



INNOVATION OUTLOOK RENEWABLE AMMONIA

in partnership with



**AMMONIA ENERGY
ASSOCIATION**

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

About the Ammonia Energy Association

The Ammonia Energy Association (AEA) is a global industry association that promotes the responsible use of ammonia in a sustainable energy economy. The AEA's mission encompasses both the decarbonisation of ammonia for existing applications, including fertilisers, chemicals, explosives, and other industrial processes, as well as the adoption of low-carbon ammonia in new applications, including direct use as a fuel for electric power generation or maritime transport, and indirect use as a hydrogen carrier and carbon-free energy commodity. www.ammoniaenergy.org

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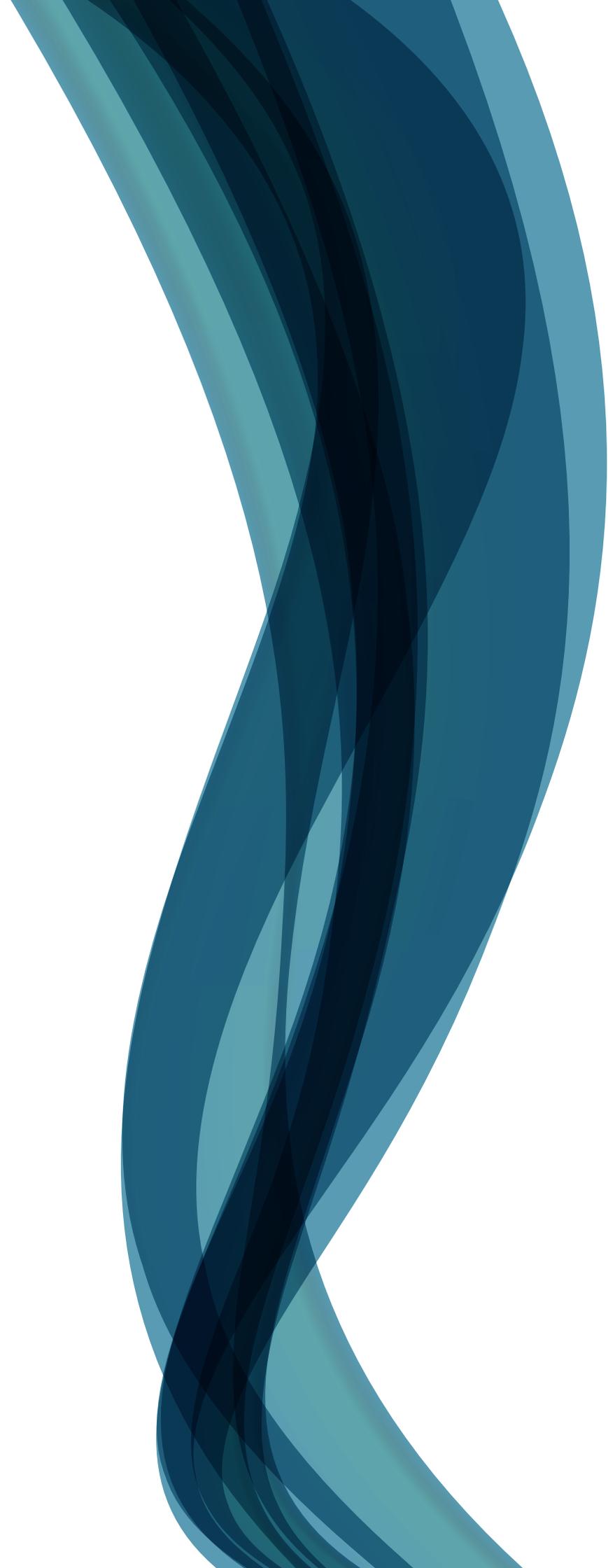
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ABBREVIATIONS

ATR	Autothermal reforming
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CfD	Contract for difference
CH₃OH	Methanol
CH₄	Methane
CO	Carbon monoxide
CO₂	Carbon dioxide
CO(NH₂)₂	Urea
DAC	Direct air capture
eSMR	Electrified steam methane reforming
EU	European Union
H₂	Hydrogen
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
LHV	Lower heating value
LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carrier
LPG	Liquefied petroleum gas
N₂	Nitrogen
N₂O	Nitrous oxide
NH₃	Ammonia
NO_x	Nitrogen oxides
OPEX	Operational expenditure
PEM	Polymer electrolyte membrane
R&D	Research and development
SCR	Selective catalytic reduction
SMR	Steam methane reforming
SO_x	Sulphur oxides
USD	United States dollar

UNITS OF MEASURE

°C	Degree celsius
Btu	British thermal unit
GJ	Gigajoule
Gt	Gigatonne
GW	Gigawatt
kg	Kilogram
km	Kilometre
kt	Kilotonne
kW	Kilowatt
kWh	Kilowatt hour
L	Litre
MJ	Megajoule
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt hour
m³	Cubic metre
ppm	Parts per million
t	Tonne
t/d	Tonnes per day
t/yr	Tonnes per year



KEY FINDINGS

Ammonia is an essential global commodity. Around 85% of all ammonia is used to produce synthetic nitrogen fertiliser. A wide range of other applications exist such as refrigeration, mining, pharmaceuticals, water treatment, plastics and fibres, abatement of nitrogen oxides (NO_x), etc.

Ammonia production accounts for around 45% of global hydrogen consumption, or around 33 million tonnes (Mt) of hydrogen in 2020. Only the refining industry uses more hydrogen today. Replacing conventional ammonia with renewable ammonia produced from renewable hydrogen presents an early opportunity for action in decarbonising the chemical sector.

New applications being explored include renewable ammonia as a zero-carbon fuel in the maritime sector and for stationary power generation. Ammonia is also proposed as a hydrogen carrier for long-range transport.

Projections from the International Renewable Energy Agency (IRENA) estimate that by 2050, in a scenario aligned with the Paris Agreement goal of keeping global temperature rise within 1.5 degrees Celsius (°C), this transition would lead to a 688 Mt ammonia market, nearly four times larger than today's market. This ammonia would be decarbonised, with 566 Mt of new renewable ammonia production (from renewable hydrogen and renewable power), complemented with fossil-based ammonia production in combination with carbon capture and storage (CCS).

Today's high prices for natural gas create an exceptional opportunity for renewable ammonia. With the right policies, renewable ammonia manufacturing could be widely cost competitive from 2030 onwards. These cost reductions would be achieved through renewable hydrogen cost reductions, gigawatt (GW)-scale deployment, driving down costs of renewable electricity, creating high-volume demand for electrolyzers, de-risking novel combinations of mature technologies and stimulating innovation through market creation.

Certification schemes, contracts for difference (CfD) and other mechanisms will therefore be important to support the development of renewable ammonia markets.

The first of many proposed multi-gigawatt renewable ammonia production plants are already under construction. The first renewable hydrogen supply was retrofitted onto an existing ammonia plant in 2021. Renewable ammonia is expected to dominate all new ammonia production capacity after 2025. Around 2025, the first movers are expected to have demonstrated innovative renewable ammonia deployment technologies. Gas turbines, furnaces and internal combustion engines can be retrofitted to use renewable ammonia as a fuel.

Industry is showing clear signals in moving renewable ammonia technologies forward. The first dedicated ammonia-fuelled vessels will be operating at sea, with two-stroke and four-stroke engines commercially available for new-builds and retrofits. The first 1 GW power plant will be co-combusting ammonia with coal, and ammonia gas turbines and fuel cells will be available. The first gigawatt-scale renewable ammonia production plants at remote locations will ship their output to distant consumer markets.

Ammonia

- Ammonia is a key product in the fertiliser and chemical industries. It is used mainly for producing fertilisers, such as urea and ammonium nitrate. Around 183 Mt of ammonia is produced annually, nearly all of which is generated from fossil fuels: natural gas (72%), coal (22%), naphtha and heavy fuel oil.
- Ammonia life-cycle emissions amount to 0.5 gigatonnes (Gt) of carbon dioxide (CO₂) annually (around 15-20% of total chemical sector emissions and 1% of global greenhouse gas emissions).
- Ammonia fertiliser demand has been rising steadily in recent decades, driven by growing food demand.
- In the IRENA 1.5°C scenario, the main market growth is expected from the maritime sector, representing new demand of 197 Mt by 2050, and from international trade of ammonia as a hydrogen carrier, representing new demand of 127 Mt by 2050.
- Significant amounts of CO₂ from fossil-based ammonia production are stored in the on-site production of urea fertiliser (1.3 tonnes per tonne of ammonia feedstock). This CO₂ is released as the fertiliser is applied in the field. Urea fertiliser is deployed in developing countries in particular. Carbon accounting rules and pricing for this CO₂ can have a significant impact on the future decarbonisation strategies for nitrogen fertiliser manufacturing.

Renewable ammonia

- Renewable ammonia is produced from renewable hydrogen, which in turn is produced via water electrolysis using renewable electricity. This hydrogen is converted into ammonia using nitrogen that is separated from air.
- Renewable ammonia has been produced on a commercial scale since 1921. However, less than 0.02 Mt of renewable ammonia was produced in 2021.
- Industrial production is shifting towards renewable ammonia. The annual manufacturing capacity of announced renewable ammonia plants is 15 Mt by 2030 (around 8% of the current ammonia market across 54 projects, notably in Australia, Mauritania and Oman). A pipeline of 71 Mt exists out to 2040, but investment decisions are still pending for most projects.
- Around 80 Mt of existing ammonia production capacity constitutes an early opportunity for decarbonisation.
- IRENA analysis suggests that in a 1.5°C scenario, renewable ammonia production capacity will need to reach 566 Mt by 2050. The 71 Mt of announced projects therefore represents slightly over 10% of the zero-carbon ammonia manufacturing capacity that would need to be operational by 2050.
- Renewable ammonia is expected to dominate all new capacity after 2025. In the long term, renewable ammonia is likely to become the main commodity for transporting renewable energy between continents.

Cost competitiveness of renewable ammonia

- The cost of renewable ammonia is currently an estimated USD 720 per tonne at locations with the best solar and wind resources, and this is expected to decrease to USD 480 per tonne by 2030 and USD 310 per tonne by 2050. These cost estimates are confirmed by other literature. A carbon price of around USD 150 per tonne of CO₂ is required for renewable ammonia to be competitive with existing fossil-based ammonia production.
- Renewable ammonia is expected to achieve cost parity with fossil-based ammonia with CCS beyond 2030.
- An electricity price below USD 20 per megawatt-hour is required for renewable ammonia to be competitive with fossil-based ammonia. In the right regional markets – for example, explosives manufacturing in Chile – local renewable ammonia production may already be competitive with imported fossil-based ammonia.
- The cost of producing fossil-based ammonia is typically in the range of USD 110-340 per tonne, depending on the fossil fuel price. Fossil-based ammonia production can be decarbonised with CCS technology. CCS adds costs that vary by technology and by capture efficiency, typically yielding an ammonia production cost of USD 170-465 per tonne and a mitigation cost of USD 60-90 per tonne of CO₂.
- The costs associated with carbon emissions, CCS, premium price off-take agreements, as well as CfD schemes will shift this dynamic. A carbon price of USD 60-90 per tonne of CO₂ is required for CCS to be competitive with existing fossil-based ammonia production.
- The new autothermal reforming (ATR) technology is better suited for CCS than today's steam methane reforming (SMR) technology. Around 2.6 Mt/yr of facility capacity exists today, producing low-carbon-fossil-based ammonia and the planned facility capacity accounts for 17.4 Mt/yr.
- The cost of renewable ammonia depends to a large extent on the cost of renewable hydrogen, which represents 90% of the production cost of renewable ammonia.
- The future cost of renewable hydrogen depends mainly on the combination of further reductions in the cost of renewable power generation and electrolyzers, and gains in efficiency and durability.
- The number of operational hours per year plays a key role in reducing the cost of renewable ammonia production. Locations with complementary variable wind and solar energy profiles can yield electrolyser capacity factors of up to 70%.
- The cash cost of operating a large-scale renewable ammonia plant that includes renewable energy generating assets is well below USD 100 per tonne.
- Partial revamping of fossil-based ammonia plants to introduce renewable hydrogen reduces the cost, compared to stand-alone new-builds.

Benefits and challenges for renewable ammonia

- Ammonia is a versatile fuel for stationary power and heat and for maritime transport that can be used in internal combustion engines, gas turbines, industrial furnaces, generator sets and fuel cells. It can be stored as a liquid at 8 bar or above and at ambient temperature, or at atmospheric pressure at -33°C .
- Around 18-20 Mt of ammonia is shipped internationally per year. Substantial investments will be required to expand the shipping infrastructure and allow ammonia refuelling.
- Renewable ammonia can displace fossil fuels at scale in hard-to-abate areas of the power and transport sectors. However, the use of ammonia as a fuel could increase emissions of nitrogen oxides (NO_x and nitrous oxide, N_2O), which must be avoided.
- Most of the proposed renewable ammonia plants use variable solar photovoltaics (PV) and wind. A number of electrolysis technologies exist. Technological and operational innovations, in combination with careful site selection and project design, can facilitate the integration of high shares of solar and wind.
- The current global electrolyser production capacity of a reported 2.1 GW per year (in 2020) needs to scale up more than 20-fold to meet the renewable ammonia manufacturing objectives for 2050.
- Demonstrations, technology commercialisation and regulatory development will be required for the ammonia fuel market to take off.

Creating enabling frameworks: 10 recommendations



- 1 Put a sufficiently high price on CO_2 emissions.
- 2 Translate political will into policies.
- 3 Focus on deployment of existing renewable ammonia technologies.
- 4 Support the development of entire supply chains.
- 5 Devise trade strategies that mitigate supply risks.
- 6 Invest in electrolyser manufacturing.
- 7 De-risk early investment projects.
- 8 Retrofit technology towards renewable ammonia production.
- 9 Support the demand-side phase-out of fossil fuels.
- 10 Re-assess the role of ammonia in hydrogen strategies.

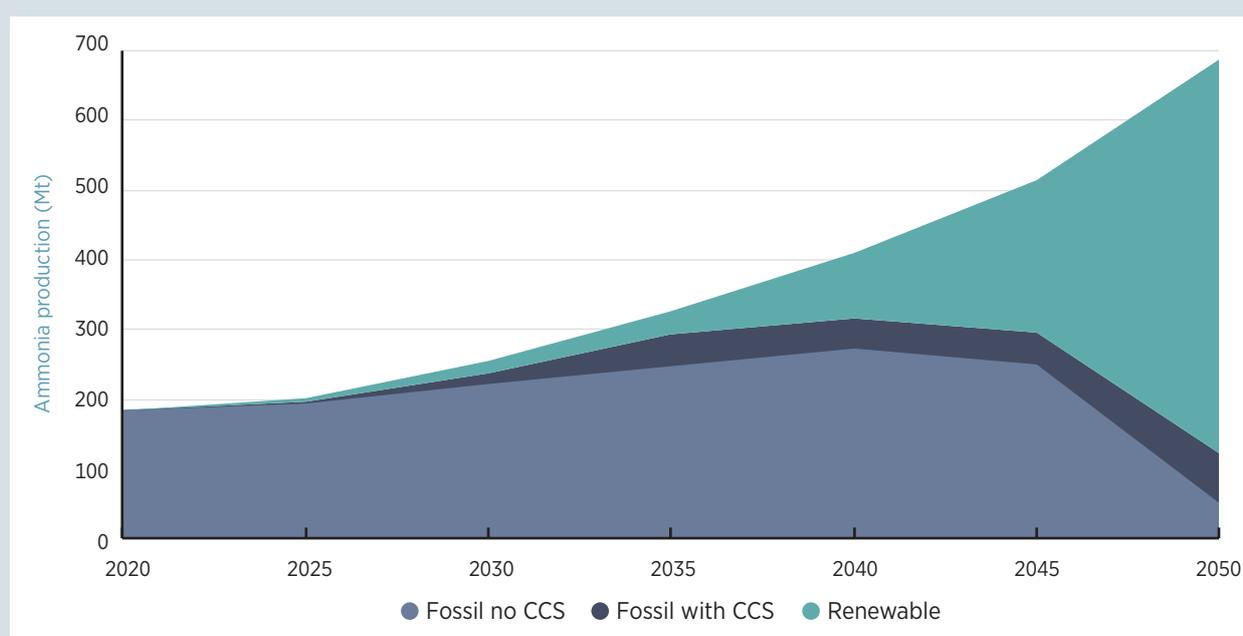
SUMMARY FOR POLICY MAKERS

Ammonia is one of the seven basic chemicals – alongside ethylene, propylene, methanol and BTX aromatics (benzene, toluene and xylene) – that are used to produce all other chemical products. It is the second most produced chemical by mass, after sulphuric acid. Around four-fifths of all ammonia is used to produce nitrogen fertilisers, such as urea and ammonium nitrate; as such, it supports food production for around half of the global population.

Ammonia's use as a carbon-free fuel and hydrogen carrier has been proposed but is not yet implemented at significant scale. For these new markets to materialise, large additional volumes of ammonia will be required – demand in 2050 is projected to be roughly three times what it was in 2020 – and these volumes must be low-carbon.

Although renewable ammonia has been produced at an industrial scale using hydropower since 1920, most ammonia today is produced from natural gas (72%) and coal (22%). The ammonia production industry has annual emissions of 0.5 gigatonnes (Gt) of carbon dioxide (CO₂), representing around 1% of global CO₂ emissions and 15-20% of the chemical sector's CO₂ emissions. Addressing emissions from ammonia production is therefore a key component of the decarbonisation of the chemical and agricultural sectors. Decarbonisation of ammonia would also extend its use as a carbon-free fuel in the transport and stationary power sectors.

Figure 1 Expected ammonia production capacity up to 2050 for the 1.5°C scenario



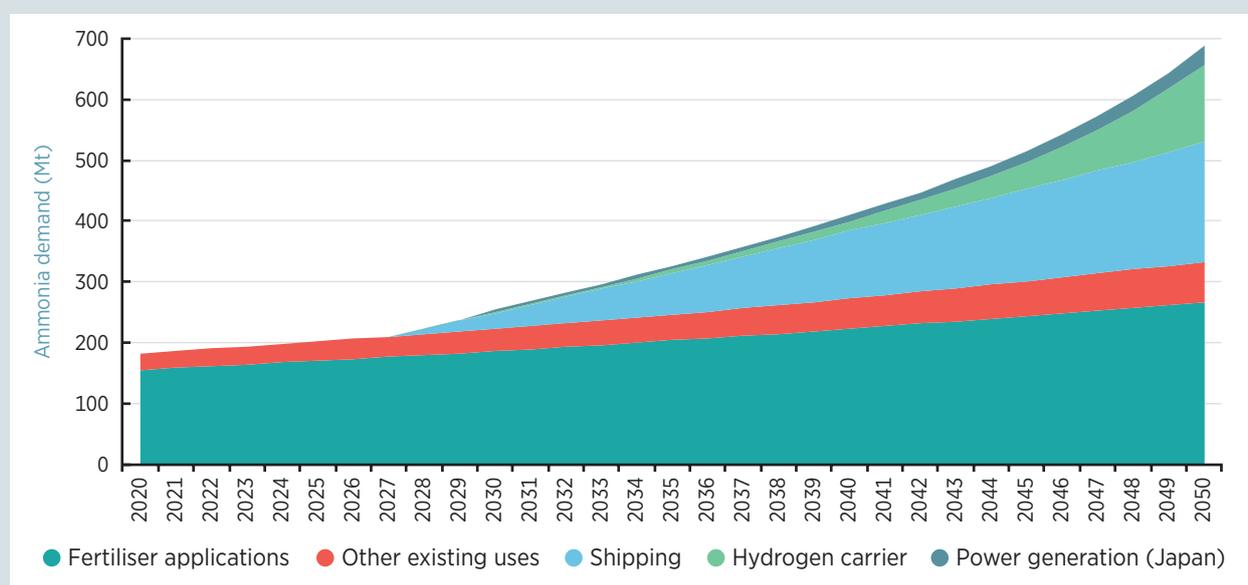
Source: IRENA, 2019b.

Market status and production process

Worldwide production of ammonia was 183 million tonnes (Mt) in 2020, and existing markets are expected to increase demand to 223 Mt by 2030 and reach 333 Mt by 2050 in a 1.5°C scenario. This steady rise in demand is driven primarily by population growth, with ammonia demand for fertiliser applications projected to grow from 156 Mt in 2020 to 267 Mt in 2050.

In addition, significant new markets are expected to develop over the coming decades for ammonia as a hydrogen carrier, as a fuel for stationary power and heat, and as a transport fuel, particularly in the maritime industry. While current markets contribute most of the growth in demand this decade, energy markets may account for a much faster growth rate after 2030. By 2050, global ammonia demand is estimated to reach 688 Mt in a 1.5°C scenario, more than three times the demand expected in 2025 (see section 4.6).

Figure 2 Expected ammonia demand up to 2050 for the 1.5°C scenario



Renewable ammonia

Renewable ammonia is produced using renewable electricity for hydrogen production and nitrogen purification from air. Renewable ammonia is chemically identical to ammonia produced from fossil fuels, and it is not possible to identify its origins via any chemical analysis. Thus, all feedstocks and energy used to produce ammonia need to be of renewable origin (e.g. biomass, solar, wind, hydro, geothermal) to qualify the ammonia produced as renewable.

Historically, renewable ammonia has been produced from hydropower since 1921, but only one commercial plant is still operational. Less than 0.02 Mt of renewable ammonia is currently produced annually, equivalent to 0.01% of today's global ammonia production. Various demonstration plants are operating, based on variable solar and wind energy coupled with electrolyzers to produce renewable hydrogen. The first renewable hydrogen feed to be tied in to an existing ammonia plant became operational in December 2021 in Spain, and the first gigawatt (GW)-scale renewable ammonia plant, with a capacity of 1.2 Mt per year, is under construction in Saudi Arabia and is slated to begin operations in 2025.

The combined capacity of all the currently announced renewable ammonia projects represents 15 Mt of renewable ammonia by 2030. This is around 8% of the current global ammonia production and shows that there is momentum from the industry to move towards renewable ammonia, especially given that most of these projects were announced only in 2020 and 2021. However, while one of these projects is already operational, and some other projects are under construction, most of the announced projects have not yet reached a final investment decision. New projects are being announced every month.

More than 60 renewable ammonia plants were announced during 2020 and 2021 (Table 2), while only 10 carbon fossil-based ammonia plants with CCS or with methane pyrolysis technology have been announced (Table 1). This indicates a strong momentum towards renewable ammonia.

While low-emission fossil-based ammonia may play a transitional role in decarbonising current markets, such as fertilisers, renewable ammonia is expected to play the dominant role in the long term, in both current and future markets.

Cost competitiveness of renewable ammonia

Renewable ammonia production costs for new plants are estimated to be in the range of USD 720 - 1400 per tonne today, falling to USD 310-610 per tonne by 2050.

For existing ammonia plants, co-production of fossil-based hydrogen and renewable hydrogen could enable the introduction of renewable ammonia by utilising existing assets and infrastructure to reduce costs. For hybrid plants, costs are estimated to be USD 300-400 per tonne by 2025, falling to around USD 250 per tonne by 2040.

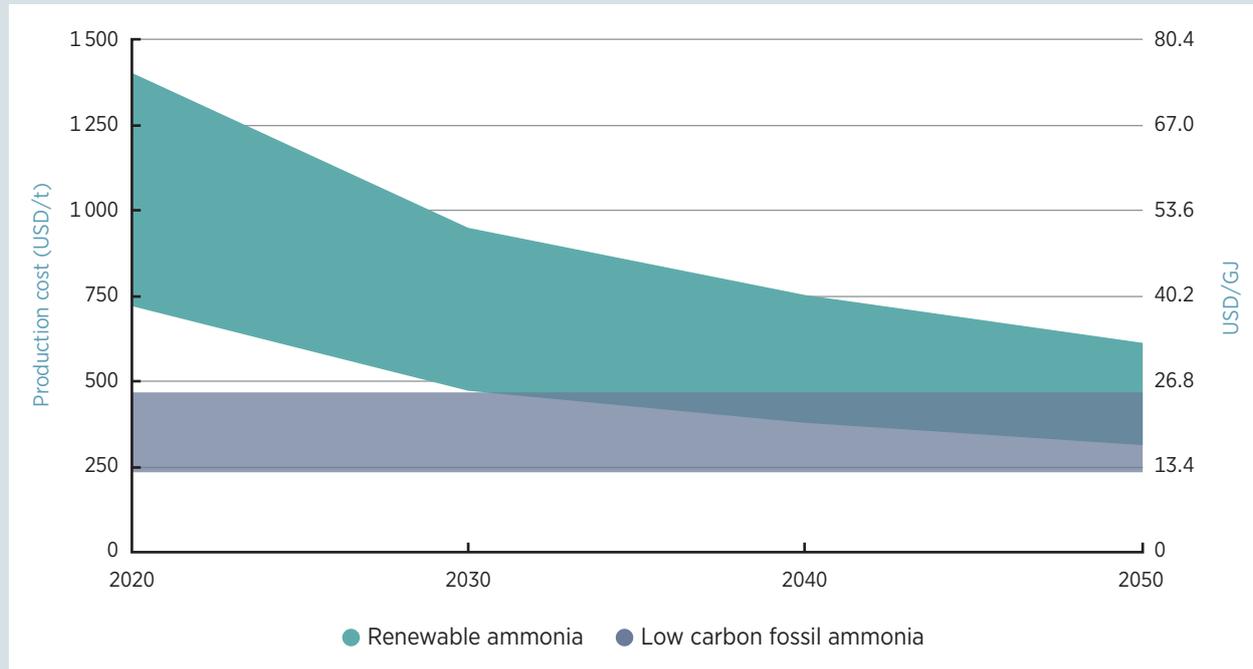
While the cost of producing renewable ammonia today is higher than that of producing fossil-based ammonia with no mitigation of emissions, renewable ammonia is expected to become cheaper than fossil-based ammonia before 2050.

The production cost of natural gas-based ammonia and coal-based ammonia is in the range of USD 110-340 per tonne today, but carbon capture and sequestration would add USD 100-150 per tonne to these costs (Haldor Topsøe *et al.*, 2020), bringing low-emission fossil-based production costs up to USD 210-490 per tonne. The cost of low-emission fossil-based ammonia is similar to renewable ammonia from hybrid plants in 2025, and more expensive than renewable ammonia from some new plants in 2050.

The cost of renewable ammonia depends mainly on the cost of renewable hydrogen, representing more than 90% of the cost for ammonia production. The two other significant steps in ammonia production – nitrogen purification and the Haber-Bosch process – represent only a minor fraction of the total cost.

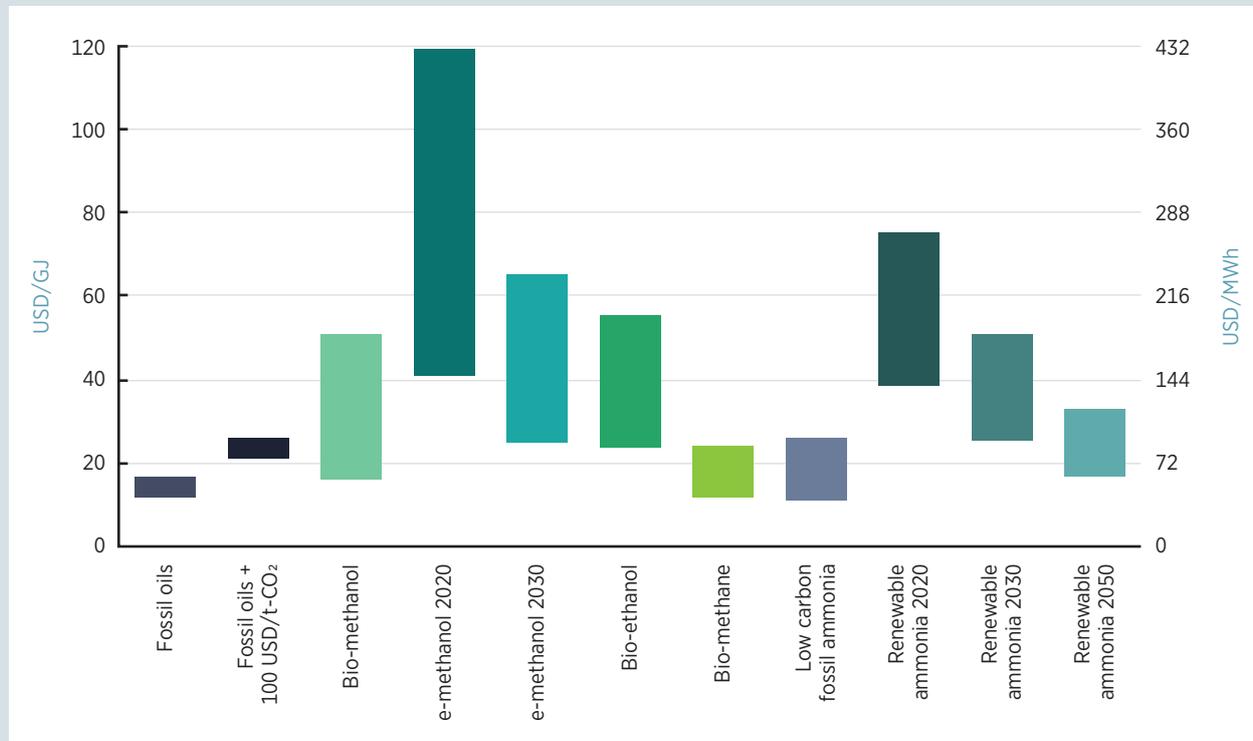
Future cost reductions in renewable hydrogen production depend mainly on reductions in the cost of renewable power and the cost of electrolysers, as well as on gains in efficiency and optimised storage, buffering, sizing and flexibility of the Haber-Bosch ammonia synthesis loop. The number of operational hours per year (capacity factor) plays a key role in determining production costs, as any increase in the utilisation rate of these capital-intensive assets directly reduces the product cost. This can create a challenge for projects using variable renewable electricity inputs; but, by combining complementary generation profiles of wind and solar energy, the capacity factor of the electrolyser can reach up to 70%. In optimal locations, renewable ammonia could be cost competitive with fossil-based ammonia with CCS from 2030.

Figure 3 Current and future production costs of renewable ammonia, compared with production cost range for low-carbon fossil ammonia (USD 2-10/GJ)



Note: GJ = Gigajoules.

Figure 4 Comparison of renewable ammonia with other fuels based on the price per unit of energy



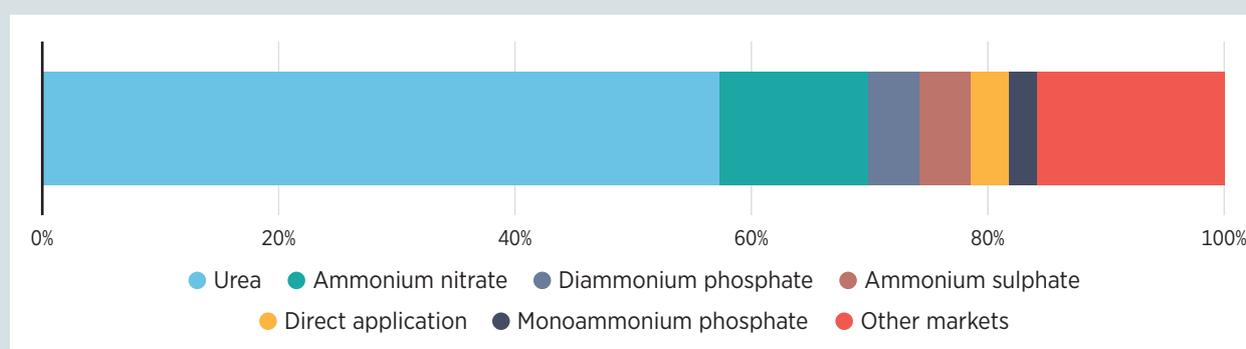
Source: Low-carbon fossil ammonia from Haldor Topsøe et al. (2020). Fossil fuel values are based on average values (2010-2020); see IRENA and Methanol Institute (2021). Methanol cost values are based on IRENA and Methanol Institute (2021). Bio-ethanol and bio-methane estimates are based on IRENA data.

Outlook for renewable ammonia

Ammonia has the same chemical structure (NH_3) whether it is produced from fossil or renewable sources. Renewable ammonia is therefore a direct substitute for fossil-based ammonia in all its current uses, meeting demand of 183 Mt annually as a feedstock for fertilisers, chemicals, and materials (Figure 5), although urea fertiliser represents a special case (see section 5). Existing fossil-based ammonia plants can begin decarbonising using today's technologies, introducing renewable hydrogen in the plant to replace 10-20% of the natural gas.

Beyond its existing markets, the outlook for renewable ammonia includes low-carbon energy markets where ammonia could be used as a hydrogen carrier or as a fuel for shipping or stationary power and heat generation. Compared to carbon-based hydrogen carriers, ammonia benefits from requiring nitrogen as the hydrogen carrier: at 780 000 parts per million (ppm), purifying atmospheric nitrogen has a lower cost basis than purifying atmospheric CO_2 , and no CO_2 is emitted during combustion of ammonia. By 2050, these new energy markets represent additional renewable ammonia demand of 354 Mt in a 1.5°C scenario (Figure 2).

Figure 5 Global ammonia demand in 2019



Note: Ammonia production in 2020 was 183 Mt (Hatfield, 2020).

Action areas to foster renewable ammonia production

Demand and supply can be prompted by proper regulations, mandates, and suitable policies, as is the case with all other decarbonisation technology alternatives. Examples include renewable fuel standards, carbon taxes, incentives such as project funding support and low-cost finance, long-term guaranteed price floors, contracts for difference, cap-and-trade schemes, lower taxes on renewable fuels and feedstocks, eco-labelling for low-carbon ammonia and information campaigns. Definition and harmonisation of methodologies for carbon intensity and life-cycle analysis, and other standards and benchmarks, will support the development of these new markets. These should include meaningful supply chain emissions; for example, upstream methane emissions for fossil-based ammonia with carbon mitigation.

In addition to fostering the development of new renewable ammonia plants, the gradual and increasing co-production of renewable ammonia in existing fossil-based ammonia plants should be stimulated, to begin decarbonising current ammonia production assets at an early stage. This will support incumbent ammonia producers and their workforce by providing them with operational experience in renewable hydrogen production.

Box 1 Facilitating the transition to renewable ammonia: Recommendations for industry and governments

Suitable policies and incentives are essential to meet the goals of the Paris Agreement and to sustain energy security and improve quality of life. Without confidence in strong, stable, predictable, and sustained government policy, sufficient investment in long-lived, capital-intensive renewable technologies is not likely to occur and flourish.

1 Put a sufficiently high price on CO₂ emissions

A penalty on CO₂ of around USD 60-90 per tonne of CO₂ is required to bridge the gap between fossil-based ammonia with unmitigated emissions and fossil-based ammonia with CCS. A CO₂ penalty of up to USD 150 per tonne of CO₂ would bridge the gap between fossil-based and renewable ammonia (see section 2.3). In the long term, renewable ammonia is expected to be cost competitive with fossil-based ammonia with CCS. Thus, CCS can play a role in decarbonising current ammonia facilities, but newly built fossil-based ammonia plants with CCS may result in stranded assets in the long term unless supported by very low natural gas prices.

2 Translate political will into policies

With or without a price on CO₂ emissions, strong, stable and sustained regulatory measures for fuel standards and renewable quotas or mandates will facilitate price incentives to provide stability of sustained growth and investment. These can be supported by robust certification that can account for the carbon intensity of ammonia.

Suitable policy instruments are paramount to ensure equitable tax treatment and a long-term guaranteed price floor for wider adoption of renewable ammonia and other promising sustainable fuels. While energy tax reduction can be provided for renewable fuels, including renewable ammonia, fuel excise and other taxes should be based on energy content and not volume (e.g. USD per kilowatt-hour [kWh], not USD per litre).

For example, a contract for difference (CfD) scheme in which advanced renewable fuel production projects bid for CfDs, and the winners are awarded them in so-called reverse auctions (lowest bid wins) is an appropriate taxation policy that can “make or break” alternative fuels; this could motivate investments as a meaningful production support system. Moderate carbon taxation levels can be obtained via earmark and return principles.

3 Focus on deployment of existing renewable ammonia technologies

The current focus should be on implementing existing technologies at scale rather than developing new, breakthrough technologies, because most elements in the renewable ammonia value chain have already been demonstrated. Deployment will drive innovations such as improving the flexibility of the ammonia synthesis loop, improving the performance of the electrolyser, and improving the performance of ammonia crackers, as well as driving down costs of today’s technologies.

Near-term market creation through deployment of existing technologies will accelerate innovation in the longer term.

4 Support the development of entire supply chains

Funding programmes should extend their scope to include ammonia and other hydrogen carriers. Programmes that focus on a single technology (e.g. hydrogen or solar panels) tend to support early-stage R&D and pilot projects. However, broader funding programmes that focus on applications for these technologies (e.g. electro-fuels, energy storage) support deployment by connecting the value chain across production, distribution and use. Programmes may also wish to allow foreign participation, to support development of global supply chains, recognising that demand may not be met by domestic production.

5 Devise trade strategies that mitigate supply risks

To create jobs and encourage competitive new industries for renewable ammonia in both producing and consuming regions, international co-operation must be fostered – for example, between project developers, ammonia users and ammonia production companies. Increasing the investments in renewable ammonia production capacity could broaden the energy and feedstock supply range and minimise political risks.

6 Invest in electrolyser manufacturing

Multiple gigawatt-scale electrolyser factories will be required this decade. The development of such large-scale electrolyser factories will inherently decrease the cost of electrolyser production due to an accelerated learning curve and economies of scale, which will in turn make renewable ammonia more competitive with fossil-based alternatives.

7 De-risk early investment projects

Governments can help to de-risk the billions of USD in investment of first movers seeking to build gigawatt-scale renewable ammonia plants. For instance, grants, investments, loans and loan guarantees can de-risk part of the capital expenditure (CAPEX) side of the investment. On the operational expenditure (OPEX) side, investments can be de-risked with CfD or green premiums, renewable mandates, procurement contracts and off-take guarantees, or an intermediate secured buyer of auctioned projects.

8 Retrofit technology towards renewable ammonia production

Ammonia plants that do not currently produce urea can be decarbonised without delay, either by integrating CCS, by retrofitting them with eSMR (electrified steam methane reforming) technology or by replacing fossil feedstock with renewable hydrogen. This represents around 80 Mt per year of existing ammonia capacity, which can be regarded as low-hanging fruit to decarbonise.

9 Support the demand-side phase-out of fossil fuels

Governmental and regulatory incentives should be provided to existing fossil-based assets to accelerate the transition to renewables. This prevents locked-in CO₂ emissions from continued operations, reduces demand for ongoing fossil fuel discovery and extraction, and reduces the likelihood of stranded assets. Retrofitting existing assets may often be more cost effective than building new assets, especially during the initial scale-up phase.

This is also valid for ammonia utilisation technology. For both the power sector and the maritime sector, current technology can often be retrofitted to operate on ammonia fuel at a lower cost than building new assets. In the maritime sector, ammonia tankers can be converted to use ammonia as a fuel first, in the knowledge that fuel availability will not be an issue for this vessel type at any port.

10 Re-assess the role of ammonia in hydrogen strategies

Most hydrogen strategies consider ammonia only as a consumer of hydrogen, in the context of fertiliser production, and omit consideration of its potential roles as a fuel and hydrogen carrier.

In locations where ammonia will be imported as a hydrogen carrier, it should be utilised directly where possible, rather than using hydrogen obtained from the decomposition of ammonia. Ammonia may be the most cost-effective vector for large-scale hydrogen imports, but its cost-effectiveness increases with direct use. Novel technologies to use ammonia in centralised and decentralised power generation, as well as transport applications, are approaching commercialisation and may offer an opportunity to re-assess the roles of hydrogen and ammonia in the context of a national hydrogen strategy.

1. CURRENT AMMONIA MARKET

Key findings

Ammonia is an essential global commodity.

- It is the second most produced chemical worldwide.
- Used mainly for nitrogen fertilisers, it supports food production for around half of the global population.
- Ammonia is also used in many corners of society, from refrigeration and mining to pharmaceuticals, electronics, water treatment, polymers, nitrogen oxide abatement, furniture and nylon.

The Haber-Bosch process for synthesising ammonia is energy efficient, but fossil feedstocks and fuels cause significant CO₂ emissions.

- Renewable ammonia has been produced at an industrial scale since the 1920s, with hydroelectricity powering the alkaline electrolyzers to feed the Haber-Bosch process with renewable hydrogen.
- In the 1940s, natural gas started to become the dominant feedstock, and larger plant designs delivered economies of scale. Only one renewable ammonia plant remains in commercial operation, in Peru.
- Today, fossil-based ammonia production causes global emissions of 0.5 Gt of CO₂ annually, or around 1% of total greenhouse emissions.

Renewable ammonia represents a viable decarbonisation pathway for industries that use ammonia today, and opens new markets for ammonia as a fuel and hydrogen carrier in the future.

- The first fossil-free fertilisers are expected to be available in 2023, derived from renewable ammonia produced in Norway with an anticipated carbon footprint reduction of 80-90%.
- Nitrate fertilisers contain no carbon, whereas urea fertilisers contain carbon. This suggests an opportunity to eliminate emissions at ammonia plants that manufacture nitrates, and an opportunity to use circular sources of CO₂ at ammonia plants that produce urea.
- Other industries that consume ammonia can substitute renewable ammonia for fossil-based ammonia.
- The anticipated availability of renewable and low-carbon ammonia suggests that ammonia will see significant future demand as a fuel and hydrogen carrier (see section 4).

The market price of ammonia is currently linked to natural gas and remains volatile.

- Between 2000 and 2020, the market price for ammonia ranged from USD 100 to USD 600 per tonne.
- In 2021, driven by natural gas shortages, ammonia prices exceeded USD 1000 per tonne in all regions.
- A shift to renewable ammonia would decouple ammonia pricing from natural gas markets.

In 2020, global ammonia production capacity was around 243 Mt, with global demand of 183 Mt.

- Around 90% of ammonia is consumed on-site as a feedstock for derivative products.
- Each year, 25-30 Mt of ammonia is transported by road, train, ship and pipeline.
- Each year, 18-20 Mt is transported by ship. Around 170 vessels are in operation that can carry ammonia, of which 40 carry ammonia on a continuous basis.

Ammonia is a hazardous chemical, but its risks can be managed.

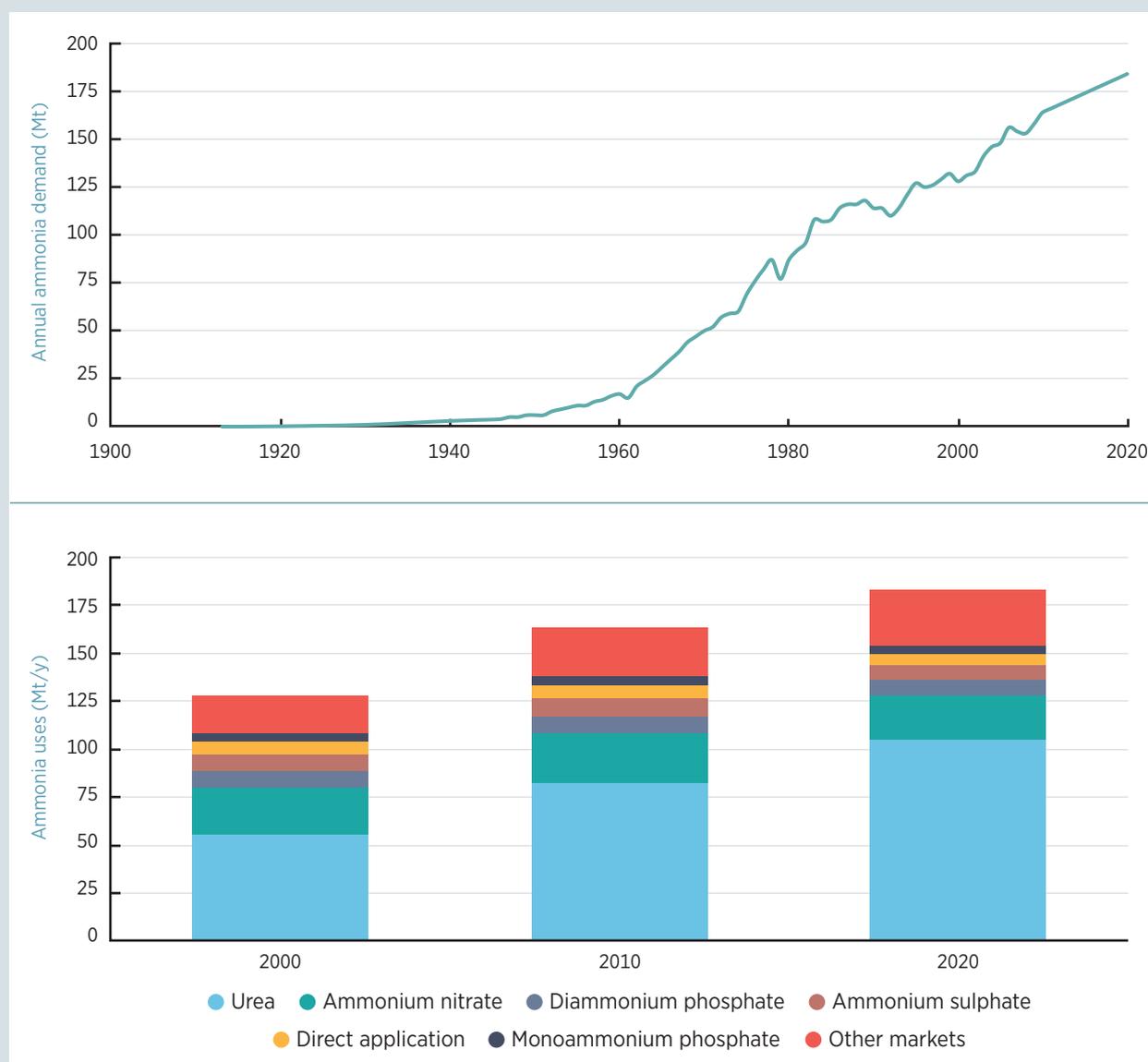
- Ammonia has a well-known hazard profile and has been handled safely for more than a century, with few fatal incidents reported when handled by trained personnel.
- There is a high maturity of storage, transport, and distribution technologies, as well as training, industry codes and standards, and regulations that ensure safety and security.



Ammonia (NH₃) is one of the seven basic chemicals – alongside ethylene, propylene, methanol and BTX aromatics (benzene, toluene and xylene) – that are used to produce all other chemical products. It is the second most produced chemical by mass, after sulphuric acid. Around four-fifths of all ammonia is used to produce nitrogen fertilisers, such as urea and ammonium nitrate; as such, it supports food production for around half of the global population (Erisman *et al.*, 2008).

Global demand for ammonia was around 183 Mt in 2020 (Hatfield, 2020) (Figure 6), while the global production capacity has reached 243 Mt (Haldor Topsøe *et al.*, 2020). Roughly 90% of all ammonia produced today is consumed on-site as a feedstock for downstream processes, and 18-20 Mt of merchant ammonia is transported annually by ship (Hatfield, 2020, 2021).

Figure 6 Global ammonia demand, 1900-2020 (top), and uses (bottom)

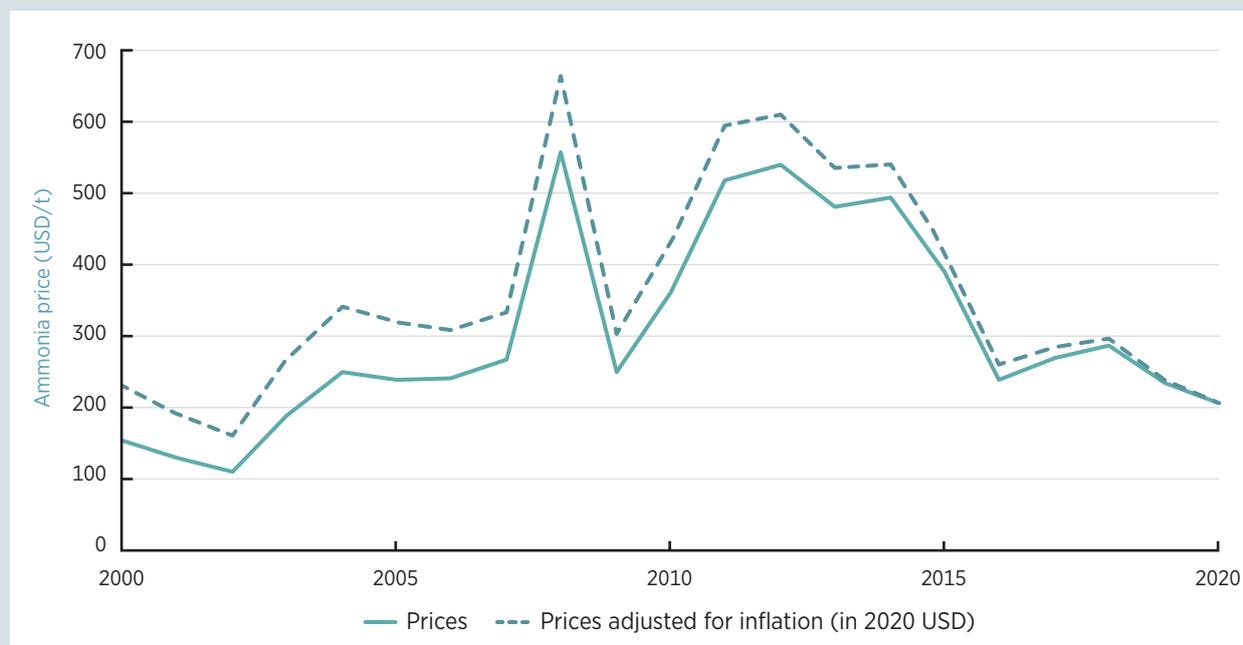


Note: Direct application refers to the use of ammonia as fertiliser. Other markets include the textile industry, the explosives and mining industry, pharmaceuticals production, refrigeration, plastics manufacturing, waste treatment and air treatment, such as nitrogen oxide (NO_x) abatement.

Sources: Reproduced from Appl (1999), Brightling (2018), Hatfield (2020) and Smil (2004).

Between 2000 and 2020, the average contract price for ammonia fluctuated between USD 100 and USD 600 per tonne in the Gulf Coast, Europe and the Middle East when adjusting for inflation (Figure 7). In recent years, ammonia prices fluctuated between USD 200 and USD 300 per tonne (Haldor Topsøe *et al.*, 2020; Hatfield, 2020) until, natural gas shortages of 2021, ammonia prices exceeded USD 1000 per tonne at each of these trading hubs (S&P Global Platts, 2021).

Figure 7 Ammonia market price in the Black Sea region, 2000-2020



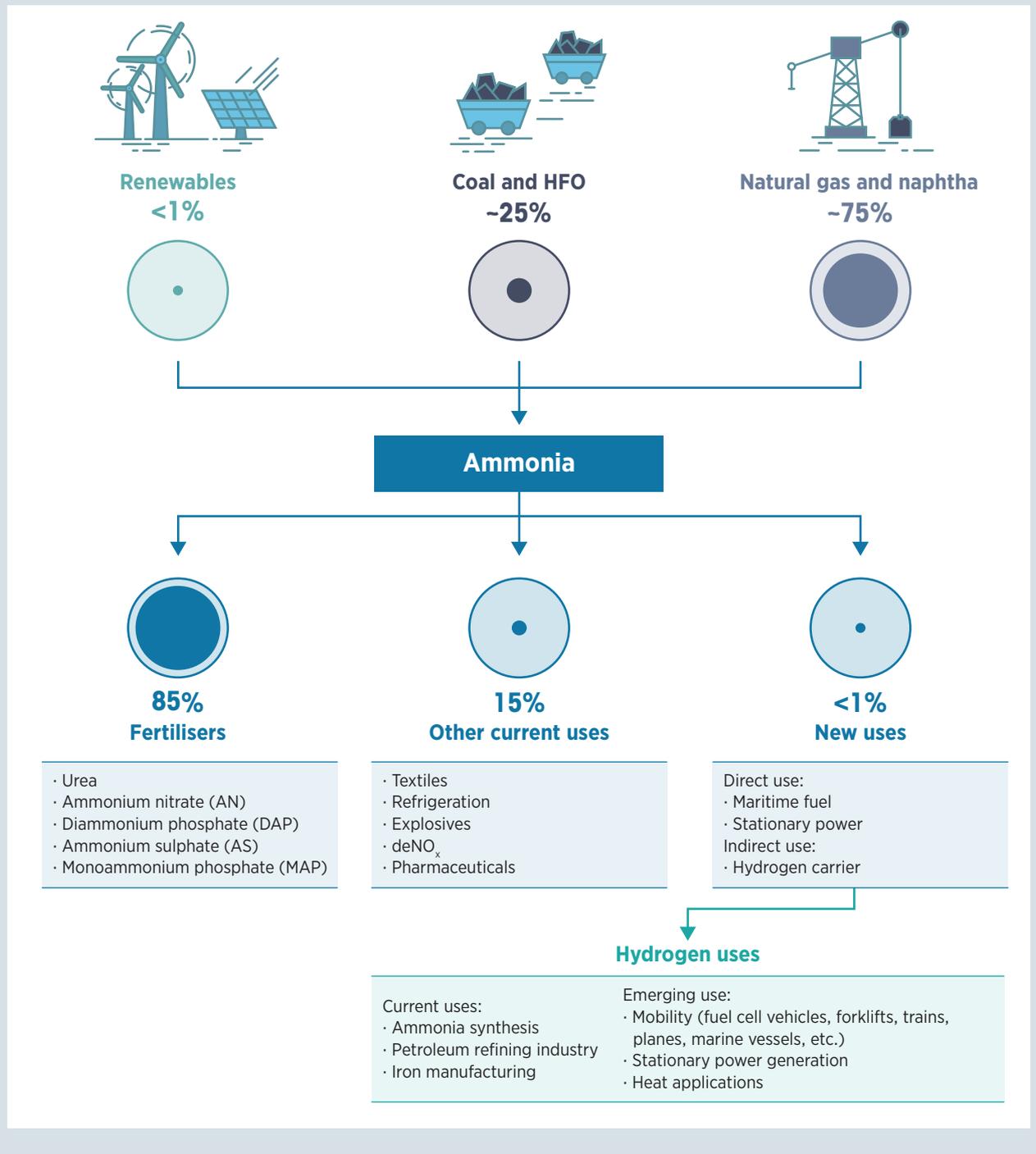
Source: Hatfield, 2020.

1.1 Uses of ammonia

Nitrogen fertilisers account for around 80% of today's total ammonia demand. Other markets include manufacturing of chemicals, plastics and textiles (acrylonitrile, melamine); the mining industry (low-density ammonium nitrate explosives, metals brightening processes), pharmaceuticals; refrigeration; waste treatment; and air treatment, such as abatement of nitrogen oxide (NO_x). While the use of ammonia in fertiliser markets began in the 1920s following the scale-up of the Haber-Bosch synthesis process, ammonia had already been used as a refrigerant since 1850. Around 0.36 Mt of ammonia annually is currently used as a refrigerant in North America (Haldor Topsøe *et al.*, 2020), and while it has to be carefully managed as it is a poisonous chemical, it has the advantage of having a global warming potential of zero.

Ammonia is also proposed as a carbon-free fuel and hydrogen carrier (Royal Society, 2020; Valera-Medina *et al.*, 2018). However, ammonia is currently not used for these applications beyond research, development and demonstration projects. The role of ammonia as a fuel and hydrogen carrier is discussed in section 4.

Figure 8 Production and uses of ammonia



Ammonia for fertiliser applications

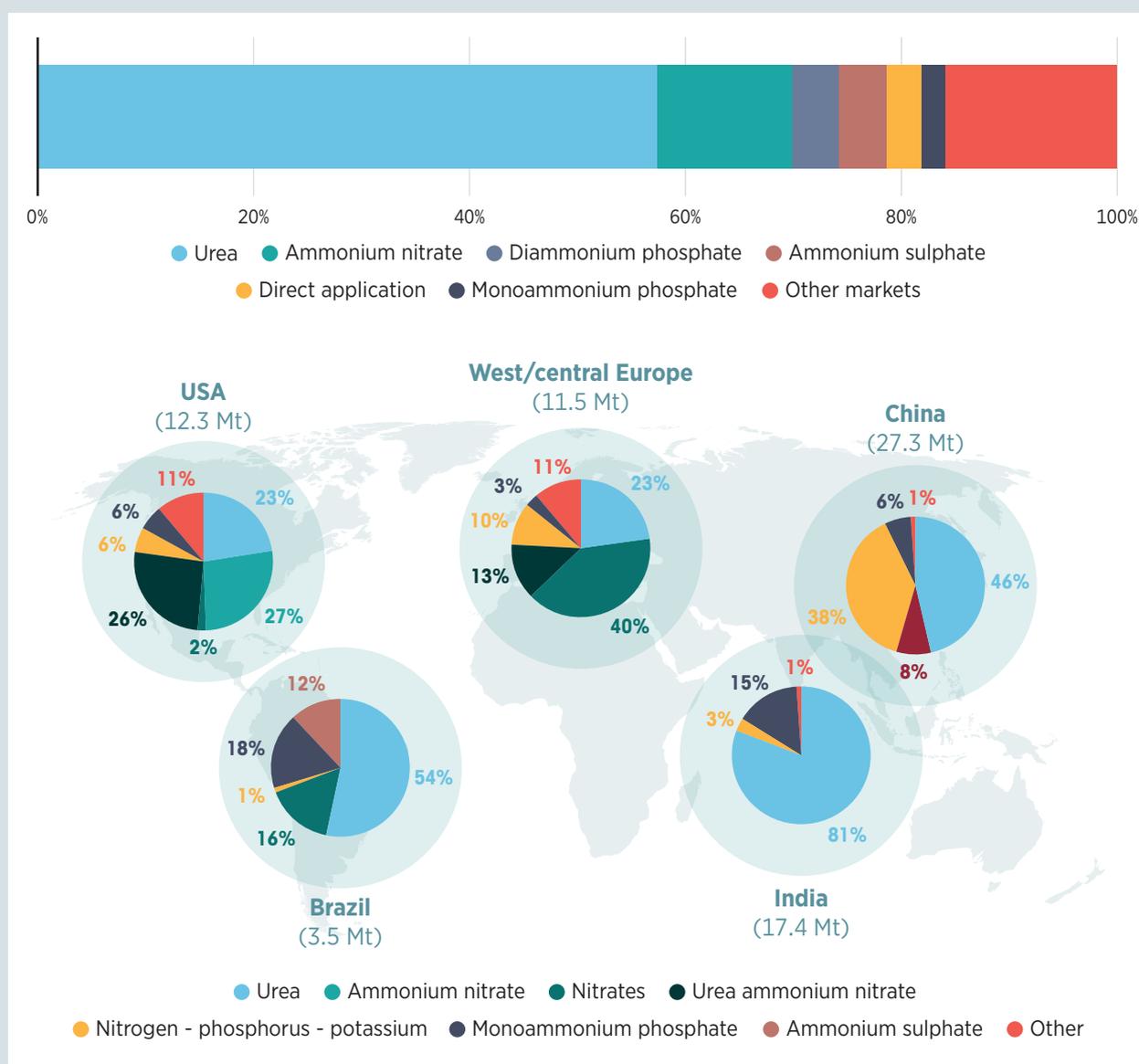
The Haber-Bosch process for ammonia synthesis was invented and commercialised during the 1900s and the 1920s. Following the adoption of natural gas as the preferred fuel and feedstock for the Haber-Bosch process in the 1940s and 1950s, and with increases in plant size and energy efficiency that delivered economies of scale, the use of ammonia-based fertilisers accelerated globally, increasing agricultural yields to support the ever growing population. Over the years, ammonia-derived fertilisers have become indispensable for modern agriculture, currently sustaining around half the global population (Erisman *et al.*, 2008). The impact of these fertilisers on the global nitrogen cycle is discussed in Annex B.

Urea ($\text{CO}[\text{NH}_2]_2$) accounts for around 55% of all ammonia produced, and ammonium nitrate (NH_4NO_3) accounts for around 15% (Figure 9). Other nitrogen fertilisers include various nitrates, monoammonium phosphate and diammonium phosphate, ammonium sulphate, as well as mixtures of nitrogen fertilisers such as urea ammonium nitrate solution and NPK fertilisers, which mix nitrogen with the other key nutrients, such as potassium and phosphate (Yara, 2018).

The preferred fertiliser depends strongly on the crop and location. Nitrates account for nearly half of the fertiliser application in Europe, whereas direct application of ammonia as fertiliser accounts for a quarter of the total fertiliser application in the United States (Figure 9). In the rest of the world, urea is the dominant fertiliser.

The first fossil-free fertilisers are expected to be available in Europe in 2023, when Swedish agricultural co-operative Lantmännen begins marketing nitrate fertilisers derived from renewable ammonia produced in Norway by Yara, with an anticipated carbon footprint reduction of 80-90% (Yara, 2022).

Figure 9 Nitrogen fertiliser application by region and product



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Sources: Hatfield, 2020; Yara, 2018.

Ammonium nitrate (NH_4NO_3) is produced from ammonia and nitric acid, an intermediate produced from ammonia. Ammonium nitrate is the building block for all inorganic nitrate fertilisers, and it does not contain carbon, so elimination of production emissions may be achieved by decarbonising the ammonia feedstock.

On the other hand, urea is produced by combining ammonia with CO_2 . Urea requires 0.75 tonnes of CO_2 per tonne of urea, or around 1.3 tonnes of CO_2 feedstock per tonne of ammonia feedstock, approximately equal to the high-purity CO_2 stream produced as a by-product of hydrogen production from natural gas reforming. Integrated natural gas-based ammonia-urea plants are therefore common, with low on-site CO_2 emissions.

However, all of the CO_2 contained in the urea molecule is released to the atmosphere when applied as a fertiliser. Decreasing the carbon footprint of urea can be achieved by combining CO_2 from other sectors, such as steel or energy production, with low-carbon ammonia (Driver *et al.*, 2019). Urea can be completely decarbonised by combining renewable ammonia with circular carbon sources, such as atmospheric CO_2 or biomass.

Similar challenges for decarbonisation exist for methanol (IRENA and Methanol Institute, 2021), causing competition for circular CO_2 . A transition from urea to other fertilisers may be required (Energy Transitions Commission, 2018).

The role of biomass for urea production is expected to be limited due to the limited availability of low-cost biomass (see section 2.5), and to uses in other hard-to-abate sectors. CO_2 removal from the atmosphere via direct air capture (DAC) is currently expensive, also due to small-scale equipment. In the long term, DAC may cost around USD 65 per tonne of CO_2 (Fasihi, Efimova and Breyer, 2019), resulting in an added cost of USD 50 per tonne of urea. For reference, the urea market price was around USD 200-300 per tonne in 2020, resulting in a price increase of around 20% upon using DAC for CO_2 purification.

Decarbonising the entire value chain of current markets, from ammonia production to use, requires significant infrastructure changes as well as major investment. Large ammonia producers are now committing to decreasing their carbon footprint (van den Broeck, 2020; Brown, 2020a). In the United States, CF Industries, the largest ammonia producer with 10 Mt of capacity, announced that it will only produce net zero carbon ammonia by 2050 (Brown, 2020b). Similarly, the Norwegian ammonia producer Yara, the world's second largest with around 8.5 Mt of capacity across 17 units, has committed to a CO_2 -neutral value chain by 2050 (van den Broeck, 2020).

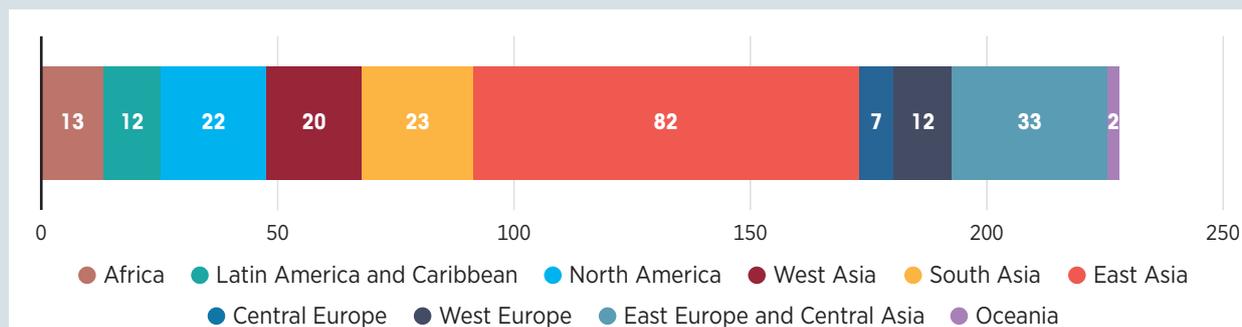
Certification of fertilisers, governmental regulations, carbon taxes and carbon permits are incentives for value-added zero-carbon fertilisers, as this allows for food production with a zero-carbon value chain. In the end, the impact is driven by pledges made for net zero emissions by big food companies, as well as by consumer behaviour. Big food companies that have pledged to be carbon neutral by 2050 rely on contract farmers, which can be an incentive for decarbonised fertilisers. However, fertilisers are a significant cost for farmers, so the risk of fertiliser price increases should not be borne solely by the farmer but mitigated and distributed through the value chain.

In addition to supply chain decarbonisation, the agricultural sector requires improved nutrient use efficiency, as half of the nitrogen applied to a field is currently emitted to the environment (Galloway and Cowling, 2002). Land-use changes account for nearly half of the CO_2 -equivalent emissions in agriculture, however, so a main challenge in the agricultural sector is balancing the need for increased yields from limited land against improved fertiliser use efficiency.

1.2 Locations for ammonia production and consumption

Ammonia is produced mainly in Asia, which has more than half of the global ammonia production capacity (Figure 10). The Asia-Pacific region also accounts for more than half of the world's ammonia consumption, mainly for agricultural activities. The largest consumers of ammonia-based fertiliser are China and India (Figure 9). Other ammonia consumers from largest to smallest are: North America, Europe, South America, and the Middle East and Africa.

Figure 10 Ammonia production capacity by region in 2020



Source: FAO, 2019.

1.3 Storage, transport and distribution of ammonia

Ammonia has been handled in large quantities for many decades, and there is a high maturity of storage, transport, and distribution technologies, as well as training, industry codes and standards, and regulations that must be observed to ensure safety and security (Fecke, Garner and Cox, 2016; FSDF, 2016; OSHA, n.d.). Ammonia is transported by road, train, ship and pipeline (Haldor Topsøe *et al.*, 2020). In total, around 25-30 Mt of ammonia are transported annually.

Around 18-20 Mt of ammonia are transported annually by ship (Hatfield, 2020). Around 170 ships are in operation that can carry ammonia, of which 40 carry ammonia on a continuous basis (Brown, 2019a). A map of ammonia import/export terminals and trade routes is shown in Figure 11.

Ammonia can be transported by pipeline, and both natural gas pipelines and liquids pipelines can be retrofitted for this purpose (Nayak-Luke *et al.*, 2020). Around 1.5 Mt of ammonia is transported annually in the United States through 3 220 kilometres of mild carbon-steel pipelines connecting seven states (Acker, 2021; Fertilizers Europe, 2012; NuStar, n.d.; Papavinasam, 2014). In the Russian Federation, ammonia is transported across 2 424 kilometres by pipeline from a production site in Tolyatti to the port city of Odessa in Ukraine (Fertilizers Europe, 2012; Haldor Topsøe *et al.*, 2020). The Tolyatti-Odessa pipeline has a capacity of 3-5 Mt of ammonia annually (Argus Media, 2019).

Transport of ammonia by pipeline is also common across short distances in Europe, with typical pipelines spanning 1-12 kilometres in industrial areas, although a longer pipeline of 74 kilometres is located in Italy (Fertilizers Europe, 2012). Ammonia is transported mainly by train within Europe, totalling around 1.5 Mt annually (Haldor Topsøe *et al.*, 2020).

Figure 11 Ammonia shipping infrastructure, including a heat map of liquid ammonia carriers, as well as the ammonia loading and unloading facilities



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Reproduced from Royal Society (2020).

At a large scale (> 5 kilotonnes [kt] of ammonia), ammonia is liquefied by refrigeration, at -33°C and atmospheric pressure (Rouwenhorst *et al.*, 2019). The largest ammonia storage tanks can store up to 50 kt (Appl, 2011; Nielsen, 1995). Large ammonia storage facilities are typically located at ports near ammonia production facilities, with up to 150 kt of ammonia storage capacity divided over multiple tanks. At a smaller scale (< 1.5 kt of ammonia), ammonia is liquefied by pressure, stored at ambient temperature and 16-18 bar (Rouwenhorst *et al.*, 2019).

In the United States, where ammonia is directly used as a fertiliser, there are more than 10 000 ammonia storage locations, mainly in the Midwestern corn belt; in Iowa alone, more than 1 000 ammonia storage facilities exist, with a total capacity of around 800 kt (Papavinasam, 2014). Ammonia storage is also common in coastal areas at ports and import/export terminals, as well as at coal-fired power plants, wastewater treatment facilities and cold storage facilities.

1.4 Safety aspects

Ammonia is a hazardous chemical, which in ambient conditions is a toxic gas. In liquid form, risks of exposure increase if under pressure, as large quantities have the potential to be rapidly released into the air. For this reason, it is often preferable to store ammonia as a liquid under refrigeration (-33°C) and not under pressure (7.5 bar). To address the risks associated, the industry has been engaged in developing standards and codes for the safe handling of ammonia in different applications.

So far, ammonia has been handled safely for more than a century, with few fatal incidents reported¹ when handled by trained personnel (Anderson, 2017). Most high-profile “ammonia” accidents reported in the media have actually involved ammonia derivatives, such as ammonium nitrate, instead of ammonia itself.

Ammonia can be detected at concentrations as low as 2-5 ppm (Clark and Goff, 2014), far below concentrations where ammonia exposure can cause lasting health hazards. If ammonia leaks from a refrigerated storage tank at atmospheric pressure, it rapidly disperses in the gas phase because it is lighter than air (Afif *et al.*, 2016). However, if ammonia leaks from a pressurised storage tank, it results in the formation of an aerosol, leading to a dense cloud that is heavier than air (Mott, 2019).

¹ A total of 18 cases was reported in the period 1994-2013; see Anderson (2017).

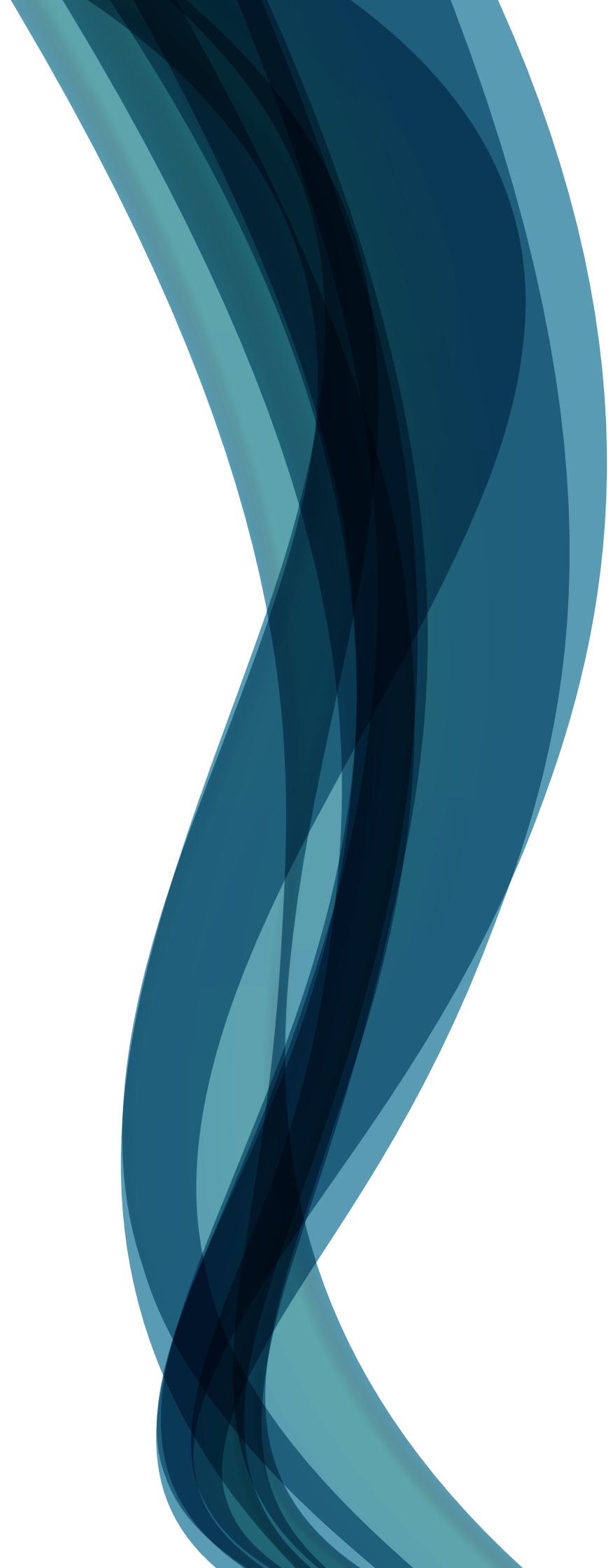
Ammonia has a low reactivity compared to other fuels and a narrow flammability range of 15-28 volume-percent (Clark and Goff, 2014; Valera-Medina *et al.*, 2018), reducing the risk for fires or explosions. Thus, even though ammonia is corrosive, toxic and potentially life-threatening upon inhalation in high concentrations (above 0.1 volume-percent (Clark and Goff, 2014; Wan *et al.*, 2021)), these risks can be effectively mitigated by using established industry best practices (Fecke, Garner and Cox, 2016). In the case of aquatic spills, ammonia can cause severe pH changes, which disrupts life in the aquatic ecosystem.

Box 2 Risks associated with ammonia used as a fuel for ships

Ammonia is currently not approved as fuel by various regulators, including the IMO and many power sector authorities. Although technological challenges are not expected to be a significant hurdle, experience with ammonia fuel is required before it can be widely adopted, not least to inform the development of new or revised codes and standards. Hereby, operational experience is essential to establish protocols for safe handling and product standards are required to establish safe purity levels across multiple applications. Further, emission testing and verification is required to ensure that ammonia combustion does not exceed acceptable emission levels across a range of pollutants. These actions must be completed before it is possible to achieve broad regulatory approval of ammonia as a fuel. In the meantime, the use of ammonia as fuel is likely to be limited to demonstrations and pilots.

Although ammonia is a hazardous chemical, its risks can be managed as there is a high maturity of storage, transport, and distribution technologies, as well as training, industry codes and standards, and regulations that ensure safety and security. Developing solid regulations is a top priority on the agenda for ship owners & operators, technology developers, ports, and particularly for the classification societies, who are deeply engaged in hazard identification analyses, mitigation strategies and clean energy technologies to ensure that the use of ammonia as a fuel meets existing safety standards. In this context, the classification societies are studying the risks and developing frameworks for the future ammonia code. Accordingly, numerous classification societies including DNV (Det Norske Veritas), ABS (American Bureau of Shipping), Lloyds Register, RINA (Registro Italiano Navale), Korean Register, Class NK, and Bureau Veritas have recently produced documents.

Besides, the Ammonia Energy Association is tracking approximately 20 separate industry, government and NGO projects around the world that look at the safety considerations of ammonia as a maritime fuel. Accordingly, much of the activity in the area is driven by Singapore. The port of Singapore serves as a living lab with a physical and digital test environment, and as a regulatory sandbox, to develop safe bunkering procedures for ammonia and gain operational experience. For instance, a coalition of the American Bureau of Shipping, Nanyang Technological University, Singapore and the Ammonia Safety and Training Institute (ASTI) aims to study the potential of ammonia for Singapore, exploring supply, bunkering and safety challenges with ammonia as a maritime fuel. Safety protocols and possible gaps in the supply chain will be identified within the scope of the project. ExxonMobil, Hoegh LNG, MAN Energy Solutions Singapore, Jurong Port, PSA Singapore and ITOCHU Group are contributing technical information.



2. PRODUCTION PROCESSES, TECHNOLOGY STATUS AND COSTS

Key findings

The Haber-Bosch process combines hydrogen and nitrogen to form ammonia.

- In today's ammonia plants, fossil fuels are both reformed to produce hydrogen feedstock and combusted to power the process.
- Of the world's ammonia plants, 72% use natural gas, emitting on average 1.6-1.8 tonnes of CO₂ per tonne of ammonia, and 22% use coal, emitting on average 4.0 tonnes of CO₂ per tonne of ammonia.

Fossil-based ammonia plants can be decarbonised with today's technologies.

- Renewable hydrogen can be introduced in a fossil-based ammonia plant, replacing 10-20% of the natural gas. This concept has already been implemented, in late 2021, by Fertiberia at Puertollano in Spain.
- In a natural gas-based ammonia plant, two-thirds of the CO₂ is from hydrogen production (process gas), which is pure and easy to capture, but one-third of the CO₂ is from combustion (flue gas), which is dilute and expensive to capture.
- Alternative technologies for reforming natural gas, including autothermal reforming (ATR) and eSMR (electrified steam methane reforming), could reduce or eliminate the dilute flue gas emissions. Methane pyrolysis would essentially eliminate all CO₂ emissions, producing hydrogen and solid carbon instead.
- Many fossil-based ammonia plants already use carbon capture and utilisation (CCU) or source hydrogen from by-product or waste streams. Globally, the installed annual capacity is more than 4 Mt of lower-carbon ammonia.
- Carbon capture and storage (CCS) is technologically and economically feasible in the presence of a carbon tax, and many new ammonia plants have been proposed using CCS. The combined capacity of announced CCS ammonia plants is more than 5 Mt of low-carbon ammonia.

Renewable ammonia is on track to dominate all new capacity after 2025.

- Renewable ammonia is a mature, century-old technology. Commercial ammonia plants used alkaline electrolyzers as big as 150 MW, many times larger than any electrolyser in service today and powered by baseload hydropower.
- Most of the proposed renewable ammonia plants, however, use variable solar photovoltaics and wind to power various electrolysis technologies, including solid oxide and polymer electrolyte membrane (PEM).

Technological and operational innovations, as well as careful site selection and design, can overcome the challenges presented by variability.

- Around 15 Mt of low-carbon ammonia capacity has been announced to be operational by 2030. The total announced renewable ammonia capacity is 71 Mt, likely to be operational before 2040, but investment decisions are still pending for most projects.
- Renewable ammonia from biomass gasification is also a mature, century-old technology, although future deployment may be limited to opportunities where location-specific conditions overcome the economic hurdles.

Renewable ammonia is already cost competitive with other zero-carbon fuels, but not with fossil-based ammonia.

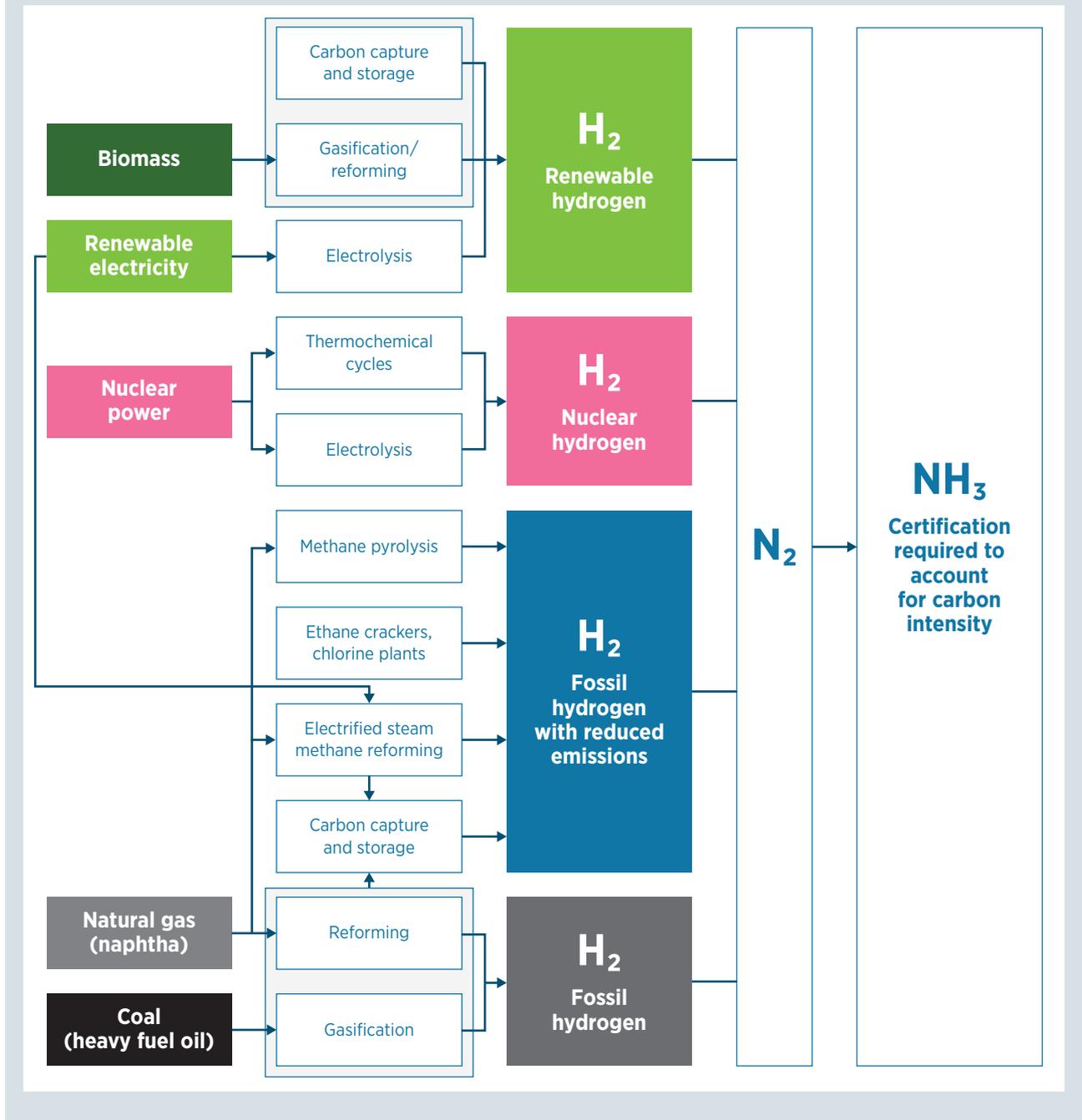
- The estimated cost of renewable ammonia is set to decrease from a range of USD 720 - 1400 per tonne (USD 39-75 per gigajoule [GJ]) in 2020 to USD 475-950 per tonne (USD 25-51 per GJ) in 2030. By 2050, the production cost of renewable ammonia is expected to reach around USD 310 per tonne (USD 17 per GJ), for a large-scale plant in a location with excellent renewable energy resources.
- Cost reductions for renewable ammonia are driven primarily by: a) scale-up to gigawatt-size, b) the cost of renewable electricity, c) the cost of electrolyzers, d) the efficiency of electrolyzers, and e) optimised storage, buffering, sizing and flexibility of the Haber-Bosch ammonia synthesis loop.
- In optimal locations, renewable ammonia could be cost competitive with fossil-based ammonia with CCS from 2030.
- Low-carbon ammonia, whether renewable or fossil-based with CCS, is currently not cost competitive at the conventional commodity price of USD 200-300 per tonne. Therefore, it is expected that separate markets will need to develop, supported by certification schemes, contracts for difference and other mechanisms.

Ammonia can be produced from various fossil-based hydrogen sources, such as natural gas, coal, naphtha and heavy fuel oil. Decarbonised hydrogen sources include biomass and water. The nitrogen is purified from air. To produce ammonia using the Haber-Bosch process, hydrogen and nitrogen are combined at high temperature and pressure (350-500°C and 100-400 bar) in the presence of an iron catalyst (Appl, 1999; Liu, 2013; Nielsen, 1995). The ammonia is subsequently condensed and stored.

Various production pathways are shown in Figure 12. Colours are commonly used to refer to different energy inputs and technologies for hydrogen as well as for ammonia production. Renewable ammonia, whether produced from biomass or renewable electricity, is generally termed green. On the other hand, brown ammonia (fossil) can be grey (natural gas) or black (coal). Colour coding becomes increasingly complex as fossil ammonia is decarbonised, becoming blue (natural gas with CCS) or turquoise (methane pyrolysis).

Alternative inputs – such as electricity from nuclear energy or from the grid, hydrogen from waste or by-product streams, and heat – are less easily communicated with colours. In practice, many ammonia plants are integrated hybrids, incorporating more than one colour. Moreover, while some colours refer to carbon-free inputs or carbon abatement technologies, these colours lack legal definition and do not communicate the greenhouse gas emission intensity of the product, which can vary greatly (e.g. blue ammonia with a 70% carbon capture rate versus blue

Figure 12 Production pathways of ammonia from various feedstocks



ammonia with a 98% carbon capture rate) (see section 3.2). For this reason, robust certification schemes that can calculate and verify the emission intensity of ammonia will be essential (see section 3.3).

For mostly economic reasons, the hydrogen feedstock for ammonia is produced almost entirely from fossil fuels today. Around 72% of ammonia production uses natural gas; coal accounts for around 22%; heavy fuel oil and naphtha account for around 4% and 1%, respectively, while 1% of ammonia is derived from other feedstocks (Bicer *et al.*, 2016). Most ammonia production capacity using coal is located in China, where vast coal reserves are available (Zhou *et al.*, 2010). Production from natural gas is the norm in the rest of the world.

Ammonia production currently emits around 0.5 Gt of CO₂ annually, or 1% of global CO₂ emissions (Royal Society, 2020), making ammonia the largest CO₂ emitter in the chemical industry. Ammonia is considered one of the “big

four” industrial processes – along with cement, steel and ethylene production – that need a decarbonisation plan and implementation in order to meet net zero carbon emission targets by 2050 (de Pee *et al.*, 2018). This decarbonisation can be achieved by transitioning ammonia feedstocks from fossil-based to renewable hydrogen.

2.1 Coal-based ammonia production

Technology and production process

To produce ammonia from coal, the coal must be converted to synthesis gas (syngas), a mixture of carbon monoxide (CO), hydrogen (H₂), and carbon dioxide (CO₂), following pre-treatment to remove impurities and poisons. Air is added to provide nitrogen (N₂). The syngas is obtained by coal gasification processes that combine partial oxidation and steam treatment at high temperature (800-1800°C depending on the process and feedstock). Substantial pre-treatment is required for coal feedstock, to remove impurities and poisons. The CO is converted to CO₂ via the water-gas shift reaction, and the CO₂ is subsequently removed from the mixture. The resulting mixture of H₂ and N₂ is fed to the ammonia synthesis section. On average, around 4 tonnes of CO₂ are produced per tonne of ammonia produced from coal (Brightling, 2018; IRENA, 2020a).

Costs

The capital intensity of a coal-based ammonia plant is around USD 2 900 per annual tonne of ammonia capacity for a plant with a capacity of 630 kt of ammonia per year (Appl, 1999). The specific cost of ammonia produced from coal ranges from USD 225 to USD 315 per tonne of ammonia, depending on the coal feedstock cost, ranging from USD 0.5 to USD 2.5 per million Btu (Appl, 1999).

The cost of CO₂-equivalent emissions for coal-based ammonia production is also estimated, assuming USD 75 per tonne of CO₂, resulting in an CO₂ cost of USD 300 per tonne of ammonia and a cost range of USD 525-615 per tonne of ammonia for coal-based ammonia production with carbon pricing.

Current installed capacity

The global coal-based ammonia production capacity is estimated to be around 53 Mt. Coal-based ammonia production is mainly located in China, where vast coal reserves are available (Zhou *et al.*, 2010). These coal-based ammonia synthesis plants are typically relatively small, energy inefficient and young (IEA, 2021a). They typically consume 55-65 GJ per tonne of ammonia (Ma, Hasanbeigi and Chen, 2015), have a capacity in the range of 100-300 kt of ammonia per year (Zeng, 2014) and have an average age of only 12 years (IEA, 2021a).

China recently introduced an emission trading system (ETS) to put a price on CO₂ emissions (Argus Media, 2021a). Although current prices are low, increases to match the current price levels of the European Union (EU) would result in a prohibitively high cost of USD 525-615 per tonne of ammonia. Although CCS can provide mitigation, production costs would still be in the range of USD 360-450 per tonne of ammonia. For reference, renewable ammonia production is expected to cost below USD 500 per tonne in China beyond 2030 (Fasihi *et al.*, 2021), which suggests that coal-based ammonia production may be phased out beyond 2030.

2.2 Natural gas-based ammonia production

Technology and production process

To produce ammonia from natural gas, natural gas is converted to syngas by a number of processes, including steam methane reforming (SMR), partial oxidation (POX), autothermal reforming (ATR), dry reforming of methane (DRM), or a combination thereof (Rostrup-Nielsen, 1984). Air is added to provide nitrogen (N₂). These processes typically operate at temperatures above 800°C. The CO is converted to CO₂ via the water-gas shift reaction, and the CO₂ is subsequently removed from the mixture. The resulting mixture of H₂ and N₂ is fed to the ammonia synthesis section. Typically around 1.6-1.8 tonnes of CO₂-equivalent is produced during ammonia synthesis. Including upstream emissions from natural gas extraction and distribution, roughly 2.2 tonnes of CO₂-equivalent is produced per tonne of ammonia produced from natural gas (see section 3.2).

A state-of-the-art, world-scale natural gas ammonia plant has a production capacity of around 2 000 to 3 300 tonnes per day or 0.7 to 1.2 Mt per year (Brightling, 2018). The largest single-train ammonia plants have a capacity of 3 760 tonnes per day or 1.3 Mt per year (ThyssenKrupp, 2019). Novel large-scale technology using ATR may allow for ammonia production capacities up to 4 000 to 6 000 tonnes per day or 1.4 to 2.1 Mt per year (Haldor Topsøe A/S, 2020). The largest ammonia production sites operating today contain multiple ammonia plants, resulting in site capacity as high as 4.0 Mt per year.

Costs

Natural gas-based ammonia plants typically have capacities between 200 kt and 1 200 kt of ammonia per year. Such large-scale plants benefit from economies of scale – for example, building larger plants decreases the capital investment per amount of ammonia product. The capital intensity of a natural gas-based ammonia plant is typically USD 1 500 to USD 2 000 per tonne of ammonia produced annually (Appl, 1999; Argus Media, 2020; Brown, n.d.).

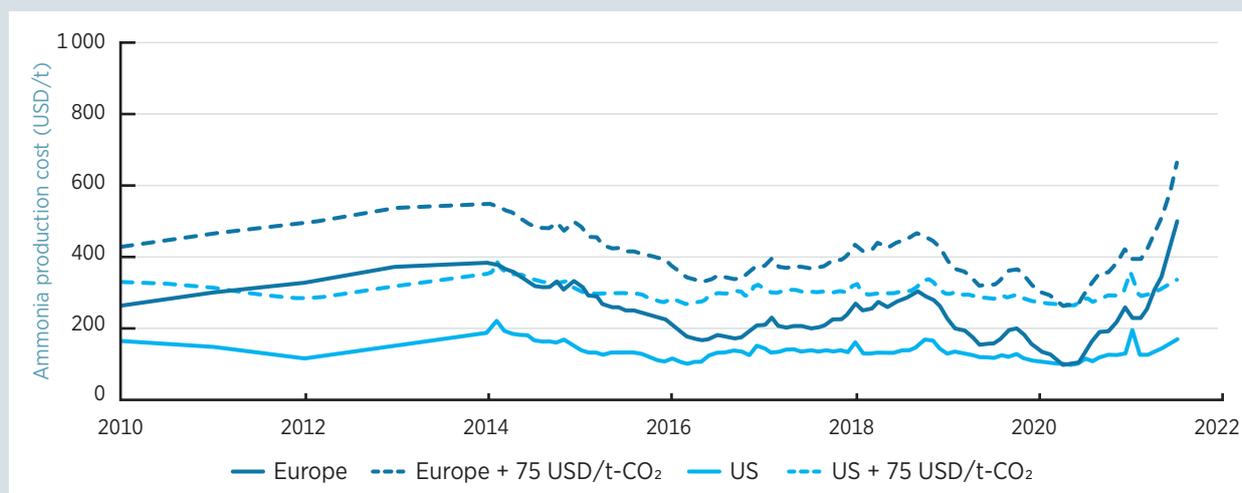
The cost of natural gas-based ammonia production is in the range of USD 110-340 per tonne of ammonia, depending on natural gas prices ranging from USD 2 to USD 10 per million Btu (Haldor Topsøe *et al.*, 2020). The cost of natural gas-based ammonia production in Europe and the United States for the period 2010 to 2021 is shown in Figure 13. In 2021, the cost of ammonia production in Europe and Asia increased substantially due to high natural gas prices (Thapliyal, 2021), resulting in curtailment of some European ammonia production.

The cost of CO₂-equivalent emissions for natural gas-based ammonia is also estimated, based on a CO₂ cost of USD 75 per tonne of CO₂. This results in an added cost of USD 165 per tonne of ammonia, resulting in a cost range of USD 275-505 per tonne of ammonia for natural gas-based ammonia production with carbon pricing.

Current installed capacity

The global natural gas-based ammonia production capacity is estimated to be around 132 Mt per year. Most newly built ammonia plants are located in places with low-cost natural gas of USD 3 per million Btu or below, such as countries in North Africa, Nigeria, North America, the Middle East and the former Soviet Union. European natural gas-based ammonia plants are some of the oldest plants but are also among the most efficient (IEA, 2021a). Newly built plants are typically very big, to benefit from economies of scale. Development of new natural gas fracking technologies has led to an expansion of the industry in the last decade.

Figure 13 Cost of natural gas-based ammonia production, 2010-2021



Note: USD 75 per tonne of CO₂ is added as an indication of current carbon pricing in the EU.

Source: CAPEX and OPEX from Haldor Topsøe et al. (2020).

2.3 Lower-carbon fossil-based ammonia production

Technology and production process

Various non-renewable technology pathways exist for ammonia production with reduced emissions. Examples include conventional production with the addition of CCS, CCU for enhanced oil recovery or methanol synthesis, or replacing the feedstock production process by using by-product hydrogen from other processes, such as ethane crackers, chlorine plants and plastic gasification plants (Brown, 2018a; Elgowainy, 2017 and IRENA data).

Alternatively, electrified steam methane reforming (eSMR) can be adopted to reduce the carbon footprint of the SMR unit by about a third, using renewable electricity to supply the heat input of the reformer (Wismann et al., 2019), so that only concentrated CO₂ is produced, enabling low-cost CCS. Lastly, low-emission hydrogen can be produced via methane pyrolysis, which converts natural gas to solid carbon and hydrogen (Schneider et al., 2020).

In a conventional SMR-based ammonia production unit, there are two streams of CO₂. Around two-thirds of the CO₂ is generated in concentrated form during hydrogen production (Haldor Topsøe et al., 2020). The remaining one-third of the CO₂ is generated in dilute form upon burning natural gas for heating purposes, and this stream is generally not captured in a conventional ammonia plant, resulting in an overall capture range of around 65%. If the dilute CO₂ is also captured, an overall capture rate of around 95% is achievable.

Thus, the majority of CO₂ generated during ammonia production is already captured in hundreds of ammonia plants worldwide, such that this technology is well established (IRENA 2020c). eSMR has the potential to increase the CO₂ capture rate to 98%.

On the other hand, ATR-based ammonia production combines hydrogen production and heating in a single reactor, resulting in a single concentrated CO₂ stream. This decreases the cost of CO₂ capture and increases the effective capture rate to 98% (Hydrogen Council, 2021).

Costs

The cost of CCS for a coal-based ammonia plant is around USD 135 per tonne of ammonia² (not including CO₂ penalties from fugitive CO₂ emissions), which would result in an ammonia production cost range of USD 360-450 per tonne for coal-based ammonia production with CCS.

The CCS cost for SMR-based ammonia plants is an estimated USD 100-150 per tonne of ammonia³ for the dilute CO₂ stream (Haldor Topsøe *et al.*, 2020), which results in an ammonia production cost range of USD 235-465 per tonne of ammonia from SMR with CCS.

The cost of CCS for ATR-based ammonia is around USD 40-80 per tonne of ammonia,⁴ resulting in an ammonia production cost range of USD 170-400 per tonne of ammonia from ATR.

As shown in Figure 14, the current CO₂ cost in the EU closes the cost gap for CCS (ISPT, n.d.), especially for ATR-based ammonia, making it an economically viable option in today's market.

Figure 14 CO₂ cost over time in the EU, and the effect of the CO₂ cost on the carbon offset cost for fossil-based ammonia with carbon capture and storage



Note: Assumes a EUR to USD conversion factor of 1.18.

A CO₂ penalty of around:

- USD 60-90 per tonne of CO₂ is required to bridge the gap between fossil-based ammonia with unmitigated emissions and fossil-based ammonia with CCS; and
- USD 150 per tonne of CO₂ would bridge the gap between fossil-based and renewable ammonia (Saygin and Gielen, 2021).

² Assuming a 95% capture rate of 3.8 tonnes of CO₂ per tonne of ammonia, as well as a transport and storage cost of USD 25-50 per tonne of CO₂ (Haldor Topsøe *et al.*, 2020).

³ Estimate assumes a 95% capture rate of 1.6 tonnes of CO₂ per tonne of ammonia (IRENA, n.d.), and including a transport and storage cost of USD 25-50 per tonne of CO₂.

⁴ Estimate assumes a 98% capture rate of the 1.6 tonnes of CO₂ per tonne of ammonia (Brightling, 2018; Hydrogen Council, 2021), as well as a transport and storage cost of USD 25-50 per tonne of CO₂ (Haldor Topsøe *et al.*, 2020).

Fossil-based ammonia with CCS can be especially interesting for places where the natural gas price is usually below USD 3 per million Btu, such as in countries in North Africa, North America, and the Middle East, as well as in the Russian Federation and Trinidad and Tobago, resulting in costs below USD 300 per tonne of ammonia for fossil-based ammonia with CCS (Haldor Topsøe *et al.*, 2020). An industrial consortium expects that the market value of natural gas-based ammonia with CCS will be around USD 350-400 per tonne of ammonia (Haldor Topsøe *et al.*, 2020). On the other hand, coal-based ammonia with CCS always costs more than USD 300 per tonne of ammonia. Thus, coal-based ammonia with CCS is not expected to play a significant role in decarbonising ammonia despite the fact that CO₂ capture rates of up to 99% can be achieved for coal gasification (IEA Greenhouse Gas R&D Programme, 2007).

At certain locations, by-product hydrogen from, for instance, ethane crackers can be available at fuel value (\leq USD 10 per million Btu), and an ammonia plant can be established with only nitrogen purification and an ammonia synthesis loop. Thus, the capital intensity is typically below USD 1000 per tonne of ammonia annually for large-scale plants. The cost of hydrogen should be at most USD 1.1 per kilogram of hydrogen to produce ammonia at the market value of USD 250 per tonne of ammonia.

Current installed capacity and announced capacity

In recent years, various projects have been commissioned for ammonia production with a reduced carbon footprint. In most cases the hydrogen is a by-product from an ethane cracker or CO₂ is used for enhanced oil recovery, while one other plant also uses hydrogen derived from waste plastic (Table 1).

By-product hydrogen from an ethane cracker has an estimated 25% lower CO₂ footprint than hydrogen from SMR (Elgowainy, 2017). The first plant to utilise by-product hydrogen from an ethane cracker is located in Joffre, Canada, which started operation in 1987 and has a production capacity of around 490 kt of ammonia annually (Adair, 2020). In 2018, Yara started operating an ammonia plant in Freeport, United States, also utilising by-product hydrogen from the nearby BASF ethane cracker facility (Brown, 2018b), with a capacity of around 750 kt of ammonia annually. In 2019, Yara also started using by-product hydrogen from Dow Chemicals at its Sluiskil facility, producing around 22 kt of reduced-carbon ammonia annually, which represents a small portion of the total capacity of 1500 kt of ammonia annually at Sluiskil (Brown, 2019b).

In Japan, Showa Denko has produced ammonia from waste plastic gasification since 2003, resulting in a carbon footprint around 35% lower than SMR-based ammonia (Showa Denko K.K., n.d.). The plant capacity is around 60 kt of ammonia annually, which is sold as a premium NO_x-reduction product under the tradename EcoAnn™.

Another example is the use of CO₂ from SMR for enhanced oil recovery or for methanol production. Hydrogen with CO₂ used for enhanced oil recovery has an estimated 62.5% lower CO₂ footprint (Elgowainy, 2017).

The first plant to produce ammonia with CO₂ utilisation via enhanced oil recovery is located in Enid, Oklahoma, United States, where a plant started producing 285 kt of ammonia annually in 1982 (MIT, 2016). In Beulah, North Dakota, another ammonia plant with CO₂ utilisation via enhanced oil recovery started operating in 1991 (Brown, 2016). Nutrien operates two similar plants in Geismar, Louisiana, which started operation in 2013 with a production capacity of 200 kt of ammonia annually, and in Redwater, Alberta, Canada, which started operation of the CO₂ trunk line in 2020 with a production capacity of 245 kt of ammonia annually (Adair, 2020). In 2021, SAFCO started operating a lower-carbon ammonia facility in Saudi Arabia, where CO₂ is used for enhanced oil recovery and methanol synthesis (Herh, 2020).

Various new CCS projects have been announced over the past few years, with some already realised, allowing for the production of ammonia with a low carbon footprint.

For example, OCI recently announced the production of 365 kt of ammonia annually from natural gas with CCS (Ewing, 2021).

Horisont Energy and Haldor Topsøe announced another ammonia plant based on ATR with CCS, which is expected to be operational by 2025, producing 1000 - 1400 kt of ammonia annually (Horisont Energi, 2021a). Recently, it was announced that this capacity could be tripled to 3000 kt annually (Horisont Energi, 2021b).

CF Industries has announced feasibility studies for the Ince and Billingham ammonia plants in the United Kingdom, totalling around 1.0 Mt of CO₂ sequestered on an annual basis, thereby producing around 875 kt of low-carbon ammonia annually (CF Fertilisers, 2021).

Yara is investigating natural gas-based ammonia production with CCS at its Pilbara site, to provide Japanese power producer JERA with low-carbon ammonia for co-firing in its coal-fired power plants by 2024-2025 (Hasegawa, 2021).

ADNOC announced a 1000 kt low-carbon ammonia plant in Ruwais, United Arab Emirates, based on natural gas with CCS (ADNOC, 2021). The plant is expected to be operational by 2025.

Recently, a feasibility study on a low-carbon ammonia plant was announced in Central Sulawesi, Indonesia. The CO₂ emitted from hydrogen production from natural gas will be captured and stored, producing up to 660 kt of low-carbon ammonia annually (Argus Media, 2021b).

A low-carbon ammonia plant based on natural gas with CCS was recently proposed in Port Bonython, Australia, potentially producing 16 - 1235 kt ammonia annually (Pendlebury, Meares and Tyrrell, 2021).

An ammonia plant was recently announced in Nebraska, United States, based on methane pyrolysis technology, in which natural gas is converted to hydrogen and carbon black instead of CO₂ (Philibert, 2020a; Schneider *et al.*, 2020). The carbon footprint of this process during ammonia production is low, as the carbon black is used in, for instance, steel, car tyres, and printers, and thus not emitted to the atmosphere. Notably, around 25-45% more methane is required for methane pyrolysis as compared to SMR and ATR (IEA, 2021a), resulting in higher upstream methane emissions.

As carbon black production is currently a polluting industry, utilising methane pyrolysis decreases the environmental footprint of both hydrogen and carbon black. The company Monolith Materials plans to use thermal plasma technology for methane pyrolysis, and the hydrogen will be used to produce about 275 kt of ammonia from 2024 (Brown, 2020c).

Hazer Group recently announced biomethane production at a wastewater treatment plant, which will also be combined with methane pyrolysis to produce ammonia (Hazer Group Ltd., 2018).

Table 1 Overview of existing and planned facilities for fossil-based ammonia with a lower carbon footprint (existing capacity of 2.6 Mt/yr; planned capacity of 17.4 Mt/yr)

Location	Company	Start-up year	Capacity (kt/yr)	Carbon footprint reduction relative to SMR (%)	Hydrogen source	Source
Enid, US	Koch Nitrogen Company, Chaparral Energy	1982	285	62.5%	CO ₂ is used for enhanced oil recovery.	(MIT, 2016)
Joffre, Canada	Nutrien	1987	490	25%	By-product hydrogen from ethane cracker.	(Adair, 2020)
Beulah, US	Dakota Gasification Company	1991	355	62.5%	CO ₂ is used for enhanced oil recovery.	(Brown, 2016)
Kawasaki, Japan	Showa Denko	2003	60	35%	65% of hydrogen is from recycled plastic.	(Showa Denko K.K., n.d.)
Coffeyville, US	CVR Energy, Chaparral Energy, Blue Source	2013	375	62.5%	CO ₂ is used for enhanced oil recovery.	(MIT, 2016)
Geismar, US	Nutrien	2013	200	62.5%	CO ₂ is used for enhanced oil recovery.	(Adair, 2020)
Freeport, US	Yara, BASF	2018	750	25%	By-product hydrogen from ethane cracker.	(Brown, 2018b)
Sluiskil, Netherlands	Yara, Dow	2019	22 (only part of existing facility)	25%	By-product hydrogen from ethane cracker.	(Brown, 2019b)
Redwater, Canada	Nutrien	2020	245	62.5%	CO ₂ is used for enhanced oil recovery.	(Adair, 2020)
Jubail, Saudi Arabia	SAFCO	2021	1 160	62.5%	CO ₂ is used for methanol synthesis and enhanced oil recovery.	(Herh, 2020)
Beaumont, US	OCI Nitrogen	2021	365	≥ 70%	Hydrogen is produced from natural gas with CCS.	(Ewing, 2021)
Nebraska, US	Monolith Materials	2024	275	≥ 70%*	Hydrogen is produced by methane pyrolysis.	(Brown, 2020c)
Pilbara, Australia	Yara (revamp)	2024-2025 or earlier	≤ 800	≥ 70%	Hydrogen is produced from natural gas with CCS, to be used by JERA (Hasegawa, 2021).	(Hasegawa, 2021)

Note: SMR = steam methane reforming; ATR = autothermal reforming; CCS = carbon capture and storage; CCUS = carbon capture, utilisation and storage; TBD = to be determined; US = United States; UAE = United Arab Emirates; UK = United Kingdom.

* This concerns the CO₂ emissions from the methane feedstock. The carbon intensity also depends on the electricity source (Bicer et al., 2016); see also section 3.2.

Location	Company	Start-up year	Capacity (kt/yr)	Carbon footprint reduction relative to SMR (%)	Hydrogen source	Source
Finnmark, Norway	Horisont Energy, Haldor Topsøe	2025	1 000 - 1 400	≥ 70%	Hydrogen is produced with ATR with CCS.	(Horisont Energi, 2021a)
Ruwais, UAE	ADNOC	2025	1 000	≥ 70%	Hydrogen is produced from natural gas with CCUS.	(ADNOC, 2021)
Central Sulawesi, Indonesia	PAU, Mitsubishi, Jogmec, Bandung IoT	2026 or before	≤ 660	≥ 70%	Hydrogen is produced from natural gas with CCS.	(Argus Media, 2021b)
Western Australia	Hazer Group	TBD	TBD	≥ 70%*	Hydrogen is produced by methane pyrolysis.	(Hazer Group Ltd., 2021)
Billingham, UK	CF Industries (revamp)	TBD	595	≥ 70%	Hydrogen is produced from natural gas with CCS; 700 000 tonnes of CO ₂ sequestered annually.	(Reed, 2021)
Ince, UK	CF Industries (revamp)	TBD	280	≥ 70%	Hydrogen is produced from natural gas with CCS; 330 000 tonnes of CO ₂ sequestered annually.	(CF Fertilisers, 2021)
Port Bonython, Australia	TBD	TBD	16 - 1 235	≥ 70%	Hydrogen is produced by CCS.	(Pendlebury, Meares and Tyrrell, 2021)

Note: SMR = steam methane reforming; ATR = autothermal reforming; CCS = carbon capture and storage; CCUS = carbon capture, utilisation and storage; TBD = to be determined; US = United States; UAE = United Arab Emirates; UK = United Kingdom.

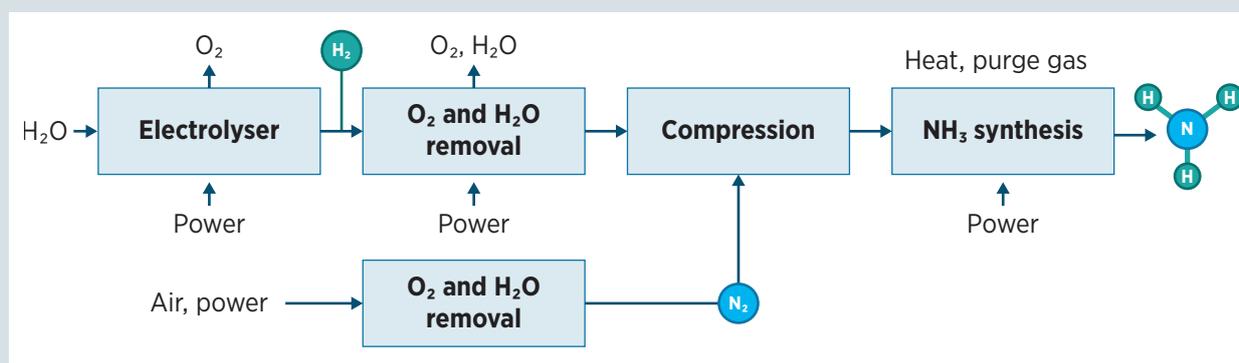
* This concerns the CO₂ emissions from the methane feedstock. The carbon intensity also depends on the electricity source (Bicer et al., 2016); see also section 3.2.

2.4 Renewable ammonia production from renewable electricity

Technology and production process

To produce renewable ammonia, water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) via electrolysis. Various electrolysis technologies can be used (Schmidt *et al.*, 2017a), which vary in temperature and energy consumption (see section 3.1). Nitrogen (N_2) is purified from air. The hydrogen and nitrogen are converted to ammonia in a Haber-Bosch synthesis loop. A schematic overview is shown in Figure 15.

Figure 15 Schematic overview of steps involved in ammonia synthesis from water and air



Reproduced from Rouwenhorst *et al.* (2020a) and Sousa Cardoso *et al.* (2021).

The production of hydrogen from water using electrolysis requires around 1.6 tonnes of water per tonne of ammonia (Ghavam *et al.*, 2021). Additional water is required for cooling the ammonia plant, and support systems. Water desalination may be required prior to feeding water to the electrolyser. The required footprint of renewables is discussed in Annex E.

As early as 1920, renewable ammonia has been produced with electricity from hydropower (Ernst, 1928; Ernst and Sherman, 1927). In 1930, renewable ammonia accounted for around one-third of the global ammonia production (Ernst, 1928), while coal-based ammonia accounted for the remainder. Most electrolysis-based ammonia plants were abandoned when natural gas became abundantly available and at a lower cost (Krishnan *et al.*, 2020). Hydroelectric ammonia plants were located in Canada, Egypt, France, Iceland, India, Japan, the Republic of Korea, Norway, Switzerland, the United States, the former Yugoslavia, and Zimbabwe, with electrolyser capacities of up to 150 MW, many times larger than any electrolyser currently in service (Rouwenhorst, Travis and Lefferts, 2022).

Hydroelectric ammonia have electrolyser capacities of up to 150 MW, many times larger than any electrolyser currently in service

The only “classical” electrolysis-based Haber-Bosch plant still in operation is located in Cusco, Peru, which was built in 1962 (below) (Brown, 2020d). In the last few years, however, numerous new renewable ammonia plants have been announced (Table 2).

Image 1 Electrolysis-based hydrogen production for renewable ammonia production in Cusco, Peru



Image courtesy of Industrie Haute Technologie.

Costs

The rate at which renewable ammonia plants are currently being announced is closely linked to the speed at which the cost of renewable electricity is decreasing. Renewable ammonia may already be cost competitive with imported fossil-based ammonia in some locations (Smith and Torrente-Murciano, 2021). Today, renewable ammonia production costs for new plants are estimated to be in the range of USD 720 - USD 1400 per tonne, falling to USD 310-610 per tonne by 2050.

Electricity is the dominant operational cost factor for large-scale renewable ammonia production, which typically accounts for more than half of the cost of renewable ammonia. For this reason, unlike fossil-based ammonia plants, many of the renewable ammonia plants currently under development include the electricity generating capacity within the proposed investment, effectively shifting electricity input from an operational cost (OPEX) to a capital cost (CAPEX).

The investment for a renewable ammonia plant, excluding power generation, is dominated by either the electrolyser or the ammonia synthesis loop. The cost of the synthesis loop dominates for small-scale plants (< 10 kt per year of ammonia), while the cost of the electrolyser dominates for larger plants. The capital cost of electrolysers is expected to decrease in the coming decades (Schmidt *et al.*, 2017a) (Figure 17). The combined investment cost of nitrogen purification, water desalination and ammonia storage accounts for only around USD 5-30 per tonne of ammonia and is minor compared to the cost of electrolysis and the ammonia synthesis loop (Batool and Wetzels, 2019; Morgan, 2013).

Notably, the capacity factor may have a significant impact on the investment cost of electrolysis-based ammonia production. This is due to the variability of renewables such as solar and wind energy, which, without additional buffering and storage, implies that annual ammonia production will be lower than the nameplate capacity. Thus, an islanded renewable ammonia plant – for example, not connected to the grid – is typically oversized to account for the lower productivity, resulting in a higher capital intensity. It is important to have a high capacity factor to limit the capital intensity of a renewable ammonia plant. Combined solar and wind resources can be used to maximise the full load capacity fraction of the electrolyser to around 70% (Armijo and Philibert, 2020; Tancock, 2020).

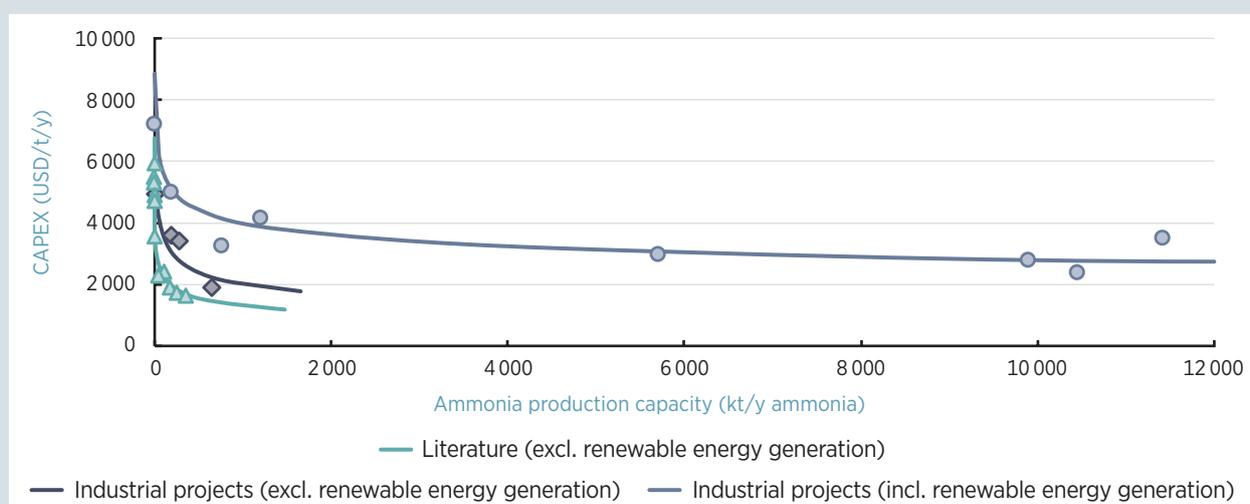
There is an important difference in the business case of fossil-based ammonia and renewable ammonia. In the case of fossil-based ammonia, the feedstock is purchased during operations and may be variable in cost. Only the hydrogen plant (e.g. the SMR or gasification unit) and ammonia plant are constructed upfront. For renewable ammonia, on the other hand, all assets may be constructed upfront, including electricity generation assets, implying that the cost of renewable ammonia production is driven mainly by the capital investment. As a result, the weighted average capital cost (WACC) has a profound effect on the cost of a renewable ammonia.

Renewable hydrogen can also be introduced in an existing fossil-based ammonia plant, replacing 10-20% of the natural gas without causing significant fluctuations in the ammonia synthesis loop. Accounting for avoided CO₂ emission and methane feedstock, this results in an estimated net renewable ammonia cost of around USD 300-400 per tonne of ammonia by 2025-2030, and a cost of around USD 250 per tonne of ammonia by 2040 (Haldor Topsøe *et al.*, 2020). While a hybrid plant, combining both electrolysis and natural gas with CCS, is insufficient for full decarbonisation, it can reduce emissions from ammonia synthesis (Hansen and Han, 2018). As the technologies involved are mature, a hybrid production strategy lowers the barriers for near-term investment decisions, enabling the immediate deployment of electrolysers at existing sites.

Capital cost of renewable ammonia plants for current and proposed projects

Various renewable ammonia production projects have reported investment costs, as shown in Figure 16. For many renewable ammonia projects, the investment cost includes the full cost of developing renewable electricity. Direct comparisons to existing ammonia plants are not possible, because the cost of natural gas extraction and pipelines is omitted. For an integrated renewable ammonia plant, the hydrogen, nitrogen and ammonia production units themselves may represent less than 50% of the total cost, with the majority invested in upstream development for the renewable electricity generation.

Figure 16 Capital intensity of renewable ammonia synthesis as a function of ammonia production capacity



Based on sources in Table 10 and Table 11.

As with fossil-based ammonia production, however, the cost of renewable ammonia benefits from economies of scale, with the lowest costs at large scale (≥ 1 Mt per year of ammonia). The capital intensity for the largest announced renewable ammonia plants (including electricity generation) to start operation beyond 2030 decreases from around USD 4 800 per tonne annually at a capacity of 0.5 Mt of ammonia per year, to around USD 3 000 per tonne annually at a capacity of 10 Mt per year. In addition, operational and asset-sizing decisions, as well as strategic site selection, are factors that can reduce costs by increasing the capacity factor.

Decreasing the cost of renewable ammonia this decade

The cost of renewable ammonia will decrease substantially over the coming decades. The first driver for cost reduction is a scale-up to gigawatt-scale. Renewable ammonia benefits from economies of scale (Figure 16), and the relative capital intensity decreases at larger scales. Furthermore, the capacity factor may increase upon scale-up, due to decreasing fluctuations of variable renewables (Tancock, 2020). As project developers expand from pilot and demonstration-scale plants to full commercial scale, the observed capital intensity of announced projects will fall.

The cost of renewable electricity is a dominant factor, accounting for more than 90% of the expected cost reduction for renewable ammonia over the coming decade (Figure 17). Every incremental USD 10 per MWh adds around USD 100 per tonne of ammonia for a typical alkaline electrolysis-based ammonia plant with an energy consumption of 36 GJ per tonne of ammonia, equivalent to 10 MWh per tonne of ammonia (Grundt and Christiansen, 1982).

In 2021, the average levelised cost of electricity (LCOE) for new solar and onshore wind auctions was USD 39 per MWh and USD 43 per MWh respectively. These prices imply an electricity input cost of USD 390-430 per tonne of ammonia. Further deployment of renewable energy results in an LCOE below USD 20 per MWh from solar and wind power (IRENA, 2021a; Tancock, 2020), resulting in an electricity cost below USD 200 per tonne of ammonia.

A reduction in electrolyser cost is expected upon large-scale deployment (IRENA, 2020b), as this accelerates the learning curve (Schmidt *et al.*, 2017b; Schoots *et al.*, 2008). ISPT (2022) estimates that the cost of a 1 GW electrolysis factory will halve between 2020 and 2030. Furthermore, an increase in electrolyser efficiency results in less renewable energy consumption per amount of ammonia produced (IRENA, 2020b), and subsequently a lower cost for renewable ammonia production.

While some hydrogen storage can be used to buffer fluctuations in feedstock supply from electrolysers, flexibility of the Haber-Bosch ammonia synthesis loop allows for ammonia production to be ramped down if necessary, at least as far as 10-30% of nominal capacity (Cheema and Krewer, 2018; Ostuni and Zardi, 2012). This flexible operation allows for minimising the relatively expensive hydrogen storage capacity (Armijo and Philibert, 2020). One-day-equivalent hydrogen storage costs around USD 35-150 per tonne of ammonia (Armijo and Philibert, 2020; Vrijenhoef, 2016). Hydrogen storage in salt caverns has the lowest cost at USD 35 per tonne of ammonia, while storage in lined rock caverns costs around USD 65 per tonne of ammonia (Ahluwalia *et al.*, 2019).

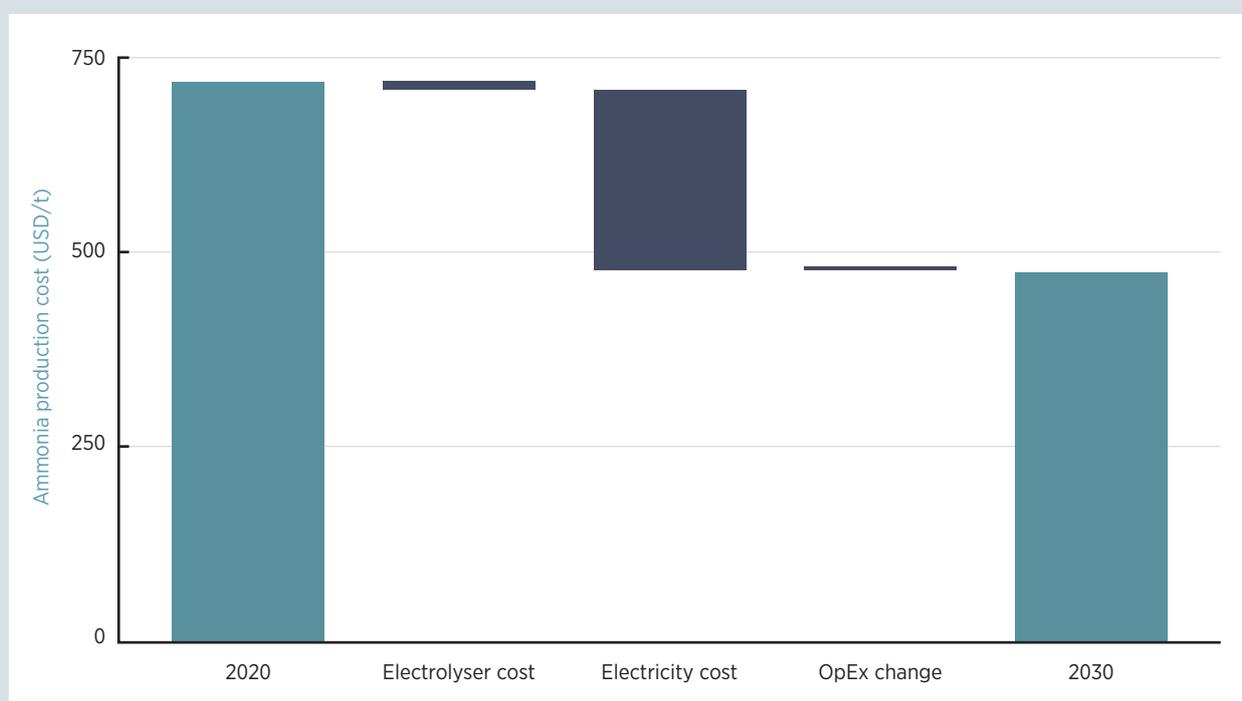
The development of renewable energy hubs can further decrease the capital intensity of renewable ammonia. Integrating renewable ammonia into a facility with existing infrastructure (brownfield projects) results in a lower capital investment than building a completely new facility (greenfield projects). Such deployment could limit the cost of new port infrastructure to below USD 5 per tonne of ammonia (Salmon, Bañares-Alcántara and Nayak-Luke, 2021).

Transport by ship can add up to USD 45-100 per tonne of ammonia, depending on distance, fuel cost and ship type (Hank *et al.*, 2020; Salmon and Bañares-Alcántara, 2021). This cost is low enough that international transport of renewable energy can be competitively achieved using ammonia. However, this transport cost also provides incentives for smaller-scale plants, which can be economical when located near renewable energy hubs and/or the point of consumption. Renewable ammonia production hubs near use locations can be beneficial.

If demand for local renewable ammonia plants materialises, small-scale ammonia plants operating at a few megawatts of capacity may benefit from cost reductions due to modular design and rapid manufacturing. Upon standardisation of equipment and realisation of production and installation efficiencies, the capital cost of small-scale ammonia synthesis may decrease up to 25% (Sievers *et al.*, 2017).

An overview of the expected cost reduction for renewable ammonia production over the coming decade is shown in Figure 17.

Figure 17 Expected cost decrease for renewable ammonia production for best locations by 2030

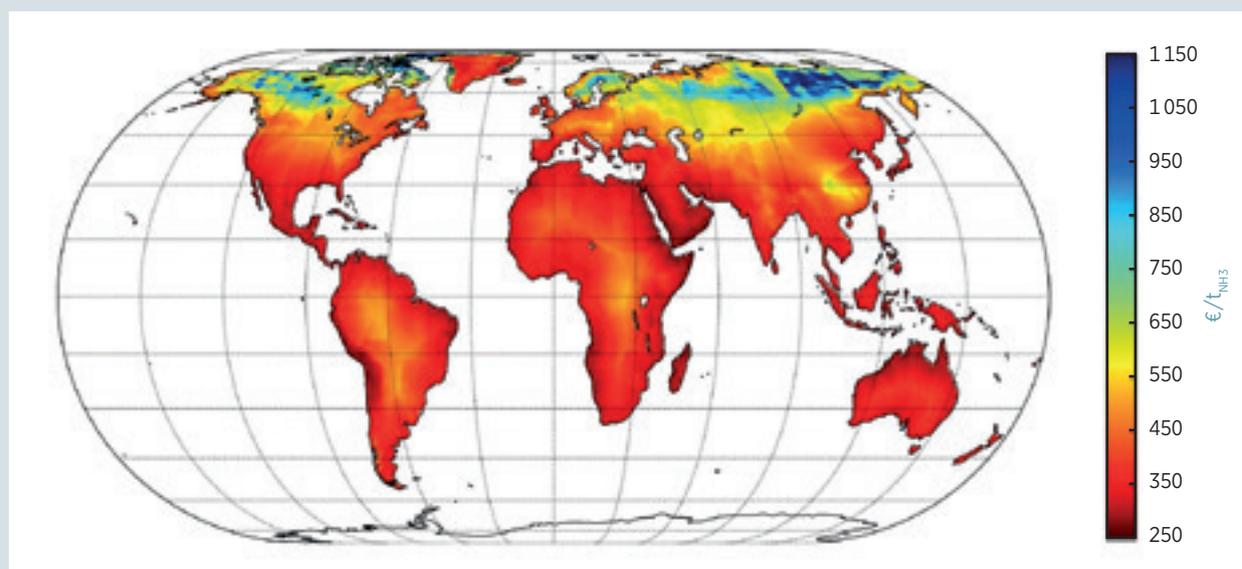


Note: Assumes a plant size of 1 Mt annually, an operational load factor of 70%, an annual interest rate of 7% and linear depreciation over 20 years. The annual OPEX is assumed to be 3% of the CAPEX.

Locations for renewable ammonia

The optimal locations for renewable ammonia production combine high solar irradiation and a high wind load factor, resulting in a high capacity factor for production. Recent studies analysed the production cost of renewable ammonia at hundreds of locations worldwide (Fasihi *et al.*, 2021; Nayak-Luke and Bañares-Alcántara, 2020), as is visualised in the heat map in Figure 18.

Figure 18 Heat map for the production cost of renewable ammonia by 2050



Reproduced from Fasihi et al. (2021).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

As shown in Figure 18, various regions in Africa, Asia, Australia, North America, South America and Southern Europe have high potential for low-cost renewable ammonia. It should be noted that geopolitical factors play a role in developing renewable projects. Favourable legislation and political stability are required to allow for developing large-scale projects with a low risk factor (Eastman, 2021). Furthermore, large-scale projects typically require off-take markets, which is determined by international collaboration. Thus, collaborations among ammonia producers, transport companies and consumers are currently set up (Proton Ventures B.V., 2021).

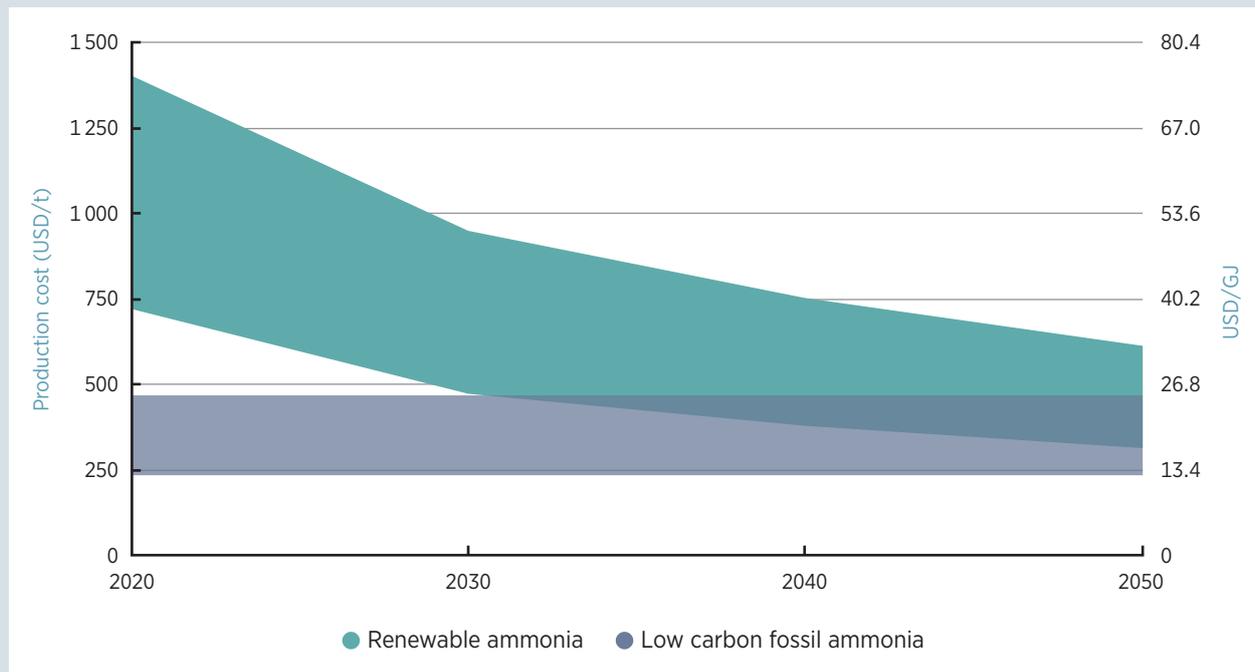
Gigawatt-scale projects can span thousands of square kilometres for renewable energy generation (CWP, 2021; Tancock, 2020) and are not viable in densely populated areas. In Europe, this implies that offshore wind is typically used for large projects. On the other hand, a number of gigawatt-scale projects with onshore wind and solar energy have been announced in, for example, Australia, Chile, Mauritania, Namibia, Oman, and Saudi Arabia, such announcements involving areas that are not densely populated. Also, port areas are preferable for export-oriented projects, as well as for the supply of sea water to feed the electrolyzers.

Future cost of renewable ammonia

By 2050, the production cost of renewable ammonia is expected to reach around USD 310 per tonne, for a large-scale plant in a location with excellent renewable energy resources. Accounting for expansion into areas with lower-quality renewables, the total ammonia demand in 2050 can be met with renewable ammonia at an estimated cost below USD 355 per tonne (Fasihi et al., 2021).

The estimated cost of renewable ammonia in various scenarios up to 2050 is shown in Figure 19. The cost of renewable ammonia in 2020 was estimated to be around USD 720 to USD 1400 per tonne (IRENA, 2020a). By 2030, this could be around USD 475 per tonne of ammonia in the best locations (Fasihi et al., 2021; Nayak-Luke and Bañares-Alcántara, 2020). In the long term, the gap with fossil-based ammonia production will be closed (Figure 19).

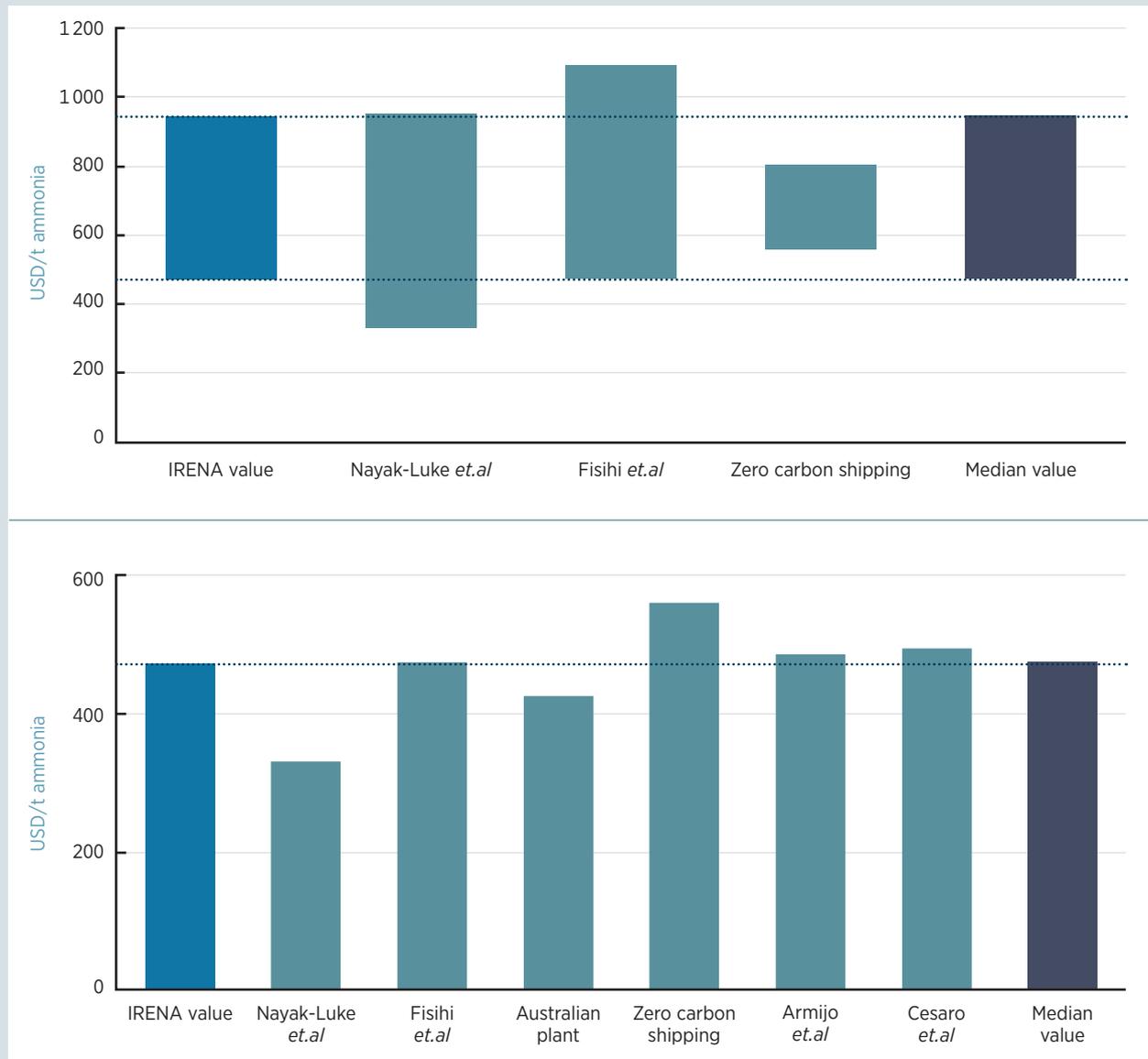
Figure 19 Estimated costs of renewable ammonia up to 2050



Note: CAPEX and OPEX for the production of hydrogen and nitrogen are already included in the respective cost of hydrogen and nitrogen. The hydrogen price is based on IRENA (2020a), which assumes a low electricity cost, a long electrolyser lifetime and low CAPEX. The ammonia synthesis loop is estimated to add USD 25-50 per tonne (Salmon, Bañares-Alcántara and Nayak-Luke, 2021), and nitrogen purification is estimated to add USD 2.5-5 per tonne.

The future cost estimate for renewable ammonia production in the current report is compared to other sources (Armijo and Philibert, 2020; Burgess and Washington, 2021; Cesaro *et al.*, 2021; Fasihi *et al.*, 2021; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021; Nayak-Luke and Bañares-Alcántara, 2020). The cost estimates of the International Renewable Energy Agency (IRENA) and other authors for the best locations in 2030 are shown in Figure 20. IRENA estimates are in line with the median cost of previous estimations.

Figure 20 Estimated cost range for renewable ammonia production in 2030 for IRENA and other sources (top); cost estimates for renewable ammonia in the best locations in 2030 for IRENA and other sources, as well as a median value (bottom)



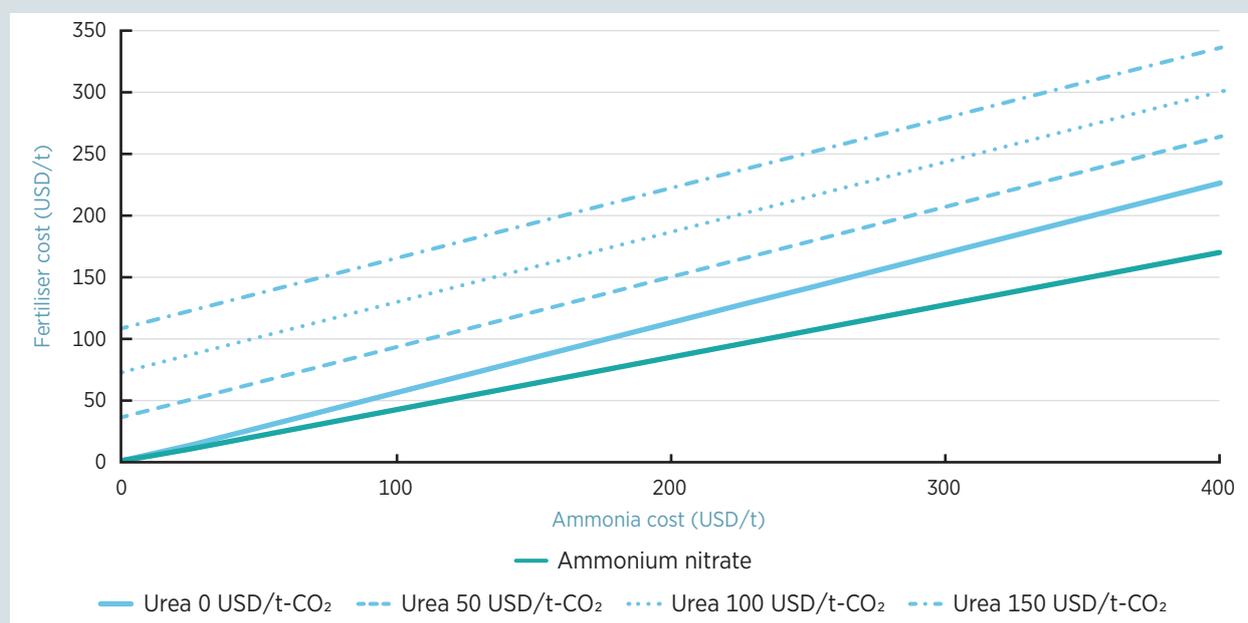
Renewable fertiliser cost

Fertiliser production dominates today's ammonia market, specifically urea and ammonium nitrate, which consume 55% and 15%, respectively, of all ammonia produced today (Hatfield, 2020). Because these fertilisers have comparable yields per mass of fertiliser applied (Heuermann, Hahn and von Wirén, 2021; Moreira *et al.*, 2021), they can be compared on a cost per mass basis.

Urea requires CO₂, which implies that a carbon-neutral source such as direct air capture (DAC) or biomass will be required over the long term. Currently, DAC is relatively expensive with a reported cost in the range USD 160-455 per tonne of CO₂ (Fasihi, Efimova and Breyer, 2019; Shayegh, Bosetti and Tavoni, 2021). In the long term, estimates for DAC vary in the range of USD 65-200 per tonne of CO₂ (Fasihi, Efimova and Breyer, 2019; Shayegh, Bosetti and Tavoni, 2021).

A cost comparison between urea and ammonium nitrate is shown in Figure 21, based on the ammonia and CO₂ feedstock cost. The CAPEX and OPEX for urea production and ammonium nitrate production are excluded, but these costs are well below USD 50 per tonne of fertiliser.

Figure 21 Fertiliser production cost as a function of ammonia and CO₂ cost



Note: CAPEX and OPEX for ammonium nitrate and urea production not included.

Figure 21 suggests that urea is not cost competitive in a decarbonised landscape – for example, without “free” CO₂ as a by-product from fossil fuel-based hydrogen production. However, ammonium nitrate has safety concerns, due to an explosion hazard, and significant regulatory restrictions. Lastly, urea is not easily replaced for rice cultivation, the main crop in Asia.

Current installed capacity and announced capacity

Currently, only one commercial renewable ammonia plant remains in operation. Operating since 1965, the Cusco plant in Peru produces less than 0.02 Mt annually of ammonia as feedstock for ammonium nitrate, serving the explosives market.

In the last three years, however, more than 60 renewable ammonia plants have been announced, and beyond 2025 renewable ammonia is expected to dominate capacity additions (Table 2). Revamps of existing fossil-based ammonia plants were announced by various fertiliser companies. These are listed in Table 2, as well as various technology providers.

Renewable ammonia plants with a combined capacity of 15 Mt per year have been announced to begin operations within this decade, accounting for 6% of total ammonia production by 2030. The total announced renewable ammonia capacity is 71 Mt per year, likely to be operational before 2040. Although some of these projects are fully financed and under construction, most have not yet reached financial close. Nonetheless, the projected renewable ammonia capacity is expected to increase further, as industrial demonstration-scale projects scale up, from multi-megawatt to gigawatt-scale, and additional large-scale projects are announced.

The announced renewable ammonia plants can be categorised as 1) brownfield projects, or revamps of existing fossil-based plants, for both current markets and energy markets, and 2) greenfield projects, or new-build plants, mainly for the energy market.

Yara, the second largest ammonia producer, has announced various projects around the world. For example, a 5 MW alkaline electrolyser will be installed at Porsgrunn, Norway by 2022, which represents around 1% of the total hydrogen production in Porsgrunn (Brown, 2019c). The Porsgrunn plant aims to completely decarbonise by 2025, totalling around 500 kt per year of renewable ammonia, fed by the hydroelectric grid. Elsewhere, renewable hydrogen from offshore wind power will be supplied to the plant at Sluiskil, in the Netherlands, by 2024 or 2025, resulting in 75 kt per year of renewable ammonia (Brown, 2020c). Lastly, Yara recently published a feasibility study to expand its Pilbara site with 800 kt of renewable ammonia capacity per year by 2030 (Brown, 2020e; ENGIE and Yara, 2020). The Australian Renewable Energy Agency (ARENA) granted AUD 42.5 million (USD 30.5 million) to Yara and ENGIE for a 10 MW electrolyser to be operational by 2023 (Blackbourn, 2021).

CF Industries, the largest ammonia producer in the world, has also announced a 20 kt per year renewable ammonia project at its location in Donaldsonville, Louisiana, United States, to be operational by 2023. The Donaldsonville site has a total ammonia production capacity of 4 Mt per year (Brown, 2020b).

Both Yara and CF Industries recently committed to a target of net zero emissions by 2050, for which significant scale-up of their existing renewable ammonia announcements will be required.

At the end of 2021, Iberdrola and Fertiberia integrated renewable hydrogen into an existing ammonia plant at Puertollano in Spain. A renewable ammonia capacity of 6 kt per year is expected immediately, with plans to expand to 57 kt per year by 2025 (Brown, 2020f; Fertiberia and Iberdrola, 2020). The site revamp includes batteries and hydrogen storage to manage the intermittency of solar power (Fertiberia and Iberdrola, 2020).

Greenfield renewable ammonia plants have also been announced. These projects mostly appear at commercial scale from 2025 onward (Figure 22). In 2022, the first newly built, commercial-scale renewable ammonia plant is expected to begin operations in Western Jutland, Denmark, fed with onshore wind power and with a capacity of 5 kt per year of ammonia (Ravn, 2020), developed by Skovgaard Invest and supported by Vestas and Haldor Topsøe.

Most of the announced renewable ammonia capacity is located in Australia. By far the largest announced projects in the country are the Asian Renewable Energy Hub (AREH) in Pilbara and the Western Green Energy Hub (WGEH) in Western Australia (Tancock, 2020; WGEH, 2021). At these two sites, as much as 30 Mt of renewable ammonia will be produced annually, based on 76 GW of onshore wind and solar energy (Brown, 2020b; Tancock, 2020; WGEH, 2021). Numerous other projects have been announced in Australia with capacity in the range of 1-3 Mt per year of renewable ammonia (Table 2).

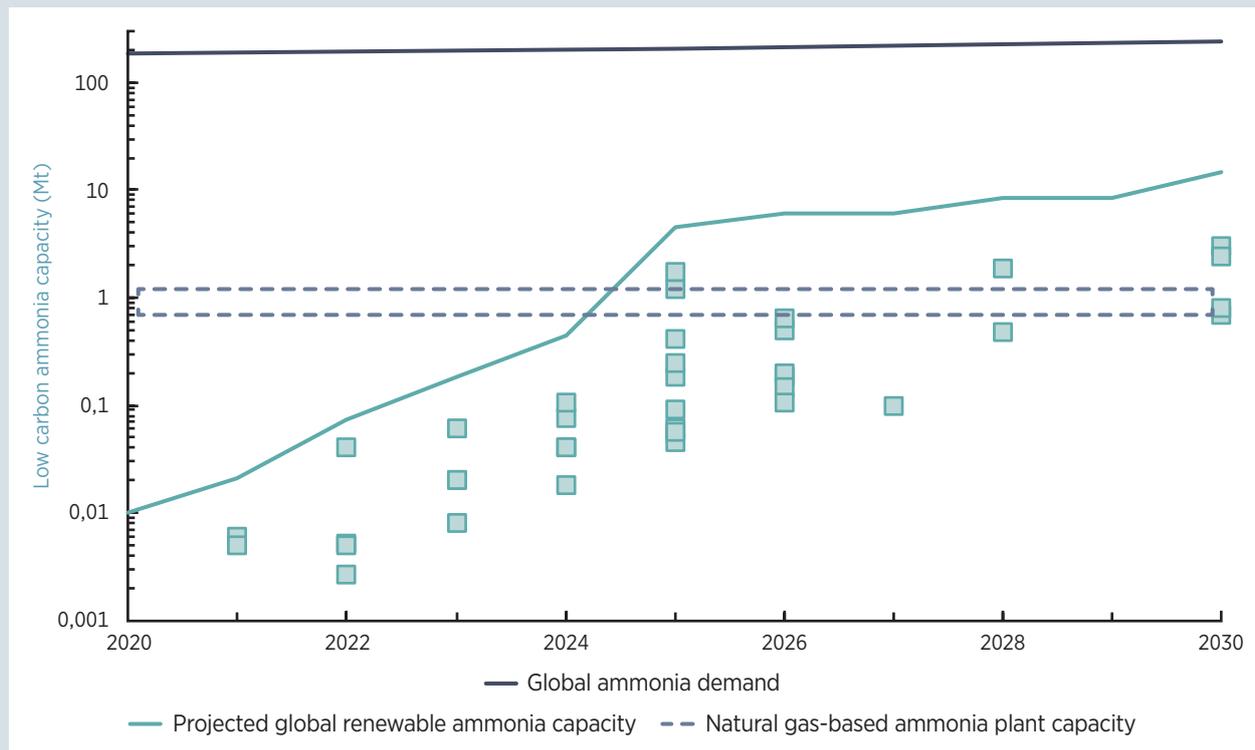
Renewable ammonia projects have also been announced in locations across the Middle East. In NEOM, a planned city in Saudi Arabia, an ammonia plant powered by onshore wind and solar energy will produce around 1.2 Mt of renewable ammonia per year by 2025 (Brown, 2020g); this plant is currently under construction. The ammonia will be exported and sold into hydrogen markets by Air Products. Other renewable ammonia plants have been announced in Oman and the United Arab Emirates (Table 2).

Renewable ammonia projects have also been announced in Latin America, especially in Chile, due to optimal wind and solar conditions (Armijo and Philibert, 2020) and an existing mining industry using ammonium nitrate-based explosives. ENGIE and Enaex are building a pilot plant that is expected to start operating in 2024, while reaching full capacity of 700 kt per year of renewable ammonia by 2030 (Power Engineering International, 2020). (Enaex already operates the electrolysis-based ammonia plant in Cusco.) Various other projects have been announced in Latin America (Table 2).

Maire Technimont has announced the first greenfield renewable ammonia plant in the United States, based on solar and wind (Stamicarbon, 2021a). Furthermore, Hy2Gen announced a hydropower-based ammonia plant in Quebec, Canada, to be operational in 2025 (Hy2Gen AG, 2021).

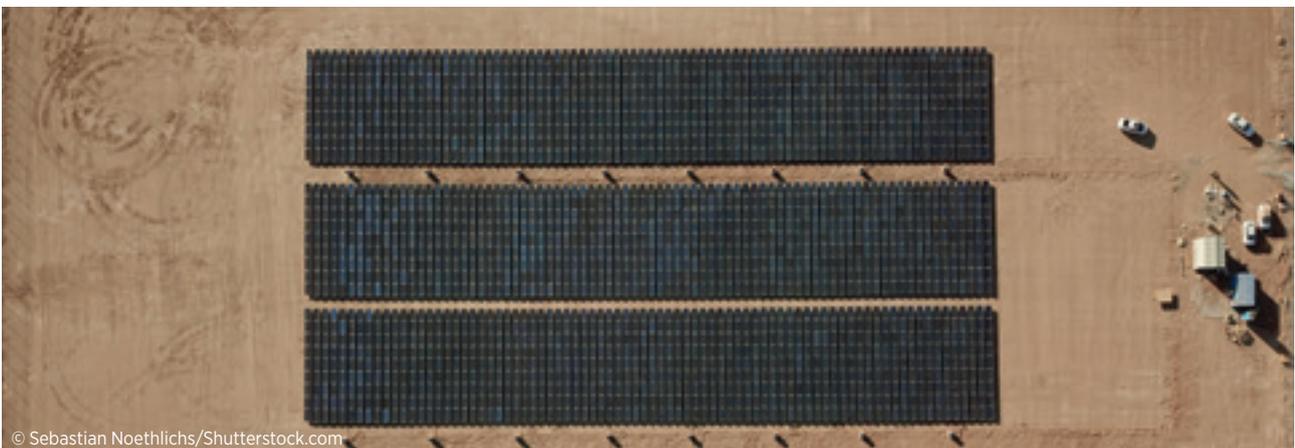
African ammonia producer OCP has announced a renewable ammonia pilot plant based on solar energy, in collaboration with Fraunhofer IMWS in Germany (Ayvalı, Tsang and Van Vrijaldenhoven, 2021; Brown, 2018c). Furthermore, Stamicarbon subsidiary Maire Technimont aims to produce renewable fertiliser in Kenya by 2025 (Stamicarbon, 2021a). The largest renewable ammonia project in Africa is proposed for Mauritania, where 30 GW of wind and solar capacity could produce 11 Mt per year of renewable ammonia (CWP, 2021).

Figure 22 Projected annual renewable ammonia production and planned projects, 2020-2030



Note: The full green line represents projected annual renewable ammonia production. The green dots represent planned renewable ammonia projects (Table 2). The full black line represents the projected global ammonia production. The dotted brown line represents a world-scale natural gas-based ammonia plant producing around 0.7-1.2 Mt of ammonia per year.

Source: Brightling, 2018.



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Table 2 Overview of existing and planned facilities and technology providers for renewable ammonia production (existing capacity of 0.02 Mt/yr; planned capacity of 15 Mt/yr (2030) and 71 Mt/yr (total))

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Commercial plants						
Cusco, Peru	Enaex	1965	10	Alkaline	Hydro	(Brown, 2020d)
Taranaki, New Zealand	Ballance Agri-Nutrients, Hiringa Energy (revamp)	2021	5	-	Wind	(Ayvali, Tsang and Van Vrijaldenhoven, 2021; Brown, 2020e)
Puertollano, Spain	Fertiberia, Iberdrola (revamp)	2021 2025	6.1 57	-	Solar, battery	(Brown, 2020f; Fertiberia and Iberdrola, 2020)
Duqm, Oman	ACME, Tatweer	2021 TBD	TBD (pilot) 770	-	Solar	(Zawya, 2021)
Port Lincoln, Australia	H2U, Mitsubishi, Government of South Africa, ThyssenKrupp	2022 Unknown	40 705 – 1 410	Alkaline	Wind, solar	(Brown, 2018d; Pendlebury, Mearns and Tyrrell, 2021)
Porsgrunn, Norway	Yara (revamp)	2022 2025-2026	5 500	Alkaline	Hydro	(Brown, 2019c; Tullo, 2020)
Western Jutland, Denmark	Skovgaard Invest, Vestas, Haldor Topsøe	2022	5	-	Onshore wind, solar	(Ravn, 2020)
Ogata Village, Japan	Tsubame BHB	2022	TBD	-	Wind, solar	(Atchison, 2021a)
Rabat, Morocco	Fusion Fuel	2026	183	PEM	Wind, solar	(Fusion Fuel, 2021)
Pilbara, Australia	Yara (revamp and new)	2023 2026 2028 2030	< 8 48-160 480 800	Alkaline or PEM	Onshore wind, solar	(ENGIE and Yara, 2020) Feasibility study
Louisiana, US	CF Industries, ThyssenKrupp (revamp)	2023	20	-	Grid electricity	(Brown, 2020b)
Palos de la Frontera, Spain	Fertiberia, Iberdrola (revamp)	2023 2027	62 100	-	Solar	(Ludecke, 2021)
Northern Germany	Haldor Topsøe, Aquamarine	2024	105	Solid oxide	Offshore wind	(Frøhlke, 2021a)
Sluis, Netherlands	Yara, Ørsted (revamp)	2024-2025	75	Alkaline	Offshore wind	(Brown, 2020c)

Note: TBD = to be determined; US = United States; UAE = United Arab Emirates; UK = United Kingdom.

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Commercial plants						
Antofagasta, Chile	Enaex, ENGIE	2024 2030	18 700	-	Solar	(Power Engineering International, 2020) Feasibility study
Abu Dhabi, UAE	KIZAD, Helios Industry	2024 2026	40 200	Alkaline	Solar	(KIZAD, 2021)
NEOM, Saudi Arabia	NEOM, Air Products, ACWA Power	2025	1 200	Alkaline	Onshore wind, solar	(Brown, 2020g)
Berlevåg, Norway	Varanger Kraft	2025	90	-	Wind	(Hydrogen.no , 2020)
Bell Bay, Australia	Origin	2025	420	-	-	(Origin, 2020)
Gladstone, Australia	H2U	2025	1 750	-	-	(Brown, 2020h)
Tasmania, Australia	Fortescue	2025	250	-	-	(Crolius, 2020a)
Lake Naivasha, Kenya	Maire Tecnimont	2025	45	-	Solar, geothermal	(Stamicarbon, 2021a)
Norway	Grieg Edge, Arendals Fossekompani	2025	TBD	-	Wind	(Atchison, 2021b)
Quebec, Canada	Hy2Gen	2025	183	Alkaline or PEM	Hydro	(Hy2Gen AG, 2021)
Chile	AustriaEnergy, Ökowind	2026 or before TBD	TBD 850 – 1 000	-	Onshore wind	(Atchison, 2021c; Trammo, 2021)
Esbjerg, Denmark	Copenhagen Infrastructure Partners, Maersk, DFDS	2026	650	-	Offshore wind	(Barsoe, 2021)
Duqm, Oman	DEME Concessions, OQ	2026 TBD	150 520	-	Solar, wind	(DEME, 2021)
Pilbara, Australia	InterContinental Energy	2030 2035	3 000 9 900	Alkaline, and/or PEM & solid oxide	Onshore wind, solar	(Brown, 2020b; Tancock, 2020)
Murchison, Australia	MRHP, Copenhagen Infrastructure Partners	2028	1 900	PEM	Onshore wind, solar	(Matich, 2020) Final decision for ammonia not made, can also be liquid hydrogen
Al Wusta, Oman	OQ, InterContinental Energy, EnerTech	2028 2038	TBD 9 500 – 11 400	-	Onshore wind, solar	(OQ, InterContinental Energy and EnerTech, 2021)

Note: TBD = to be determined; US = United States; UAE = United Arab Emirates; UK = United Kingdom.

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Commercial plants						
Canarvon, Australia	Province Resources, Total-Eren	2030 or before	2 400	-	Onshore wind, solar	(Province Resources Limited, 2021)
Gladstone, Australia	Austrom Hydrogen	TBD	1 125	-	Solar	(Brown, 2020i)
Western Australia	InterContinental Energy	TBD	20 000	-		(Burgess and Washington, 2021)
Moranbah, Australia	Dyno Nobel, Incitec Pivot	TBD	60	-	Solar	(Brown, 2019d, 2020d) Feasibility study
Skive, Denmark	Siemens Gamesa, Energifonden Skive	TBD	TBD	-	Wind	(Brown, 2018e)
Moura, Australia	Queensland Nitrates, Incitec Pivot, Wesfarmers JV, Neoen, Worley	TBD	20	-	Onshore wind, solar	(ARENA, 2019; Brown, 2020d; Crolius, 2020b) Feasibility study
Port Adelaide, Australia	TBD	TBD	170-450	-		(Pendlebury, Meares and Tyrrell, 2021)
Geraldton, Australia	BP, GHD, ARENA	TBD TBD	20 1 000	-	Wind, solar	(Brown, 2020j)
Canarvon, Australia	HyEnergy	TBD	300	-	Onshore wind, solar	(Peacock, 2021)
Portland, Australia	Countrywide Energy, Glenelg Shire Council, Port of Portland	TBD	56	-	-	(Pendlebury, Meares and Tyrrell, 2021)
Orkney, Scotland	Eneus Energy	TBD	7	-	Wind	(Brown, 2020k; reNEWS.BIZ, 2021a)
Laos	Tsubame BHB	TBD	TBD	-	Hydro	(Tsubame BHB, 2020)
Abu Dhabi, UAE	TAQA Group, Abu Dhabi Ports	TBD	1 200	-	Solar	(TAQA Group, 2021)
Finnmark, Norway	St1 Nordic Oy, Horisont Energi	TBD	TBD	-	Wind	(Atchison, 2021b)
Mauritania	CWP	TBD	11 425	-	Wind, solar	(CWP, 2021)
Egypt	ThyssenKrupp	TBD	TBD	-	-	(Egypt Today Staff, 2021)
Espirito Santo, Brazil	AmmPower	TBD	TBD	-	-	(AmmPower, 2021)
Iowa, US	Maire Tecnimont	TBD	84	-	Onshore wind, solar	(Stamicarbon, 2021b)

Note: TBD = to be determined; US = United States; UAE = United Arab Emirates; UK = United Kingdom.

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Technology demonstration plants (past and current)						
Morris, US	University of Minnesota	2014 TBD	0.025- 0.035 0.35	Alkaline	Onshore wind	(Brown, 2020d; RTI International, 2021)
Koriyama, Japan	FREA, JGC Corporation	2018	0.007	-	Onshore wind, solar	(Brown, 2020d)
Harwell, UK	Siemens, Cardiff University, University of Oxford	2018	0.010	-	Onshore wind	(Brown, 2020d)
Kawasaki, Japan	Tsubame BHB	2019	0.020	-	-	(Crolius, 2021)
Foulum, Denmark	Haldor Topsøe	2025	0.3	Solid oxide	Onshore wind	(Brown, 2020d)
Ben Guerir, Morocco	OCP, Fraunhofer IMWS	TBD	0.7	-	Solar	(Ayvali, Tsang and Van Vrijaldenhoven, 2021; Brown, 2018c)
Selected technology providers						
Germany	ThyssenKrupp	Technology provider	2 – 1 750	Alkaline	N/A	(Will and Lüke, 2018)
Denmark	Haldor Topsøe	Technology provider	-	Solid oxide	N/A	(Hansen and Han, 2018)
Switzerland	Casale	Technology provider	-	-	N/A	(Casale, 2021)
US	KBR, Cummins	Technology provider	-	PEM	N/A	(KBR, 2021)
Netherlands	Stamicarbon	Technology provider	-	-	N/A	(Stamicarbon, 2021c)
Netherlands	Proton Ventures	Technology provider	1-20	-	N/A	(Proton Ventures B.V., 2019)
Japan	Tsubame BHB	Technology provider	1-100	-	N/A	(Crolius, 2021)
US	Starfire Energy	Technology provider	17.5	-	N/A	(Starfire Energy, n.d.)

Note: TBD = to be determined; US = United States; UAE = United Arab Emirates; UK = United Kingdom.

Technology development for dealing with fluctuations in electricity

The variability of wind and solar electricity generation poses challenges for renewable ammonia production because the Haber-Bosch process prefers steady-state operation. Addressing this issue, a number of pilot-scale plants have been built over the past few years that demonstrate new technologies for managing fluctuating electric inputs for renewable ammonia synthesis.

The University of Minnesota in the United States started operating a wind-to-ammonia plant in 2014, with a capacity of 25-35 tonnes of ammonia per year (Image 2) (Brown, 2020d; Reese *et al.*, 2016). Recently, with the support of the US Department of Energy's ARPA-E, a bigger demonstration was announced that aims to produce local fertiliser (RTI International, 2021).

Image 2 Morris wind-to-ammonia demonstrator



Image courtesy of Michael Reese, 2013.

In 2018, the Japanese research institute FREA and JGC Corporation started operating a solar- and wind-powered pilot plant with a capacity of 7 tonnes of ammonia per year, in order to test a novel ammonia synthesis catalyst operating at lower temperature and pressure (Image 3) (Brown, 2020d). The site also has a demonstrator for ammonia combustion in gas turbines.

Image 3 FREA wind-to-ammonia demonstrator



Image courtesy of Trevor Brown, 2018.

A consortium including Siemens, Cardiff University and the University of Oxford also operated its wind-to-ammonia-to-power demonstrator since 2018 (Image 4) (Brown, 2020d), aiming to improve the understanding of ammonia synthesis from electricity, ammonia combustion in an internal combustion engine, as well as management of fluctuating energy inputs.

Image 4 Green ammonia demonstration system, Rutherford Appleton Laboratory, Oxfordshire, UK



Image courtesy of UK Science and Technology Facilities Council, 2019.

Haldor Topsøe announced a wind-powered ammonia demonstrator with a capacity of around 300 tonnes of ammonia per year, which is expected to be operational in Foulum, Denmark by 2025 (Brown, 2020d). The aim is to demonstrate novel solid oxide electrolysis technology, producing both hydrogen and purified nitrogen in the same unit, thereby eliminating the cost of the air separation unit for nitrogen production. This technology has the potential to improve the energy efficiency of ammonia synthesis to just 7.2 MWh per tonne, compared to 7.8 MWh per tonne for SMR and 10 MWh per tonne for current alkaline electrolyser technologies.

Additional innovations for ammonia synthesis under milder conditions may lead to better dynamic load response. For example, a more thorough understanding of the Haber-Bosch process is required, to elucidate the effects of temperature and feedstock fluctuations on catalytic activity. Kinetic models are required that describe the industrial iron catalysts for ammonia synthesis under a wide range of conditions – for example, outside conventional steady-state operation. This may allow for a more controlled ramp to and from full load operation.

Operational strategies for dealing with fluctuations

While the pilot-scale projects discussed above focus on technologies for managing the fluctuations of renewable energy inputs, various operational strategies have also been proposed, which do not require R&D but rather can be adopted in both new and existing sites using today's technology.

Variability can be managed with storage buffers, including batteries (Pallys and Daoutidis, 2020; Rouwenhorst *et al.*, 2019) and hydrogen storage (Armijo and Philibert, 2020) to manage short-term and long-term variability, respectively. For example, in late 2021 both battery and hydrogen storage assets were integrated into Fertiberia's solar-to-ammonia project at Puertollano in Spain (reNEWS.BIZ, 2021b). Large-scale hydrogen storage is also possible in places with salt caverns, lined rock caverns, and other underground shafts, as well as through hydrogen pipeline networks (Gabielli *et al.*, 2020).

Project scale also plays a role in mitigating variability, not least because economies of scale reduce the relative cost of battery and hydrogen storage assets. The sheer size of gigawatt-scale wind and solar fields, which can span hundreds to thousands of square kilometres, can level out local fluctuations (CWP, 2021; Tancock, 2020). Very large projects may also contain multiple ammonia plants of different sizes, operating in parallel, which can be scheduled to be on standby according to anticipated fluctuations.

Combining complementary sources of renewable energy can decrease the fluctuations and thus increase the capacity factor. For example, the combination of solar (strongest at daytime) and wind (strongest at morning and night) can enable full load factors of 60-70% in the right locations (Armijo and Philibert, 2020; Tancock, 2020), while the full load factors for each separately are typically around 20-60%. The main drawback of this approach is that investment in parallel electricity sources is required, but the impact of this additional cost can be outweighed by the higher capacity factor.

Another strategy to maintain a minimum baseload is firming with a steady decarbonised electricity source, such as geothermal, hydropower, nuclear power or a connection to the grid. However, this latter option is possible only at locations with a stable grid at the scale of the renewable ammonia plant, and it raises issues of additionality. Any marginal electricity from the grid should be decarbonised otherwise the carbon intensity of electrolysis-based hydrogen production may be higher than that of natural gas-based hydrogen production (Ausfelder *et al.*, 2021; Tunå, Hulteberg and Ahlgren, 2014).

A Haber-Bosch synthesis loop can be operated at a low load factor, down to at least 10-30% of the nameplate capacity (Cheema and Krewer, 2018; Ostuni and Zardi, 2012). The trade-off here is lower energy efficiency. The energy consumption of the ammonia synthesis loop is estimated to increase from 2.2 GJ per tonne of ammonia at full load to 14.4 GJ per tonne of ammonia at 10% load (Bañares-Alcántara *et al.*, 2015). This ramp-up/ramp-down (dynamic load response) can generally be achieved within a few hours (Rossi, 2018; Verleysen, Parente and Contino, 2021). However, the ammonia synthesis loop is not necessarily directly coupled with electrolysis, due to hydrogen storage. Electrolysers operate more efficiently at low load due to a lower current density – for example, from 33 GJ per tonne of ammonia at full load to below 30 GJ per tonne at 10% load (Brauns and Turek, 2020).

Similarly, the Haber-Bosch synthesis loop can be operated with inerts, nitrogen and argon, displacing hydrogen. Up to 50 volume-percent of the gases circulating in the synthesis loop can be replaced with inerts, effectively reducing the load factor without reducing the standard operating temperature and pressure (Ostuni and Zardi, 2012).

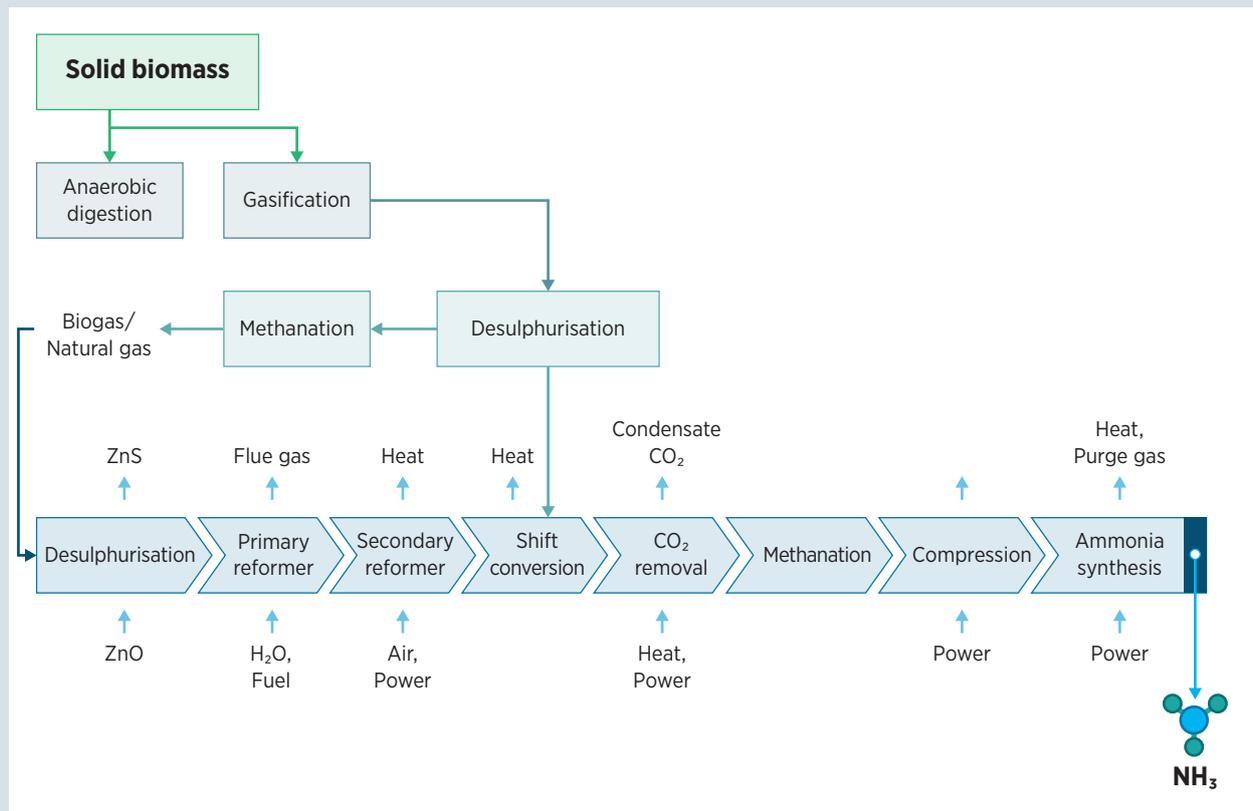
2.5 Renewable ammonia production from biomass

Technology and production process

Biomass is another feedstock for hydrogen and also a circular source of CO₂, which means that ammonia produced from biomass can be upgraded to renewable urea, for use in fertiliser or industrial NO_x-reduction applications. Like renewable ammonia from electrolysis, this technology pathway is mature: in the 1920s, around 5 kt per year of renewable ammonia was produced in Peoria, Illinois from corn fermentation (Ernst and Sherman, 1927).

Biomass can be processed to ammonia along various pathways (Figure 23). Solid biomass can be gasified with air to form syngas (a mixture of hydrogen and CO). Syngas can be processed to form ammonia after carbon removal. Alternatively, biomass can be gasified and methanated to form bio-methane or biogas, which is then used as feedstock. Or, bio-methane can be produced by anaerobic digestion of biomass. Although bio-ammonia is not commercially produced today, all of the process steps for biomass-to-ammonia have been commercially demonstrated.

Figure 23 Schematic overview of steps involved in ammonia synthesis from biogas and solid biomass



Partially adapted from *Fertilizers Europe (2000)*.

Biomass is already a feedstock for methanol production (IRENA and Methanol Institute, 2021), where at least part of the fossil feedstock is replaced by renewable biomass. Biomass-based methanol plants currently have a production capacity typically an order of magnitude lower than fossil-based plants, and this would also be the case for biomass-based ammonia plants.

Around 10-12 exajoules of affordable biogas and biomethane is available for sustainable fuel production in 2040 (IEA, 2020a; de Pee *et al.*, 2018). This would be sufficient feedstock to produce around 535-745 Mt of ammonia. However, only a fraction of global ammonia production is expected to shift to biomass. The limited availability of affordable biomass may be required to produce other biofuels (such as aviation fuels) and feedstocks for the chemical industry.

Costs

The capital intensity of a biomass-based ammonia plant exhibits economies of scale, ranging from USD 2 300 to USD 4 500 per tonne of annual ammonia capacity, depending on the plant size (5-150 kt per year of ammonia) (Akbari, Oyedun and Kumar, 2018; Tunå, Hulteberg and Ahlgren, 2014). In terms of geographic footprint, the energy density of biocrops is around two orders of magnitude lower than for solar power, implying that bio-based ammonia production at gigawatt-scale would be difficult. For small-scale production, the relatively high investment costs may be prohibitive.

Bio-based ammonia production is estimated to cost USD 455 to USD 2 000 per tonne of ammonia, depending on the source of the biomass and the plant size (Arora *et al.*, 2016; Sánchez, Martín and Vega, 2019). This is substantially higher than the typical market value of USD 200-300 per tonne of ammonia (Haldor Topsøe *et al.*, 2020).

Biomass can also be introduced into an existing fossil-based ammonia plant, to decarbonise 10-15% of its feedstock. An estimated CO₂ price of USD 250-400 per tonne of CO₂ would be required for this to be cost competitive (Saygin and Gielen, 2021).

Current installed capacity and announced capacity

There are no commercial-scale bio-based ammonia plants in operation today. Various biomass-to-ammonia and -urea plants were announced in the late 2000s and early 2010s (Brown, 2013), based on feedstocks such as woody biomass, harvest leftovers and biogas. However, these projects have not materialised, and some of the companies involved ceased operations. An important reason for this was the low cost penalty for using fossil feedstocks, such as natural gas, oil, and coal, during a period of low natural gas prices.

Co-feeding of biomass or biogas may play a role in the partial decarbonisation of fossil-based ammonia plants, especially if supported by higher carbon emission penalties. CCS of this biomass or biogas can produce carbon-negative ammonia, offsetting emissions from fossil-based ammonia production.

In general, however, biomass is not expected to play a major role in the global trade of decarbonised ammonia (de Pee *et al.*, 2018) and may be limited to opportunities where location-specific conditions overcome the economic hurdles. For example, low-cost biomass or animal waste can be used as a feedstock for bio-based ammonia in isolated communities with limited access to fossil-based or electrolysis-based ammonia, and with requirement for urea fertiliser.

2.6 Cost comparison of renewable ammonia and fossil-based ammonia with carbon capture and storage

Renewable ammonia production costs for new plants are estimated to be in the range of USD 720 - 1 400 per tonne (USD 39-75 per GJ) today. This is expected to fall to USD 310-610 per tonne (around USD 17-33 per GJ) by 2050, driven by decreasing prices for renewable power and electrolyzers, and by technological and operational improvements leading to higher utilisation rates. For hybrid plants, in which some amount of renewable hydrogen is introduced to an existing fossil-based ammonia plant, renewable ammonia costs are estimated to be USD 300-400 per tonne by 2025, falling to around USD 250 per tonne by 2040.

Bio-based ammonia production is estimated to cost USD 455 to USD 2 000 per tonne, substantially higher than low-carbon fossil ammonia and electrolysis-based renewable ammonia.

Natural gas-based ammonia production with CCS costs around USD 170-465 per tonne of ammonia or USD 9-25 per GJ (on a lower heating value basis), depending on the cost of natural gas. Coal-based ammonia production with CCS has a cost range of USD 360-450 per tonne or USD 19-24 per GJ.

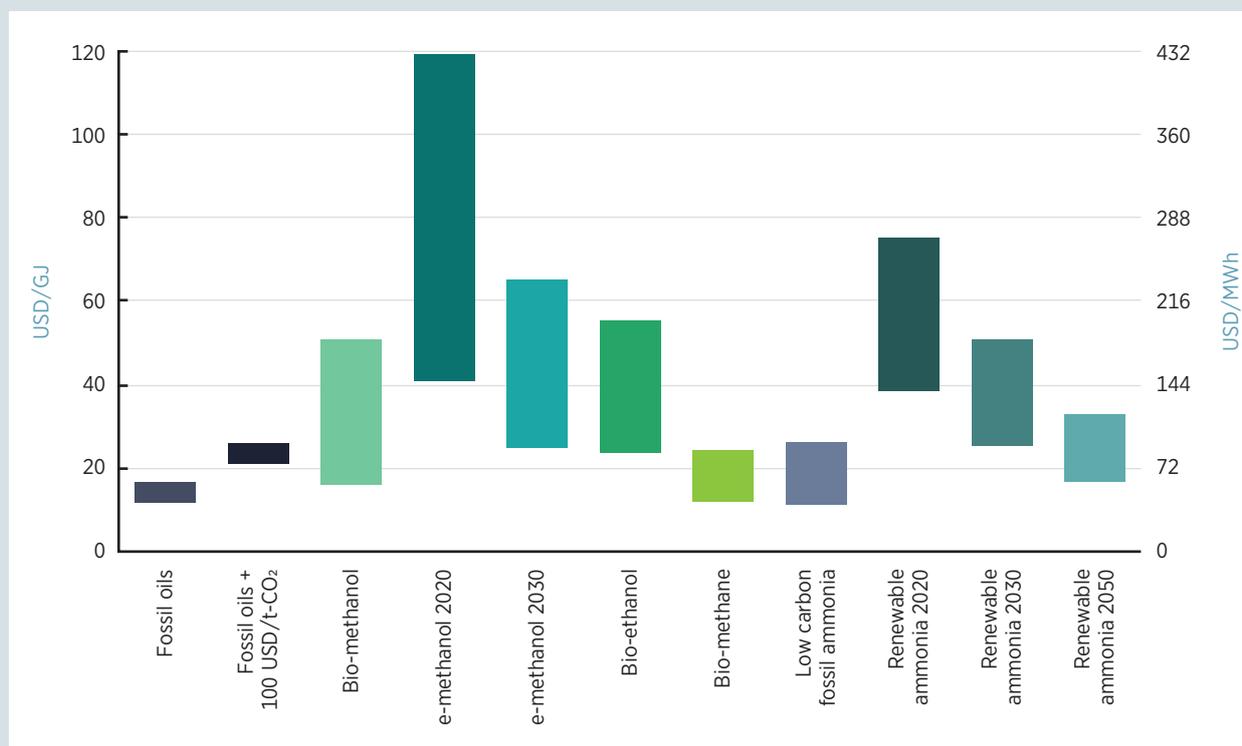
Most low-carbon ammonia, whether renewable or fossil-based with CCS, is currently not cost competitive at the conventional commodity price of USD 200-300 per tonne in recent years (Hatfield, 2020). (Recent natural gas shortages have resulted in a substantially higher ammonia market price, above USD 1 000 per tonne.) Therefore, it is expected that separate markets will need to develop, supported by certification schemes, contracts for difference and other mechanisms.

The cost of renewable ammonia is expected to decrease substantially, such that renewable ammonia can become competitive in the long term, and this could be accelerated with substantial carbon mitigation incentives (Figure 24).

In optimal locations, renewable ammonia is expected to be cost competitive with fossil-based ammonia with CCS beyond 2030. This suggests that imported renewable ammonia may be preferred over domestic fossil-based production in some cases. For import projects, ammonia transport by ship may add up to USD 45-100 per tonne or USD 2-5 per GJ to the local production cost (Hank *et al.*, 2020; Salmon and Bañares-Alcántara, 2021).

Notably, low-carbon fossil-based ammonia is already competitive with fossil oils on an energy basis, and ammonia is competitive with other zero-carbon fuels (Figure 24).

Figure 24 Comparison of renewable ammonia with other fuels based on the price per unit of energy



Source: Low-carbon fossil ammonia from Haldor Topsøe *et al.* (2020). Fossil fuel values are based on average values (2010-2020); see IRENA and Methanol Institute (2021). Methanol cost values are based on IRENA and Methanol Institute (2021). Bio-ethanol and bio-methane estimates are based on IRENA (n.d.).

The cost of renewable ammonia is expected to decrease substantially, such that renewable ammonia can become competitive

2.7 Novel ammonia production technologies

The Haber-Bosch process has been the dominant process for nitrogen fixation for more than a century (Erisman *et al.*, 2008; Liu, 2014; Smil, 2004). The source of hydrogen has varied over the years, but the ammonia synthesis loop has stayed remarkably similar to BASF's original design (Travis, 2018). As a result, Haber-Bosch is highly optimised, and the energy efficiency of the natural gas-based ammonia production process is as high as 60-70% (on a lower heating value basis) (Smith, Hill and Torrente-Murciano, 2020). This creates a high hurdle for new technologies.

A wide range of novel ammonia production technologies has been researched, such as electrochemical and photochemical processes, plasma-based processes, chemical looping approaches, homogeneous synthesis, biological processes, and ammonia purification from animal waste or waste water (Cherkasov, Ibhadon and Fitzpatrick, 2015; Nørskov *et al.*, 2016; Rouwenhorst *et al.*, 2020b).

Furthermore, modifications to Haber-Bosch have also been proposed to allow efficient operation at lower temperatures and pressures (Malmali *et al.*, 2017; Rouwenhorst *et al.*, 2020b), which may allow for better integration of variable renewable energy inputs.

Novel ammonia production technologies are especially relevant for small-scale ammonia synthesis, typically with a capacity below 10 tonnes per day (Rouwenhorst *et al.*, 2020b). At such small scales, the energy consumption of Haber-Bosch is typically high due to heat losses (Rouwenhorst *et al.*, 2019) and downscaling is costly due to the high pressures (Yoshida *et al.*, 2021).

Electrochemical ammonia synthesis has received substantial research interest over the past decades (Giddey, Badwal and Kulkarni, 2013; MacFarlane *et al.*, 2020; McPherson *et al.*, 2019), as it potentially allows for the direct formation of ammonia from water and nitrogen. However, this has remained a scientific challenge with low rates of formation (Kibsgaard, Nørskov and Chorkendorff, 2019), and false positives were previously reported due to the presence of ammonia in the surroundings (Andersen *et al.*, 2019; Choi *et al.*, 2020).

Two companies, Tsubame BHB in Japan and Starfire Energy in the United States, are commercialising ammonia synthesis with low-temperature catalysts and separation by adsorption or absorption – for example, a sorbent-enhanced Haber-Bosch synthesis loop (Crolius, 2021; Starfire Energy, n.d.). This allows for milder temperatures and pressures, which may facilitate variable operation as well as cost-effective scale-down of the process.

So far, novel ammonia technologies have not been fully commercialised, and Haber-Bosch is expected to remain the dominant technology for ammonia synthesis in the coming decades, especially at large scale (Rouwenhorst *et al.*, 2020c). Novel technologies with decarbonisation potential that can be integrated with Haber-Bosch are already in development, including electrified SMR units, autothermal reforming, methane pyrolysis and solid oxide electrolyzers.

3. PERFORMANCE AND SUSTAINABILITY

Key findings

Renewable hydrogen production takes 90% of the energy needed to make renewable ammonia.

- Renewable ammonia synthesis using electrolysis currently consumes about 36 GJ per tonne of ammonia (around 50% energy efficiency). Of this, the hydrogen production consumes 90% or around 33 GJ per tonne of ammonia.
- Improvements in electrolyser efficiency will therefore have a significant impact on the energy efficiency of renewable ammonia.
- From another perspective, the energy required to make renewable ammonia is a small premium on renewable hydrogen.

The energy input of renewable ammonia production is similar to that of fossil-based ammonia.

- High-temperature electrolysis (solid oxide) promises efficiency improvements over low-temperature electrolysis (alkaline or PEM), and typically consumes 30 GJ per tonne of ammonia today, with potential to reach 26 GJ per tonne (up to 70% energy efficiency).
- Renewable ammonia from biomass consumes about 37-42 GJ per tonne (45-50% energy efficiency).
- By contrast, modern natural gas-based ammonia plants can operate at 26-29 GJ per tonne of ammonia, while the global average energy consumption for ammonia production today is around 36 GJ per tonne of ammonia.

Renewable ammonia can reduce global greenhouse gas emissions.

- Ammonia production currently generates around 0.5 Gt of CO₂-equivalent annually, accounting for 1% of global greenhouse gas emissions.
- Greenhouse gas emissions from fossil-based ammonia production vary depending on the feedstock, with natural gas generating at least 1.6 tonnes of CO₂ per tonne of ammonia and coal generating around 4.0 tonnes of CO₂ per tonne of ammonia.
- Additional greenhouse gas emissions occur upstream, with embedded emissions and fugitive methane, and downstream, during storage, transport and distribution.
- Including upstream and downstream emissions, renewable ammonia from electrolysis could have a carbon footprint below 0.1 tonne of CO₂ per tonne of ammonia by 2050.

- Beyond greenhouse gas emissions, other sustainability criteria should be considered, including the availability of water and land, scarcity of certain metals and impacts on the global nitrogen cycle.

Ammonia certification schemes are under development to support the development of a market for renewable and low-carbon ammonia.

- An ammonia molecule derived from any source is the same, but the carbon footprint is not.
- Guarantees of origin would allow producers and consumers to reach agreements on the value of ammonia based on its carbon intensity, as well as other sustainability criteria.
- A book-and-claim system, or similar, could enable the trading of certificates separate from the physical ammonia product.
- Ammonia certification could be used to support regional and sectoral policies, for example a carbon tax or border adjustment mechanism, or a low-emission zone port.

3.1 Performance and efficiency

Modern renewable ammonia synthesis from low-temperature electrolysis (alkaline or PEM) typically consumes around 36 GJ per tonne of ammonia (Smith, Hill and Torrente-Murciano, 2020), a 50% energy conversion efficiency. Hydrogen production typically consumes most of the energy, around 33 GJ per tonne of ammonia. Nitrogen purification from pressure swing adsorption (PSA) consumes around 0.6-0.9 GJ per tonne of ammonia, typically for small-scale ammonia plants, while nitrogen purification from cryogenic distillation consumes around 0.3 GJ per tonne of ammonia, typically for large-scale ammonia plants (Rouwenhorst *et al.*, 2019). The ammonia synthesis loop typically consumes at least 2 GJ per tonne of ammonia (Bañares-Alcántara *et al.*, 2015; Smith, Hill and Torrente-Murciano, 2020).

Renewable ammonia synthesis from high-temperature electrolysis (solid oxide) typically consumes around 30 GJ per tonne of ammonia (Cinti *et al.*, 2017; Smith, Hill and Torrente-Murciano, 2020) and is expected to decrease to 26 GJ per tonne in the long term (Hansen, 2015), around a 60-70% energy conversion efficiency. The lower energy consumption, compared to low-temperature electrolysis, is due to more efficient hydrogen production and greater heat integration across the process (Hansen, 2015; Hauch *et al.*, 2020).

Renewable ammonia synthesis from solid biomass feedstock consumes around 37-42 GJ per tonne (IEA, 2021a; H. Zhang *et al.*, 2020), around a 45-50% energy conversion efficiency. Bio-gas and biomethane produced from biomass can be processed like natural gas, with similar efficiency.

The energy consumption for ammonia synthesis from various feedstocks is tabulated in Table 3, and the historical development of the best available technology per feedstock is shown in Figure 25.

A typical modern natural gas-based ammonia plant consumes around 29 GJ per tonne of ammonia (CEFIC, 2013). The most energy-efficient plants consume 26-27 GJ per tonne of ammonia, and further optimisation is not expected, as the process approaches a technological asymptote (Figure 25). However, older plants can be optimised through revamps (Kermeli *et al.*, 2017). The overall energy conversion efficiency on a lowering heating value basis for a large-scale, modern natural gas-based ammonia plant is around 65% (CEFIC, 2013). The addition of CCS technology would increase this energy consumption to around 33 GJ per tonne of ammonia (Rouwenhorst *et al.*, 2020b), around a 55% efficiency. Replacing SMR with ATR technology, with CCS, may decrease the energy consumption to 29 GJ per tonne of ammonia (IEA, 2021a).

Ammonia production from methane pyrolysis consumes around 49 GJ per tonne of ammonia (IEA, 2021a), of which the majority comprises the natural gas feedstock and the minority electricity feedstock, equivalent to around 40% energy conversion efficiency. The efficiency for coal to ammonia is around 45% (Brightling, 2018).

The global average energy consumption today is around 36 GJ per tonne of ammonia (IFA, 2014). Ammonia plants in industrialised countries typically have a lower energy consumption (33-36 GJ per tonne of ammonia) compared to developing countries (36-47 GJ per tonne) (Saygin *et al.*, 2011), which has implications for locations where renewable ammonia may be more competitive in the near-term.

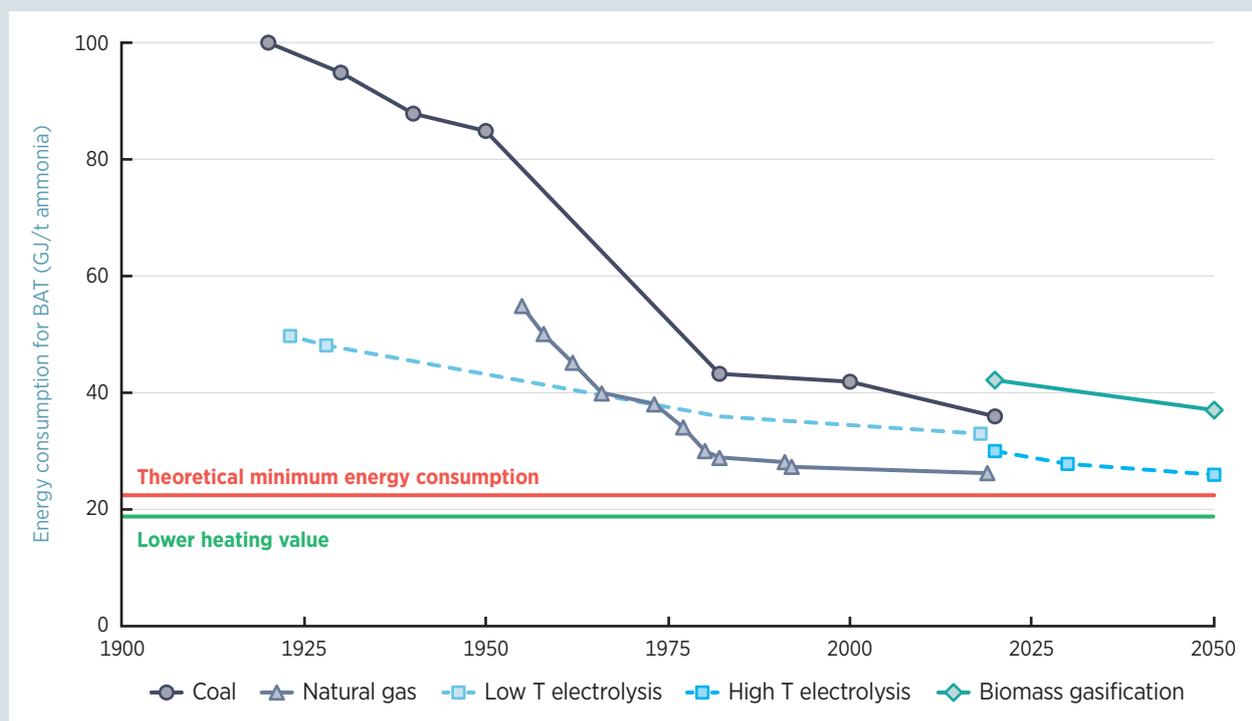
Table 3 Typical gross energy consumption for ammonia synthesis from various feedstocks, based on modern technology

Feedstock	Typical energy consumption (GJ/t ammonia)	Potential (GJ/t ammonia)	Source
Ammonia from natural gas (SMR, ATR or eSMR)	28-29	26	(CEFIC, 2013; IEA, 2021a)
Ammonia from naphtha	35	-	(Brightling, 2018)
Ammonia from heavy fuel oil	38	-	(Brightling, 2018)
Ammonia from coal	42	36	(Brightling 2018; IEA, 2021a)
Ammonia from natural gas (SMR, ATR or eSMR) with carbon capture and storage	33	29	(IEA, 2021a; Rouwenhorst <i>et al.</i> , 2020b)
Ammonia from coal with carbon capture and storage	-	39	(IEA, 2021a)
Ammonia from methane pyrolysis	49	46	(IEA, 2021a)
Ammonia from low-temperature electrolysis	36	33	(Smith, Hill and Torrente-Murciano, 2020)
Ammonia from high-temperature electrolysis	30	26	(Cinti <i>et al.</i> , 2017; Hansen, 2015; Smith, Hill and Torrente-Murciano, 2020)
Ammonia from biomass gasification	42	37	(CEFIC, 2013; IEA, 2021a; H. Zhang <i>et al.</i> , 2020)

Note: For reference, the lower heating value of ammonia is 18.6 GJ per tonne. SMR = steam methane reforming; ATR = autothermal reforming.



Figure 25 Best available technology (BAT) for ammonia synthesis from various feedstock



Note: The red line represents the theoretical minimum energy consumption required for ammonia synthesis from water and air (22.5 GJ per tonne of ammonia), and the green line represents the lower heating value of ammonia (18.6 GJ per tonne).

Source: Based on original data from CEFIC (2013); Ernst (1928); Fertilizers Europe (2000); Grundt and Christiansen (1982); Hansen and Han (2018); IEA (2021a); Smil (2004); Smith, Hill and Torrente-Murciano (2020); H. Zhang et al. (2020).



Case study 1 Facilitating the transition to renewable ammonia: Recommendations for industry and governments

One strategy to decrease global primary energy consumption is the use of more energy-efficient technologies. This is also relevant for ammonia synthesis and utilisation, for instance in the maritime sector.

Currently, renewable ammonia is based on low-temperature electrolysis. This operates at a typical energy consumption of 36 GJ per tonne of ammonia, while the energy consumption may decrease to 33 GJ per tonne of ammonia in the long term (Smith, Hill and Torrente-Murciano, 2020). This is equivalent to an energy conversion efficiency of 52-57% on a lower heating value basis.

However, renewable ammonia produced via solid oxide electrolysis requires an energy input of only around 26-30 GJ per tonne of ammonia (Hansen, 2015; Smith, Hill and Torrente-Murciano, 2020). This is equivalent to an energy conversion efficiency of 62-72% on a lower heating value basis. A large-scale solid oxide electrolyser manufacturing facility was announced in 2021, with an annual electrolyser capacity of 500 MW in 2023, with an option to expand to 5 GW (Frøhlke, 2021b).

Ammonia can be used as a marine fuel. The current technology for maritime propulsion is the two-stroke engine, which can be retrofitted to use ammonia as a fuel (MAN Energy Solutions, 2019), with an energy efficiency of about 45-50% on a lower heating value basis (MAN Diesel & Turbo, 2017). Likewise, four-stroke engines are under development for marine applications, with ambitions to convert existing engines and new builds from 2023 onward (Wärtsilä Corporation, 2020), with energy efficiencies up to around 50% on a lower heating value basis.

Alternatively, however, ammonia may be fed directly to a solid oxide fuel cell with potentially higher energy efficiency, around 55-60% on a lower heating value basis (Afif *et al.*, 2016). Solid oxide fuel cell technology is currently in development, and costs are expected to decrease with deployment (Schmidt *et al.*, 2017b; Staffell *et al.*, 2019). Currently, solid oxide fuel cells are available only for small-scale applications (< 1 MW) (Palys and Daoutidis, 2020). For reference, a typical size for a ship engine is tens of megawatts (MAN Energy Solutions, 2020).

Other minor energy losses in the ammonia value chain for maritime fuel use include conversion and transmission losses in solar and wind energy, cooled ammonia transport, and ammonia usage for NO_x reduction (only required for the two-stroke engine) (Johannessen, 2020). These other losses amount to a total of around 8.3% energy loss for the current technology and 6.4% energy loss for solid oxide technology (Johannessen, 2020), equivalent to a 92% and 94% efficiency in the supply chain.

Comparing the current technology for renewable ammonia production and utilisation with the solid oxide technology, it is clear that the total round-trip efficiency for solid oxide technology is higher (Table 4). The round-trip efficiency is important, as solar and wind electricity typically account for the majority of the cost (Sánchez and Martín, 2018) and, upon increasing the round-trip efficiency, the requirement for renewable electricity generation decreases. The lower investment in solar and wind capacity may outweigh the slightly higher cost of solid oxide technology. Furthermore, a higher round-trip efficiency results in 30-35% less land use for renewable energy generation.

Table 4 Round-trip efficiency of ammonia production and utilisation for the maritime sector

	Current technology	Solid oxide technology
Hydrogen production technology	Alkaline or PEM electrolysis	Solid oxide electrolysis (SOE)
Energy consumption (GJ/t ammonia)	33-36	26-30
Energy conversion efficiency	50-57% on LHV basis	62-72% on LHV basis
Ammonia conversion technology	Two-stroke engine	Solid oxide fuel cell (SOFC)
Energy conversion efficiency	45-50% on LHV basis	55-60% on LHV basis
Other losses	8.3%	6.4%
Round-trip efficiency	21-26%	32-40%
Relative renewables footprint (area)*	1.7-1.9	1.0-1.2

Note: See also Table 3, and the text above. *Indexed relative to 26 GJ per tonne of ammonia for ammonia production and 60% (lower heating value) energy efficiency for conversion of ammonia to energy. LHV = lower heating value.

3.2 Emissions and sustainability of ammonia production

The current ammonia production technology generates around 0.5 Gt of CO₂-equivalent annually (Royal Society, 2020), accounting for 1% of global greenhouse gas emissions.

The carbon footprint of ammonia production processes can be quantified using life-cycle analysis. All stages of ammonia production, distribution and consumption are taken into account in a thorough life-cycle analysis, also known as cradle-to-grave analysis. Such analyses are highly dependent on numerous factors, including the production pathway, the nature of feedstocks, and applications, making a comparison with other fuels and feedstocks challenging. Nonetheless, these types of analyses will be increasingly needed to assess the environmental impact of different fuels/materials and processes.

The presence of global standards for low-carbon fuels will be essential. The greenhouse gases emitted for ammonia production from various resources are listed in Table 9 in Annex C, expressed as CO₂-equivalents. The greenhouse gas emissions for both renewable ammonia and fossil-based ammonia with CCS are substantially lower than those for fossil-based ammonia without emission mitigation (Figure 26). For example, SMR-based ammonia production results in at least 1.6 tonnes of CO₂ per tonne of ammonia (Brightling, 2018).

In addition, depending on the infrastructure for natural gas production, processing, and transport, methane emissions can be substantial, up to 0.9 tonnes of CO₂-equivalent per tonne of ammonia (GIE-MARCOGAZ, 2019). This is a hidden CO₂-equivalent emission that should be accounted for when determining the carbon footprint for ammonia production (Howarth and Jacobson, 2021). Methane (CH₄) has a 30-times higher global warming potential than CO₂ on a 100-year time scale, and as much as 85 times on a 20-year time scale. Thus, methane emissions have a much more profound impact on estimating the global warming potential on a 20-year time scale.

Upstream methane leaks are identical for ammonia produced with or without CCS. In addition, with CCS, potential downstream CO₂ slippage from storage must also be accounted for. As a result, the life-cycle emission reductions achievable by implementing CCS on a SMR-based production site may be limited to 60-85% (Committee on Climate Change, 2018). Thus, fossil-based ammonia with CCS serves only as an intermediate step towards fully decarbonised ammonia production.

For renewable ammonia, the sustainability of electrolysis depends on the choice of technology and of water source. The availability of scarce metals may become a limitation for gigawatt-scale PEM electrolysis (Kiemel *et al.*, 2021), but such limitations do not exist for alkaline or solid oxide electrolysis (Salmon and Bañares-Alcántara, 2021). Water security should not be compromised and, therefore, desalinated sea water should be used for gigawatt-scale ammonia plants in most locations, while limiting brackish water disposal. Ammonia from electrolysis requires about 1.6 tonnes of water feedstock per tonne of ammonia (Ghavam *et al.*, 2021), with additional water required for cooling and support systems. Ammonia from SMR requires around 0.6 tonnes of water feedstock per tonne of ammonia (Ghavam *et al.*, 2021).

Notably, electrolysis-based hydrogen production should generally not be based on marginal electricity from the grid, as this may result in higher greenhouse gas emissions than from fossil-based ammonia production (Ausfelder *et al.*, 2021), unless the electric grid has a very low fraction of fossil-based production.

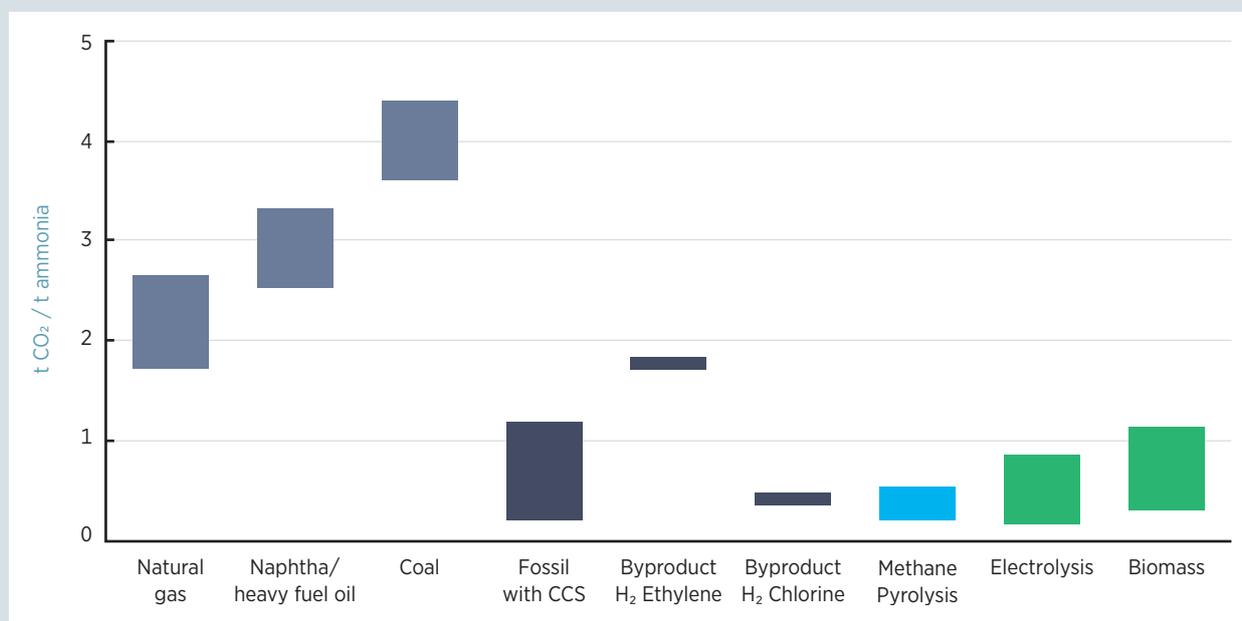
Accounting for emissions from transport, utilising today's infrastructure, can add up to 10 grams of CO₂-equivalent per megajoule (MJ) of ammonia (Bicer *et al.*, 2016), equivalent to 0.2 tonnes of CO₂ per tonne of ammonia.

Regarding embedded emissions, wind and solar power are currently produced with fossil-based technologies. Upon decarbonising the entire value chain, the carbon footprint of renewable ammonia could decrease from the current level of around 0.5 tonne of CO₂ per tonne of ammonia to below 0.1 tonne by 2050 (Hydrogen Council, 2021).

If ammonia is used as a fuel for ships and stationary power, nitrous oxide (N₂O) emissions must be suppressed. N₂O has a global warming potential 298 times that of CO₂ (US EPA, 2020). N₂O emissions have been reduced over the years through legislation. Already, ammonia and its derivatives (urea solution, known as diesel exhaust fluid or AdBlue) are already used to decrease these emissions in the stationary power and transport sectors using selective catalytic reduction (SCR) technology (Busca *et al.*, 1998). Ammonia emissions can be suppressed through an ammonia oxidation catalyst (AMOX).

As discussed in Annex B, ammonia emissions have a more local effect on the environment, rather than causing global warming. Ammonia emissions must be suppressed as much as possible to prevent eutrophication.

Figure 26 Illustrative ranges of estimated greenhouse gas emissions of ammonia production from various feedstock



Note: Data are represented as median values with standard deviation, and are drawn from multiple literature references based on various methodologies and boundary assumptions. The development of Guarantees of Origin with standardised calculation methods are required to verify the actual emissions intensity of ammonia from any specific production unit.

Source: Values are from Table 9 in Annex B.

3.3 Certification schemes, CO₂ penalties and legislation

Certification schemes will be required to distinguish between fossil-based ammonia, fossil-based ammonia with CCS, and renewable ammonia. The ammonia molecule derived from any source is the same, but the carbon footprint is not. Therefore, guarantees of origin are required, indicating the CO₂-equivalent footprint of the ammonia from raw material extraction to the use phase, which allows ammonia producers and consumers to reach agreements on the value of low-carbon ammonia. Similar certificates already exist for electricity production. Certificates could in theory be traded separate from the physical ammonia product, for example within a book-and-claim system.

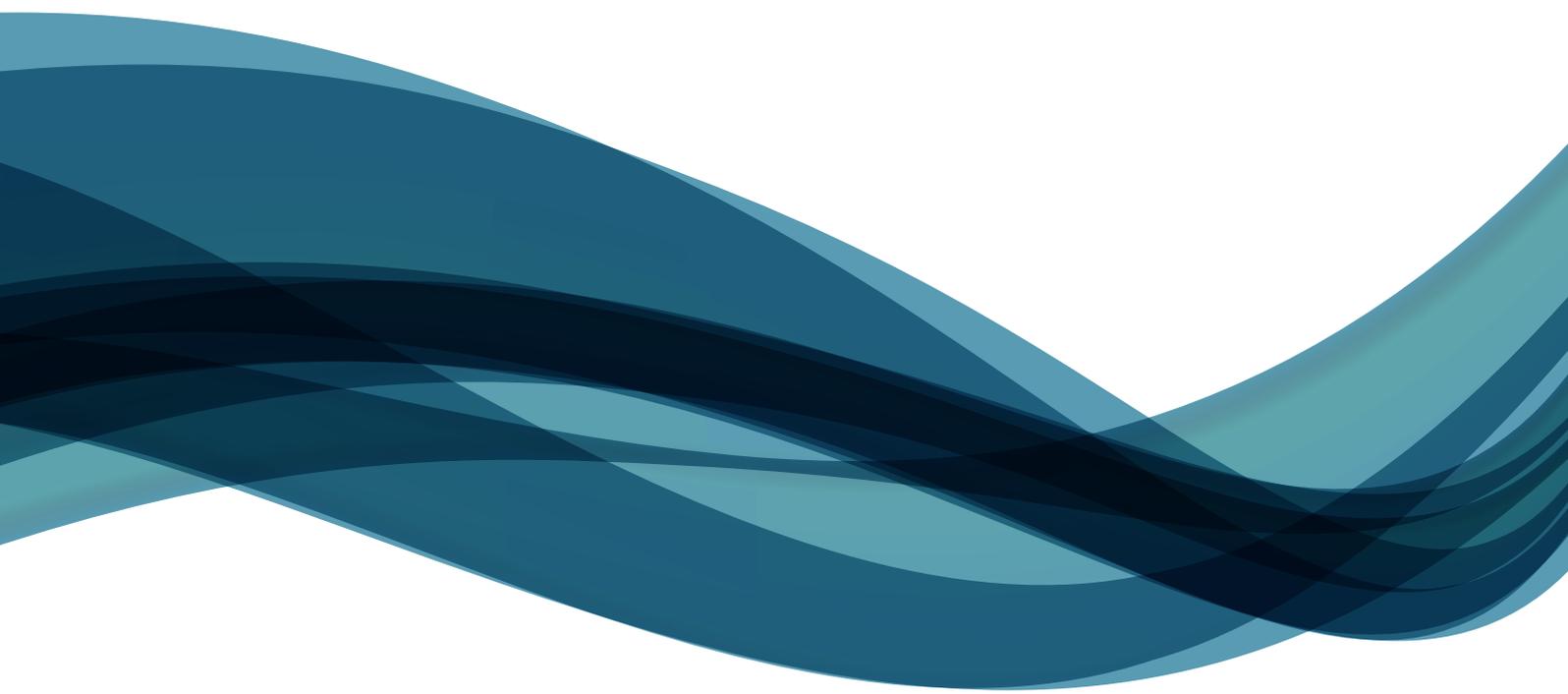
The classification of low-carbon ammonia should be straightforward. Inspiration can be obtained from hydrogen production. One such system uses the term “low carbon” for hydrogen with a carbon footprint at least 60% lower than for SMR (Barth, 2016). Comparison of lower-carbon fuels based on energy content rather than on mass basis allows for a level playing field among alternative fuels. The focus should not only be on-site CO₂ emissions but on all greenhouse gases as well as other criteria including water use and upstream emissions.

Using such certification schemes may also allow for an overall market cap on the carbon emissions for ammonia production. On the other hand, using a market-based approach, rather than a specific cap for all ammonia produced, allows for a smoother transition, as a specific cap can result in market disruption due to the regulatory shock. Various schemes are being pursued, including methodology development by IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy) and an ammonia certification scheme under development by the Ammonia Energy Association.

Depending on the application, different ammonia purity levels may be required. Minor metal impurities from the ammonia feedstock may cause problems in, for instance, solid oxide fuel cells. Thus, solid oxide fuel cells require highly purified ammonia (Makhloufi, 2020). Certification schemes could provide both the CO₂-equivalent footprint and the purity grade of the ammonia.

Certificates of origin may also support policies to develop a level playing field within an economic zone. A carbon tax is applied for ammonia production within the EU, with current levels at around USD 75 per tonne of CO₂-equivalent, on top of which the EU recently announced a carbon border adjustment mechanism (CBAM) on external CO₂ emissions imported to the EU (Haahr, 2021). Certification schemes would enable the determination of a carbon footprint for imported ammonia, and thus could support the levy of a carbon tax on ammonia produced outside the EU. The revenue from carbon taxes can be used as subsidies for supply chains of renewable fuels or for research on decarbonised solutions, which would favour the import-export infrastructure of renewable ammonia (and fossil-based low-carbon ammonia) in Europe and elsewhere.

The Port of Tokyo recently waived the entry fee for ships powered by liquefied natural gas (LNG) and hydrogen in an effort to promote cleaner marine fuels (Reuters Staff, 2021). Such policies may also be applied to ammonia as a maritime fuel.



4. FUTURE MARKETS FOR DECARBONISED AMMONIA

Key findings

Ammonia is being considered as a zero-carbon fuel for the maritime sector.

- Ammonia has been demonstrated as a fuel since the 19th century. Most famously, the US National Aeronautics and Space Administration (NASA) used ammonia to fuel its X-15 hypersonic aircraft in the 1960s.
- Maritime engine manufacturers expect to commercialise ammonia-fuelled two-stroke and four-stroke engines by 2024 or 2025, for new builds and retrofits. Ammonia engine developers believe that they can deliver commercial performance within existing regulatory limits for nitrogen oxides.
- Solid oxide fuel cells are also being demonstrated, with potentially higher energy efficiency (55-60% compared to 45-50% for two-stroke engines).
- Various consortia have been announced, and the first ammonia-fuelled vessels are expected to be operating at sea by 2024 or 2025.

Ammonia is being considered as a fuel for stationary power.

- Ammonia can displace coal and natural gas in both baseload and peaker plants, at large or small scale, using gas turbines, furnaces, engines and fuel cells.
- Ammonia can also be used to replace diesel in back-up and off-grid applications, using engines or alkaline or solid oxide fuel cells.
- Partial cracking, to produce an ammonia-hydrogen blend, can improve the combustion properties of ammonia.
- In Japan, JERA is demonstrating co-combustion of 20% ammonia and 80% coal in a 1 GW power plant. The Japanese government roadmap targets the use of 30 Mt of fuel ammonia in 2050, starting with co-combustion technologies and phasing out fossil fuels for 100% ammonia combustion.

Ammonia is also proposed as a hydrogen carrier, to overcome the storage and distribution challenges of hydrogen.

- During decomposition, ammonia is cracked to produce hydrogen and atmospheric nitrogen.
- Hydrogen produced from imported renewable ammonia can be cheaper than local renewable hydrogen.

- Large-scale ammonia crackers have been proposed to meet national hydrogen import demand, including at the Port of Rotterdam in the Netherlands and at Wilhelmshaven in Germany, with capacities of up to 0.5 Mt per year of hydrogen (3.7 Mt per year of ammonia).
- Direct use of imported ammonia, where possible, would reduce conversion losses.

By 2050, in the 1.5°C scenario, the market for ammonia as a fuel for maritime transport and for stationary power is larger than all current markets for ammonia combined.

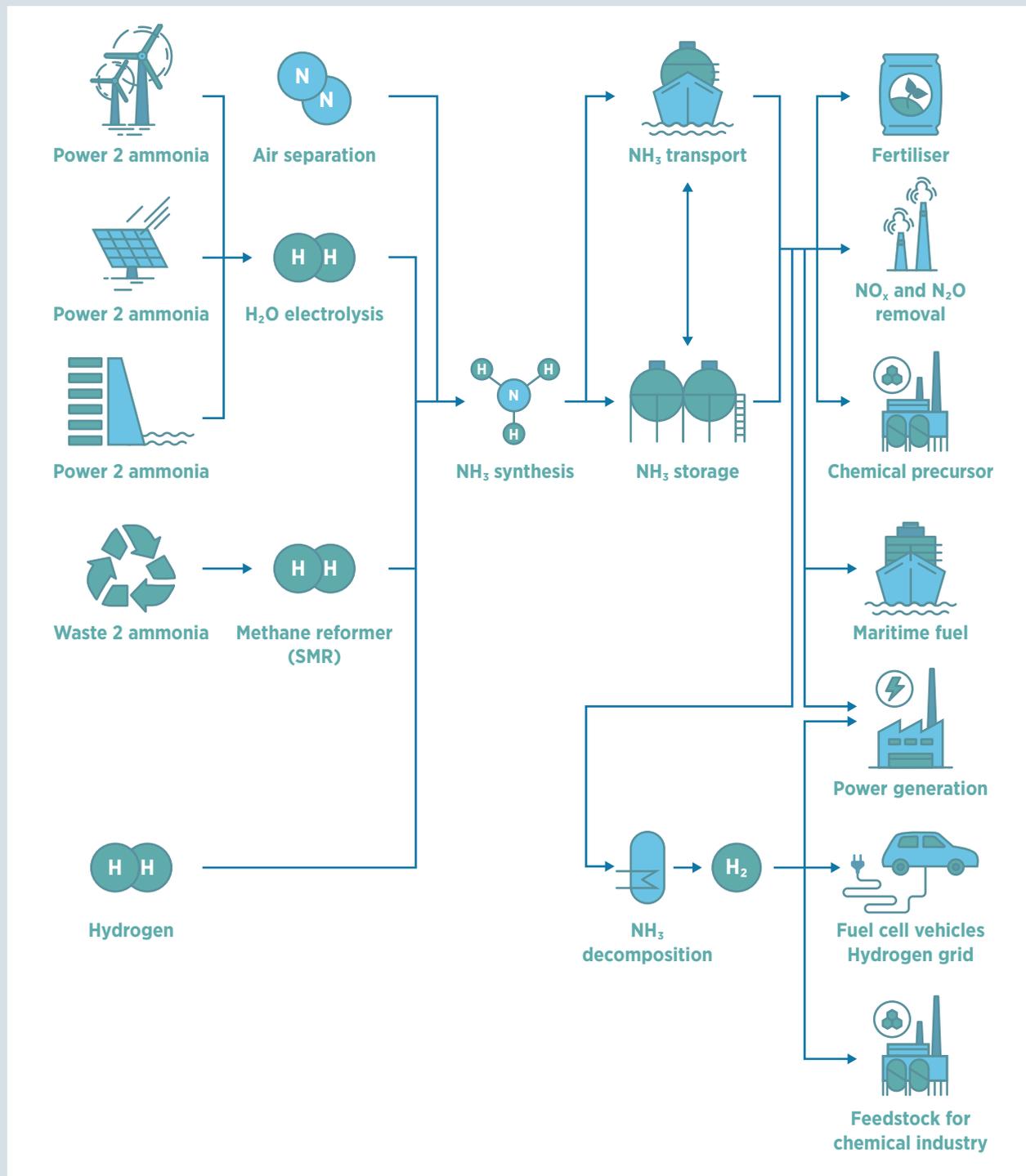
- Global ammonia demand increases from 183 Mt in 2020 to 688 Mt in 2050.
- Existing uses grow to 267 Mt of ammonia for fertiliser and 67 Mt for other uses.
- By 2050, the maritime sector is expected to consume 197 Mt of ammonia as fuel.
- By 2050, ammonia imports as a hydrogen carrier reach 127 Mt, supplying decarbonised feedstock and fuel for the chemical and industrial sectors.
- Demand for ammonia as a fuel for power generation reaches 30 Mt by 2050, based only on stated policies within Japan.

While many of these technologies are already commercial at scale, bottlenecks and barriers exist that may limit the speed at which ammonia is deployed as a fuel and hydrogen carrier.

- Government policies to reduce greenhouse gas emissions are uncertain, causing doubt and limiting investment.
- Electrolyser production capacity was reported to be 2.1 GW per year in 2020, while the required capacity is 40-65 GW per year to produce 566 Mt per year of renewable ammonia by 2050.
- Ammonia infrastructure must expand by a factor of 10-15, requiring tens of billions of USD in annual investment in storage and transport assets.
- The use of ammonia in energy markets is driven by the need to reduce greenhouse gas emissions, and therefore new renewable or low-carbon ammonia is required.
- Demand for ammonia in energy applications should not put fertiliser supply, and thus food production, at risk.

Ammonia is currently used in various applications, but primarily as a fertiliser (see section 1.1). New markets for decarbonised ammonia may include its use as a fuel for the maritime industry and for power generation, or as a hydrogen carrier (IRENA, 2020c). An overview of the potential roles of ammonia in the hydrogen economy is shown in Figure 27.

Figure 27 Schematic of the ammonia economy



Source: Adapted and modified from Proton Ventures (2021) and Sousa Cardoso et al. (2021).

As early as the 19th century, ammonia was proposed as a fuel (Sousa Cardoso et al., 2021). It was used to fuel buses in Belgium during the Second World War (Image 5), due to the scarcity of other fuels (Kroch, 1945). Most famously, NASA used ammonia to fuel its X-15 hypersonic rocket-powered aircraft in the 1960s (Valera-Medina et al., 2018). More recently, ammonia has gained interest as a fuel for stationary power generation (Valera-Medina et al., 2018) and for international shipping (Haldor Topsøe et al., 2020).

Image 5 Ammonia-fuelled bus in Belgium during the Second World War



Image courtesy of Camprigaz, Ltd., 1945.

Dahlberg, Green Jr., and Avery were among the first to advocate for ammonia as an energy vector in the hydrogen economy in the 1980s (Avery, 1988; Dahlberg, 1982; Green, 1982). A scenario where ammonia plays a dominant role in the energy landscape can be coined the ammonia economy (MacFarlane *et al.*, 2020; Morlanés *et al.*, 2020). The current energy landscape depends strongly on carbon-based fuels. Using ammonia as an energy vector allows to break the carbon cycle by not introducing carbon in the first place. With renewable ammonia, the energy conversion process starts with air and water, and ends with air and water.

The potential market size for ammonia as a fuel is larger than the combined current markets for ammonia (MacFarlane *et al.*, 2020). However, the right technologies, the right markets, the right cost structures and the right certification schemes need to be in place for implementation of decarbonised fuels. The rate at which the renewable ammonia market will expand in the coming decade depends on how fast ammonia is adopted as a hydrogen carrier and fuel, as well as on the electrolyser production capacity and ammonia transport infrastructure deployment. As discussed in section 4.5, the electrolyser production capacity and ammonia transport infrastructure should be scaled by at least an order of magnitude to produce sufficient renewable fuels up to 2050.

Various commercial-scale projects and products have been announced, but currently only small-scale demonstrations are in operation. These demonstrations assess the technological viability of the power-to-ammonia-to-power value chain in Denmark, Japan, the United Kingdom and the United States (Brown, 2018a; Valera-Medina *et al.*, 2021). However, the ammonia value chain must be demonstrated at a commercially relevant scale (Johannessen, 2020), to convince investors of its viability. Most of the announced commercial-scale projects are expected to be complete around 2025.

4.1 Ammonia as a hydrogen carrier

Ammonia is proposed as a hydrogen carrier (Smith, Hill and Torrente-Murciano, 2020), to overcome storage and distribution challenges of hydrogen supply for the chemical industry or as a fuel (Cesaro, Thatcher and Bañares-Alcántara, 2020; Valera-Medina *et al.*, 2018; Zamfirescu and Dincer, 2008). In a 1.5°C scenario, demand for imported ammonia as a hydrogen carrier would reach 127 Mt of ammonia.

During the decomposition reaction, ammonia is cracked to produce hydrogen (H₂) and nitrogen (N₂). Hydrogen can be produced from ammonia via catalytic cracking or via plasma decomposition (Makepeace *et al.*, 2019); however, the latter generally has too high of an energy cost for industrial applications (Rouwenhorst *et al.*, 2020d). Typical catalysts for catalytic cracking include metals such as cobalt, iron, nickel and ruthenium (Bell and Torrente-Murciano, 2016; Ganley *et al.*, 2004; Nielsen *et al.*, 2021). More recently, abundant materials such as calcium imide, lithium imide and sodium imide have also been proposed (Makepeace *et al.*, 2019).

Depending on the application, partial decomposition of ammonia may be all that is required, producing a fuel mix of ammonia and hydrogen at various ratios. However, for applications requiring pure hydrogen, complete decomposition must be followed by an additional purification of the hydrogen. Notably, ammonia decomposition should be reserved for scenarios where direct ammonia use is not feasible, as the ammonia decomposition reaction is endothermic – it requires additional energy. In the best case, ammonia decomposition consumes 13% of the stored energy at 100% conversion efficiency to hydrogen and nitrogen (Makepeace *et al.*, 2015).

Residual ammonia may be removed with solid materials (Christensen *et al.*, 2006; Helminen *et al.*, 2000), or converted with oxygen to water and nitrogen (Laan *et al.*, 2019; Lan *et al.*, 2020). In case pure hydrogen is required without nitrogen, such as for PEM fuel cells, hydrogen can be purified with membranes, pressure swing adsorption or cryogenic distillation (Lamb, Dolan and Kennedy, 2019; Lu *et al.*, 2007).

Nowadays, ammonia decomposition systems, also termed ammonia crackers, are commercially available for the metallurgy industry. Typical commercial ammonia crackers have capacities of 1 to 1500 kilograms of hydrogen per day, equivalent to around 0.2 to 118 kt of ammonia per year on a mass basis, at energy efficiencies of 30-60% on a lower heating value basis. These units operate at temperatures of 850°C to 1000°C (Makepeace, 2020), and both improvements in energy efficiency and milder operating conditions will be required for more widespread application, especially for large-scale hydrogen production. Two ammonia crackers are also operational for heavy water production, with the largest plant requiring around 490 kt of ammonia per year (Comisiones de Presupuesto y Hacienda y de Ciencia y Tecnología, 2003).

In recent years, feasibility studies on large-scale ammonia crackers were reported (Siemens *et al.*, 2020), and large-scale ammonia crackers were recently proposed for hydrogen production in northern Europe (Table 5). The produced hydrogen can be fed to the European hydrogen grid, which is proposed to span 6 800 kilometres by 2030 and 22 900 kilometres by 2040 (Janssen, 2020). Around 75% of the European hydrogen grid will be based on the existing natural gas grid (Janssen, 2020).

The Transhydrogen Alliance, a consortium including Trammo, Varo, Proton Ventures, and the Port of Rotterdam, announced plans for 500 kt of hydrogen production annually from ammonia decomposition, with the initial stage of the project to be completed by 2024 (Proton Ventures B.V., 2021). For reference, the current industrial hydrogen demand in the Netherlands is around 1500 kt of hydrogen annually (TNO, 2020). The ammonia fed to the proposed cracker is 3.7 Mt per year based on 75% ammonia conversion to hydrogen on a mass basis (Nielsen *et al.*, 2021). The Port of Rotterdam has announced that it will import up to 18 Mt of hydrogen by 2050, equivalent to 135 Mt of ammonia (Port of Rotterdam, 2020).

Furthermore, Uniper announced an ammonia cracker for the port of Wilhelmshaven in Germany. The proposed hydrogen output is 295 kt of hydrogen per year, equivalent to 10% of the projected hydrogen demand in Germany by 2030 (Uniper, 2021). The ammonia to be fed to the cracker is 2.2 Mt per year, based on 75% ammonia conversion to hydrogen on a mass basis. The produced hydrogen could be used to fire two combined-cycle gas turbines of 500 MW, for example, or multiple refineries.

Importing renewable ammonia from locations with low-cost renewable resources of below USD 20 per MWh and converting to hydrogen would be competitive with producing local renewable hydrogen in northern Europe with offshore wind at about USD 50 per MWh, despite conversion losses in the former case (IEA and NEA, 2020; IRENA, 2021a).

Table 5 Overview of planned facilities for large-scale ammonia decomposition

Location	Company	Start-up year	Ammonia feed (Mt/yr)	Hydrogen output (kt/yr)	Hydrogen application	Source
Commercial plants						
Rotterdam, Netherlands	Transhydrogen Alliance	2024 long-term	- 3.7	- 500	One-third of current Dutch hydrogen demand	(Proton Ventures B.V., 2021)
Wilhelmshaven, Germany	Uniper	2030	2.2	295	10% of German hydrogen demand by 2030	(Uniper, 2021)

4.2 Ammonia as a stationary fuel

Ammonia can also be used directly as a fuel (IEA, 2021b). Similar to hydrocarbon fuels, energy is stored in chemical bonds and is released by reacting ammonia with oxygen, forming water and dinitrogen (atmospheric nitrogen).

In stationary power applications, ammonia can be used as a fuel to displace coal and natural gas (Bicer and Dincer, 2018; Japan Science and Technology Agency, 2017; Kobayashi *et al.*, 2019; Valera-Medina *et al.*, 2018) in both baseload applications and peaker plants, operating below 25% capacity factor, to provide stability in the grid with a high penetration of intermittent solar and wind power (Cesaro *et al.*, 2021). Alternatively, ammonia may be used to displace diesel in back-up or off-grid applications.

In a 1.5°C scenario, demand for ammonia as a fuel for power generation reaches 30 Mt by 2050, based only on stated policies within Japan.

In the case of coal-fired power plants, ammonia can reduce the carbon footprint by co-firing a mixture of up to 60% ammonia by energy content (Tamura *et al.*, 2020; J. Zhang *et al.*, 2020). This was recently demonstrated in a 1.2 MW furnace (Tamura *et al.*, 2020). Ammonia can decrease NO_x emissions from coal combustion, although an ammonia concentration above 40% results in emissions of unburnt ammonia (Ishihara, Zhang and Ito, 2020; J. Zhang *et al.*, 2020). Following successful burner tests in August 2021 (JERA, 2021), by 2024 JERA aims to demonstrate co-firing up to 20% ammonia in a 1 GW coal-fired power plant (Image 6). The transition to 50-60% ammonia co-firing is expected by the 2030s, and 100% ammonia firing is targeted by the 2040s.

Similarly, the Norwegian government proposes to replace the existing coal-fired power plant in Longyearbyen on the island of Svalbard with a multi-fuel engine capable of running on ammonia (Holsen, 2021).

Ammonia can also be co-fired with natural gas or kerosene in gas turbines (Kobayashi *et al.*, 2019; Valera-Medina *et al.*, 2017a; Xiao *et al.*, 2017). Furthermore, fully decomposed ammonia into hydrogen and nitrogen (ISPT, 2017), or partially decomposed ammonia with around 30% decomposed ammonia, can be fired in gas turbines at high stability (EPRI, 2021; Valera-Medina *et al.*, 2017b, 2019). NO_x emissions below 50 ppm have been reported for ammonia-hydrogen blends (Kobayashi *et al.*, 2019; Kurata *et al.*, 2017; Valera-Medina *et al.*, 2019). Steam injection is a promising practice to reduce NO_x emissions below established regulatory limits in these blends without sacrificing efficiency (Guteša Božo *et al.*, 2019).

Partial decomposition of ammonia to an ammonia-hydrogen-nitrogen blend compensates for the low flame speed of ammonia and also the high flame speed of hydrogen (Valera-Medina *et al.*, 2018). Ammonia-hydrogen blends have similar fuel characteristics as town gas produced from coal or oil (Valera-Medina *et al.*, 2017b). Various industrial combined-cycle gas turbine manufacturers have committed to 100% hydrogen firing capability by 2030 (EUTurbines, 2019); however, it would be undesirable to fully decompose ammonia to purified hydrogen for this application, due to the energy penalty of ammonia decomposition and hydrogen purification. Therefore, research also focuses on combustion of pure ammonia, and partially decomposed ammonia, noting that exhaust heat can be used for the cracking process.

In the case of coal-fired power plants, ammonia can reduce the carbon footprint by co-firing a mixture of up to 60% ammonia by energy content. The transition to 50-60% ammonia co-firing is expected by the 2030s, and 100% ammonia firing is targeted by the 2040s.

So far, stable operation of gas turbines with pure ammonia has been demonstrated only at a small scale (50 kW) (Kurata *et al.*, 2017, 2019), using cyclonic burners (Sorrentino *et al.*, 2019). IHI is developing a 2 MW gas turbine that can combust 100% ammonia with a liquid ammonia injection system, which is expected to be commercial by 2023 (Muraki, 2018). Mitsubishi Power is developing a 40 MW class gas turbine that can combust 100% ammonia (Image 7), which is expected to be commercial by around 2025 (Patel, 2021). According to the Japanese SIP energy carriers programme, an ammonia-fed gas turbine with a capacity above 100 MW will be commercially available by 2030 (Muraki, 2019). Ammonia has also been proposed as a fuel for gas turbines in other countries, such as in the Netherlands (Proton Ventures B.V., 2016) and the United States (EPRI, 2021).

Solid oxide fuel cells and alkaline fuel cells can be used for small-scale applications (< 1 MW) (Palys and Daoutidis, 2020; Zhao *et al.*, 2019), where the efficiency of other technologies is too low. Ammonia can be used for off-grid applications, such as telecommunication towers or back-up aggregates (Cesaro, Thatcher and Bañares-Alcántara, 2020; Fuel Cells Bulletin, 2013; Klerke *et al.*, 2008; Royal Society, 2020). For instance, off-grid electricity produced from ammonia in an alkaline fuel cell can cost less than USD 0.26 per kWh, lower than a diesel generator at USD 0.31 per kWh (Oviroh and Jen, 2018).

Alternatively, ammonia-driven generator sets are small-scale combustion engines for off-grid power (Royal Society, 2020). These may find applications in isolated communities in, for example, the Arctic and Africa, in particular for peak generation, displacing diesel.

However, for centralised applications, conventional power plants will remain dominant. As combined-cycle gas turbine systems can approach 60% efficiency on a lower heating value basis, the efficiency gains by using solid oxide fuel cells are not expected to outweigh the additional cost required, at least not within this decade. Existing gas turbine assets may be retrofitted to combust ammonia, further minimising the cost. Especially when the utilisation rate is low, for example for peaker plants, the capital cost disadvantage of solid oxide fuel cells negatively affects the overall economics (Cesaro *et al.*, 2021). PEM fuel cells can also be used, although these currently have a high capital cost and can only be fed with high purity hydrogen. Alkaline fuel cells require a lower hydrogen purity, but require a relatively large area (Cesaro *et al.*, 2021).

Ammonia firing in coal-fired power plants and gas turbines suggests that existing assets can be decarbonised, thereby preventing locked-in CO₂ emissions or stranded assets.

Image 6 Mitsubishi Power's H-25 Series gas turbines



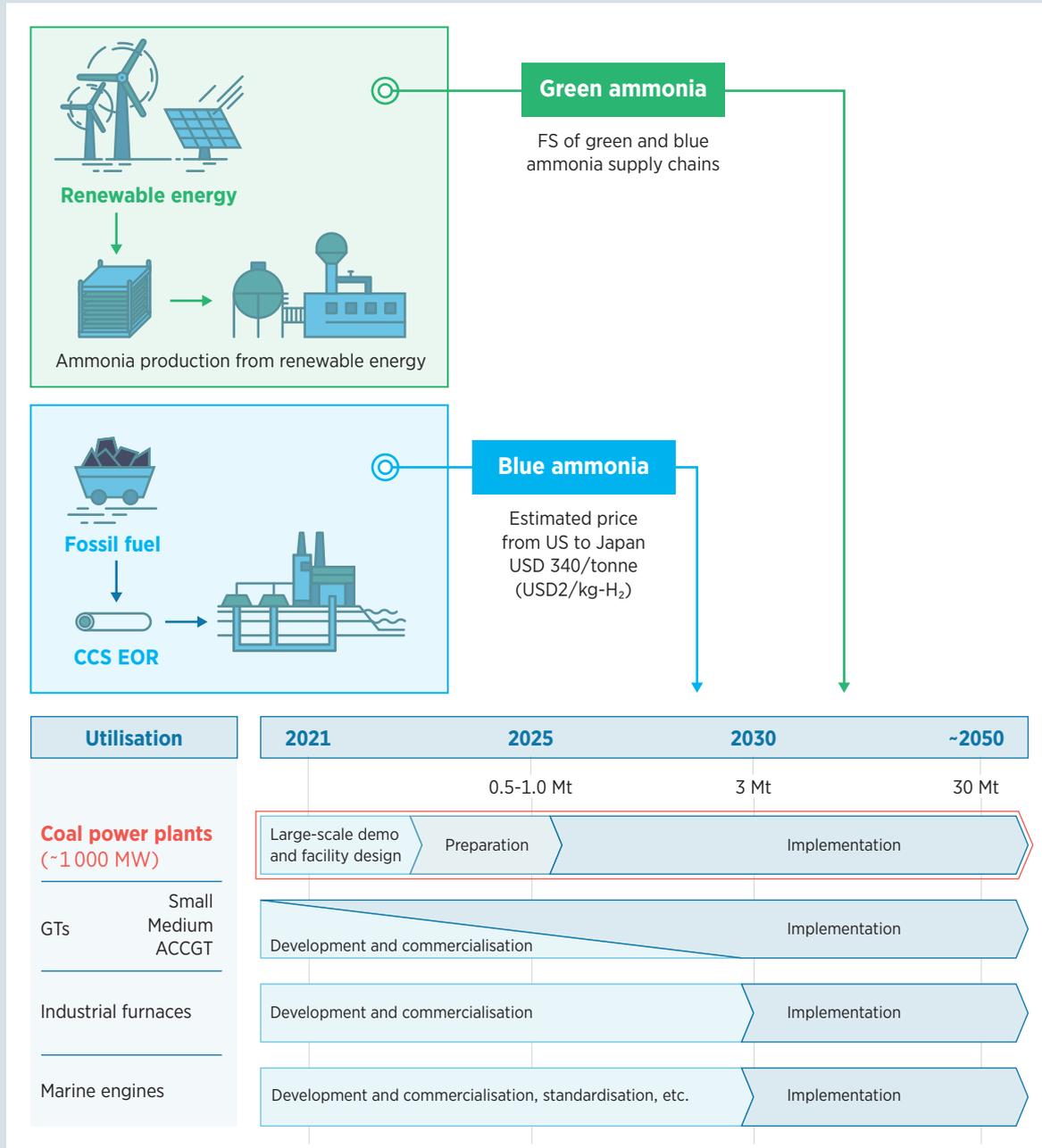
Image courtesy of Mitsubishi Heavy Industries, 2021.



Case study 2 Ammonia at fuel value in Japan

Japan has been one of the main proponents of renewable ammonia as an energy carrier, with a concrete roadmap for implementation of ammonia as a fuel (Figure 28). Already in 2014, Japan launched a technology development consortium, Energy Carriers, promoted by the Cross-ministerial Strategic Innovation Promotion Program (SIP). This is part of the Japanese framework to achieve carbon neutrality by 2050.

Figure 28 Roadmap of the ammonia fuel value chain for Japan



Adapted from Muraki (2021).

In the short term, Japan plans to import low-carbon fossil-based ammonia, while renewable ammonia will be imported beyond 2030 (IEA, 2021b). Ammonia is considered in Japan at an earlier stage than in other countries, which can be attributed to the high prices for imported fossil fuel in Japan. LNG cost around USD 7-16 per GJ in Japan over the past 10 years, and emits around 56.1 kilograms of CO₂ per GJ of energy generation (Senter Novem, 2005). Current carbon taxes in Japan cost around USD 3 per tonne of CO₂ (Arimura and Matsumoto, 2020), resulting in an added cost of only USD 0.2 per GJ. However, if higher carbon taxes of USD 50-100 per GJ are introduced in the longer term, this added cost increases to USD 2.8-5.6 per GJ, roughly a 25% premium on the cost of LNG. This would make low-carbon ammonia competitive in the long term (Figure 19).

Low-carbon fossil-based ammonia is expected to have a market value of around USD 350-400 per tonne of ammonia (Haldor Topsøe *et al.*, 2020) or, in another analysis, USD 340 per tonne of ammonia (Muraki, 2021), equivalent to around USD 19-21 per GJ or USD 18 per GJ. In the long term, renewable ammonia will probably be available at a cost below USD 400 per tonne of ammonia (see section 2.4), equivalent to less than USD 21 per GJ. Thus, ammonia provides a cost-competitive alternative to fossil fuels in the long term.

Initial shipments of ammonia for power generation were delivered from Saudi Arabia to Japan in 2020, starting with 40 tonnes of “blue” fossil-based ammonia (Saudi Aramco, 2020), launching a new international market for ammonia as a fuel. Japan expects to import ammonia for power generation, totalling 0.5-1 Mt per year by 2025, 3-5 Mt per year by 2030 and 30 Mt per year by 2050 (Argus Media, 2021c, 2021d).

The infrastructure of Japan is especially suitable for using ammonia directly, as the nation has insufficient renewable resources to satisfy its energy demand, and most power plants are located in port areas. It is expected that the ammonia receiving and storage facilities in Japan will be expanded over the next few years, to facilitate ammonia co-firing in gas turbines and coal-fired plants (Muraki, 2021). The gradual increase in ammonia use in the power sector goes hand in hand with the supply chain scale-up. For reference, if all Japanese coal-fired power plants would be co-fed with 20% ammonia, this would require around 20 Mt of ammonia, similar to the amount of ammonia currently shipped worldwide each year.

4.3 Ammonia as a maritime fuel for international shipping

In recent decades, ammonia has been proposed as a transport fuel for buses, trams, locomotives and aircraft (Giddey *et al.*, 2017; Sousa Cardoso *et al.*, 2021; Valera-Medina *et al.*, 2018). While numerous R&D projects are focused on those areas, ammonia is proposed for more widespread use as a marine fuel for international shipping, to replace heavy fuel oil and LNG (Haldor Topsøe *et al.*, 2020; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021; Philibert, 2020b). Direct electrification of international shipping is not possible due to the long distances travelled.

Around 95% of all freight transport takes place at sea, consuming around 10% of the total transport energy worldwide (BP, 2020; US EIA, 2017) and accounting for 2.6% of global greenhouse gas emissions (Ayvali, Tsang and Van Vrijaldenhoven, 2021). According to its Initial GHG Strategy, the International Maritime Organization (IMO) aims to reduce the sector’s emissions 50% by 2050 as compared to 2008 levels (IMO, 2019).

Various shipping companies have committed to more ambitious emission reduction targets, driven by national targets, customer demand and/or sustainability goals. For example, Maersk has committed to net zero carbon emissions by 2050 (Maersk, 2019). Its current fleet, around 750 container ships, would require around 20 Mt of ammonia per year if ammonia alone is used as a fuel. Ships typically have lifetimes of 20-25 years or longer, implying that investments for decarbonisation of new-built ships must be made soon and that net zero vessels must be operational by 2030, to meet the greenhouse gas emission reduction targets by 2050.

Recently, a consortium of various industrial companies expressed the opinion that ammonia is likely the preferred fuel for the international maritime sector (Haldor Topsøe *et al.*, 2020). Recent outlooks estimate a demand for ammonia as a marine fuel ranging from 100 Mt to more than 1000 Mt of ammonia by 2050 (Table 13 in Annex F), depending on the fuel mix share of ammonia, the future demand scenario and the speed of sectoral decarbonisation.

By 2050, in a 1.5°C scenario, the estimated demand for ammonia as a marine fuel would amount to 197 Mt, of which 183 Mt would be for international shipping and 15 Mt would be for domestic shipping. For reference, the current total ammonia production amounts to around 183 Mt of ammonia, of which around 18-20 Mt is shipped internationally (Hatfield, 2020, 2021).

Various consortia for the commercialisation of ammonia as a fuel in the maritime sector are listed in Table 6.

Table 6 List of selected consortia for ammonia demonstrations in the maritime sector

Project	Duration	Aim	Source
MAN two-stroke ammonia engine (Denmark)	2019-2024	USD 5 million project led by MAN Engines to develop the first ammonia-fuelled two-stroke engine by 2022, and commercialise it by 2024.	(MAN Energy Solutions, 2019, 2021)
Getting to Zero Coalition (Global)	2019-	Global coalition investigating pathways to decarbonise international shipping. Headed by Friends of Ocean Action, Global Maritime Forum and World Economic Forum.	(Getting to Zero Coalition, 2019)
Wärtsilä four-stroke ammonia engine (Norway)	2020-2023	Project led by Wärtsilä to test an ammonia-fuelled four-stroke engine at full scale and in the long term, supported by a USD 2 million grant from the Norwegian Research Council.	(Wärtsilä Corporation, 2020)

Project	Duration	Aim	Source
ShipFC Ammonia project (Europe)	2020-2024	A 14-member consortium of European industrial companies and research organisations, co-ordinated by NCE Maritime CleanTech. The Viking Energy ship will be retrofitted with a 2 MW ammonia-fuelled solid oxide fuel cell. The total project budget is around USD 28 million.	(Eidesvik, 2020)
Zero Emissions from Ships Using Ammonia Fuel (Japan)	2020-	NYK Line, Japan Marine United Corporation, IHI Power Systems, and Nippon Kaiji Kyokai (ClassNK) signed a joint R&D agreement for the commercialisation of ammonia-fuelled ships, including a gas carrier, a barge for offshore bunkering and a tugboat.	(NYK Line, 2020)
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (Denmark)	2020-	This research institute intends to develop new fuel types and technologies to decarbonise the maritime sector. The launching partners are the American Bureau of Shipping, A.P. Møller – Maersk, Cargill, MAN Energy Solutions, Mitsubishi Heavy Industries, NYK Lines and Siemens Energy. The institute launched with a start-up donation of around USD 60 million from the A.P. Møller Foundation.	(Maersk, 2020)
The Castor Initiative (Singapore)	2020-	A coalition of Lloyd’s Register, MISC Berhad, MAN Energy Solutions, Samsung Heavy Industries (SHI), Yara, and the Maritime and Port Authority of Singapore aims to build an ammonia-fuelled tanker by 2025.	(Lloyd’s Register, 2021)
Potential for Ammonia as a Marine Fuel in Singapore (Singapore)	2021-	A coalition of the American Bureau of Shipping, Nanyang Technological University, Singapore and the Ammonia Safety and Training Institute (ASTI) aims to study the potential of ammonia for Singapore, exploring supply, bunkering and safety challenges with ammonia as a maritime fuel. Safety protocols and possible gaps in the supply chain will be identified. ExxonMobil, Hoegh LNG, MAN Energy Solutions Singapore, Jurong Port, PSA Singapore and ITOCHU Group are contributing technical information.	(ABS, 2021a)
Ammonia as marine fuel in Singapore (Singapore)	2021-	A feasibility study for renewable ammonia ship-to-ship bunkering is being conducted at the Port of Singapore by A.P. Møller – Maersk A/S, Fleet Management Limited, Keppel Offshore & Marine, Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, Sumitomo Corporation and Yara International ASA.	(Maersk, 2021)

Maritime engine manufacturers expect to commercialise ammonia-fuelled two-stroke and four-stroke engines by 2024 or 2025, for both new builds and retrofits (MAN Energy Solutions, 2019; Wärtsilä Corporation, 2021). Dual-fuel engines allow for fuel flexibility during the implementation of ammonia as a fuel. The first ammonia-fuelled vessels are expected to be operating at sea by 2024 and 2025 (Table 6), with more widespread adoption by 2030 (Brown, 2020l, 2020m; Grieg Star, 2020).

Preliminary studies show that the combustion characteristics of ammonia — slow flame velocity, slower heat release — do not prohibit its use as a fuel (Ayvali, Tsang and Van Vrijaldenhoven, 2021). Rather, the high NO_x production during combustion, the low flammability and low radiation intensity present research challenges. Nonetheless, engine developers believe that the technology can deliver commercial performance within existing regulatory limits for NO_x emissions (Wärtsilä Corporation, 2021).

In addition to conventional engine technologies, solid oxide fuel cells are considered. A benefit of this technology is the higher energy efficiency (around 55-60% on a lower heating value basis), as compared to the two-stroke engine (around 45-50% on a lower heating value basis) (MAN Diesel & Turbo, 2017), thereby decreasing the fuel requirement. The ShipFC consortium aims to demonstrate the use of ammonia fuel using a 2 MW solid oxide fuel cell, starting in 2024 (Image 8) (Eidesvik, 2020). Solid oxide fuel cells are mainly suitable for still, inland waterways rather than for harsh conditions in the oceans.

Image 7 The Viking Energy, which will be retrofitted with an ammonia-fuelled solid oxide fuel cell



Image courtesy of Eidesvik, 2021.

Although technological challenges are not expected to be a significant hurdle, experience with ammonia fuel is required before it can be widely adopted, not least to inform the development of new or revised codes and standards. Therefore, ammonia fuel will be demonstrated in the port of Singapore in various consortia (Table 6). LNG was demonstrated as a fuel in Singapore from 2017 to 2020, and inspiration can be drawn from this for ammonia. The port of Singapore serves as a living lab with a physical and digital test environment, and as a regulatory sandbox, to develop safe bunkering procedures for ammonia and gain operational experience (Atchison, 2022a). Codes and standards for the safe use of ammonia have been long established within the refrigeration, chemical, and power industries, which can also be applied and strengthened for the maritime sector (ABS, 2021a).

A first step to decarbonise shipping is to convert ammonia tankers to use ammonia as a fuel, such as the Nutrien/Exmar low-carbon ammonia vessel (Nutrien, 2021), and the ZEED's MS Green Ammonia (Grieg Edge, 2021).

If ammonia were adopted across the broader gas carrier sector, this would represent 5% of the shipping sector's fuel demand. This is roughly the amount of zero-carbon fuel adoption required in the maritime sector by 2030, to comply with the Paris Agreement's 1.5°C scenario (Osterkamp, Smith and Søgård, 2021).

On the regulatory side, some steps are required for widespread adoption of ammonia as a maritime fuel (ABS, 2021b). Ammonia is not currently approved as a fuel by the IMO under either the IGC or IGF Code and so, for now, every ship needs individual approval to use ammonia. After the initial demonstration vessels have proven safe operations, and proponents develop new codes within the IMO to assure the safe use of ammonia as a maritime fuel, the roll-out of ammonia-fuelled ships will accelerate. The support of a flag state can aid to introduce ammonia as a fuel, similar to the case of methanol as a fuel.

4.4 Renewable ammonia versus other energy carriers

Low-carbon ammonia can be used as a hydrogen carrier and as a fuel, but alternatives such as liquid organic hydrogen carriers (LOHCs), and carbon-based biofuels and e-fuels are also proposed, such as methanol and synthetic methane. Fossil-based ammonia without carbon mitigation does not have significant benefits over other fossil fuels in terms of carbon footprint and should be avoided for energy applications (Al-Aboosi *et al.*, 2021).

Some characteristics of ammonia as a fuel include (Al-Aboosi *et al.*, 2021; Bartels and Pate, 2008; Valera-Medina *et al.*, 2018):

- Ammonia has a gravimetric energy density of 22.5 MJ per kilogram on a higher heating value basis, which is comparable to carbon-based fuels such as methanol (22.7 MJ/kg), ethanol (29.7 MJ/kg), and coal (15 MJ/kg for lignite, and 27 MJ/kg for anthracite). The energy density of ammonia is lower than that of natural gas (55 MJ/kg), diesel (45 MJ/kg) and hydrogen (142 MJ/kg) by weight.
- Liquid ammonia has a volumetric energy density of 12.7 MJ per litre (L), which is lower than for heavy fuel oil (35 MJ/L) but comparable to methanol (15 MJ/L), and higher than for liquefied hydrogen (8.5 MJ/L). Thus, a tank of ammonia contains 1.5 times the energy of the same size tank of liquefied hydrogen.
- Ammonia can be liquefied under relatively mild conditions, either by compression to 8 bar at 20°C or by cooling to -33°C at atmospheric pressure. This also makes transport of ammonia affordable compared to hydrogen (Bartels and Pate, 2008).
- Ammonia has an established worldwide infrastructure for ammonia production, storage and distribution with around 200 port terminals for ammonia currently in operation. Ammonia has a proven track record of safe handling.
- Ammonia has a narrow flammability range (15-28% in air), making fire accidents unlikely to occur.
- Ammonia has a high octane rating of 120, compared to petrol (86-93). Thus, it can be used in internal combustion engines with some modifications. Furthermore, ammonia can be directly used in solid oxide fuel cells.
- CO₂ is not required for ammonia production, and CO₂ is not emitted during combustion. Also, sulphur is not present, eliminating SO_x emissions from combustion. Rather, atmospheric nitrogen is required, which is abundant in air (at 780 000 ppm) and much cheaper to capture than CO₂ (at 420 ppm).

The specifications discussed above establish the technical feasibility for ammonia to be considered as an alternative fuel. However, the decisive enabler for ammonia as a fuel compared to alternatives is the cost per energy unit.

Hydrogen carrier

As compared to hydrogen, ammonia is shipped under milder conditions, leading to a lower transport cost (Hank *et al.*, 2020). Alternatively, liquid organic hydrogen carriers (LOHCs) are considered for hydrogen transport. However, various analyses show that transport, storage and reconversion of hydrogen in ammonia has a lower cost than liquid hydrogen or LOHCs (Aziz, Wijayanta and Nandiyanto, 2020; IEA, 2019a; Wijayanta *et al.*, 2019). To an extent, this is because ammonia has a higher volumetric hydrogen density than liquefied hydrogen and LOHCs.

Ammonia is already a global commodity, transported internationally by ship and pipeline, whereas a global infrastructure for LOHCs or liquid hydrogen does not exist yet. In the case of directly using ammonia, rather than decomposition to hydrogen, ammonia becomes even more competitive (Wijayanta *et al.*, 2019).

Maritime sector

Ammonia is considered as one of the dominant options for the international maritime sector, as it is already widely available at a relevant scale with international port infrastructure in place (Royal Society, 2020), although further scale-up is required. A comparison of properties for various fuels is provided in Table 7.

Table 7 Comparison of physical and chemical fuel properties for international shipping

Fuel	Supply energy (MJ/kg, LHV)	Energy density (MJ/L, LHV)	Relative tank volume	Supply pressure (bar)	Injection pressure (bar)	CO ₂ emission from complete combustion (g CO ₂ /km)	SO _x emission from complete combustion (g SO _x /km)
Heavy fuel oil	40.5	35	1.00	7-8	950	49	0.36
Liquefied natural gas (-162°C)	50	22	1.59	300-380	300-380	37	0.02
Liquefied petroleum gas	46	26	1.35	50	600-700	-	-
Methanol	19.9	15	2.33	13	500	43	0.02
Ethanol	26	21	1.75	10	500	-	-
Ammonia (-33°C)	18.6	12.7	2.76	83	600-700	0	0
Hydrogen (-253°C)	120	8.5	4.12	-	-	0	0
Corvus, battery rack	0.29	0.33	106.1	-	-	0	0
Tesla Model 3 battery cell 2170	0.8	2.5	14.0	-	-	0	0

Note: SO_x = sulphur oxide; LHV = lower heating value.

Adapted from Ayvali, Tsang and Van Vrijaldenhoven (2021) and MAN Energy Solutions (2019).

As compared to hydrogen, ammonia is shipped and stored under milder conditions, resulting in a lower cost as a shipping fuel (Hank *et al.*, 2020). Carbon-based synthetic fuels such as methanol and methane can also be used as a maritime fuel (Goepfert, Olah and Surya Prakash, 2017) but these will require a circular carbon source, namely direct air capture (DAC), which is expected to be affordable later than decarbonisation is required, in part because the current cost of DAC is prohibitively high for fuel production (Fasihi, Efimova and Breyer, 2019; IEA, 2013). Furthermore, methane slippage from (synthetic) natural gas may actually cause higher greenhouse gas emissions than from heavy fuel oil, if combustion is not complete (Lindstad and Riialand, 2020).

Biofuels may not be able to scale sufficiently to satisfy maritime demand, because only a small amount of the available biomass can be processed for fuel applications affordably, and additional capacity would increase the cost substantially (IEA, 2020a). CO₂ emissions can be captured post-combustion from ship engines, or pre-combustion during fuel reformation, although this requires additional on-board capacity for CO₂ storage (IEA, 2021b).

Thus, hydrogen and carbon-based fuels are not expected to be sufficient to achieve the 50% greenhouse gas emission reduction by 2050 targeted by the IMO (IMO, 2019).

A comparison of ammonia and methanol as maritime fuels is provided in Table 8, as these are among the main fuel options considered for decarbonising the maritime sector (DNV GL, 2020). In conclusion, ammonia is expected to become the dominant fuel for decarbonised deep sea shipping, whereas batteries may play a dominant role for decarbonised inland shipping and coastal shipping, and other fuels such as biofuels, methanol and hydrogen may be used for passenger ships and large ferries (Liebreich, Grabka and Pajda, 2021). If ammonia is not accepted as a maritime fuel, this will slow the decarbonisation of the maritime sector by around five years (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021).

Table 8 Comparison of ammonia and methanol as a maritime fuel

	Ammonia	Methanol
Cost effectiveness	Ammonia has an advantage, due to lower cost of nitrogen purification versus CO₂ purification	
Safety	Relatively safer than hydrogen, but still presents challenges due to toxicity. Flammability is not an issue.	Relatively safer than ammonia, similar toxicity as diesel. Flammability may be an issue.
Existing infrastructure	Similar benefits	
Technology availability	Ammonia engines expected to be commercial by 2025.	Dual methanol-heavy fuel oil engines are already commercially available.
International Maritime Organization approval as fuel	Not yet.	Approved November 2020 (ShipInsight, 2020).
CO ₂ emissions	Zero emissions at combustion; NO _x emissions controlled with SCR systems.	CO ₂ emissions at combustion, although lower than conventional fuels and net zero if renewable methanol; NO _x emissions controlled with SCR systems.

Note: SCR = Selective catalytic reduction; NO_x = nitrogen oxide.

4.5 The ammonia supply chain

Various applications for ammonia have been proposed. Below, the technology status and regulatory aspects of a potential ammonia economy are discussed. An overview of the technology status for ammonia production technologies, ammonia transport and storage, as well as ammonia utilisation technologies is listed in Table 12 in Annex E.

Many technologies are already commercial at the required scale; however, a few bottlenecks can be identified:

- **Governmental incentives to decrease CO₂ emissions.** Investment is driven by clear and consistent policy. Current measures for greenhouse gas emission reduction are uncertain, causing doubt and limiting investment, thereby slowing the learning curve of clean technologies and delaying the tipping point for cost-competitive renewable ammonia.
- **Electrolyser production capacity.** The global capacity was reported to be 2.1 GW per year in 2020 (ESMAP and World Bank, 2020), while the required capacity is around 40-65 GW per year to produce 566 Mt per year of renewable ammonia by 2050 in the 1.5°C scenario (Figure 29). Scale-up of electrolyser production is expected to accelerate the learning curve, thereby decreasing the cost of electrolysis (Schmidt *et al.*, 2017b).
- **Ammonia transport infrastructure.** By 2050, the ammonia transport infrastructure must increase by a factor of 10-15, requiring tens of billions of USD in annual investment in the ammonia supply chain for storage and transport. For example, around 235 ships with a capacity of 85 000 cubic metres (m³) (58 kt of ammonia) are required by 2050 to accommodate 354 Mt of additional ammonia shipped around the world, assuming a voyage every two weeks. This implies that a ship for ammonia transport must be built or revamped from LPG transport roughly every two months until 2050.
- **Ammonia's approval as a maritime fuel by inter-governmental bodies.** Until inter-governmental bodies approve ammonia as a maritime fuel, every vessel requires separate permission, thereby limiting broad adoption.

Regulation and certification

Comprehensive legislation and regulation is required for the use of ammonia as a fuel. Legislation for the production, storage, transport and use of ammonia already exists in various economic zones (Valera-Medina, Ifan and Chong, 2021), and these regulatory frameworks can be adapted for new ammonia markets. Furthermore, legislation for other fuels can be used as a blueprint for ammonia. For example, limits are already well established for NO_x emissions from combustion of fossil fuels, and these should not be relaxed for ammonia.

However, new legislation may be required to limit emissions of ammonia and nitrous oxide (Van Damme *et al.*, 2018). This should be such that there is a level playing field with emissions from other fuels, such as CO₂, carbon monoxide slippage, methane slippage, SO_x and soot formation.

Certification will be essential to allow market participants to distinguish between ammonia produced from various sources and with different carbon intensities, as well as to distinguish between ammonia and other fuels, as discussed in section 3.3.

4.6 Outlook for the ammonia economy

Although ammonia is not used in energy applications today, it is increasingly likely that ammonia will be one of the renewable energy vectors of the 21st century, especially in inter-continental trade of carbon-free energy. Ammonia can be used as a hydrogen carrier, as a maritime fuel and as a stationary fuel. In the past few years, low-carbon ammonia production and utilisation projects have been announced, and, especially since 2020, the momentum has been substantial, in line with commitments in various locations towards carbon neutrality by 2050. The demand for ammonia is set to increase to 688 Mt by 2050 in the IRENA 1.5°C scenario from the current demand of around 183 Mt (Figure 29), with more than half the 2050 demand coming from new applications for ammonia in energy markets.

The question does not appear to be whether ammonia will play a dominant role in the hydrogen economy, but rather, when. International organisations such as the Ammonia Energy Association, and regional ones like the Clean Fuel Ammonia Association in Japan and the Green Ammonia Alliance in the Republic of Korea, bring together companies working on ammonia production and utilisation, governments, and institutes, to identify knowledge gaps and accelerate the transition towards decarbonisation. Local hydrogen and ammonia centres are required to generate knowledge along the entire value chain.

Public perception is key in a successful transition towards an ammonia economy. A study on the Yucatan Peninsula, Mexico showed that people are open to ammonia as a fuel, as long as the cost is similar to natural gas but with better environmental performance, while any negative initial impression of ammonia is due mainly to a lack of information, showing the importance of education and community engagement (Mercado-Guati Rojo and Valera-Medina, 2018). The general perception of ammonia is more positive in rural areas as compared to urban areas, which may be attributed to a higher fertiliser use in rural areas. Ammonia storage in densely populated areas is not preferred in any case, and should be avoided where possible.

Increasingly, policy makers are aware of the feasibility of ammonia energy, especially in the context of the hydrogen economy and renewable energy imports. Ammonia is a central pillar in national hydrogen strategies, and was discussed as a maritime fuel in the US Senate in 2020 (Lewis, 2020). In 2019, the concept of ammonia energy was introduced to Canadian Prime Minister Justin Trudeau and Dutch Prime Minister Mark Rutte by Jacco Mooijer, Sales Director of Proton Ventures, who presented them with the company mascot, Monia (Image 9).

Image 8 Jacco Mooijer (right) of Proton Ventures gives Canadian Prime Minister Justin Trudeau (second from left) and Dutch Prime Minister Mark Rutte (middle) Monia, the mascot of Proton Ventures, an ammonia solutions provider



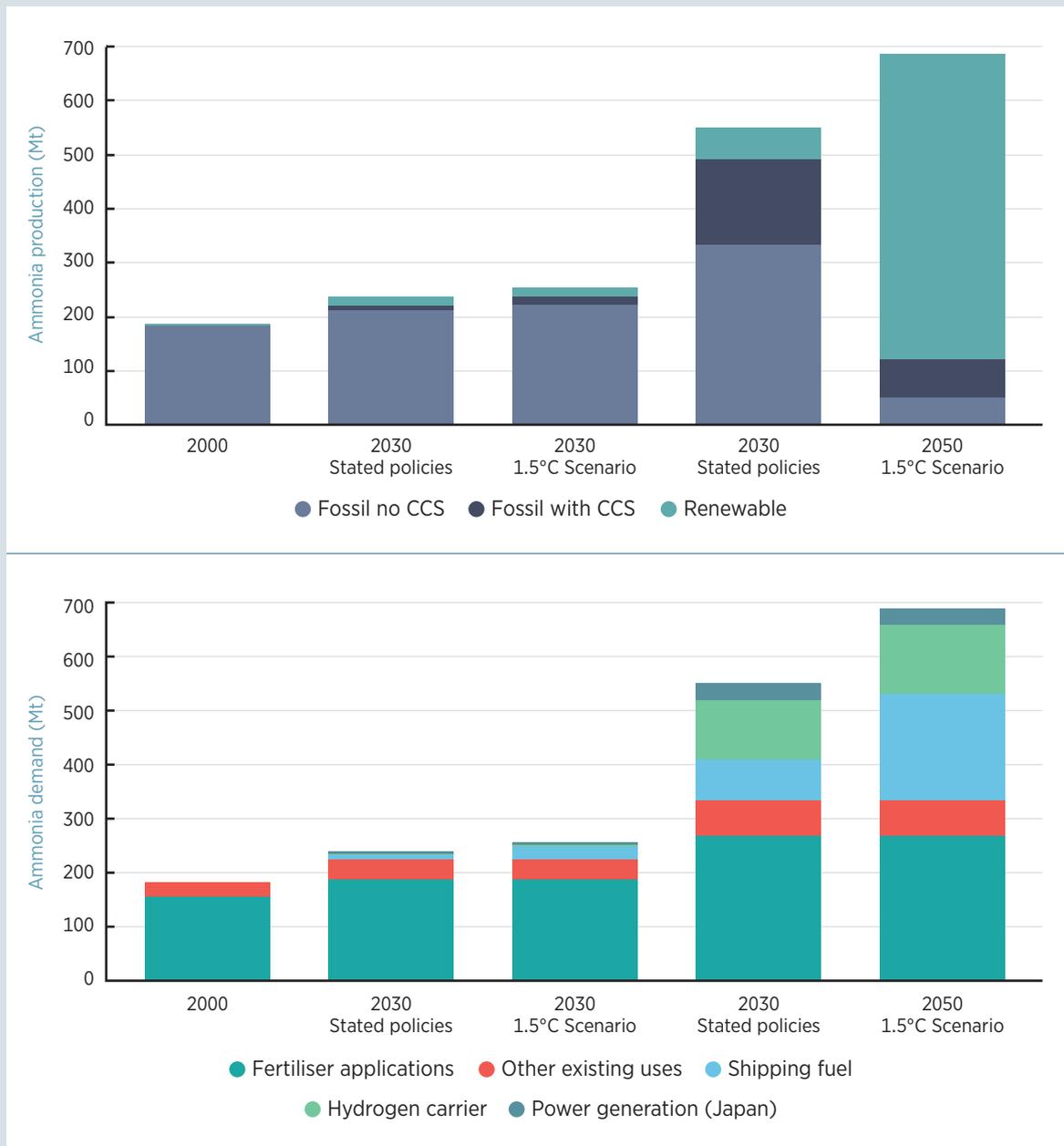
Image courtesy of Adam Scotti, 2018.



Case study 3 Decarbonised ammonia demand and production forecast

The future demand for ammonia is made up of two distinct markets, namely the current markets as a fertiliser and an industrial chemical, and future markets as a hydrogen carrier and a fuel. Ammonia production and demand, both current and projected for 2020, 2030, and 2050, are shown side by side in Figure 29 for two scenarios, a stated policies scenario and a 1.5°C scenario (see Annex G), illustrating both the expected decarbonisation of ammonia production, and its adoption in energy markets in the coming decades. The 1.5°C scenario sees the total ammonia market growing to 688 Mt by 2050.

Figure 29 Current and projected ammonia production by source and demand by sector



The current market demand is around 183 Mt, and these existing markets are expected to grow at a rate of 2-3% annually, resulting in demand in 2050 of 334 Mt in the 1.5°C scenario, of which 267 Mt will be for fertiliser applications and 67 Mt for other existing markets.

In the 1.5°C scenario, the expected market volumes for ammonia’s new applications as a hydrogen carrier and as fuel for shipping and power generation grow from zero today to a combined 15 Mt by 2030. However, over the coming two decades these new markets grow rapidly and they exceed current market volumes by 2050, reaching a total of 354 Mt of ammonia. As a hydrogen carrier, 127 Mt of ammonia is traded internationally, providing hydrogen imports primarily as a chemical feedstock and industrial fuel (equivalent to 2 363 petajoules). As a maritime fuel, 197 Mt of ammonia is consumed in 2050, with 183 Mt used for international shipping and 15 Mt in domestic shipping. The use of ammonia as a fuel for power generation is projected to reach 30 Mt by 2050, which represents the stated policies of Japan only (as ammonia power generation technologies develop, and as other nations include ammonia in their plans, this figure may grow).

Reflecting the uncertainty of future policy and market adoption, projections of future demand for ammonia in energy applications vary widely among other organisations and publications, from 140 Mt to more than 1 000 Mt (see Table 13 in Annex F). The extent to which ammonia is implemented in these applications depends strongly on climate-driven regulations, and on choices regarding decarbonised feedstock.

The expected ammonia demand up to 2050 for the 1.5°C scenario is shown in Figure 30, while the stated policies scenario is shown in Figure 37 in Annex G. The primary difference between the 2050 volumes seen in these scenarios is in the extent to which ammonia is adopted as a hydrogen carrier and as a fuel for shipping. Both applications are significant in the stated policies scenario, with 2050 demand of 109 Mt as a hydrogen carrier and 77 Mt as a shipping fuel, contributing to total demand of 550 Mt of ammonia in 2050. However, the stated policies scenario sees a market reduction of more than 130 Mt relative to the 1.5°C scenario total demand of 688 Mt of ammonia in 2050. A comparison of the estimates for ammonia use as a shipping fuel, hydrogen carrier, and for power generation are shown in Figure 31, Figure 32 and Figure 33.

A far greater difference between the stated policies scenario and the 1.5°C scenario can be observed on the supply side of the market, reflecting the speed at which ammonia production capacity can be decarbonised.

Figure 30 Expected ammonia demand up to 2050 for the 1.5°C scenario

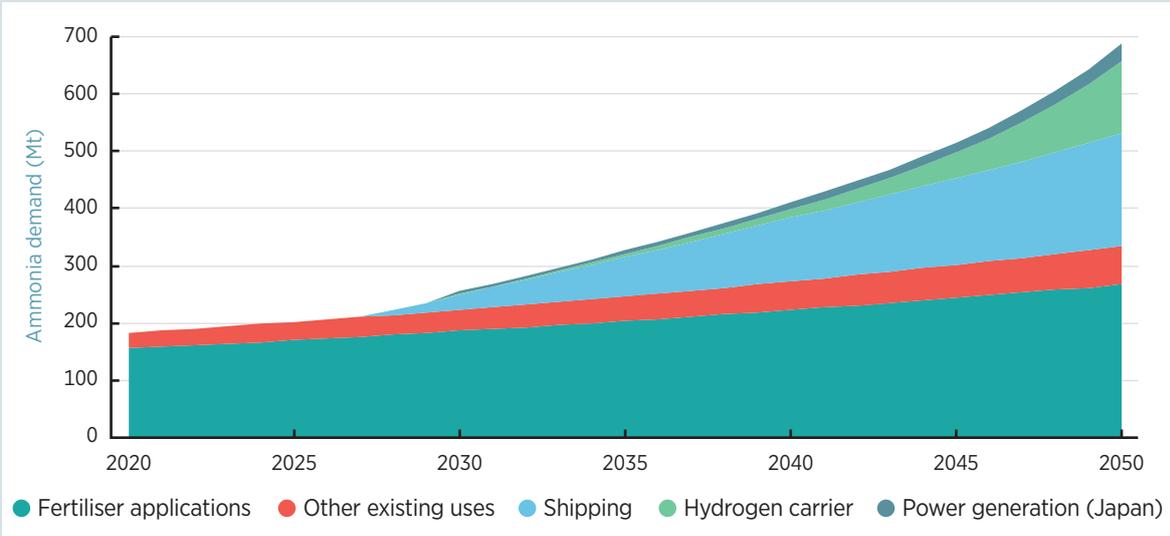


Figure 31 Ammonia demand estimates for use as maritime fuel by 2050 from various sources (see Table 13)

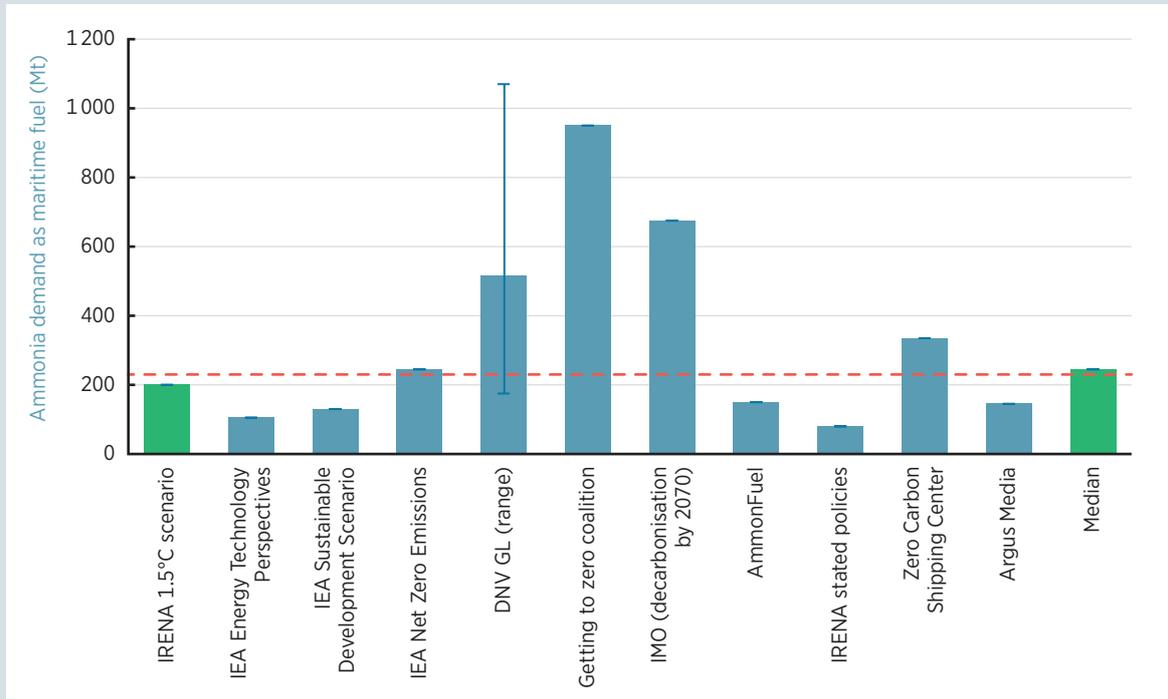
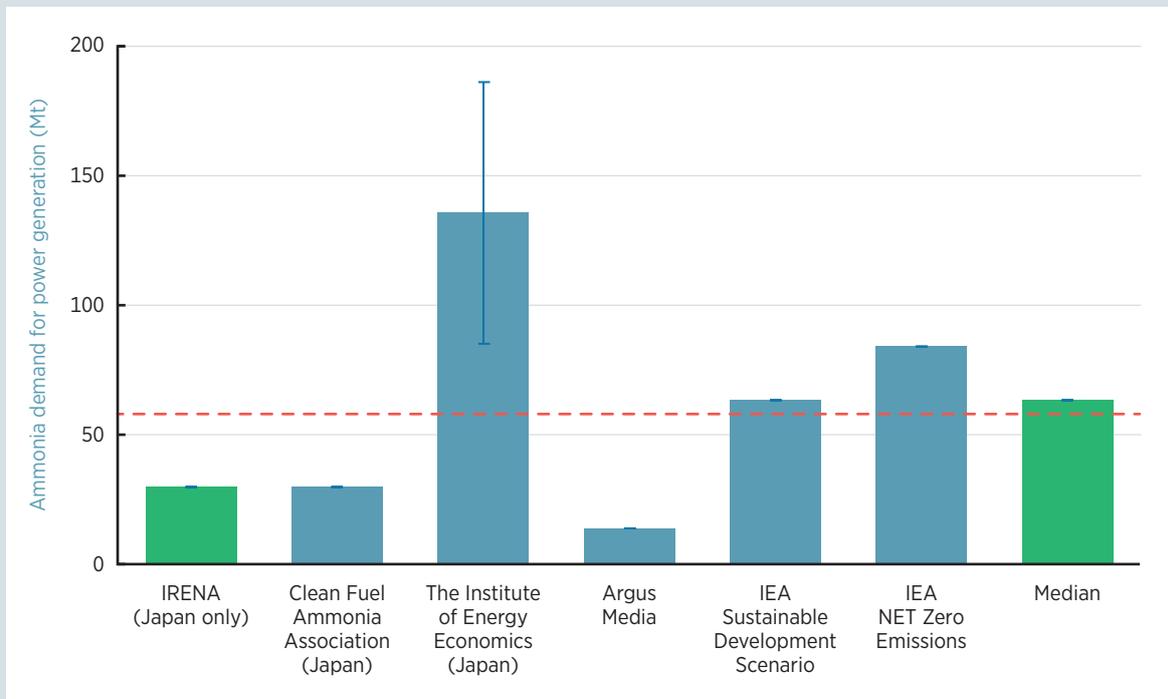
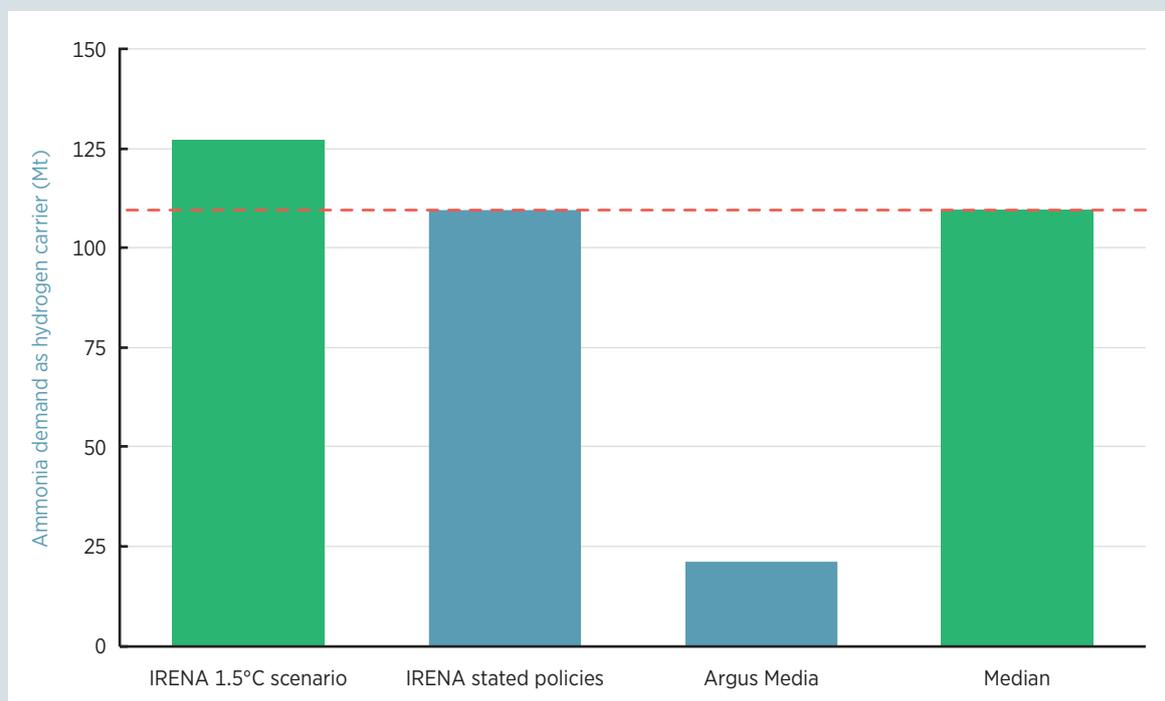


Figure 32 Ammonia demand estimates power generation by 2050 from various sources (see Table 13)



Note: The IRENA demand for power generation is based on the stated policy of the Clean Fuel Ammonia Association.

Figure 33 Ammonia demand estimates for use as hydrogen carrier by 2050 from various sources (see Table 13)



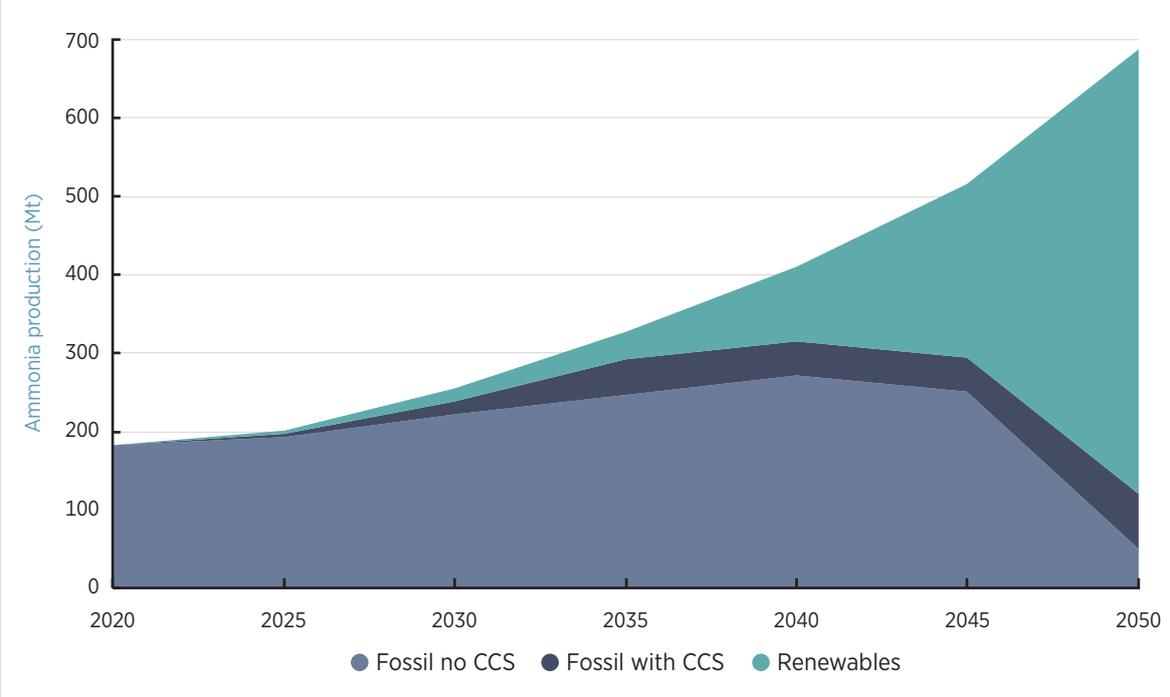
Additional ammonia production is required to meet the added demand. Ammonia for energy applications should not put fertiliser supply, and thus food production, at risk. Currently, there is around 40-60 Mt per year of overcapacity, ensuring the near-term availability of sufficient ammonia if new markets develop (Haldor Topsøe *et al.*, 2020; Hatfield, 2020).

Furthermore, low-carbon ammonia production pathways must be adopted to decrease the carbon footprint of ammonia, for energy applications and also for current markets. The announced 2030 capacity of proposed low-carbon fossil-based and renewable ammonia plants already exceeds 10% of total global ammonia production (see sections 2.3 and 2.4).

By 2050, in a 1.5°C scenario, renewable ammonia production levels must rise to an estimated 566 Mt per year, more than 80% of the total global market of 688 Mt of ammonia. While most of this ammonia supply will come from electrolysis-based production, additional supply from biomass-based production assumes a transition where urea remains a dominant fertiliser. Fossil-based ammonia production shrinks from 183 Mt in 2020 to 122 Mt in 2050, of which 71 Mt includes CCS and only 51 Mt does not include CCS.

The expected ammonia supply up to 2050 for the 1.5°C scenario is shown in Figure 34, while the stated policies scenario is shown in Figure 38 in Annex G.

Figure 34 Expected ammonia production by feedstock up to 2050 for the 1.5°C scenario



In the stated policies scenario, in contrast to the 1.5°C scenario, conventional fossil-based ammonia production doubles, reaching 333 Mt of fossil-based ammonia with no emissions mitigation, and an additional 159 Mt of fossil-based ammonia with CCS, for a total of 492 Mt of fossil-based ammonia. In the stated policies scenario, only 58 Mt of ammonia, less than 10% of the market, would be renewable by 2050.

The difference between the 1.5°C scenario and the stated policies scenario illustrates starkly the gap between climate ambitions and the policies that still need to be enacted in order to reach them.

The combined capacity of all the renewable ammonia projects announced so far is around 15 Mt per year by 2030 and around 71 Mt per year by 2040 (Table 2), relying solely on electrolysis, which already relates to more than 10% of the estimated 566 Mt of demand in the 1.5°C scenario. Even though it is unlikely that all announced renewable ammonia projects will materialise, there is substantial momentum with multiple large-scale projects announced over the past few months. For reference, before 2020, the total announced renewable ammonia production was below 0.1 Mt per year.

5. POTENTIAL AND BARRIERS

Key findings

Renewable ammonia can decarbonise existing ammonia markets and displace fossil fuels in new energy markets.

- The greening of the industrial sector, especially the chemical and fertiliser industries, should be the initial target application for renewable ammonia, especially for retrofits of existing ammonia plants.
- The stationary power sector is also expected to use ammonia as a fuel, with long-term purchase commitments de-risking investments. While this is currently driven by demand from Japan, other countries may adopt this option as technologies mature.
- The maritime sector is likely to be a significant driver for renewable ammonia and, due to the volumes required, is likely to be most relevant for new-build projects at a multi-gigawatt scale.
- Ammonia as a hydrogen carrier can provide feedstock for industry and enable hydrogen imports with a lower cost than local renewable hydrogen. Again, due to the volumes required, this market is likely to be most relevant for new-build projects at a multi-gigawatt scale.
- In the long term, renewable ammonia is likely to become the main commodity for transporting renewable energy between continents.

Renewable ammonia can have a significant impact on the energy sector.

- Both the production and use of electro-fuels help to stabilise the high-renewable grid.
- Renewable ammonia production consumes power when the electricity supply is higher than demand, and provides fuel for power generation when the supply is lower than demand.
- A ready market for transportable electro-fuels will spur the development of multi-gigawatt renewable energy assets that are currently too big for their grid-constrained markets, especially in remote and sparsely populated areas.

Urea represents a special case, with its own challenges and opportunities.

- 55% of all ammonia worldwide is used for the production of urea, which also requires CO₂, currently supplied as by-product of fossil-based hydrogen production.
- In an integrated ammonia-urea plant, therefore, fossil-based ammonia cannot simply be substituted with renewable ammonia, because new sources of CO₂ would be required.

- On the other hand, a biomass-to-ammonia process would produce more CO₂ than is required for urea production, creating an opportunity to combine urea production and CCS.
- This would be a scalable pathway for bioenergy with carbon capture and storage (BECCS), producing carbon-negative urea.
- Policies, regulations and mandates must be used to induce demand. The main barriers to renewable ammonia are the same as for other carbon-free fuels and feedstocks: the cost of production and the absence of regulations on CO₂ emissions.
- A CO₂ penalty of around USD 60-90 per tonne of CO₂ may be required to transition towards low-carbon ammonia.

Strong, stable and sustained policies are essential, as the investment in long-lived, capital-intensive renewable technologies cannot disseminate in the market without confidence. This report concludes with the following recommendations:

- Put a sufficiently high price on CO₂ emissions.
- Translate political will into policies.
- Focus on deployment of existing renewable ammonia technologies.
- Support the development of entire supply chains.
- Devise trade strategies that mitigate supply risks.
- Invest in electrolyser manufacturing.
- De-risk early investment projects.
- Retrofit technology towards renewable ammonia production.
- Support the demand-side phase-out of fossil fuels.
- Re-assess the role of ammonia in hydrogen strategies.

5.1 Demand

Ammonia has the identical chemical structure, NH₃, whether it is produced from fossil or renewable sources. As such, renewable ammonia is a direct substitute for fossil ammonia in most of its current uses.

Annual ammonia production is expected to grow from its current 183 Mt to more than 200 Mt by 2025 (de Pee *et al.*, 2018). With its adoption in energy applications, the total annual demand for ammonia is expected to reach 688 Mt by 2050 in a 1.5°C scenario (Figure 29), of which 566 Mt, or more than 80%, is expected to be renewable ammonia. Already, the combined capacity of announced renewable ammonia plants will be 15 Mt by 2030 (Table 2).

However, urea, which accounts for around 55% of current ammonia demand, requires both ammonia and CO₂, which is currently supplied as a by-product of fossil-based hydrogen production in an integrated ammonia-urea plant. As such, fossil-based ammonia for urea production cannot simply be substituted with renewable ammonia using electrolyzers. Circular carbon sources will need to be utilised, such as biomass or direct air capture, and a shift away from urea towards nitrates may be expected.

Notably, a biomass-to-urea process would produce more CO₂ than is required for urea production, creating an opportunity for scalable bioenergy with carbon capture and storage (BECCS) and carbon-negative ammonia and fertilisers.

The introduction of renewable ammonia would facilitate the transition to a sustainable circular economy in the chemical, power, transport and other energy-related sectors. Energy markets will be supplied with renewable ammonia from areas with low-cost solar and wind. Ammonia for energy-related applications must be decarbonised in order to offer meaningful benefits in terms of its carbon footprint as compared to fossil fuels (Al-Aboosi *et al.*, 2021).

As with any other low-carbon fuel or chemical feedstock, demand for renewable ammonia must be stimulated by adequate policies, regulations and mandates. For example, the Renewable Energy Directive II (RED II) in the EU mandates that 14% of the energy used in transport should come from renewable sources by 2030. The market for renewable ammonia in the transport sector is focused on international shipping, with estimated demand of 197 Mt by 2050 in a 1.5°C scenario. In the chemical and industrial sectors, ammonia as a hydrogen carrier is expected to enable low-cost hydrogen imports for fuel and feedstock, meeting demand of 127 Mt by 2050 in a 1.5°C scenario.

Furthermore, renewable ammonia will find applications for stationary power, starting in Japan. By 2030, around 3-5 Mt per year will be used for stationary power generation in gas turbines and coal-fired power plants in Japan, with demand rising to 30 Mt by 2050. Ammonia may also be used as stationary fuel in, for example, Europe and North America, as ammonia offers an alternative to natural gas for peaker plants for full decarbonisation of the electricity grid (Palys and Daoutidis, 2020). Currently, hydrogen is considered for such applications, although due to the storage challenges of hydrogen, this is likely limited to locations with salt caverns.

5.2 Sustainable production

Electrolysis

Electrolysis-based hydrogen production with solar and wind energy will play a dominant role in decarbonising ammonia production. Various world-scale renewable ammonia plants have already been announced, starting operation at the gigawatt scale around 2025. Commercial demonstration at a smaller scale became operational in Puertollano (Spain) in 2021 (Atchison, 2022b).

Alkaline electrolyzers have been commercial on the 150 MW scale for a century (Ernst, 1928), and now other technologies are being scaled up, including PEM and solid oxide. Both alkaline and PEM electrolysis are currently available at the megawatt scale, while a similar scale of solid oxide electrolysis is expected to be available by 2023 (Frøhlke, 2021b).

The potential for electrolysis-based renewable ammonia will depend mainly on further reductions in the cost of renewable power, reductions in the capital cost of electrolyzers, and gains in efficiency and durability.

Biomass

Biomass can also be used to produce hydrogen as well as biogenic CO₂. However, biomass is not expected to play a dominant role in decarbonising ammonia production, due to the limited availability of low-cost biomass, which may be required as feedstock for other chemicals (Sociaal-Economische Raad, 2020). Biomass may play a role in decarbonising 10-20% of existing fossil-based ammonia-urea plants, and for local production in areas with very low biomass cost.

5.3 Impact of renewable ammonia on the energy sector

The progress in decarbonisation of the energy, industry and chemical sectors and their associated electrification through the use of renewable energy sources is likely to have significant consequences in the power sector, considering the intermittency of renewable sources such as wind and solar. The production and use of electro-fuels such as renewable ammonia can provide an outlet for renewable power and support grid stabilisation, depending on the nature of imbalances between supply and demand.

Put differently, renewable power can be used to produce renewable fuels when the supply is higher than the demand, and, conversely, renewable fuels can be used to generate power when the supply is lower than the demand. Beyond the existing grid, however, an operational market for transportable electro-fuels will spur the development of significant renewable energy assets that are currently too big for their grid-constrained markets, especially in remote and sparsely populated areas.

5.4 Drivers

As mentioned previously, uptake of renewable ammonia is driven mainly by the need to decarbonise society and shift away from fossil fuels. In the ongoing energy transition of end-use sectors, renewable ammonia has a substantial potential to act as an energy vector to mitigate and eventually eliminate the carbon footprint of the chemical production industry and energy sectors. In the long term, renewable ammonia can be facilitated as the main commodity for transporting renewable energy between continents. However, adequate policy frameworks, regulations and subsidies are needed to stimulate the production and consumption of renewable fuels.

The EU's Energy Roadmap calls for 80-95% reductions in greenhouse gas emissions by 2050 (European Commission, 2012). This will require a complete transformation of the energy sector, with around two-thirds of energy coming from renewable sources. A similar transition will be required in the rest of the world to ensure a secure, competitive and sustainable energy system in the long term (IRENA, 2019). According to IRENA, 70% of the world's energy-related CO₂ emissions must be cut by 2050 (IRENA, 2020a). This is an opportunity for the development of cost-competitive renewable ammonia as part of the solution.

Fossil-based ammonia has been available on the market as a commodity chemical for a long period of time. Renewable ammonia could substitute fossil-based ammonia in most applications, given that renewable ammonia and lower-carbon fossil-based ammonia are ideal raw materials for the chemical industry and the fertiliser industry, and potentially as fuel.

The following are some of the most important drivers for the development of the renewable ammonia market:

- Renewable ammonia can be used as feedstock in a wide range of applications in the chemical industry.

- It can be produced via low-carbon emission production routes.
- Renewable ammonia is a liquid energy storage medium that is easy to store and transport.
- It requires an uncomplicated production route that uses abundant atmospheric nitrogen and renewable electrolysis based on hydrogen.
- It is compatible with existing distribution infrastructure and can be blended with conventional fuels, leading to a reduction in other harmful emissions (SO_x, particulate matter, etc.).

Decarbonisation of the industrial sector, especially the chemical and fertiliser industries, should be the initial target application for renewable ammonia, especially for retrofits of existing ammonia plants. Renewable ammonia can be a feedstock for existing products currently obtained from fossil-based ammonia, although in some cases CO₂ may be required as additional feedstock.

The maritime sector is also likely to be a significant driver for expanding the production capacity of renewable ammonia, due to mandates and legislation being put in place by regulators to reduce greenhouse gas emissions. Because of the volumes required to deliver meaningful decarbonisation across the sector, this application is likely to be most relevant for new-build projects at a multi-gigawatt scale.

The stationary power sector is also expected to use ammonia as a fuel, led by Japan. This is an important driver for renewable ammonia, as long-term purchase commitments are agreed upon between producers and off-takers for power generation, de-risking investments (Kumagai, 2021; Yara, 2021).

Islanded locations where renewable energy can be produced at a comparably lower cost, and where fuel imports are costly, could also be good candidates for the production of renewable ammonia at a smaller scale. Finally, ammonia can be a hydrogen carrier, providing feedstock for the chemical industry and enabling hydrogen imports. Imported renewable ammonia may have a lower delivered cost of hydrogen than local renewable hydrogen production in, for example, Northern Europe and Japan (Atchison, 2021b; IEA, 2019a).

The potential use of renewable ammonia as a globally traded energy commodity supports massive export-scale renewable energy development, especially from coastal deserts where the availability of inexpensive but stranded renewable power is an inherent driver for renewable ammonia. This also generates sustained jobs in such areas. Production of renewable ammonia could also prompt global trade opportunities between renewable energy-rich regions such as North Africa, the Middle East, Oceania, and South America, and energy-importing regions such as Asia and Europe. Political stability and willingness to co-operate is required for ammonia off-take agreements between countries.

5.5 Barriers

The high cost of production and the absence of strong regulations on CO₂ emissions hampers the development of a renewable ammonia market, as it is the case for other renewable and carbon-free fuels or feedstocks. Adequate regulatory framework and policies are essential to kick start and sustain the mass deployment of renewable ammonia in the market. Substantive governmental incentives are required to decrease CO₂ emissions. A CO₂ penalty of an estimated USD 60-90 per tonne of CO₂ is required to transition towards low-carbon ammonia for current ammonia synthesis infrastructure (Figure 14). Current CO₂ penalties vary widely by country. Furthermore, costs are typically below USD 60 per tonne of CO₂ outside the EU, and fluctuating. Investment is driven by clear policy trends.

Without a price on carbon, the cost of renewable ammonia must decrease in order to be competitive on the global market. Renewable energy accounts for more than half the cost of ammonia, and, to be competitive, renewable energy prices of USD 20 per MWh and below are required. Such prices are already achievable in a few locations and will become more widespread beyond 2030 (IRENA, 2021a; Tancock, 2020). In the long term, new-build renewable ammonia plants are expected to produce ammonia at less than USD 400 per tonne in most places, and less than USD 350 per tonne in the most suitable locations.

Uncertainty in policy and technology implies a high weighted average capital cost (WACC), resulting in a high levelised cost of renewable ammonia. This is especially true because renewable ammonia production requires high upfront capital investment. Technology demonstrations can decrease the WACC (IEA, 2019b). The operating cost of renewable ammonia plants is low, resulting in a low cash cost of ammonia production for existing facilities.

Currently, around 25-30 Mt of ammonia is transported annually across land and sea. However, new energy-related markets may require greatly expanded ammonia infrastructure, capable of transporting around 300 Mt per year. There is no technological limitation to the scale-up of ammonia infrastructure, which is a function of demand. However, co-ordinated policies and investment support across regions and across sectors will be advantageous.

Ammonia is currently not approved as a fuel by various regulators, including the IMO and many power sector authorities. Operational experience is required to establish protocols for safe handling. Product standards are required to establish safe purity levels across multiple applications. Emission testing and verification is required to ensure that ammonia combustion does not exceed acceptable emission levels across a range of pollutants. These actions must be completed before it is possible to have broad regulatory approval of ammonia as a fuel. In the meantime, use of ammonia as a fuel will be limited to demonstrations and pilots.

Some research gaps exist, such as the low burning velocities compared with conventional fuels, higher energy demand for ignition, and the potential of high NO_x emissions from combustion (Elishav *et al.*, 2020; Kobayashi *et al.*, 2019; Valera-Medina *et al.*, 2018).

5.6 Policies and recommendations

Setting out the appropriate policy frameworks and support mechanisms is crucial to reaching the goals of carbon emission mitigation, sustainability and energy security. Adequate investment in enduring and capital-intensive renewable energy technologies is not likely to emerge without giving confidence to investors through strong, predictable, forward-looking and decisive policies.

Put a sufficiently high price on CO₂ emissions

A CO₂ penalty of around USD 60-90 per tonne of CO₂ is required to bridge the gap between fossil-based ammonia with unmitigated emissions and fossil-based ammonia with CCS. A CO₂ penalty of up to USD 150 per tonne of CO₂ would bridge the gap between fossil-based and renewable ammonia (see section 2.3). In the long term, renewable ammonia is expected to be cost competitive with fossil-based ammonia with CCS. Thus, CCS can play a role in decarbonising current ammonia facilities, but newly built fossil-based ammonia plants with CCS may result in stranded assets in the long term, unless supported by very low natural gas prices.

Translate political will into policies

With or without a price on CO₂ emissions, strong, stable and sustained regulatory measures for fuel standards and renewable quotas or mandates will facilitate price incentives to provide stability of sustained growth and investment. These can be supported by robust certification that can account for the carbon intensity of ammonia.

Suitable policy instruments are paramount to ensure equitable tax treatment and a long-term guaranteed price floor for wider adoption of renewable ammonia and other promising sustainable fuels. While energy tax reduction can be provided for renewable fuels, including renewable ammonia, fuel excise and other taxes should be based on energy content and not volume (e.g. USD per kilowatt-hour [kWh], not USD per litre).

For example, a contract for difference (CfD) scheme in which advanced renewable fuel production projects bid for CfDs, and the winners are awarded them in so-called reverse auctions (lowest bid wins) is an appropriate taxation policy that can “make or break” alternative fuels; this could motivate investments as a meaningful production support system. Moderate carbon taxation levels can be obtained via earmark and return principles.

Focus on deployment of existing renewable ammonia technologies

The current focus should be on implementing existing technologies at scale rather than developing new, breakthrough technologies. The latter is not necessarily required, as most elements in the renewable ammonia value chain have already been demonstrated. Rather, combinations of technologies should be demonstrated at relevant scale and under relevant conditions, which is the breakthrough required. This concerns innovations such as improving the flexibility of the ammonia synthesis loop, improving the performance of the electrolyser, improving the performance of ammonia crackers and driving down the costs of today’s technologies. Near-term market creation through the deployment of existing technologies will accelerate innovation in the longer term.

Support the development of entire supply chains

Funding programmes should extend their scope to include ammonia and other hydrogen carriers. Programmes that focus on a single technology (e.g. hydrogen or solar panels) tend to support early-stage R&D and pilot projects. However, broader funding programmes that focus on applications for these technologies (e.g. electro-fuels, energy storage) support deployment by connecting the value chain across production, distribution and use. Programmes may also wish to allow foreign participation, to support development of global supply chains, recognising that demand may not be met by domestic production.

Devise trade strategies that mitigate supply risks

To create jobs and encourage competitive new industries for renewable ammonia in both producing and consuming regions, international co-operation must be fostered – for example, between project developers, ammonia users and ammonia production companies. Increasing the investments in renewable ammonia production capacity could broaden the energy and feedstock supply range and minimise political risks.

Invest in electrolyser manufacturing

Substantial scale-up of electrolyser factories is required. The reported electrolyser production capacity in 2020 was only 2.1 GW per year (ESMAP and World Bank, 2020), but 40–65 GW per year will be required to supply the volume of hydrogen needed for decarbonising the fertiliser, power and maritime sectors with renewable ammonia. Thus, multiple gigawatt-scale electrolyser factories will be required. The development of such large-scale factories will inherently decrease the cost of electrolyser production due to an accelerated learning curve and economies of scale, which will in turn make renewable ammonia more competitive with fossil-based alternatives.

De-risk early investment projects

Governments can help to de-risk the billions of USD in investment of first movers seeking to build gigawatt-scale renewable ammonia plants. For instance, grants, investments, loans and loan guarantees can de-risk part of the CAPEX side of the investment. On the OPEX side, investments can be de-risked with contracts for difference (CfD) or green premiums, renewable mandates, procurement contracts and off-take guarantees, or an intermediate secured buyer of auctioned projects.

No conventional fossil-based ammonia plant finances its own natural gas extraction and pipeline supply; however, most gigawatt-scale renewable ammonia plants do the equivalent, by developing full renewable electricity generation assets. This means that while the CAPEX for renewable ammonia is higher, the OPEX can be much lower than for fossil-based ammonia. Once a renewable ammonia plant has been depreciated, its operating expenses, or cash cost, will be low. This makes renewable ammonia competitive, both on the chemical commodity market and as an alternative to fossil fuels in energy markets.

Alternatively, a separately financed wind and solar project can provide electricity to a renewable ammonia plant via a long-term power purchase agreement (PPA).

Retrofit technology towards renewable ammonia production

Ammonia plants that do not currently produce urea can be decarbonised without delay, either by integrating CCS, by retrofitting eSMR technology or by replacing fossil feedstock with renewable hydrogen. This represents around 80 Mt per year of existing ammonia capacity, which can be regarded as low-hanging fruit to decarbonise, with a cost gap of USD 60-150 per tonne of CO₂ (Haldor Topsøe *et al.*, 2020; Saygin and Gielen, 2021).

Support the demand-side phase-out of fossil fuels

Governmental and regulatory incentives should be provided to existing fossil-based assets to accelerate the transition to renewables. This prevents locked-in CO₂ emissions from continued operations, reduces demand for ongoing fossil fuel discovery and extraction, and reduces the likelihood of stranded assets. Retrofitting existing assets may often be more cost effective than building new assets, especially during the initial scale-up phase. This is also valid for ammonia utilisation technology. For both the power sector and maritime sector, current technology can often be retrofitted to operate on ammonia fuel at a lower cost than building new technology.

In the maritime sector, ammonia tankers can be converted to use ammonia as a fuel first, in the knowledge that fuel availability will not be an issue for this vessel type at any port. Vessel conversions will be required this decade, as ships typically have a lifetime of 20-25 years. To comply with the 1.5°C scenario, an estimated 5% of the maritime fuel mix should be zero-carbon fuels by 2030 (Osterkamp, Smith and Sjøgaard, 2021). The ammonia and LPG gas carrier segment of the global fleet represents roughly 2% of maritime fuel consumption.

Re-assess the role of ammonia in hydrogen strategies

Most hydrogen strategies consider ammonia only as a consumer of hydrogen, in the context of fertiliser production, and omit consideration of its potential roles as a fuel and hydrogen carrier.

In locations where ammonia will be imported as a hydrogen carrier, ammonia should be utilised directly where possible, rather than using hydrogen obtained from the decomposition of ammonia. Ammonia may be the most cost-effective vector for large-scale hydrogen imports, but its cost-effectiveness increases with direct use. Novel technologies to use ammonia in centralised and decentralised power generation, as well as transport applications, are approaching commercialisation and may offer an opportunity to re-assess the roles of hydrogen and ammonia in the context of a national hydrogen strategy.

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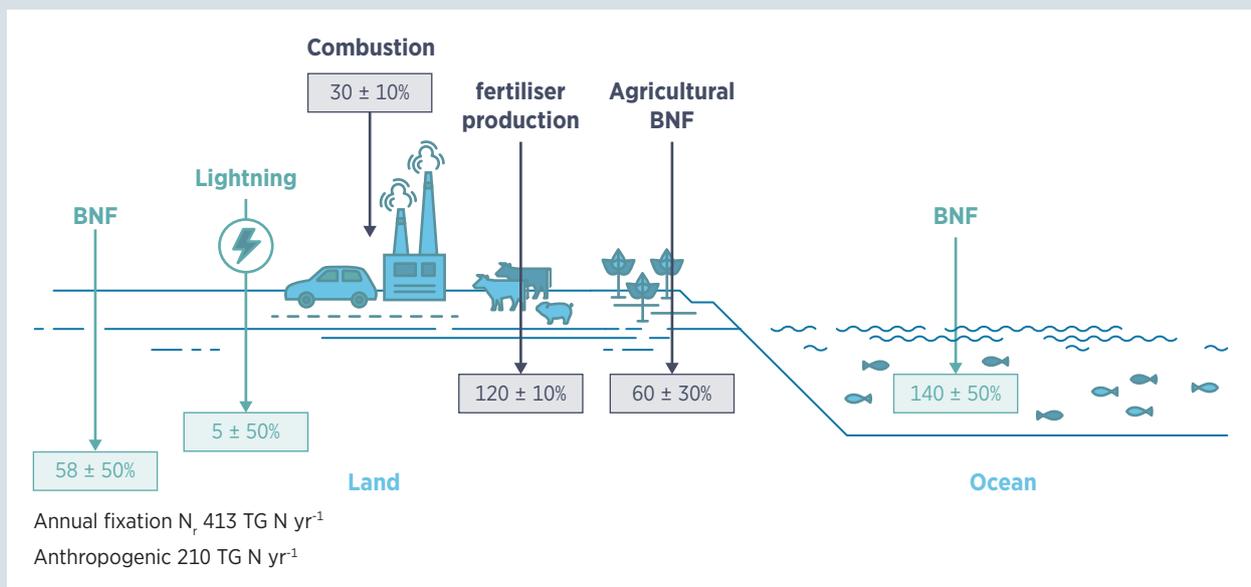
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ANNEXES

Annex A The nitrogen cycle

Atmospheric nitrogen is fixated through natural processes, such as microbes with the ability to fixate nitrogen (biological nitrogen fixation (BNF)) and lightning. Furthermore, atmospheric nitrogen is fixated through anthropogenic processes, such as fertiliser production with associated agricultural biological nitrogen fixation and the combustion of fuels. A schematic of the global atmospheric nitrogen fixation process is shown in Figure 35.

Figure 35 Global nitrogen fixation, both natural and anthropogenic in oxidised and reduced forms, formed through combustion, biological fixation, lightning, and fertiliser application, for the year 2010



Reproduced from Fowler *et al.* (2013).

The biologic nitrogen fixation process consists of fixation of atmospheric nitrogen by microbes in soils and in oceans, totalling around 200 Mt of ammonia-equivalent nitrogen fixation per year (Fowler *et al.*, 2013). Lightning accounts for another 5 Mt of ammonia-equivalent nitrogen fixation per year (Fowler *et al.*, 2013). Industrial nitrogen fixation for fertilisation and emissions thereof to the environment, agricultural biological nitrogen fixation, as well as NO_x emissions from combustion contribute to a total of 210 Mt of ammonia-equivalent nitrogen fixation per year (Fowler *et al.*, 2013; X. Zhang *et al.*, 2020). This is equal in size to the biological nitrogen fixation processes.

Only 14-20% of the nitrogen fertilisers applied in vegetarian agriculture is consumed by humans, while the remainder leaches into the soil, air and water (Galloway and Cowling, 2002; Leach *et al.*, 2012), thereby causing eutrophication. For reference, less than 5% of the nitrogen fertiliser applied for a carnivorous diet is consumed by humans (Galloway and Cowling, 2002). Eutrophication is the effect where minerals and nutrients, in this case nitrogen fertilisers and NO_x emissions, impact the terrestrial and aquatic ecosystems, as some organisms grow much faster than other organisms through excessive nitrogen nutrient enrichment, leading to a loss in biodiversity. Upon deposition of ammonia to soil, it may be converted to nitrous oxide (N_2O) by nitrogen fixation microbes in the soil. Nitrous oxide is a strong greenhouse gas with 298 times the global warming potential of CO_2 (US EPA, 2020). Furthermore, N_2O causes stratospheric ozone loss through the formation of NO_x (Erisman *et al.*, 2013; Revell *et al.*, 2015).

Nitrogen emissions from ammonia for energy applications should only be atmospheric dinitrogen (N_2), in order to limit the effect of decarbonising the energy infrastructure to an ammonia economy. Unconverted ammonia and NO_x formed during incomplete combustion should be converted to atmospheric nitrogen and water. Technologies to convert ammonia and NO_x to atmospheric dinitrogen and water are already commercially available for exhaust clean-up in vehicles, for ships, and for stationary power. NO_x emissions have been reduced over the years through legislation. Ammonia and ammonia derivatives can be used to decrease the NO_x emissions in the stationary power sector and transport sector through selective catalytic reduction (SCR) technology (Busca *et al.*, 1998). This technology enhances the conversion of NO_x through a reaction with ammonia on metal surfaces and metal oxide surfaces to form dinitrogen and water.

Annex B Life-cycle assessment

Table 9 Greenhouse gas intensity of ammonia production process from various resources

Feedstock	Original system boundaries*	Raw material to final use GHG emitted in g CO ₂ -eq/MJ**	Source
Resource type: Fossil fuel-based			
Natural gas	A	116.4	(Hydrogen Council, 2021)
Natural gas	B	85.8	(Brightling, 2018)
Natural gas	B	136.8	(Liu, Elgowainy and Wang, 2020)
Natural gas	A	129.8	(Al-Breiki and Bicer, 2021)
Natural gas	B	162.6	(Singh, Dincer and Rosen, 2018)
Natural gas	B	89.7	(Smith, Hill and Torrente-Murciano, 2020)
Natural gas	B	150.7	(Arora <i>et al.</i> , 2018)
Natural gas	B	101.9	(Arora <i>et al.</i> , 2017)
Natural gas	B	123.0	(Zhou <i>et al.</i> , 2010)
Natural gas	B	118.2	(Dufour <i>et al.</i> , 2009)
Naphtha	B	134.1	(Brightling, 2018)
Heavy fuel oil	B	160.9	(Brightling, 2018)
Heavy fuel oil	B	175.5	(Zhou <i>et al.</i> , 2010)
Coal	B	203.8	(Brightling, 2018)
Coal	B	193.1	(Rouwenhorst <i>et al.</i> , 2020b)
Coal	B	206.7	(Singh, Dincer and Rosen, 2018)
Coal	B	225.2	(Arora <i>et al.</i> , 2018)
Coal	B	245.7	(Zhou <i>et al.</i> , 2010)
Resource type: Lower-carbon fossil fuel-based			
Natural gas with CCS	A	97.6	(Al-Breiki and Bicer, 2021)
Natural gas with CCS	B	50.9	(Royal Society, 2020)
Natural gas with CCS	B	46.0	(Dufour <i>et al.</i> , 2009)
Natural gas with CCS (Russian Federation, 2030)	B	32.5	(Hydrogen Council, 2021)
Natural gas with CCS (Russian Federation, 2050)	B	32.5	(Hydrogen Council, 2021)

*(A) From raw material extraction until use phase; no correction needed. (B) From raw material extraction until ammonia production gate; add maximum 10 grams of CO₂-equivalent per MJ for transport and distribution of ammonia (Al-Breiki and Bicer, 2021).

** Raw material to final use greenhouse gas emissions in grams of CO₂-equivalent per MJ calculated from the original system boundary. The values for the CO₂-equivalent emissions from Dufour *et al.* (2009) and Hydrogen Council (2021) are recalculated to ammonia synthesis from hydrogen synthesis.

Note: ATR = autothermal reforming; SMR = steam methane reforming; ASU = air separation unit; PSA = pressure swing adsorption.

Feedstock	Original system boundaries*	Raw material to final use GHG emitted in g CO ₂ -eq/MJ**	Source
Resource type: Lower-carbon fossil fuel-based			
Natural gas, SMR with CCS (Norway, 2030)	B	12.5	(Hydrogen Council, 2021)
Natural gas, SMR with CCS (Norway, 2050)	B	12.5	(Hydrogen Council, 2021)
Natural gas, ATR with CCS (Norway, 2030)	B	10.0	(Hydrogen Council, 2021)
Natural gas, ATR with CCS (Norway, 2050)	B	6.7	(Hydrogen Council, 2021)
Coal gasification with CCS	B	36.1	(Singh, Dincer and Rosen, 2018)
Coal gasification with CCS (China, 2030)	B	76.7	(Hydrogen Council, 2021)
Coal gasification with CCS (China, 2050)	B	65.9	(Hydrogen Council, 2021)
Coal gasification with CCS (Australia, 2030)	B	29.2	(Hydrogen Council, 2021)
Coal gasification with CCS (Australia, 2050)	B	25.8	(Hydrogen Council, 2021)
Hydrogen from ethane cracker, nitrogen from ASU	B	92.8	(Liu, Elgowainy and Wang, 2020)
Hydrogen from ethane cracker, nitrogen from PSA	B	97.6	(Liu, Elgowainy and Wang, 2020)
Hydrogen from chlor alkali, nitrogen from ASU	B	19.8	(Liu, Elgowainy and Wang, 2020)
Hydrogen from chlor alkali, nitrogen from PSA	B	24.1	(Liu, Elgowainy and Wang, 2020)
Methane pyrolysis	B	33.8	(Dufour <i>et al.</i> , 2009)
Methane pyrolysis	B	19.9	(Dufour <i>et al.</i> , 2009)
Methane pyrolysis	B	37.6	(Dufour <i>et al.</i> , 2009)
Resource type: Power-based			
Renewable hydrogen (2030)	A	10.2	(Hydrogen Council, 2021)
Renewable hydrogen (2050)	A	4.8	(Hydrogen Council, 2021)
Electrolysis-based hydrogen	A	18.8	(Smith, Hill and Torrente-Murciano, 2020)
Electrolysis-based hydrogen	A	26.3	(Smith, Hill and Torrente-Murciano, 2020)
Low-temperature electrolysis, nitrogen from ASU	B	11.8	(Liu, Elgowainy and Wang, 2020)
Low-temperature electrolysis, nitrogen from PSA	B	16.1	(Liu, Elgowainy and Wang, 2020)
High-temperature electrolysis, nitrogen from ASU	B	13.4	(Liu, Elgowainy and Wang, 2020)

Feedstock	Original system boundaries*	Raw material to final use GHG emitted in g CO ₂ -eq/MJ**	Source
Resource type: Power-based			
High-temperature electrolysis, nitrogen from PSA	B	17.7	(Liu, Elgowainy and Wang, 2020)
Electrolysis from wind	A	34.9	(Al-Breiki and Bicer, 2021)
Electrolysis from wind	B	26.6	(Singh, Dincer and Rosen, 2018)
Electrolysis from solar	A	60.1	(Al-Breiki and Bicer, 2021)
Electrolysis from solar	B	68.5	(Singh, Dincer and Rosen, 2018)
Electrolysis from hydropower	B	20.8	(Bicer <i>et al.</i> , 2016)
Electrolysis from municipal waste	B	18.6	(Bicer <i>et al.</i> , 2016)
Electrolysis from biomass	B	46.0	(Bicer <i>et al.</i> , 2016)
High-temperature electrolysis from nuclear	B	45.2	(Bicer <i>et al.</i> , 2016)
Resource type: Bio-based			
Biomass gasification	B	20.3	(Singh, Dincer and Rosen, 2018)
Biomass gasification	B	64.4	(Arora <i>et al.</i> , 2018)
Wood ATR	B	41.5	(Arora <i>et al.</i> , 2017)
Wood steam reforming	B	45.2	(Arora <i>et al.</i> , 2017)
Wood CO ₂ reforming	B	54.7	(Arora <i>et al.</i> , 2017)
Straw ATR	B	60.1	(Arora <i>et al.</i> , 2017)
Straw steam reforming	B	68.1	(Arora <i>et al.</i> , 2017)
Straw CO ₂ reforming	B	77.2	(Arora <i>et al.</i> , 2017)
Straw gasification	B	37.5	(Ahlgren <i>et al.</i> , 2008)
Salix gasification	B	29.5	(Ahlgren <i>et al.</i> , 2008)
Bagasse ATR	B	13.0	(Arora <i>et al.</i> , 2017)
Bagasse steam reforming	B	17.6	(Arora <i>et al.</i> , 2017)
Bagasse CO ₂ reforming	B	19.0	(Arora <i>et al.</i> , 2017)
Roundwood gasification	B	35.9	(Gilbert <i>et al.</i> , 2014)
Wood chips gasification	B	0.3	(Sarkar, Kumar and Sultana, 2011)
Resource type: Nuclear			
High-temperature electrolysis	B	24.3	(Bicer and Dincer, 2017)
Low-temperature electrolysis	B	25.8	(Bicer and Dincer, 2017)
Cu-Cl Cycle (3 step)	B	30.8	(Bicer and Dincer, 2017)
Cu-Cl Cycle (4 step)	B	29.8	(Bicer and Dincer, 2017)
Cu-Cl Cycle (5 step)	B	31.3	(Bicer and Dincer, 2017)

Annex C Capital investment for renewable ammonia production

A number of literature studies has been conducted on the cost of renewable ammonia. A selected overview of these estimated production costs is presented in Table 10. Overall, the CAPEX is roughly between USD 6 000 and USD 1500 per tonne annually for renewable ammonia production plants (excluding wind and solar generation), with plant production capacities ranging from 1 kt per year of ammonia to 500 kt per year. Table 11 provides a detailed insight into the capital cost of renewable ammonia plants around the world.

A visualisation of the capital intensity of various ammonia plants is shown in Figure 16. Clearly, ammonia production depends strongly on the plant size, where large-scale operation results in a lower relative capital investment. The capital intensity of various biomass-based ammonia production plants is also shown in Figure 16, based on Akbari, Oyedun and Kumar (2018) and Tunå, Hulteberg and Ahlgren (2014).

Table 10 Production costs and production capacity of green ammonia reported in the literature

Electricity source for electrolysis	Electrolysis type	Capacity (kt/y)	CAPEX (million USD)	CAPEX (USD/t/y)	OPEX (MUSD/y)	OPEX (USD/t)	Ammonia cost (USD/t)	Source
	Alkaline	9.3 104	26.4 148	2 846 1 423	- -	- -	- -	(Grundt and Christiansen, 1982)
Grid	-	2.0 6.8	10.2 29.0	5 484 4 696	3.0 9.6	1 474 1 425	1 725 1 640	(Tunå, Hulteberg and Ahlgren, 2014)
-	-	0.035 1.8	0.83 8.7	28 302 5 919	- -	- -	- -	(Morgan, Manwell and McGowan, 2014)
Hydro	Alkaline	70 175 263 350 525	160 327 451 568 786	2 307 1 892 1 740 1 644 1 516	22.3 52.2 83.7 117 198	318 298 319 333 377	432 392 405 414 452	(Rivarolo <i>et al.</i> , 2019)
Wind, solar	Alkaline	-	-	3 955 4 583 3 830 4 709	- - - -	273 264 261 320	471 493 452 556	(Armijo and Philibert, 2020)

Table 11 Capital cost for renewable ammonia plants, including or excluding renewable energy generation cost

Location	Companies	Ammonia capacity (kt/y)	CAPEX (million USD)	CAPEX (USD/t/y)	CAPEX (USD/kW)	Source
Including energy generation						
Morris, United States	University of Minnesota	0.025	3.75	107 145	181 335	(Reese, 2007)
Puertollano, Spain	Iberdrola, Fertiberia	4	177	43 760	74 060	(Brown, 2020f; Fertiberia and Iberdrola)
		200	2 124	10 620	17 975	
Taranaki, New Zealand	Ballance Agri-Nutrients, Hiringa Energy	5	36	7 210	12 200	(Hiringa Energy, 2020) Revamp, only wind and hydrogen capacity
Pilbara, Australia	InterContinental Energy	5 710	17 080	2 990	5 060	(Brown, 2020a, 2020b)
		9 900	27 790	2 805	4 750	
Neom, Saudi Arabia	Air Products, ACWA Power, ThyssenKrupp, Haldor Topsøe	1 200	5 000	4 165	7 050	(Brown, 2020g)
Pilbara, Australia	Yara	24	200	10 000	16 925	(Brown, 2020e) Revamp, only wind, solar and hydrogen capacity
Duqm, Oman	ACME, Tatweer	770	2 500	3 245	5 495	(Zawya, 2021)
Abu Dhabi, United Arab Emirates	KIZAD, Helios Industry	200	1 000	5 000	118 170	(KIZAD, 2021)
Al Wusta, Oman	OQ, InterContinental Energy, EnerTech	10 450	25 000	2 390	4 050	(Paddison, 2021)
Mauritania	CWP	11 425	40 000	3 500	5 925	(CWP, 2021)
Excluding energy generation						
Port Lincoln, Port Bonython, Australia	H2U, Mitsubishi, SA gov, ThyssenKrupp	19	95	4 935	8 350	(Brown, 2018f)
		40	186	4 660	7 890	
Esbjerg, Denmark	Copenhagen Infrastructure Partners, Maersk, DFDS	650	1 210	1 860	3 150	(Barsoe, 2021)
South Australia	Government of South Australia, Advisian, Siemens, Acil Allen	200	680-720	3 400 – 3 600	5 755 – 6 095	(Government of South Australia et al., 2017)

Annex D Technology status for the ammonia economy

Table 12 Technology status for ammonia production technologies, ammonia transport and storage, and ammonia utilisation technologies

	Status	Notes
Renewable ammonia production		
Renewable energy	Commercial at required scale	<ul style="list-style-type: none"> The combined added solar and wind capacity was 238 GW in 2020 (IRENA, 2021b). Annual renewables requirement is around 115-170 GW per year for 566 Mt of renewable ammonia by 2050, assuming linear growth and not including renewables replacement. This assumes around 5-8 GW of renewables per 1 GW ammonia plant (Arnaiz del Pozo and Cloete, 2022). Material shortage is not expected. Current exploration of raw materials is limited to Eastern Asia, although deposits are available in other countries (Weng <i>et al.</i>, 2015).
Water purification	Commercial at required scale	<ul style="list-style-type: none"> Water security can be an issue at locations with high solar irradiation. Water use for gigawatt-scale projects can be significant. This can strain local clean water supply, if water supply is not added. Compared to electrolyser, energy consumption for desalination is low. The maximum cost of desalination is around USD 0.02 per kilogram of hydrogen (Salmon and Bañares-Alcántara, 2021).
Hydrogen production	Commercial but significant scale up required	<ul style="list-style-type: none"> In 2020, the electrolyser production capacity was around 2.1 GW per year (ESMAP and World Bank, 2020). Each 1 Mt per year of ammonia added requires around 2-3 GW of electrolysers (Arnaiz del Pozo and Cloete, 2022), depending on the capacity factor for solar and wind resources. Hydrogen storage may be required. Annual electrolysers requirement about 40-65 GW per year for 566 Mt of renewable ammonia by 2050, assuming linear growth and not including electrolyser replacement. This implies a factor 20-30 increase in electrolyser capacity required. Alkaline electrolysis relies on nickel. Material shortage is not expected (Salmon and Bañares-Alcántara, 2021). PEM electrolysis relies on platinum and iridium (Hauch <i>et al.</i>, 2020). Around 5 tonnes of iridium is produced globally, while a 1 GW electrolyser requires 0.5 tonnes of iridium (Hegge <i>et al.</i>, 2020). Thus, material shortage is expected if PEM is applied for multiple gigawatt-scale projects. Solid oxide electrolysis relies on yttrium. Material shortage is not expected (Salmon and Bañares-Alcántara, 2021). Large-scale hydrogen storage is also possible in places with salt caverns, lined rock caverns, and other underground shafts, as well as through hydrogen pipeline networks (Gabrielli <i>et al.</i>, 2020). Battery storage is relatively costly and is mainly relevant for storage of a few hours. One-day-equivalent hydrogen storage costs around USD 35-150 per tonne of ammonia (Armijo and Philibert, 2020; Vrijenhoef, 2016). Storage in salt caverns has the lowest cost at USD 35 per tonne of ammonia, while storage in lined rock caverns costs around USD 65 per tonne of ammonia (Ahluwalia <i>et al.</i>, 2019).

	Status	Notes
Renewable ammonia production		
Nitrogen purification, ammonia production	Commercial at industrial scale, demonstration required	<ul style="list-style-type: none"> World-scale fossil-based ammonia plants are already operating at 0.7-1.2 Mt per year (Brightling, 2018). Renewable ammonia has been commercial at 0.1-0.2 Mt per year since the 1920s (Ernst, 1928; Krishnan <i>et al.</i>, 2020). The main challenge of the ammonia synthesis loop is intermittent operation. Nitrogen purification requires limited energy, e.g. around 1 GJ per tonne of ammonia (Rouwenhorst <i>et al.</i>, 2019). However, intermittent operation of a cryogenic air separation unit to below 50% is difficult.
Investment	No limitations expected	<ul style="list-style-type: none"> Total investment of around USD 2 000 billion is required for 566 Mt of renewable ammonia by 2050, based on an investment of USD 3 000 to USD 4 000 per tonne per year, including renewables generation (Figure 16). This is equivalent to annual investment of around USD 75 billion, assuming linear growth. For reference, around USD 300 billion is invested annually in renewable power generation (IEA, 2020b).
Land use	No limitations expected	<ul style="list-style-type: none"> The area requirement is around 315 000 to 375 000 square kilometres (km²) for 566 Mt of renewable ammonia by 2050. The range is due to the power energy densities for solar and wind energy (van Zalk and Behrens, 2018), combined with an estimate from an actual renewable ammonia plant based mainly on onshore wind power (Tancock, 2020). Most of the area is required for renewable electricity generation. The ammonia synthesis plant accounts for 0.2% of the total area requirement (Salmon and Bañares-Alcántara, 2021). The upper area requirement estimate for 566 Mt of renewable ammonia is larger than the size of Germany (357 000 km²). More efficient solid oxide electrolysis technology can decrease the land-use requirement by around 30-35% (Table 4).
Ammonia transport		
Transport infrastructure	Commercial, but not at required scale	<ul style="list-style-type: none"> Infrastructure exists for transport by ship, pipeline, and rail, totalling 25-30 Mt (section 1.2). New markets require infrastructure of 354 Mt by 2050 (Figure 29). This implies a factor 10-15 increase required for the transport infrastructure. Around 235 ships with 85 000 m³ ammonia capacity (58 kt) are required to accommodate 300 Mt transport by 2050, assuming a voyage every two weeks. This implies that a ship for ammonia transport must be built or revamped from LPG transport roughly every two months up to 2050. Typical ammonia transport costs are USD 30-75 per tonne of ammonia (Salmon and Bañares-Alcántara, 2021), resulting in up to USD 26.5 billion in annual transport costs for the global ammonia market. Air Products announced it would invest around USD 2 billion to distribute renewable ammonia to end customers (Brown, 2020g). Safety is a significant issue. Ammonia has been handled for a century. It needs commercial demonstration for new applications with trained operators.

	Status	Notes
Ammonia transport		
Port infrastructure and bunkering	Commercial, but not at required scale	<ul style="list-style-type: none"> New markets require infrastructure of 354 Mt by 2050 (Figure 29). Around 735 ammonia storage tanks of 50 kt of ammonia are required to account for one week of ammonia storage on the production and demand sides. This requires an investment of USD 20 billion for ammonia storage capacity to 2050. CAPEX estimates from Leighthy (2017). Various demonstrations will investigate ammonia bunkering in the coming years.
Regulatory framework	Not in place, required for ammonia producers and consumers	<ul style="list-style-type: none"> Certificates of origin for low-carbon ammonia are not yet in place. These may be required to reach agreement between ammonia producers and consumers. Life-cycle assessment can be used to assess the carbon footprint (see section 3.2).
Ammonia utilisation		
General aspects	N/A	<ul style="list-style-type: none"> Low-carbon ammonia from fossil fuels with CCS de-risks the transition from current fuels to renewable ammonia. In the long term, renewable ammonia is most desirable. Partnerships between exporting and importing companies are required. Currently, various Memoranda of Understanding are being signed. Certification may be required to reach agreement between exporting and importing companies.
Hydrogen production	Not commercial yet, but no limitations expected	<ul style="list-style-type: none"> Not commercial yet at large scale, but gigawatt-scale projects are announced in the Netherlands and Germany (Table 5). Gigawatt-scale operation is expected by 2030. Technology is not a bottleneck, although demonstration is required. The technology is probably similar to steam methane reforming technology for hydrogen production.
Shipping fuel	Not commercial yet, limitation in regulatory framework	<ul style="list-style-type: none"> Not commercial yet, but engines will be ready by the mid 2020s, based on retrofit technology for two-stroke and four-stroke engines (Table 6). Solid oxide fuel cells may be introduced at a later stage or simultaneously. Commercial-scale demonstrations of ammonia as a maritime fuel is expected by the mid 2020s (Table 6). Ship owners need to make decision for a renewable fuel option soon, as ships have a lifetime of 20-25 years. Dual-fuel engines may be used to de-risk investment in ammonia-fuelled ships. Ammonia is currently not approved as a maritime fuel by the IMO, implying that roll-out of ammonia as a maritime fuel is limited. 5% zero-carbon fuels are required by 2030 to meet the 1.5°C scenario (Osterkamp, Smith and Søgaard, 2021). Decarbonising ammonia vessels is a low-hanging fruit.
Stationary power	Not commercial yet, limitations expected near residential areas, but no limitations in port areas	<ul style="list-style-type: none"> Not commercial yet, but commercial-scale technology will be ready in Japan by the mid 2020s. This includes 20% ammonia co-firing in coal-fired plants (Kumagai, 2021), and ammonia-fired gas turbines (Patel, 2021). Ammonia can be used in current fossil-fuel based infrastructure, implying locked-in CO₂ emissions are alleviated, and stranded assets are prevented. NO_x emissions should be minimised. NO_x emission control with ammonia (SCR) is sometimes already in place. In Europe, changes of permit status are required for co-firing ammonia in coal-fired power plants. Currently, there are safety concerns.

Annex E Projected ammonia use in various sectors

Table 13 Projected use of ammonia in various sectors

Location	Year	Ammonia capacity (Mt)	Notes	Source
Current uses				
World	2018	181	According to McKinsey, assuming 65% growth to 2050 due to population growth	(de Pee <i>et al.</i> , 2018)
	2020	184		
	2050	299		
World	2030	216	According to the IEA, Baseline	(IEA, 2021a)
	2050	252		
World	2030	205	According to the IEA, Sustainable Development Scenario (SDS), Net Zero Emissions (NZE)	(IEA, 2021a)
	2050	227		
Ammonia as hydrogen carrier				
European Union	2035	6.0	Announced capacity *Assuming linear growth of announced capacity to 2050	Table 5
	2050	12*		
European Union	2050	135	Assuming 18 Mt of hydrogen imported as ammonia by 2050	(Port of Rotterdam, 2020)
Republic of Korea	2030	10	Assuming the imported hydrogen is produced by ammonia decomposition *Assuming linear growth	(Salmon and Bañares-Alcántara, 2021)
	2040	33		
	2050	56*		
Global	2025	0	According to Argus Media	(Argus Media, 2021e)
	2030	2		
	2035	7		
	2040	12		
	2045	16		
	2050	21		
Global	2025	0	According to IRENA (stated policies)	(IRENA, 2022)
	2030	1		
	2035	3		
	2040	9		
	2045	32		
	2050	110		
Global	2025	0	According to IRENA (1.5°C scenario)	(IRENA, 2022)
	2030	2		
	2035	5		
	2040	15		
	2045	44		
	2050	127		

Location	Year	Ammonia capacity (Mt)	Notes	Source
Ammonia for power generation				
Japan	2025 2030 2050	0.5-1 3-5 30	According to the Clean Fuel Ammonia Association	(Argus Media, 2021d, 2021c)
Japan	2030 2035 2040 2045 2050	0 0 35 81 186	According to the Institute of Energy Economics (Japan), assumes limited role of renewables (33% by 2050)	(Lu, Kawakami and Hirai, 2018)
Japan	2030 2035 2040 2045 2050	1 2 35 54 85	According to the Institute of Energy Economics (Japan) with max. 25% ammonia in power mix, assumes limited role of renewables (36% by 2050)	(Lu, Kawakami and Hirai, 2018)
Global	2025 2030 2035 2040 2045 2050	0 3 7 11 12 14	According to Argus Media	(Argus Media, 2021e)
Global	2030 2050	3 63	According to the IEA, Sustainable Development Scenario (SDS)	(IEA, 2021a)
Global	2030 2050	54 84	According to the IEA, Net Zero Emissions (NZE)	(IEA, 2021a)
Ammonia as maritime fuel				
Global	2030 2040 2050 2060 2070	8 41 103 188 302	Energy Technology Perspectives	(IEA, 2020c)
Global	2050	173-774	DNV GL 2020, assuming IMO ambitions	(DNV GL, 2020)
Global	2050	251-1 069	DNV GL 2020, assuming decarbonisation by 2040	(DNV GL, 2020)
Global	2031 2036 2041 2046 2050	0 192 315 803 952	According to the Getting To Zero Coalition, decarbonisation by 2050 (1.5°C aligned)	(Raucci <i>et al.</i> , 2020)

Location	Year	Ammonia capacity (Mt)	Notes	Source
Ammonia as maritime fuel				
Global	2031	0	According to the Getting To Zero Coalition, decarbonisation by 2070 (IMO aligned)	(Raucci <i>et al.</i> , 2020)
	2036	178		
	2041	349		
	2046	539		
	2050	673		
Global	2050	150	Assuming 30% of maritime fuel supplied by ammonia	(Haldor Topsøe <i>et al.</i> , 2020)
Global	2050	247	According to IRENA's World Energy Transitions Outlook: 1.5°C Pathway	(IRENA, 2021c)
Global	2025	0	According to Argus Media	(Argus Media, 2021e)
	2030	1		
	2035	2		
	2040	7		
	2045	45		
	2050	146		
Global	2030	7	According to the IEA, Sustainable Development Scenario (SDS)	(IEA, 2021a)
	2050	127		
Global	2030	37	According to the IEA, Net Zero Emissions (NZE)	(IEA, 2021a)
	2050	245		
Global	2025	0	According to Zero Carbon Shipping Center (base case)	(Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021)
	2030	110		
	2035	207		
	2040	283		
	2045	336		
	2050	333		
Global	2025	0	According to IRENA (stated policies)	(IRENA, 2021d)
	2030	10		
	2035	26		
	2040	43		
	2045	59		
	2050	77		
Global	2025	0	According to IRENA (1.5°C scenario)	(IRENA, 2021d)
	2030	26		
	2035	68		
	2040	111		
	2045	152		
	2050	197		

Figure 36 Ammonia demand estimates from various sources (see Table 13)



Annex F Stated policies demand and production

Figure 37 Expected ammonia demand up to 2050 for the stated policies scenario

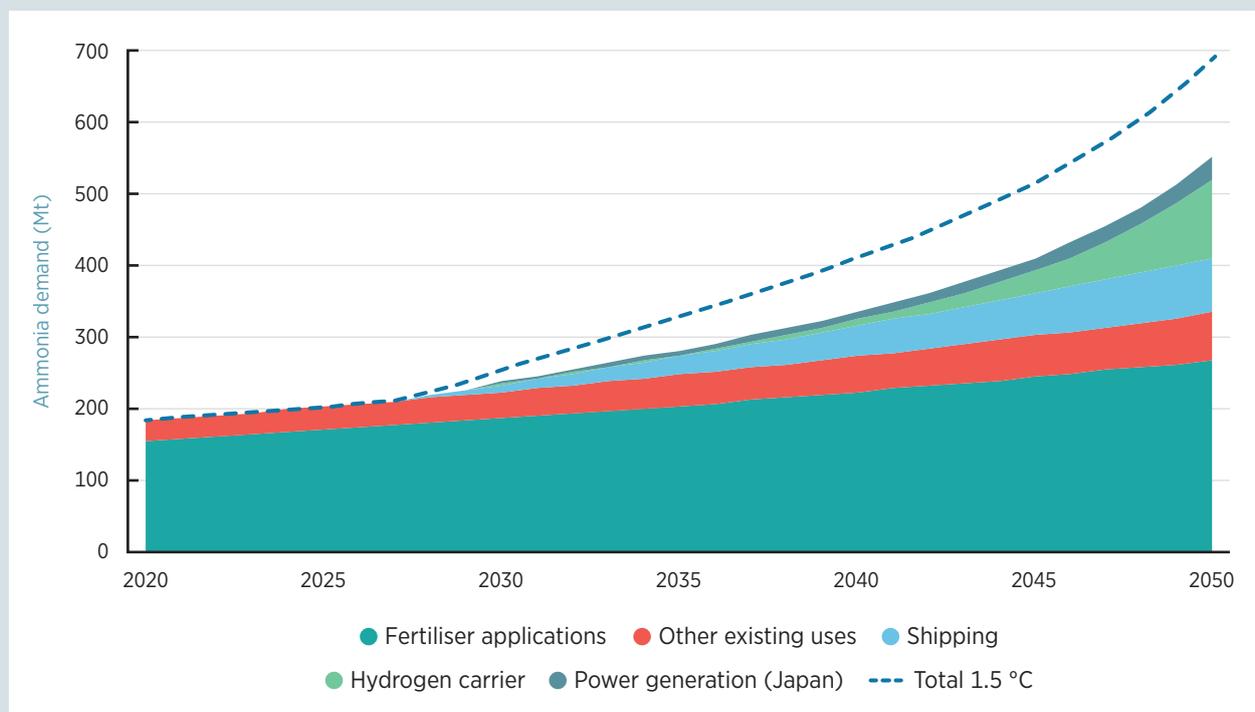
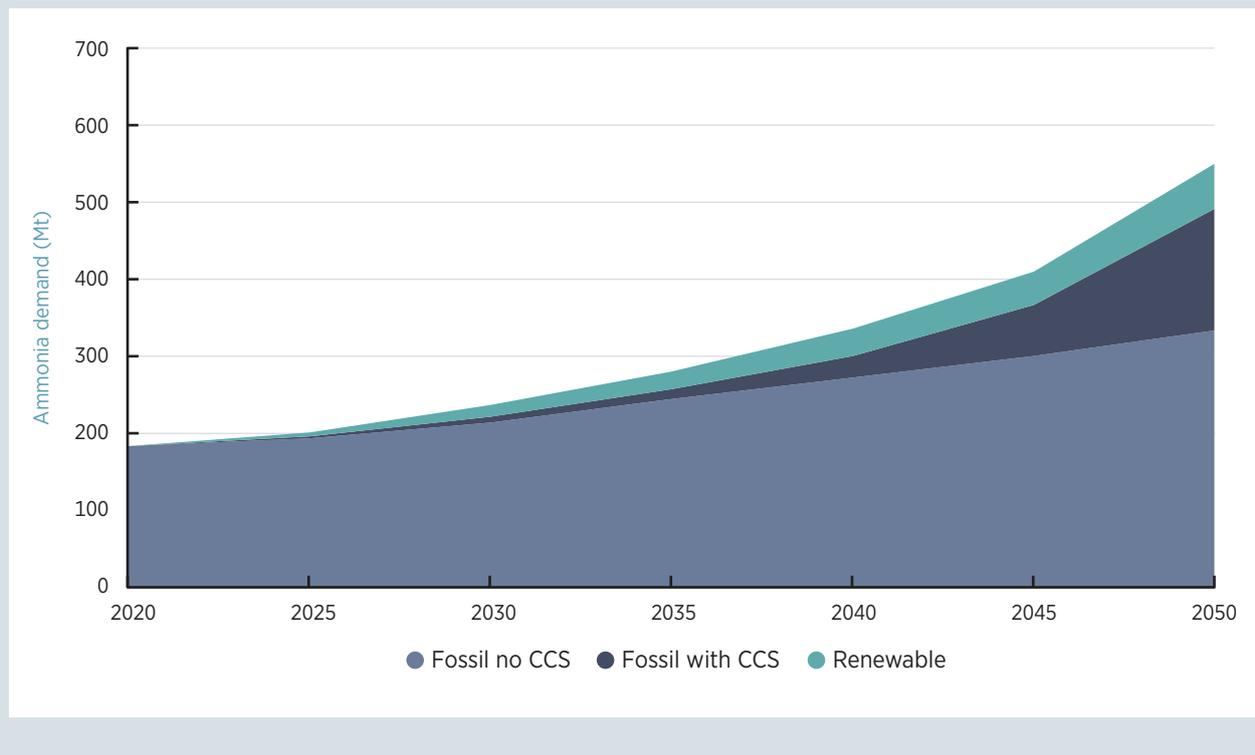


Figure 38 Expected ammonia production by feedstock up to 2050 for the stated policies scenario



Annex G Key reference data

	Coal	Natural gas	Methane	Hydrogen	Ammonia	Methanol
Molar mass (g mol ⁻¹)	207.25*	-	16.043	2.016	17.031	32.04
Density (kg/m ³)	-	0.777	0.716	0.0899	0.770	0.791
Melting point (°C)	-	-	-182.5	-259.16	-77.73	-97.6
Boiling point (°C)	-	-	-161.5	-252.88	-33.34	64.7
Lower heating value (MJ/kg)	-	47.1	50.0	120.0	18.6	19.9
Higher heating value (MJ/kg)	30-33	52.2	55.5	141.7	22.5	23.0

Coal: Anthracite or bituminous. * molar mass of anthracite.

Natural gas: US market.

Density at 0°C and 1 bar.

Annex H Future cost estimates for renewable ammonia

Table 14 Cost estimate for renewable ammonia production

Year	2020	2030	2040	2050
Low end (USD/tonne)	720	475	380	310
High end (USD/tonne)	1400	950	750	610

Note: Rounded to USD 5 per tonne.

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