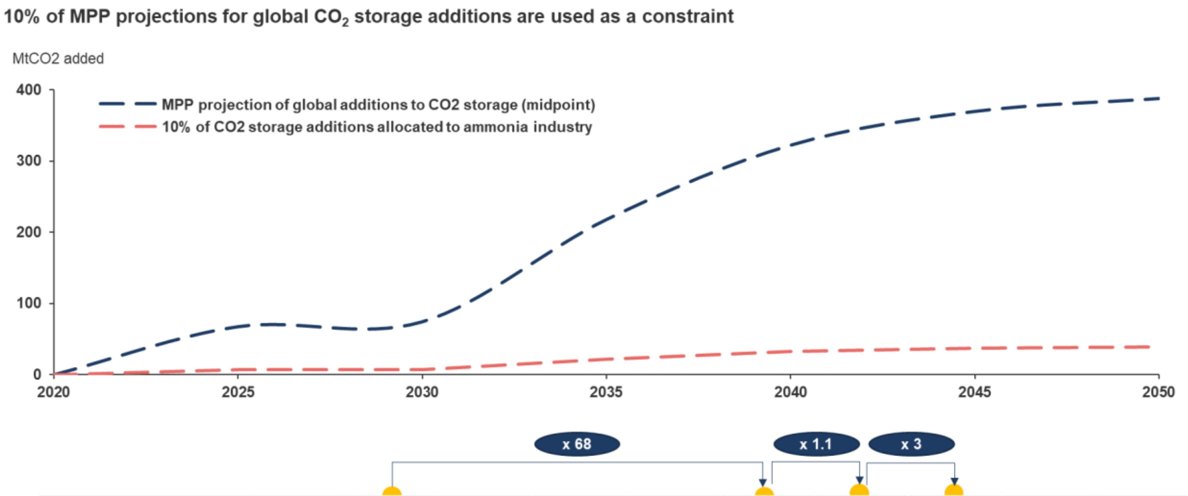
Constraint on technologies to supply new demand

In the LC and FA scenarios, almost all new demand for ammonia comes from net-zero drivers, i.e. the ammonia is used to decarbonise other sectors. Hence, the model is constrained such that new demand for ammonia can only be supplied by transitional and near-zero emissions technologies, not by Natural Gas SMR and Coal Gasification. This constraint is not in place for ammonium nitrate and urea.

Constraint on available CO_2 storage

The speed and extent at which supply technologies using CCS can be deployed depends on the availability of geological CO_2 storage.

Annual additions of production capacity using CCS are constrained by global annual additions in geological CO_2 storage, for which 10% of MPP projections for cumulative available CO_2 storage are allocated to the ammonia industry (Exhibit 32). The sectoral allocation is based on the 2020 emissions share of the ammonia industry in total industry emissions. The underlying projections have been developed internally by MPP and are aligned with projections of the ETC that will be published in a forthcoming report[56]. The constraint is applied such that the total amount of CO_2 captured by all plants using CCS cannot exceed the global addition of new CO_2 storage capacity (i.e. new storage projects coming online) in that year. The curve of annual CO_2 storage additions shown in the Exhibit hence roughly follows an S-shape, while cumulative CO_2 storage available would show an exponential increase. The MPP projection is based on announced projects until 2030, and afterwards follows an extrapolation aligned with ETC projections for CO_2 storage availability in 2050.



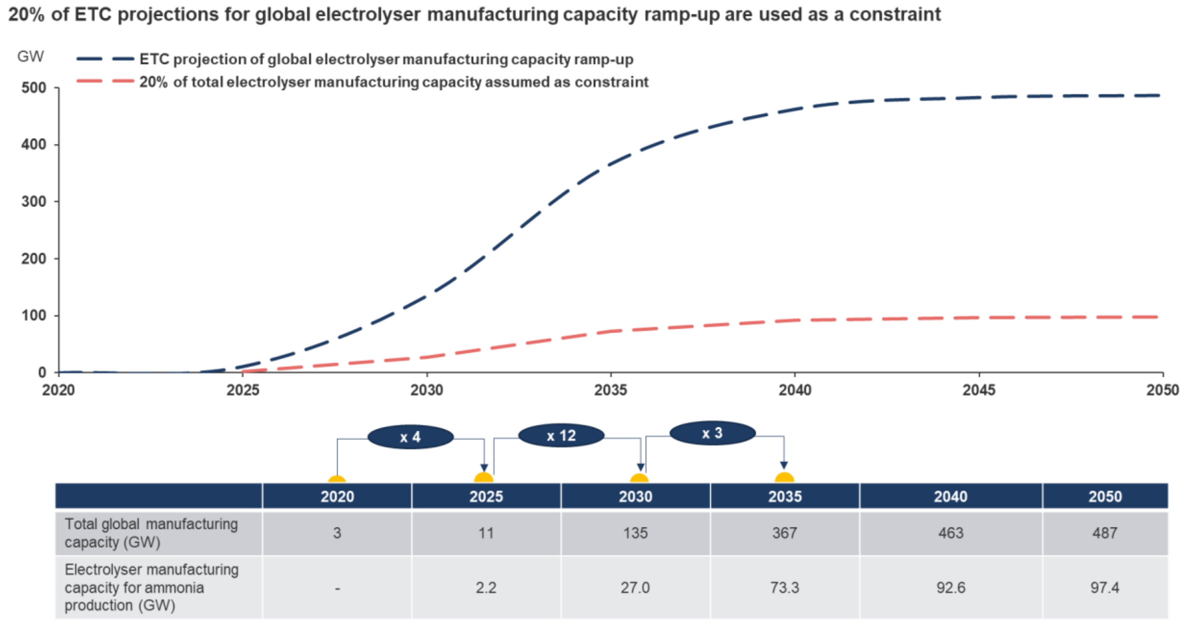
	2020	2021	2022	2023	2024	2025	2030	2035	2040	2050
Total global addition in CO_2 storage (Mt CO_2)	0	1	3	9	33	68	75	218	323	370
Global addition in CO_2 storage allocated to ammonia industry (Mt CO_2)	0	0.1	0.3	0.9	3.3	6.8	7.5	21.8	32.3	37

Exhibit 32: MPP projections for global CO_2 storage additions along with allocation to the ammonia industry as a constraint in the model.

Constraint on annual electrolysis capacity additions

The speed and extent at which supply technologies using electrolysis can be deployed depends on the global manufacturing capacity for electrolysers. Hence, in the model global annual additions of electrolysis capacity are constrained to maximum 20% of ETC projections for global electrolyser manufacturing capacity ramp-up (

Exhibit 33). For the ETC projections, which are outlined in the recent report "Making the Hydrogen Economy Possible", the highly aggressive scenario with 776 Mt of green hydrogen produced globally in 2050 was chosen[19].



20% of ETC projections for global electrolyser manufacturing capacity ramp-up are used as a constraint

	2020	2025	2030	2035	2040	2050
Total global manufacturing capacity (GW)	3	11	135	367	463	487
Electrolyser manufacturing capacity for ammonia production (GW)	-	2.2	27.0	73.3	92.6	97.4

Exhibit 33: ETC projections for global electrolyser manufacturing capacity ramp-up and allocation as a constraint for ammonia production.

Constraint on revamp of existing assets

As explained in the previous section already, maximum 5% of the entire plant stack can be revamped annually, i.e. undergo a retrofit or rebuild switch. This serves to ensure a realistic replacement rate of currently existing assets as the industry transforms to net-zero. Furthermore, to take project lead times into account, retrofit transitions can only start in 2025 and rebuild transitions in 2027.

Regional technology restrictions

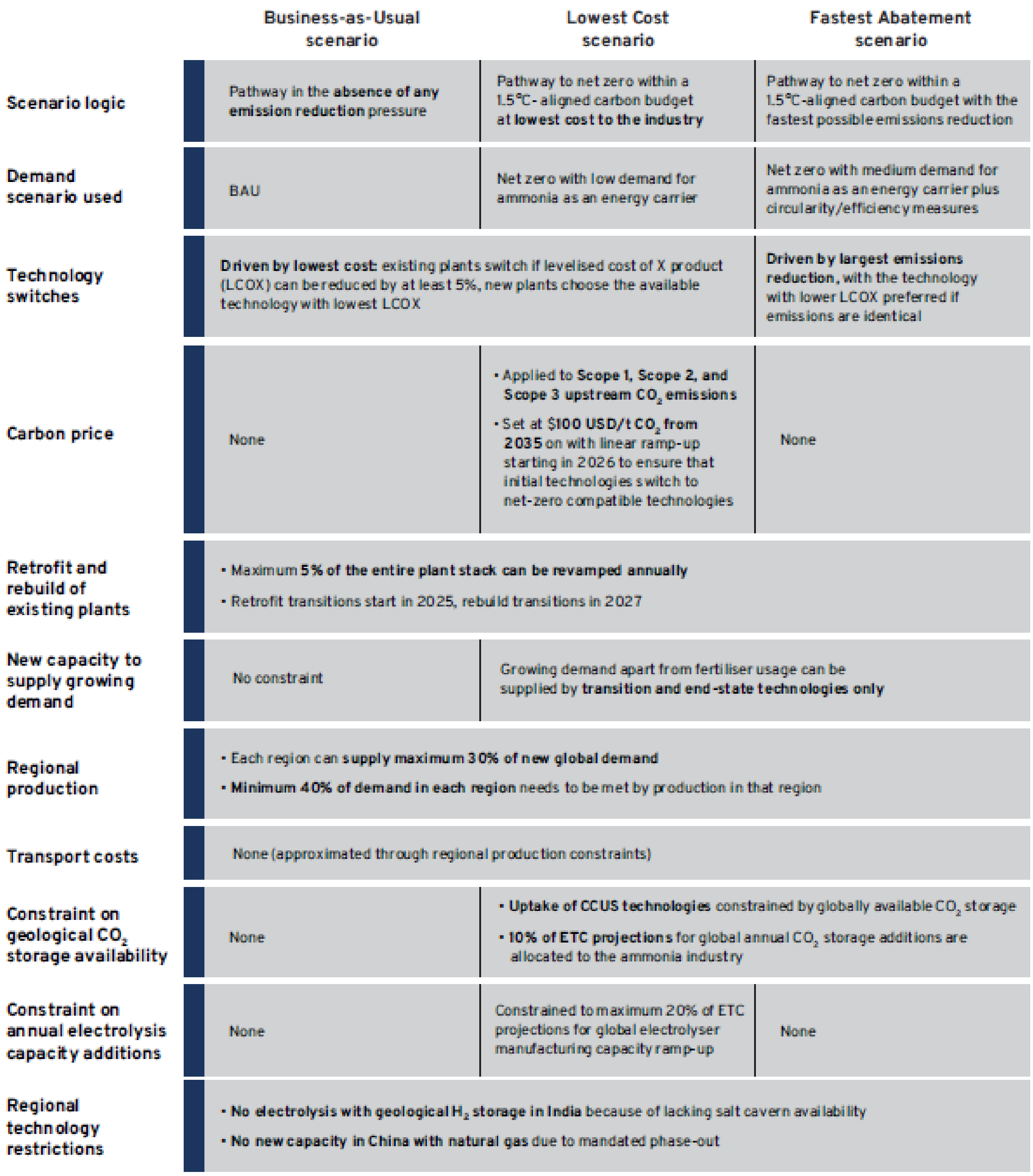
Two regional technology restrictions have been introduced to take regional specificities into account:

1. In India, electrolysis with geological H_2 storage cannot be used as a supply technology of the lack in salt cavern availability for geological H_2 storage.

2. In China, plants cannot switch to supply technologies using natural gas due to the mandated phase-out of natural gas based technologies.

5.5 Scenario logic

1. The BAU and LC scenario are driven by lowest cost, while the FA scenario choose those technology switches with the largest emissions reduction.
2. The carbon price is only applied in the LC scenario to unlock a net-zero pathway that minimises total cost to industry.
3. The electrolysis capacity addition constraint is only applied in the LC scenario, because this scenario seeks to depict an ambitious but realistic lowest-cost pathway to net-zero that should rely on a feasible uptake of both blue and green ammonia supply technologies.



	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		

Exhibit 34: Summary of the logic and key model assumptions for the three scenarios.

6 Government regulation

Policy interventions

The instauration of a public policy framework is included as a key condition in the development of the possible development routes for the new ammonia economy described in this report. The public policies listed are aimed at unblocking supply and demand and accelerating its expansion the industrial sectors described in this report.

To get the most out of these public policies, they must be deployed and sequenced in order. The way in which they are established must accompany the transformation of the sector and promote the correct incentives across stakeholders in the value chain, promoting growth and minimizing the appearance of bottlenecks. The construction of public policy frameworks will have to be carried out across various jurisdictions and over the next 3 decades, which will imply that policy implementation routes adapt to complex regional context and dynamics.

Even so, priorities and general routes can be established to maximize the return of these efforts. The public policy recommendation described in this report follows the following premises:

1. The first priority is the establishment of enabling policies, particularly to unlock the use of new applications of ammonia in power systems. These policies consist of approvals and certifications for the use of ammonia as maritime fuel, for power generation, and as a hydrogen vector. They are essential to dictate the rules for the safe handling and trade of ammonium and therefore necessary conditions to begin its incorporation into these sectors.
2. As the production of near-zero emissions ammonia begins to scale and supply reaches industrial levels, the establishment of direct regulation mechanisms gain relevance. These mechanisms are necessary to prescribe ammonium intake across sectors, even when the gaps in competitiveness against conventional alternatives remain high. These mechanisms must be addressed with a dual effect: (i) mechanisms that set the conditions for near-zero emissions ammonia uptake (e.g. fuel mandates, content requirements, etc); (ii) mechanisms that increase restrictions on the use of fossil fuel alternatives (e.g. performance standards)
3. The establishment of Market-based mechanisms (MBMs) are equally a priority, however their activation and expansion will probably be seen later in time due to the additional complexities in their design, legislation and deployment across jurisdictions. Within this portfolio of policy instruments there are also sequencing routes to be incorporated. Despite the effectiveness of carbon pricing schemes to accelerate uptake of low-emissions alternatives against conventional fossil-based sources across markets, the complexity to design, legislate and implement these mechanisms may take the course of this decade and beginning of the next. Even so, there are mechanisms with less impact but with greater ease of being implemented, such as the implementation of cap and trade systems, carbon border adjustment mechanisms, ETS, which can pave the way for broader and more ambitious MBMs.
4. Finally, and when near-zero emissions ammonia supplies and competitiveness is paired to meet the majority of the sectors' demands, then far-reaching bans and moratorium can come into force that culminate in the extinction of highly-emitting alternatives from the sectors at play.

7 The cost of inaction

Carbon emissions cause a future economic damage that is currently not internalized in the use of fossil fuels. The so-called social cost of carbon (SCC) quantifies this economic damage. In a 2018 study, the SCC has been estimated to be $417 (177-805) per tonne of CO2.[57]

However, there is mounting scientific evidence that inaction on climate change will be even more expensive than decarbonising our economies, with a new 2021 study suggesting social costs of carbon of over $3,000 per tonne of CO2.[58,59] Large uncertainties exist around the impact of climate change on long-term economic growth "and how far societies can adapt to reduce these damages; depending on how much growth is affected, the economic costs of warming this century could be up to 51% of global GDP."[58]

Using these SCC estimates, the cumulative investments of $2-3 trillion required for transitioning global ammonia to net-zero and scaling up production to meet demand from energy applications compare to a social cost of carbon of $3 (1-5) trillion if the sector were to be unmitigated until 2050 and an additional $4 (2-7) trillion if the shipping sector were to fail to decarbonise as a result. This is based upon the SCC values of the 2018 study. Using the 2021 study's estimates, these numbers could be as high as $20 trillion and $27 trillion respectively.

From a socio-economic perspective, the upsides of the transition outweigh its cost; decarbonising the ammonia sector would have a net-positive financial impact on the global economy. Despite all uncertainties inherent to such estimates, this comparison indicates that inaction is not an option: regarding climate change, in terms of long-term economic growth[59] as well as with regards to pollution and human health[60]. Human well-being will benefit from decisive action in terms of all these aspects.

8 Limitations

The modelling presented in this analysis has significant uncertainties, some of which are explored in the sensitivity analysis in the main report.
There are several other limitations highlighted below, which are not captured within any sensitivity analysis.

Limitation	Description
Geographic granularity	Energy and commodity price input assumptions were modelled on a region-by-region basis. However, the model regions such as Europe and Africa cover large areas and include many countries in which the dynamics are very different. Therefore, it is likely that the values used to represent prices in these vast regions do not reflect the reality seen by individual plants in specific locations.
Asset-level data	Due to the lack of open-source plant-level data, simplifying assumptions had to be made whereby all plants with a certain technology e.g. SMR were assumed to be the same in terms of efficiency, inputs, energy requirements etc.
Trade flows	The analysis assumes that trade friction cost are comparatively low, and therefore trade flows and costs are not modelled. Existing production is assumed to remain in its current locations, whereas new capacity can be built anywhere in the world under the constraints on regional supply and demand explained in Section 5 of the Technical Appendix.
Supply-demand modelling of the sector	The modelling is focused on the underlying production costs of the supply of ammonia. It does not attempt to model the interaction of supply and demand for ammonia via trade flows. It is likely that decarbonising the sector will result in changes to the supply of ammonia and how that interacts with demand as some customers might move faster on near-zero emissions ammonia than others.
Non-economic decision-making factors	The modelling conducted uses the levelised of ammonia production for investment decision-making. Non-economic factors for decision-making are not included, for example geopolitical

	considerations, countries deciding to impose import/export restrictions or carbon border adjustments.
Technology development	New technology has a key role in decarbonising the sector, with new electrolyser and CCS technology playing a critical role as well as emerging routes such as methane pyrolysis. The costs, performance and availability of these technologies are highly uncertain, given many technologies have not reached commercial maturity today. In addition, other technologies might emerge that offer additional benefits or transformational step changes. Furthermore, the possible deployment speed for each of these technologies is uncertain, which has been approximated in the modelling through constraints on available CO_2 storage and electrolyser manufacturing capacity.

These uncertainties are inherent in any modelling of a complex sector, particularly given the interaction of global and local markets for ammonia and ammonia derivatives, the large uncertainty in the uptake of ammonia as an energy carrier, and interlinkages with the wider energy system. Many of these limitations can be addressed when actual projects are designed and will be part of the investment decision making process for individual plants.

Furthermore, this is the first iteration of an industry backed global strategy charting multiple pathways to net-zero for the ammonia sector. Future iterations of this work should seek to address some of these limitations and improve on this approach. In addition, the open-source nature of the modelling allows others to base their own analysis on the broad approach and evidence collected by MPP. These additional insights that others generate about the sector are key to mapping out how the ammonia sector can transform to net-zero on a 1.5°C consistent trajectory.

Bibliography

1. Fortune Business Insights. Ammonia Market Size & Share | Industry Analysis Report, 2028. https://www.fortunebusinessinsights.com/industry-reports/ammonia-market-101716 (2021).
2. IEA. *Ammonia Technology Roadmap*. https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf (2021).
3. FAO. *The future of food and agriculture – Alternative pathways to 2050*. (FAO, 2018).
4. UMAS. A Strategy for the Transition to Zero-Emission Shipping. https://www3.weforum.org/docs/WEF_A%20Strategy_for_the_Transition_to_Zero_Emission_Shipping_2021.pdf (2021).
5. UMAS. *International Maritime Decarbonisation Transitions (forthcoming, accessed April 2022, subject to change)*.
6. DNV-GL. *Maritime forecast to 2050*. (2020).
7. IEA. *Energy Technology Perspectives*. (2020).
8. UMAS, Getting to Zero coalition. Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping. https://www.globalmaritimeforum.org/content/2021/12/Closing-the-Gap_Getting-to-Zero-Coalition-report.pdf (2022).
9. Llyod's Register, UMAS. *Techno-economic assessment of zero-carbon fuels*. (2020).
10. Mærsk Mc-Kinney Møller center for Zero carbon shipping. NavigaTE to Zero: Modelling of the maritime decarbonization. https://cms.zerocarbonshipping.com/media/uploads/documents/NavigaTE_Whitepaper_final.pdf (2021).
11. Al-Breiki, M. & Bicer, Y. Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon. *Energy Rep.* **6**, 1897–1909 (2020).

12. Hank, C. *et al.* Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. *Sustain. Energy Fuels* **4**, 2256–2273 (2020).
13. Sudipta Chatterjee, Rajesh Kumar Parsapur, & Kuo-Wei Huang. Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector. https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.1c02189 (2021).
14. Shoko Oda. Japan's Top Power Producer Seeks Long-Term Clean Ammonia Deal. *Bloomberg.com* (2022).
15. JERA. *2050 Road Map*. (2021).
16. MOTIE. Generate electricity from carbon-free fuels hydrogen and ammonia. http://www.motie.go.kr/motie/ne/motienewse/Motienews/bbs/bbsView.do?bbs_seq_n=155117902&bbs_cd_n=2&currentPage=1&search_key_n=&cate_n=&dept_v=&search_val_v= (2021).
17. Japanese Ministry of Economy, Trade and Industry. *Building an Ammonia Fuel Supply Chain*. (2021).
18. AFRY. The future market for low carbon hydrogen. https://afry.com/sites/default/files/2022-05/afrys_global_hydrogen_trade_model_v100_0.pdf (2022).
19. Energy Transitions Commission (ETC). *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*. https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf (2021).
20. IRENA. *Global Hydrogen Trade to meet the 1.5 °C Climate Goal*. https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II (2022).
21. FOLU. Growing Better. https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf (2019).
22. IIASA. *GLOBIOM Model*. (2019).
23. FOLU. *Growing Better: Ten Critical Transitions to Transform Food and Land Use*. https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf (2019).

24. Worell, E., Phylipsen, D., Einstein, D. & Martin, N. Energy Use and Energy Intensity of the U.S. Chemical Industry. https://www.osti.gov/servlets/purl/773773 (2000).
25. IEAGHG. Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS. https://ieaghg.org/exco_docs/2017-02.pdf (2017).
26. BEIS. *Hydrogen production costs 2021*. (2021).
27. Wood. Hydrogen Supply Programme - Novel Steam Methane / Gas Heated Reformer. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866384/Phase_1_-_Wood_-_Novel_Steam_Methane__Gas_Heated_Reformer.pdf (2020).
28. Sánchez, A., Martín, M. & Vega, P. Biomass Based Sustainable Ammonia Production: Digestion vs Gasification. *ACS Sustain. Chem. Eng.* **7**, 9995–10007 (2019).
29. Industrial Efficiency Technology Database. Ammonia | Industrial Efficiency Technology & Measures. http://www.iipinetwork.org/wp-content/Ietd/content/ammonia.html#benchmarks.
30. Alfa Laval, Hafnia, Haldor Topsoe, Vestas, & Siemens Gamesa. Ammonfuel - an industrial view of ammonia as a marine fuel. https://www.topsoe.com/hubfs/DOWNLOADS/DOWNLOADS%20-%20White%20papers/Ammonfuel%20Report%20Version%2009.9%20August%203_update.pdf.
31. Fasihi, M., Weiss, R., Savolainen, J. & Breyer, C. Global potential of green ammonia based on hybrid PV-wind power plants. *Appl. Energy* **294**, 116170 (2021).
32. DECHEMA. *Low carbon energy and feedstock for the European chemical industry*. https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf (2017).
33. Kirova-Yordanova, Z. Exergy Analysis of Ammonium Nitrate Production Plants. in (2014).
34. European Comission. Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/lvic_aaf.pdf (2007).

35. M. Batool & W. Wetzels. Decarbonisation Options for the Dutch Fertiliser Industry. https://www.pbl.nl/sites/default/files/downloads/pbl-2019-decarbonisation-options-for-the-dutch-fertiliser-industry_3657.pdf (2019).
36. IEA. Global Hydrogen Review 2021. https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf (2021).
37. IEA. The Future of Hydrogen. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf (2019).
38. BloombergNEF. *1H2021 Hydrogen Market Outlook*.
39. BloombergNEF. *Hydrogen – Economics of production from renewables*. (2019).
40. Parkinson, B., Matthews, J. W., McConnaughy, T. B., Upham, D. C. & McFarland, E. W. Techno-Economic Analysis of Methane Pyrolysis in Molten Metals: Decarbonizing Natural Gas. *Chem. Eng. Technol.* **40**, (2017).
41. World Bank. Commodity Markets Outlook - The Impact of the War in Ukraine on Commodity Markets. (2022).
42. IEA. World Energy Outlook 2021. https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf (2021).
43. BloombergNEF. *Data set: Cost and performance inputs for new-build power plants, BNEF 1H 2021 LCOE analysis*. (2022).
44. EU Joint Research Centre. *Cost development of low carbon energy technologies*. (2017).
45. EU Joint Research Centre. *The JRC-EU-TIMES model*. (2013).
46. LevelTen Energy. *Q4 2021 PPA Price Index*. https://www.leveltenenergy.com/post/q4-2021 (2021).
47. Pexapark. Pexa Euro Composite | Pexapark. https://pexapark.com/renewable-ppa-price-index-europe/?creative=543045913898&keyword=ppa%20prices&matchtype=p&network=g&device=c&gclid=EAIaIQobChMImbSnv4nz9QIVFoFQBh38zQWpEAAYASAAEgIjrvD_BwE (2022).

48. IPCC. Summary for Policymakers. in *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), 2018).
49. Roe, S. *et al.* Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Change* **9**, (2019).
50. EAT-Lancet Commission. Food Planet Health: Healthy Diets From Sustainable Food Systems. https://eatforum.org/content/uploads/2019/01/EAT-Lancet_Commission_Summary_Report.pdf (2019).
51. BloombergNEF. NEO 2021 Executive Summary. 16 (2021).
52. IEA. *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. 224 (2021).
53. University of Technology Sydney. One Earth Climate Model. https://www.uts.edu.au/research-and-teaching/our-research/institute-sustainable-futures/our-research/energy-futures/one-earth-climate-model (2022).
54. IRENA. *Innovation Outlook: Renewable Ammonia*. (2022).
55. IRENA. *Innovation Outlook: Renewable Ammonia*. (2022).
56. Energy Transitions Commission. *Carbon capture, utilisation and storage in the Energy Transition: Vital but limited (forthcoming)*.
57. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nat. Clim. Change* **8**, 895–900 (2018).
58. University College London. Economic cost of climate change could be six times higher than previously thought. https://phys.org/news/2021-09-economic-climate-higher-previously-thought.html (2021).

59. Kikstra, J. S. *et al.* The social cost of carbon dioxide under climate-economy feedbacks and temperature variability. *Environ. Res. Lett.* **16**, 094037 (2021).

60. Shindell, D. *et al.* Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *Proc. Natl. Acad. Sci.* **118**, (2021).