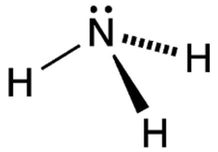
Ammonia in net-zero strategies

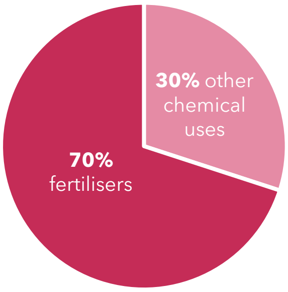
Since the 1950s, ammonia (NH_3) has become a pillar of our modern societies, mainly through its use as a base chemical for manufacturing nitrogen fertilisers. Today, virtually all of the world's ammonia is produced via the Haber-Bosch process in an overall energy- and carbon-intensive way. Decarbonising current production is a key challenge for the chemical industry, which may be all the more complex that, as for hydrogen, novel uses of ammonia might appear in order to decarbonise several hard-to-abate sectors. This explainer aims at exploring some key aspects of the future of ammonia in a net-zero world.



Ammonia (NH_3)

Current production, uses and emissions

What is ammonia used for?
Most of the current ammonia production is dedicated to manufacturing nitrogen fertilisers, which include urea, ammonium nitrate and ammonia itself. The rest is used in a variety of industrial applications, notably as a refrigerant or to produce acrylonitrile and further molecules that are involved in manufacturing specific types of plastics, resins, fibres or explosives.



185 Mt/y (2020)

Ammonia-related GHG emissions
Emissions from ammonia production represent about 1% of yearly global CO_2 emissions, and about a third of the emissions of the chemical industry. Spreading fertilisers on soils results in further greenhouse gases emissions (mainly nitrous oxide, N_2O) which are harder to accurately quantify, but are estimated to almost double the total climate burden of ammonia over its full lifecycle.

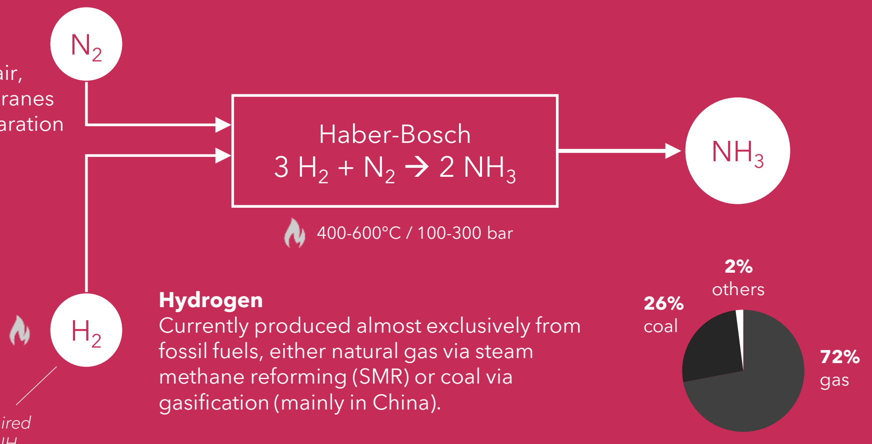
470 $MtCO_2$ Annual emissions from global ammonia production

Ammonia synthesis via the Haber-Bosch (HB) process

Developed by Fritz Haber in 1908 and industrialised by Carl Bosch for BASF in 1913, the so-called Haber-Bosch process largely dominates the current production of ammonia. It consists in combining nitrogen with hydrogen at high pressure and temperature in a reactor with the help of a metal catalyst (often copper).

Data for SMR-based ammonia production

27 GJ/tNH_3	1.8 tCO_{2e}/tNH_3	TRL 11
Energy required	**Carbon emissions**	**Maturity***



Nitrogen
Extracted from the air, via membranes or air separation units

400-600°C / 100-300 bar

Hydrogen
Currently produced almost exclusively from fossil fuels, either natural gas via steam methane reforming (SMR) or coal via gasification (mainly in China).

0,18 tH_2 is required to produce 1 tNH_3

Despite decades of optimisation of the Haber-Bosch process in terms of design, operation and efficiency, current ammonia production remains very energy- and carbon-intensive because of the hydrogen production step, which alone represents more than 90% of total CO_2 emissions and 80% of the total energy used.

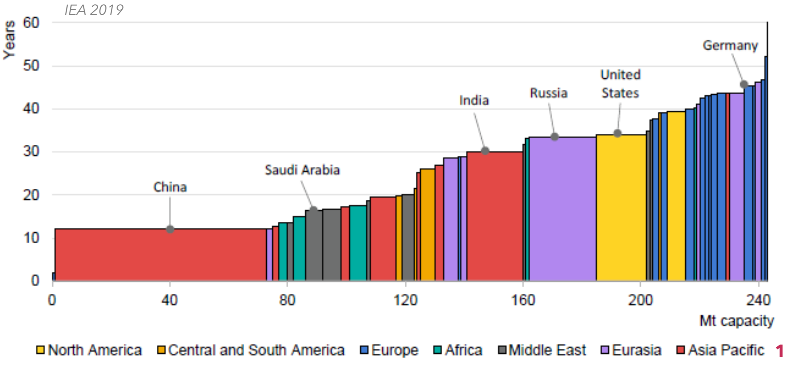
* TRL = technology readiness level, based on the IEA's scale

Ammonia plants today
Over history, the size of ammonia plants has significantly increased and benefitted from economies of scale – a phenomenon that some expect to continue in the coming decades. Ammonia plants are long-lived industrial assets, with a typical lifetime of around 50 years.

>1,000 tNH_3/day typical scale of a modern-day ammonia plant

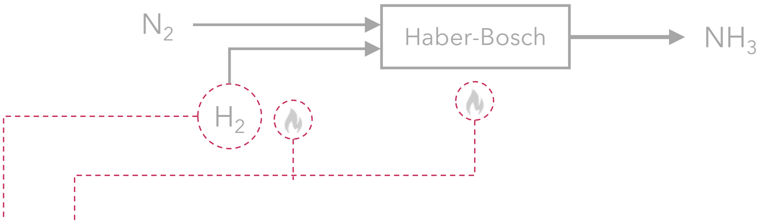
Regional disparities
About 30% of the world's ammonia production occurs in China. Chinese plants are young, however about two thirds of them rely on coal, which makes them particularly carbon-intensive. The oldest plants (above 30 years) are located in Europe and North America. ▶

IEA 2019



Decarbonising ammonia production

This section details some key technological pathways that can reduce the CO_2 emissions of ammonia production pathways, and thus only focuses on scope 1 and scope 2 emissions. Emissions reductions can result from conventional methods (**1**) or from novel pathways at different maturity levels, including 'blue' (**2**) and 'green' (**3**) ammonia as well as further options that do not rely on the Haber-Bosch process at all (**4**).



1 Incremental improvements to current processes

Gains in energy efficiency and electrification of certain parts of the process can help to partly substitute fossil fuel consumption. Such modifications can pose challenges in terms of heat integration, and only address a small share of the total gas consumption, which occurs mainly (~80%) during the SMR step to produce hydrogen. Therefore, such incremental improvements of the Haber-Bosch process only present limited potential to make conventional ammonia production less carbon- and energy-intensive.

2 CCUS-based Haber-Bosch ('blue ammonia')

A further possibility to decarbonise current production pathways consists in capturing part of the CO_2 generated during the hydrogen production step. In the SMR process, a first part of the natural gas is used as a material input to the SMR reaction and generates a concentrated CO_2 flux; the rest is burnt to provide the heat necessary to the SMR operation, which results in a dilute flux of CO_2. Emissions from both fluxes can be captured – partial capture from the concentrated flux allows to capture up to 65% of the total CO_2 emissions, while full capture on both fluxes can reach levels above 90-95%. It is to be noted that carbon capture comes with higher costs (capital costs in particular) and energy expenditure (up to additional 20% are required for full capture).

3 Electrolysis-based Haber-Bosch ('green ammonia')

Fossil-free hydrogen can be also produced via water electrolysis powered by low-carbon electricity, and later be used to produce fossil-free ammonia ('green' or 'renewable' ammonia if electrolysis is run by renewable energy). The electricity used to run the reaction can originate either from dedicated production facilities or from the local grid, which strongly influences the carbon intensity of the resulting ammonia production. Location is also a key determinant in terms of competitivity, for electricity costs are highly location-dependent and can represent up to 85% of overall ammonia production costs. Integrating electrolysis into the Haber-Bosch process poses further challenges, notably in terms of heat integration and accommodation of intermittency in the case of renewable energy systems *(detailed on the right)*.

4 Ammonia without Haber-Bosch?

While decarbonising ammonia production is mainly seen today as a challenge of decarbonising the hydrogen used in the Haber-Bosch process, some pathways explore further technological options that rely on different processes. Those options are generally less mature and are therefore not yet considered in most net-zero strategies or scenarios, although they could provide significant benefits, and are the subject of intense R&D activities.

Electrocatalysis TRL 1-4

Chemical looping TRL 1-4

Biocatalysis TRL 1

20.9 GJ/tNH_3 — **theoretical minimum energy requirement of the Haber-Bosch process** (vs. 27 GJ/tNH_3 for current SMR processes)

28-32 GJ/tNH_3

0.2-1.0 tCO_{2e}/tNH_3 — depending on the capture rate

TRL 9 — for partial capture (65%)

Urea production

Historically, a number of ammonia plants have already implemented capture on their concentrated CO_2 flux. These represent an important source of industrial CO_2 (about 130 Mt/year), which can later be combined with NH_3 to produce urea, a major fertiliser and chemical.

26-36 GJ/tNH_3

0.1-0.5 tCO_{2e}/tNH_3 — depending on the carbon intensity of the electricity grid

TRL 8-9 — depending on the type of electrolysis* ALK 8-9, PEM 6-7, SOFC 3-5

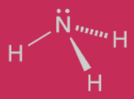
Overcoming intermittency

Haber-Bosch is a process that works best on steady-state operation to maintain high efficiencies and prevent catalyst degradation. Current designs are thus based on a continuous input of fossil fuels and characterised by long cold start-up times (hours to days). Using renewable hydrogen is thus a challenge to ensure stable ammonia production, which can be overcome by:

- → Improving the ability of the ammonia synthesis loop to ramp up and down fast
- → Combining clean energy sources (solar, wind, geothermal, nuclear)
- → Relying on buffers (batteries or hydrogen/ammonia storage)

*see our report The Hydrogen Series: Part 1

Key properties



18.65 MJ/tNH$_3$	**= 40%** the energy density of diesel
110 kgH$_2$/m^3	**= 50%** more H_2 by volume in NH_3 than in liquid H_2
17.6%	H_2 percentage per mass NH_3
-33°C	**Boiling point** (vs. -253°C for H_2)

→ A new paradigm for ammonia utilisation?

While ammonia is mainly used as a chemical today, several decarbonisation scenarios introduce a set of novel applications that rather rely on the molecule's properties as an energy/hydrogen carrier. Those pathways involve further possibilities to exploit ammonia properties, as part of combustion processes or in fuel cells. Three key application sectors are envisioned: power production, hydrogen transport and shipping fuels.

NH_3

Combustion

Since the molecule does not contain a carbon atom, ammonia can be burnt in gas turbines and industrial burners without emitting CO_2. Such combustion faces several challenges (low flame speed, long ignition delay times), therefore most strategies plan to use it as a co-fuel in the near term, notably in already existing processes (TRL 5). Direct combustion of pure ammonia is less mature (TRL 3). As in any combustion process, NOx emissions and unburnt fuel (here ammonia) have to be mitigated by optimising design and operation.

Fuel cells

Like hydrogen, ammonia could be used in fuel cells (TRL 4), either directly or indirectly (after decomposition to hydrogen), to exploit the molecule's chemical energy. Adapting current hydrogen fuel cell technologies to ammonia is not straightforward though – research is still required, and hurdles to be overcome include costly materials and the need for high temperatures and streams purity.

TRL 4-5

Power production and storage

Some actors envision a role for ammonia in stationary energy production, especially China and Japan which plan to co-fire an increasing share of ammonia in their coal power plants and gas turbines to reduce their emissions while avoiding stranded assets and maintaining peak load capacities. This does not come without hurdles, as it notably requires appropriate handling of blend compositions. Such strategies are deemed risky by certain players highlighting their limited emissions mitigation potential and the possible conflicts that might appear with the deployment of renewable energies. A further, less mature possibility is to use low-carbon ammonia in fuel cells to generate electricity. Further energy uses of ammonia for off-grid power generation or as an energy storage medium are also considered.

TRL 11

Hydrogen carrier

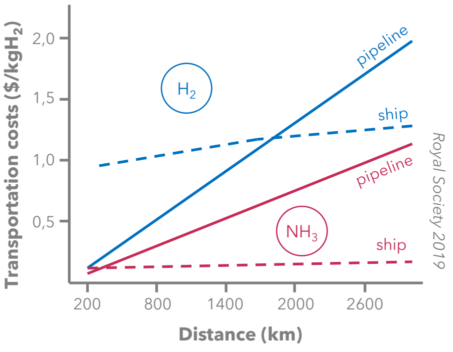
Ammonia is easier and cheaper to transport over long distances than liquid hydrogen, with a long track-record and existing infrastructures. For those reasons, some envision ammonia as a relevant hydrogen carrier, especially in places where ammonia imported from favourable locations can be cost-competitive with local hydrogen production. Whether ammonia should be fully or partially converted back to hydrogen via cracking (with energy losses around 12-15%) remains an open question, depending much on the regional context and techno-economic parameters.

Key advantages over hydrogen

- ⊕ Higher energy density (vol.)
- ⊕ Liquid at less extreme temperatures and pressures
- ⊕ Less leakage/explosion risks

Challenges

- ? Overall efficiency and costs of converting NH_3 back to H_2 (cracking: TRL 4-5)
- ? Toxicity and health risks



▲ Transportation of H_2 and NH_3 can be achieved via trucks, shipping or pipelines (Russia, US), which leads to a range of possible transport costs depending on the distance.

TRL 4-6

Low-carbon shipping

Shipping is responsible for around 3% of total global GHG emissions. Decarbonising this sector will require a shift from heavy oil fuels to sustainable and low-carbon fuels, including biofuels, methanol and other e-fuels. Ammonia has been increasingly considered by the industry as a serious candidate with key advantages: CO2-free combustion, mature value chains and infrastructure. However, upscaling its use as a fuel would require significant transformations to current vessel fleets. A first generation of prototype ammonia-powered ships has emerged in the last years, most often with a retrofitted engine running on a blend of conventional fuels and ammonia (TRL 5). For the time being, such vessels need to be certified on an individual basis. Next generations could include retrofitted and redesigned ammonia tankers, engines that run on 100% ammonia combustion, as well as vessels that embark ammonia fuel cells instead of a combustion engine (TRL 4-5).

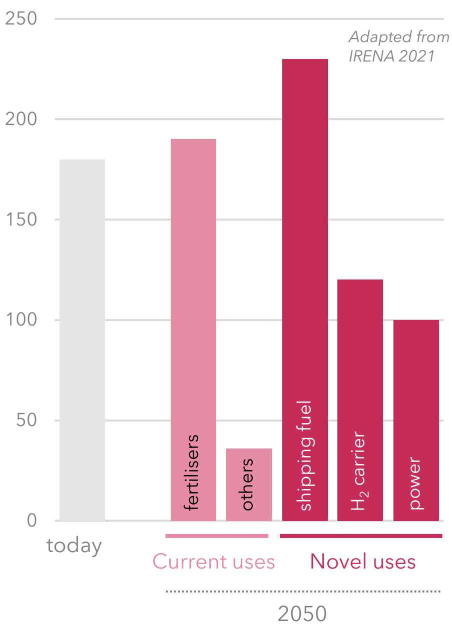
Ammonia versus methanol as a maritime fuel?

Methanol (MeOH) can be produced by combining captured CO_2 with low-carbon hydrogen. It offers interesting opportunities both as a base chemical and as a fuel, which several players see as an interesting way to decarbonise shipping in a way similar to hydrogen.

Resources	MeOH and NH_3 both necessitate large volumes of low-carbon hydrogen for their production. MeOH also requires sustainable CO_2 sources, which adds to overall production costs.
Environmental impacts	MeOH combustion releases CO_2 – the source of carbon used thus has a key impact on its overall mitigation potential. NH_3 combustion is CO_2-free, but further impacts need to be thoroughly assessed, including N_2O and NOx emissions as well as potential perturbations of the N cycle.
Safety	Both MeOH and NH_3 are toxic, which asks for robust safety guidelines to prevent any health or environmental harm.
Infrastructure	NH_3 handling requires pressurised and refrigerated infrastructure, while MeOH can be manipulated at ambient conditions.

Which future for ammonia?

Decarbonising current volumes of ammonia is already a particularly challenging perspective, and may rely on the diversity of mature and novel low-carbon production pathways in different proportions. The range of potential novel uses envisioned in some scenarios and strategies may make this transition all the more complex by increasing global ammonia demand within a few decades.



Adapted from IRENA 2021

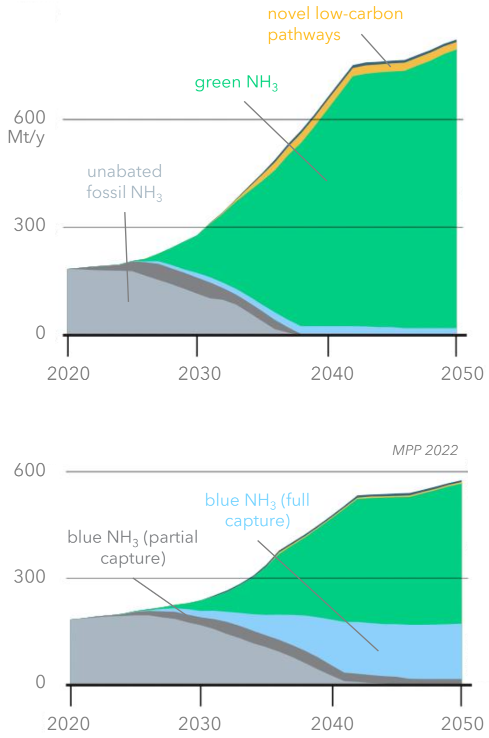
▲ **Median estimates for ammonia demand in 2050** compiled from various decarbonisation scenarios

x 2-5
by 2050?

Current and novel uses in scenarios

In most net-zero pathways, novel ammonia uses make up for a large part of the demand by 2050, which may follow a significant increase from current levels. The evolution of conventional uses strongly depends on the agricultural models that are envisioned. Key transformations include practices that allow for better nitrogen use efficiency (NUE) or rely on alternatives to ammonia-derived chemicals, which would also reduce lifecycle GHG emissions and non-CO_2 impacts.

Uses of ammonia in power generation are only considered in a handful of scenarios and regions (mainly, but not exclusively, in Asia), and opportunities for using ammonia as a hydrogen carrier are a nascent consideration. Among the range of estimates available, ammonia used as a maritime fuel represents the biggest share of novel applications and alone may even exceed current volumes for conventional uses.



MPP 2022

▲ **Two possible evolutions for ammonia production**, as developed by the Making Possible Partnership *(MPP 2022)*. Scenario 1 is dependent on widely available renewable energy and a fast, large-scale deployment of electrolysers. Scenario 2 showcases a situation where this production is limited and high capture rates are economically viable on CCUS-based Haber-Bosch processes.

A future in green and blue?

Most decarbonisation scenarios focus on the more mature technologies to produce low-carbon ammonia, i.e. 'green' and 'blue' Haber-Bosch. Both approaches have differentiated implications in terms of their energy and resource needs, emissions, economics and industrial feasibility *(see right)*, which influence their relative importance in decarbonisation strategies. Economic parameters such as electricity, CO_2 and natural gas prices are key in determining competitive alternatives to fossil-based ammonia. Green ammonia is generally the least carbon-intensive option, depending on the local electricity mix, and can only be matched in that regard by full capture on CCUS. Decisions are therefore highly location-dependent and are prone to evolve over time as technologies gain in maturity, possibly including further innovative technological pathways that overcome the Haber-Bosch process.

Ammonia plants in the future

Transforming the world's operating ammonia plants into a low-carbon fleet will imply significant changes in the industry's current practices.

- Retrofitting operating plants is a first possible strategy to abate emissions while avoiding stranded assets, which might be particularly relevant in countries such as China which have a majority of very young plants – which needs to be accurately balanced with the risk of creating a lock-in situation. Implementing a CCUS unit requires significant modifications to heat integration schemes. Such changes are even more challenging when considering retrofit to electrolysis-based HB.
- Newly-built gas-based facilities may rely on autothermal reformation (ATR) processes to produce hydrogen, which generate a more concentrated CO_2 flux and thus enable higher captures rates than SMR-based production.
- With the expected uptake of electrolysis-based Haber-Bosch, a decrease in the average size of new-built ammonia plants can be expected, at least in the near- to mid-term. This will also potentially imply a more localised production, focusing on areas with the biggest potential for affordable low-carbon electricity.

Challenges

Toxicity

Ammonia is a highly toxic and corrosive chemical that can cause serious damages to ecosystems and be harmful to human health. Those concerns require proper handling, standards and homogeneised operations to avoid any leaks along the value chain, especially if novel usages are to be developed and scaled up.

Research gaps

- Novel production pathways
- Cracking (ammonia to hydrogen)
- Direct ammonia fuel cells
- Combustion of pure and blended ammonia

Further steps

- Articulate novel ammonia uses with evolving current uses and agricultural systems
- Gain a better understanding of the real potential of novel uses, especially compared to other decarbonisation options
- Establish clear assessment, regulatory and certification frameworks for novel uses

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Key references: ADEME 2023, *Plan de Transition Sectoriel de l'industrie de l'ammoniac en France* / Armijo & Philibert 2020 (doi:10.1016/j.ijhydene.2019.11.028) / Aziz et al. 2020 (doi:10.3390/en13123062) / E3G 2023, *Challenging Japan's promotion of ammonia co-firing for coal power generation* / Hansson et al. 2020 (doi:10.3390/su12083265) / IEA 2019, *Ammonia Technology Roadmap* / IRENA 2022, *Innovation Outlook: Renewable Ammonia* / Jeerh et al. 2021 (doi:10.1039/d0ta08810b) / MacFarlane et al. 2020 (doi:10.1016/j.joule.2020.04.004) / Mounaïm-Rousselle et al. 2021 (doi:10.1007/978-981-16-8717-4_11) / MPP 2022, *Making Net-Zero Ammonia Possible* / Lee et al. 2022 (doi:10.1021/acsenergylett.2c01615) / Rouwenhorst et al. 2021 (doi: 10.1016/B978-0-12-820560-0.00004-7) / The Royal Society 2020, *Ammonia: zero-carbon fertiliser, fuel and energy store* / Smith et al. 2020 (doi:10.1039/C9EE02873K) / Valera-Medina et al. 2018 (doi: 10.1016/j.pecs.2018.07.001) /// Credits picture (p.2) : ABB