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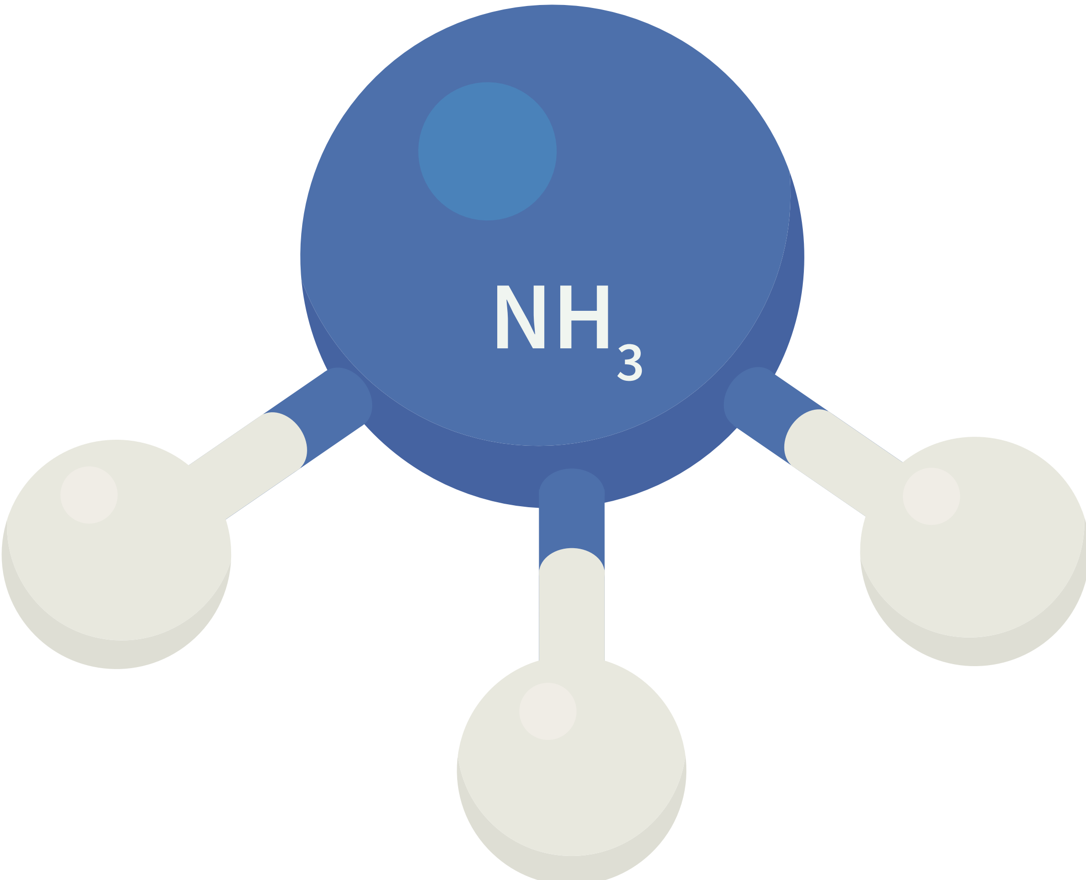
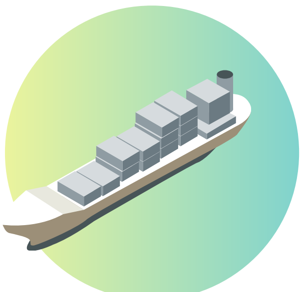
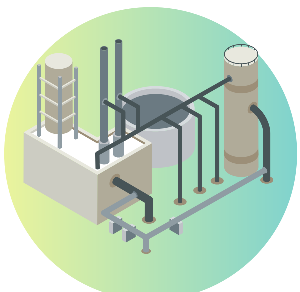
# Power-to-Ammonia



## IMPRINT

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Berlin, 30th March 2025

## ABBREVIATIONS

| | |
|---|---|
| ASU | Air Separation Unit |
| CC(U)S | Carbon Capture (Usage) Storage |
| $CO_2$ | Carbon Dioxide |
| GHG | Greenhouse Gas Emissions |
| $H_2$ | Hydrogen |
| IDLH | Immediately Dangerous to Life or Health |
| LoC | Loss of Containment |
| LCOA | Levelised Cost of Ammonia |
| LPG | Liquid Petroleum Gas |
| $N_2$ | Nitrogen |
| $NH_3$ | Ammonia |
| NPK | Nitrate – Phosphate – Potash (Kalium) |
| NZE | Net Zero Emission by 2050 Scenario |
| SMR | Steam Methane Reforming |

## Executive summary

This report examines the transformative potential of green ammonia as a critical pillar in advancing sustainable energy and agricultural systems. It highlights the economic, technological, and policy considerations essential for scaling up green ammonia production and underscores its role in addressing global challenges such as climate change, food security, and energy sovereignty. In a global energy transition with renewables at its core, ammonia contributes to the transition to renewable Power-to-X (PtX) solutions. This will not only defossilise critical industries but also enable countries to build resilient, self-sustaining economies. By leveraging collaborative innovation and targeted action, green ammonia can become a cornerstone of sustainable development, delivering both environmental and economic benefits to present and future generations.

The report serves as an initial guide for policymakers shaping climate and energy strategies, industry stakeholders, researchers, and development organisations seeking to support sustainable economic growth in the agriculture and energy sectors. It offers actionable insights to accelerate the adoption of green ammonia technologies and integrate them into the broader energy transition.

### Recommendations

**Policy Support:** So as to support the transition towards green ammonia production, policies need to be set in place on local, regional, national and international levels.  Some examples of policies are establishing carbon pricing, renewable mandates, and financial incentives to de-risk investments and accelerate adoption of green ammonia.

**Investment in R&D:** The cost competitiveness and adoption of green ammonia will depend on the affordability and development stage of the technologies supporting production. Investments in R&D are thus crucial, e.g. funding for technological innovations in electrolysis, ammonia synthesis, and energy storage reduces costs and improves efficiency.

**Public-Private Collaboration:** Allowing for greater stakeholder engagement, promoting public-private collaboration can foster partnerships to scale pilot projects, de-risk by sharing risks, and advance the commercialisation of green ammonia technologies.

**Focus on Resilience:** Encourage decentralised production models, which translated to sectors such as fertiliser production, can then enhance food and energy security in vulnerable regions.

**Overcome Legacy Systems:** The adoption and integration of decentralised green ammonia production is limited due to the legacy of integrated conventional and centralised Haber-Bosch grey ammonia production. To increase cost-competitiveness and rate of adoption, optimisation of green ammonia plants is necessary, as well as including the cost of renewable energy in CAPEX, not in OPEX.

# CONTENT

# 1 Green ammonia – Introduction

The global push towards a low-carbon economy is intensifying, with climate change mitigation as the primary driver. However, an equally pressing but often under-discussed factor is the need to bolster resilience against dependencies on traditional feedstocks (natural gas and other fossil fuels), e.g., ammonia for mineral fertiliser production. This dual imperative – climate action and resilience – has far-reaching implications for global food security, particularly in countries most vulnerable to external shocks.

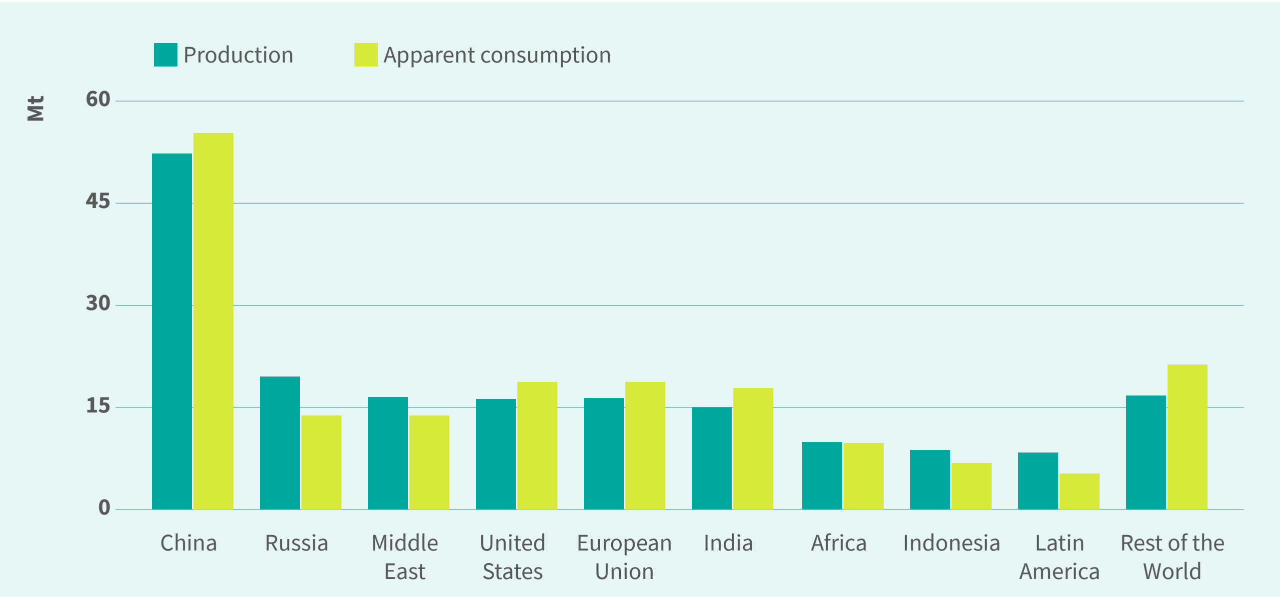


Figure 1: Ammonia production and consumption centres (International Energy Agency, 2021)


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The traditional method of producing (grey) ammonia involves steam methane reforming (SMR) of natural gas, a carbon-intensive process to produce hydrogen, which in turn is fed into the Haber-Bosch Synthesis (Liu X. K., 2022). The latter, developed in the early 20th century, synthesises ammonia from nitrogen and hydrogen. This process not only consumes significant amounts of energy, but also contributes to GHG emissions, with the production of conventional ammonia accounting for around 1 – 2% of global $CO_2$ emissions annually (Makepeace, 2022).

As countries and industries increasingly seek to reduce their carbon footprints, and efforts are intensified to transition to a more sustainable future, the demand for cleaner industrial processes and energy solutions is growing. One feedstock under scrutiny is ammonia ($NH_3$) – a compound that plays a critical role in several industries. The International Energy Agency (IEA) states that defossilisation of the ammonia industry is key to meeting global climate goals. Green ammonia has emerged as a potential alternative (Tjahjonoet al., 2023). It eliminates the $CO_2$ emissions associated with traditional production methods by utilising Power-to-X (PtX) technologies, which convert renewable energy into chemical products or energy carriers. This enables ammonia production through water electrolysis to generate hydrogen, followed by nitrogen fixation using renewable inputs.

Ammonia’s versatility underpins its importance in modern agriculture, industry, and emerging energy systems where it acts as a feedstock. As a platform chemical, it is essential to produce mineral fertilisers such as urea and ammonium nitrate, which have transformed agricultural yields and global food security. In industry, ammonia serves as a precursor for plastics, textiles, explosives, and refrigeration systems. In addition, its high energy density and storability make it a potential energy vector in the green hydrogen economy. As an energy carrier, ammonia can transport renewable hydrogen more efficiently than liquid hydrogen, and it shows promise as a carbon-free fuel for engines, gas turbines, and fuel cells, with ongoing research into $NO_x$ emissions during combustion.


Figure 2: Ammonia applications

However, safety considerations remain critical. Ammonia is a colourless gas with a noxious odour, highly soluble in water, and flammable. It is acutely toxic to humans and the environment in significant quantities, requiring stringent handling and production protocols.

As such, green ammonia represents an extraordinary opportunity to defossilise critical sectors of the global economy. The adoption of renewable energy-based ammonia over fossil-based one thus represents an important step in the transition towards sustainable production methods, in line with the Sustainable Development Goals (SDGs), as well as climate change mitigation. As technological advancements and investments in renewable energy continue to grow, green ammonia has the potential to become a major building block not only in the defossilisation of industrial processes, but also in the promotion of sound social, economic, and environmental development.


Figure 3: Green ammonia for SDGs. Icons from the UN SDGs official website:
**https://www.un.org/sustainabledevelopment/news/communications-material/**

# 2 Production of (green) ammonia

The key difference between green ammonia and current fossil-based production is the reduction of carbon emissions by using renewable electricity to produce hydrogen through water electrolysis, which is then combined with nitrogen from ambient air in the well-established Haber-Bosch process, also powered by renewable energy. This is a production process relying entirely on renewable, defossilised energy sources.

Today, the Haber-Bosch process dominates ammonia synthesis, accounting for more than 96% of global production (C. Tornatore, 2022). Typically, nitrogen is sourced from the air, and hydrogen is produced using natural gas (50%), oil (31%), or coal (19%) (Alfa Laval, 2020). This fossil-based production method is responsible for significant greenhouse gas (GHG) emissions and energy consumption.

The figure below shows the traditional Steam Methane Reforming (SMR)-based production of ammonia, detailing main inputs and scope 1 and 2 emissions.

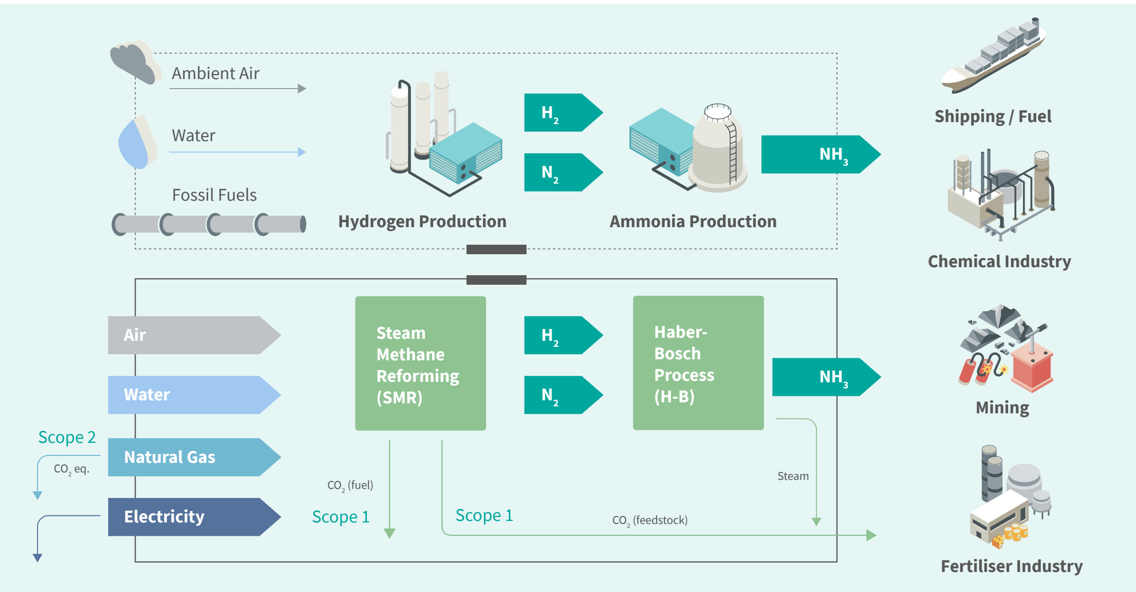


Figure 4: Traditional ammonia production route via Steam-Methane-Reforming of natural gas with scope 1 and 2 emissions


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Alternative methods for ammonia synthesis – such as thermocyclic, electrochemical, photochemical, plasma-based processes, and biological approaches – show promise, but remain in development stages. For now, the Haber-Bosch process is expected to remain dominant, with innovations focusing on integrating renewable energy into its framework (GIZ, Ministerio de Energía, Inodú, 2021) (Guidehouse Insights, 2022).

Within the renewables set-up, hydrogen is obtained through electrolysis, a process that uses electricity to split water ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$). Nitrogen ($N_2$) is sourced from ambient air via Air Separation Units (ASUs). In the Haber-Bosch process, nitrogen and hydrogen react at high pressure (100 – 200 bar) and high temperature (400–500°C) to form ammonia ($NH_3$). However, breaking the strong nitrogen bonds makes this process energy intensive. This set-up is shown in the figure below.

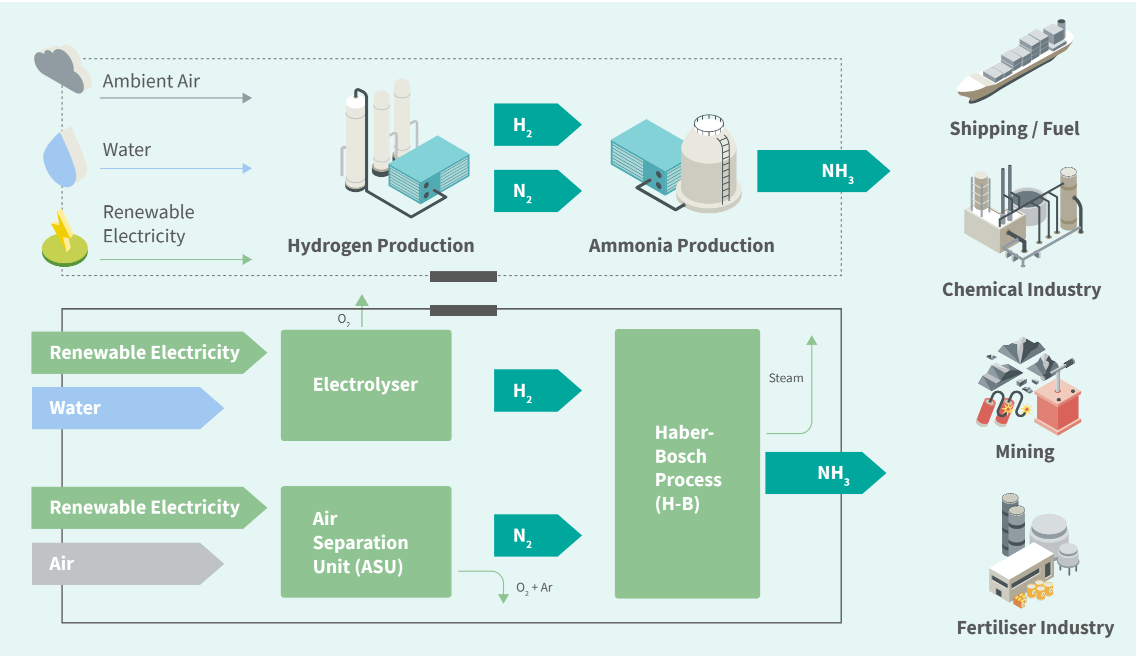


Figure 5: Green Ammonia Production via Electrolysis and ASU powered by Renewable Energies on-site.

However, since the Haber-Bosch process was designed to and optimised for a centralised fossil setup, powering it with renewable energy presents several challenges, including:

## Energy supply intermittency

The availability of renewable energy sources such as solar and wind is inherently variable, while the Haber-Bosch process requires continuous, stable energy inputs. Interruptions in energy supply can cause operational inefficiencies, downtime, or damage to equipment.


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A potential solution may lie in more robust energy systems that focus on upstream energy storage such as batteries or hydrogen buffers. These can stabilise power supply, allowing continuous operation despite fluctuations in renewable energy generation. Adoption of these technologies will eventually lead to truly 100 % renewable setups. A second option is more flexible plant design, i.e., developing Haber-Bosch plants capable of operating under variable loads. Modular, small-scale plants are thus being explored for their adaptability to renewable energy availability, and their ability to operate with any renewable energy input.

The same considerations apply to upstream green hydrogen production in terms of electrolyser operation. Green ammonia production relies on green hydrogen, hence on renewable electricity and water. This production step is also typically more efficient with a constant energy supply to the electrolyser.

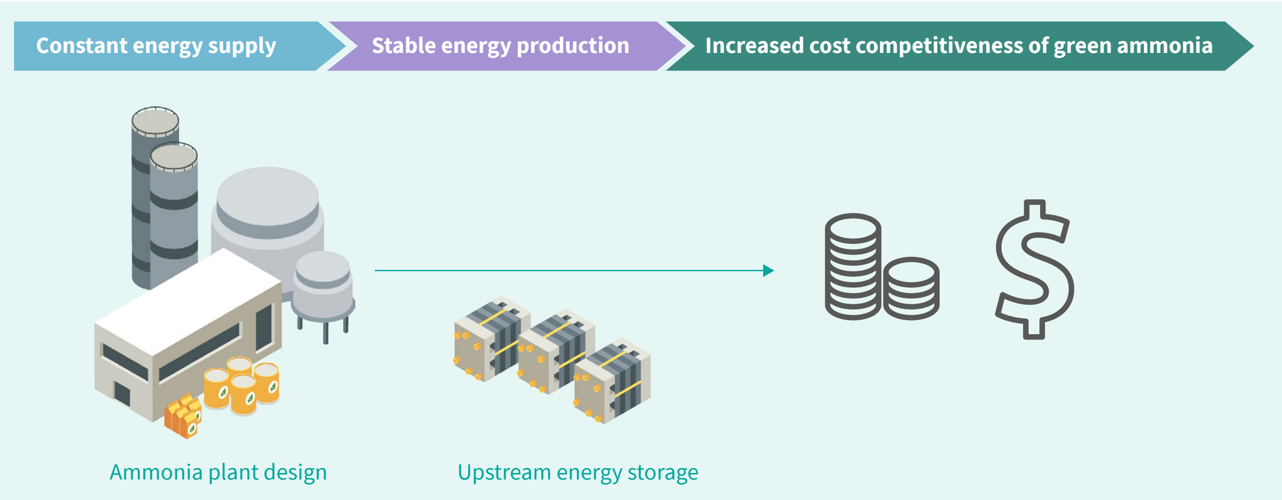


Figure 6: Energy intermittency and cost competitiveness of green ammonia

## Economic optimisation

Traditional ammonia plants derive energy from fossil fuels, while green ammonia plants use renewable electricity. The latter means higher costs for the time being. Robust carbon pricing mechanisms can alleviate the situation, but for an introductory period, a separate market is needed. When the learning curve is sufficiently advanced to compete with equivalent fossil products, the remaining challenge will be balancing energy storage and process flexibility with optimization for cost competitiveness. A more thorough elaboration of potential cost set-ups can be found in **Chapter 6**.

## Infrastructure and retrofitting costs

Converting existing ammonia production plants to run on renewable energy may require significant retrofitting of infrastructure. Retrofitting costs may be prohibitive, especially if conversion requires new energy storage systems and hydrogen production facilities.

Investment in new green ammonia plants specifically designed for renewable energy input may be more cost-effective in the long run than retrofitting existing plants. Additionally, integrating hybrid systems combining renewable energy with conventional energy sources could be a transitional approach.

According to current research, for a flexible Haber-Bosch reactor that can technically and economically operate on an intermittent renewable energy source, two key opportunities for innovation and change need to be addressed (DNV, 2021): parallel reactors to facilitate different ammonia production rates, and thermal storage to maintain the non-operating plant at operating temperature.

In summary, the transition to green ammonia is possible, if still costly (International Energy Agency, 2021). In order to produce green ammonia from the Haber-Bosch process, significant modifications to current configurations will be required, or entirely new processes will have to be implemented. Transforming ammonia production also requires strategic economic and policy interventions. By addressing the interplay between plant optimisation, energy costs, and market dynamics, stakeholders can support the development and deployment of green ammonia production technologies through coordinated action between governments, industries, and financial institutions.

# 3 Carbon footprint of ammonia production

Current ammonia production is responsible for approximately 450 million tonnes of direct net $CO_2$ emissions per year, about 1.2% of the global total. Conventional technologies release approximately 1.7 to 2.4 tonnes of $CO_2$ per tonne of ammonia produced (Hollevoet, 2022). Moreover, the production of hydrogen itself is a significant contributor to the overall emissions in the ammonia synthesis process. Notably, 90% of the carbon emissions associated with ammonia production stem from hydrogen production with fossil fuel sources (Sousa, 2022). Consequently, the conventional ammonia production process not only contributes to direct emissions but also has substantial indirect emissions associated with the extraction and processing of fossil fuels.

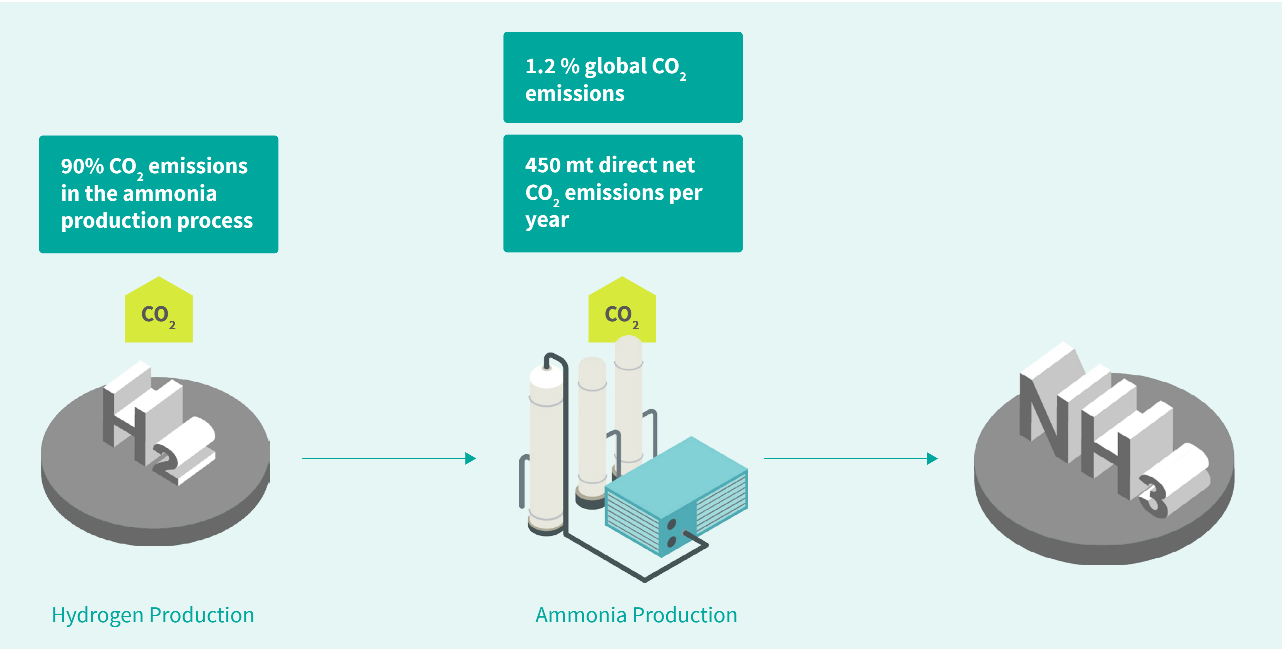


Figure 7: Grey ammonia $CO_2$ emissions from production


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As a result, several international environmental institutions have been elaborating strategies to reduce carbon emissions stemming from ammonia production (e.g. IRENA or IEA). For instance, the International Energy Agency (IEA), in its Net Zero Emissions by 2050 (NZE) scenario, proposes a pathway to reduce the carbon footprint of ammonia production by 96%, to just 0.1 tonnes of CO2/tonne of ammonia (considering only the production process) (Thor, 2019). These reports and analyses allow for the identification of suited measures and incentives needed to mitigate GHG emissions, and enable technological innovations to support the energy transition, such as that of green ammonia.

## Grey ammonia carbon footprint

The traditional Haber-Bosch process, which synthesises ammonia by combining nitrogen with hydrogen under high pressure and temperature, is a significant source of emissions, responsible for approx. 400-450 MtCO2eq per year (~2.4 $tCO_2/tNH_3$) (Hatzell, 2024). Grey ammonia, derived from natural gas, accounts for 70% of global production, with an emissions intensity of 1.6 – 1.8 $tCO_2/tNH_3$ (Hatzell, 2024). On the other hand, brown ammonia, produced from coal, accounts for 30% of global production but emits about 50% more than grey ammonia, with an emissions intensity of 2.4 – 3.2 $tCO_2/tNH_3$.

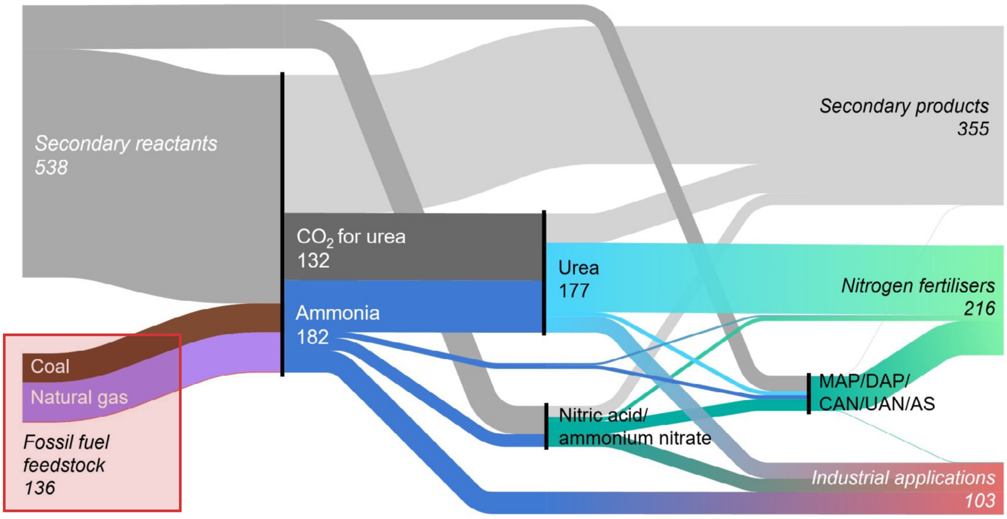


Figure 8: Mass flows in the ammonia supply chain: from fossil fuel feedstocks to nitrogen fertilisers and industrial product
https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary

Beyond direct emissions, hidden $CO_2$- equivalent emissions along the value chain should be considered when determining the carbon footprint of ammonia production. Emissions here depend on the infrastructure for natural gas production, processing, and transport, where methane emissions can be substantial: up to 0.9 tonnes of $CO_2$-equivalent per tonne of ammonia (IRENA, AEA, 2022). However, methane emissions have a much greater impact on global warming – 30 times greater than $CO_2$ on a 100-year time scale – making indirect emissions an important aspect in ammonia production.

As modern grey ammonia plants approach their theoretical minimum energy consumption – further improvements in energy efficiency cannot technically be achieved – their decarbonisation potential becomes increasingly limited, and their reliance on fossil fuels remains (U.S. Department of Energy, 2022).

Carbon Capture and Storage/Utilisation (CCUS) is used to reduce carbon emissions at ammonia production sites. When carbon is captured and used, the ammonia is termed blue. While CCUS can reduce the emission intensity of ammonia to 0.1 – 0.2 $tCO_2/tNH_3$, it increases the energy consumption of an ammonia production plant by 0.7 GJ/tNH3 (Hatzell, 2024).

However, there are upstream methane leaks for ammonia with or without CCS, and potential downstream $CO_2$ slippage from storage must also be considered. Lifecycle emission reductions achievable by implementing CCS at an SMR-based production site may thus be limited to 60 – 85% (Committee on Climate Change, 2018).

While blue ammonia can serve as a transitional solution, its dependency on fossil-based hydrogen production and CCUS's energy intensity limits its potential to decrease emissions compared to green ammonia.

## Green ammonia carbon footprint

Green ammonia production using hydrogen obtained from electrolysis could theoretically reduce the emission intensity of ammonia towards 0 $tCO_2/tNH_3$. However, if the electrolysis is connected to the grid, the emission intensity of the grid would have to decrease substantially. The carbon intensity of the electricity grid would have to be below 180 $gCO_2$/kWh for the emission intensity of electricity-driven ammonia production to be lower than the state-of-the-art of grey ammonia production (International Renewable Energy Agency, 2021).

Moreover, studies show that while the direct emissions from green ammonia production may be negligible, overall lifecycle emissions must be considered. For instance, the production of renewable energy equipment, such as solar panels and wind turbines, involves emissions that can contribute to the carbon footprint of green ammonia (Saygin, et al., 2023). However, this holds true for conventional production equipment, too.

The figure below shows the $CO_2$ emissions per tonne of ammonia produced by different production routes. The underlying figures are compiled from various resources and countries which explains the rather large stretch in potential emissions.

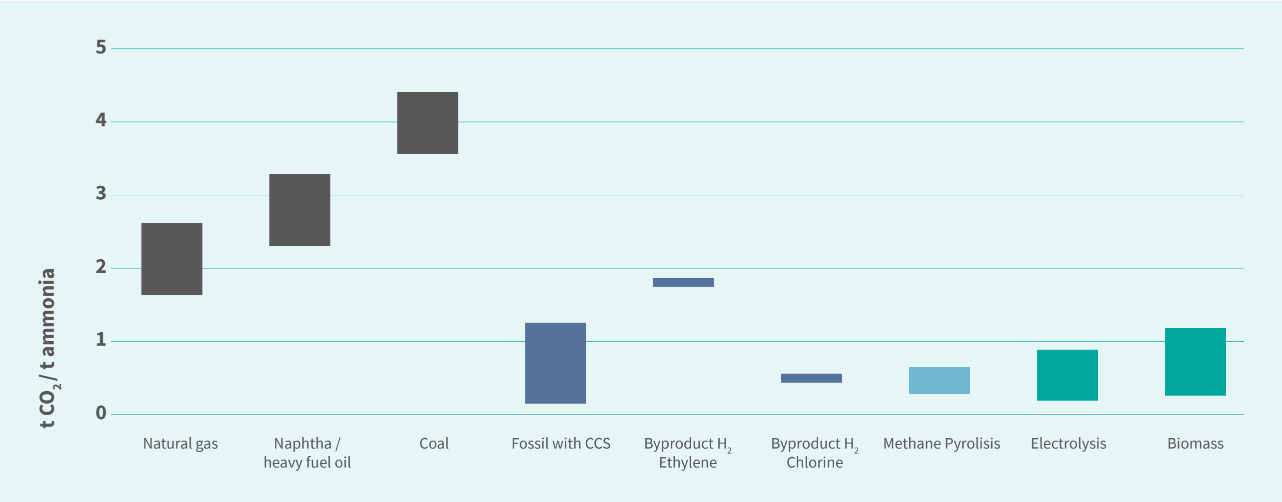


Figure 9: Illustrative ranges of estimated greenhouse gas emissions of ammonia production (IRENA, AEA, 2022, S. 71/fig.26).

As green ammonia becomes the most viable pathway for defossilisation in the long term, transitioning requires addressing technical challenges, lifecycle emissions, and economic competitiveness. Policymakers and industry stakeholders must collaborate to support innovations, implement robust carbon pricing, and incentivise green ammonia adoption to achieve global climate goals.

# 4 Storage and transport infrastructure

The infrastructure required for green ammonia production and distribution is another critical factor in its uptake. The development of a robust supply chain for green ammonia, including production facilities, storage, and transport networks, is essential for scaling up its use (Salmon, 2021) (Ankathi, 2022). As demand for green ammonia grows, particularly in sectors such as shipping, significant investments will be necessary to build the infrastructure needed to support its widespread adoption (Verschuur, 2024). This infrastructure development will also create new economic opportunities and jobs in the renewable energy sector, further incentivising the transition to green ammonia.


Figure 10: Infrastructural development for green ammonia

Major global ammonia production centres include countries such as the United States, Russia, China, and India. These countries have developed extensive ammonia transport networks that facilitate both domestic distribution and international exports.


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## 4.1. Ammonia conditioning and storage

An advantage of ammonia is that there is already infrastructure for storage, transportation, and experience in handling (Rouwenhorst, Hamb, Mulc, & Kerstenb, 2019). Mature storage facilities and technologies for ammonia have been in place for over 100 years.

Production plants require ammonia storage facilities, and it is common practice to have a storage capacity of at least 15 days of production (IRENA, AEA, 2022). This storage acts as a buffer capacity to smooth out fluctuations in production and demand between the ammonia plant and downstream units, shipments, and loading as well as unloading points. Ammonia is usually handled in liquid form, but in some cases it may be cheaper to supply ammonia (anhydrous ammonia) to downstream users due to savings in refrigeration energy in the ammonia plant. Currently, the main methods for storing ammonia are:

**Pressure storage** at ambient temperature in spherical or cylindrical pressure vessels with capacities from 150 up to 1,500 tonnes per vessel. It is suitable for storing small quantities of ammonia as intermediate storage between the ammonia plant and the customers, balancing production fluctuations with downstream units processing pressurised ammonia (Humphreys, 2020).

**Semi-refrigerated storage** at around 0°C in an insulated, usually spherical, pressure vessel for quantities up to 3,000 tonnes. Ammonia vapour is compressed, and then liquefied by water cooling. The system is similar in principle to fully refrigerated storage, but much less sophisticated and relatively inexpensive (IRENA, AEA, 2022).

**Low-temperature or atmospheric storage** at -33°C in insulated cylindrical tanks for about 50,000 tonnes per tank. While this method is preferred for storing large quantities of liquid ammonia, it presents risks associated with the presence of small gaseous impurities in the ammonia that need to be purged (e.g. nitrogen, hydrogen, argon), and ammonia stress corrosion cracking.

**Solid-state storage** in line with a shift towards small-scale ammonia plants. These use complex, 'solid', materials (e.g. metal hydrides, metal fullerides and borohydrides, amide/imide systems). This type of storage has advantages as it is inherently safer than other methods and prevents toxic leaks (T. Zhanga et al., 2018). However, as this technology is still under development, more research must be done before solid-state storage can be considered as commercially viable.

The first three forms of storage are mature technologies widely used around the world and combinations of these methods can be found in practice (Yoshida et al., 2020).

Another method of large-scale ammonia storage is cavern and underground storage, which is a common practice in the Liquefied Petroleum Gas (LPG) industry. However, due to issues related to contamination of the liquid ammonia and the lack of suitable geological sites, such storage facilities are not usually considered feasible (Brown, 2018). It is therefore not discussed further.

Storage capacity and costs are the main factors influencing the choice of storage. For large volumes, the capital investment costs for atmospheric pressure storage are significantly lower than for pressurised storage. Despite

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higher energy costs, it is still more economical. This is particularly true for the storage of ammonia coming from the synthesis loop (where low temperatures are required to separate ammonia from the reactants) and for the loading and unloading of refrigerated vehicles (Brown, 2018).

In addition to storage capacity, the required conditions and the amount of ammonia flowing in and out of storage (gaseous, warm liquid, cold liquid) are secondary factors to consider (AMMPOWER, 2022). In many cases ammonia terminals – both for export from production plants and for import from the distribution system – involve a combination of pressurised spheres and refrigerated storage tanks as ammonia must be delivered at -33°C to a ship or barge and at ambient temperature to pipeline, rail, or road transport vehicles (Humphreys, 2020).

## 4.2. Ammonia final conditioning and transport

As a global commodity, ammonia is already widely transported and traded today (IRENA, AEA, 2022). In 2021, the volume of ammonia traded worldwide was estimated at approx. 18 million metric tonnes. It is forecast to grow steadily in the coming years, reaching a volume of around 238 million metric tonnes by 2050 (Statista, 2022). Global ammonia production capacity currently stands at 240 million metric tonnes (2023) and is expected to rise to almost 290 million metric tonnes by 2030 (Statista, 2024).

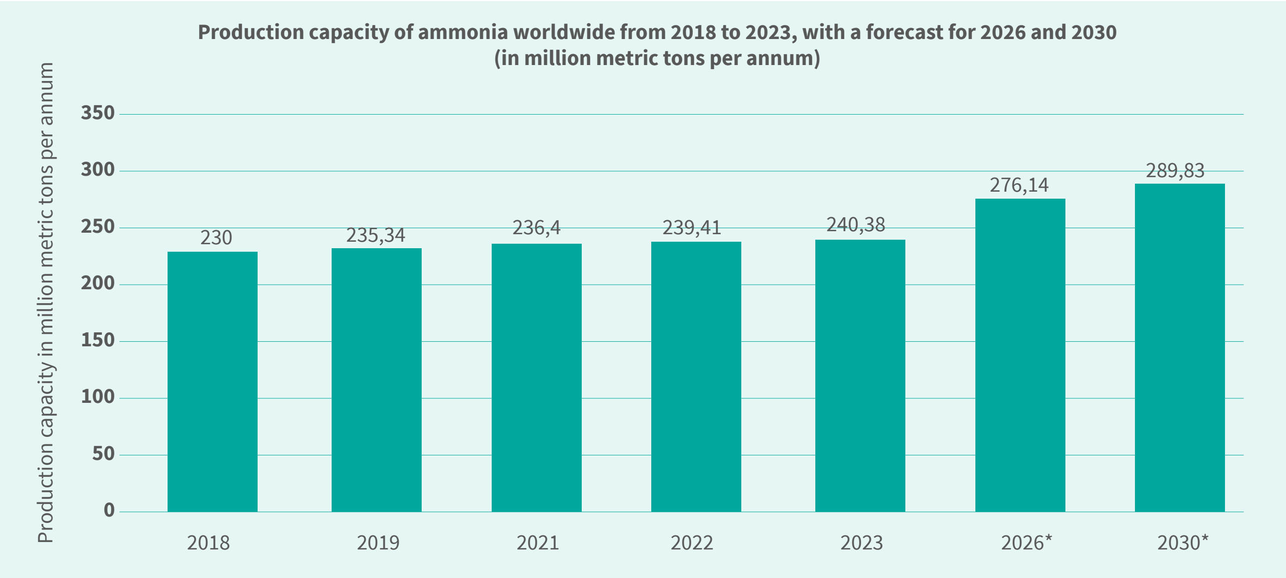


Figure 11: Production capacity of ammonia worldwide from 2018 to 2023, with a forecast for 2026 and 2030 (Global ammonia annual production capacity | Statista)

There is a large network of ports, ships, pipelines, and dedicated storage facilities in ammonia producing and consuming countries, as well as a high level of transport infrastructure maturity.

Additionally, ammonia can be transported using current fossil fuel infrastructure and all equipment suitable for transporting Liquified Petroleum Gas (LPG), thus facilities often are used interchangeably to transport the two materials (AMMPOWER, 2023).

## Current transport methods

**Pipeline transport** is the most economical option for transporting ammonia over long distances (O. Elishav, 2021). Extensive networks exist in countries such as the United States, Ukraine, and Russia, while shorter pipelines are common in Europe. Steel is typically used to prevent stress corrosion cracking, which can occur in pipelines made out of zinc, copper, or aluminium. Safety measures are critical to mitigate risks such as ruptures and gas leaks.

**Ocean and barge transportation** ship between 18 and 20 million tonnes of ammonia by sea annually. The maritime transport infrastructure is highly developed, with established international shipping routes and a global network of ports capable of handling ammonia (American Chemical Society, 2022). Freight costs depend on factors such as distance, fuel prices, ship availability, and port operations. LPG transport competes with ammonia for shipping capacity, influencing costs (Yoshida et al., 2020).

**Rail transport** mainly serves smaller processing plants and wholesalers, is used for shorter distances, and can complement large sea and pipeline shipments. Typically, rail is more expensive per tonne/kilometre than pipeline or barge; however, according to Yoshida et al. (2020), in some cases it can be cheaper than a combined pipeline/barge and truck transportation route.

**Truck transport** is the most expensive method of transporting ammonia. It is mainly used for distances of less than 150 km, or where other means of transport are not available, for instance, supplying retail distribution centres or small manufacturers of liquid synthetic fertilisers.

While the current ammonia distribution network is mature, significant expansion and upgrading will be required to meet the growing demand for ammonia, especially green ammonia, as a hydrogen carrier. Approximately 150 ports and terminals handle ammonia today, but this number may need to triple to meet growing global demand (IEA, 2024). Over 50 new export terminals have already been announced, reflecting the growing interest in ammonia infrastructure.


Figure 12: Existing and announced port infrastructure projects for hydrogen and hydrogen-based fuels trade and bunkering (IEA, 2024)

The main aspects determining mode of transport are available infrastructure, access, and cost. Furthermore, new policies to reduce GHG emissions may shift some of the transported cargo from polluting practices to more environmentally-sound ones (e.g. from trucks to barges) (Yoshida et al., 2020). Regional differences also influence transport choice. In the United States, an extensive pipeline network connects production facilities on the Gulf Coast to agricultural regions in the Midwest. Rail transport is also widely used where pipelines are unavailable, supplying the fertiliser industry (Bakir, 2023), while in Europe countries rely on shorter pipelines, rail, and barge transport. Integration with pre-existing transport systems for chemicals ensures efficient distribution across Europe. Research programmes by the European Commission aim to enhance intermodal transport and reduce emissions (Nowicki, 2023).

The ammonia transport infrastructure is a complex and well-established system that plays a crucial role in the global economy. With the increasing importance of ammonia as a potential hydrogen carrier and its contribution to defossilisation efforts, infrastructure will need to evolve to meet new demand. Investments in safety, technological innovations, and intermodal transport solutions will be key to ensuring the efficient and sustainable transport of ammonia in the future. As the industry adapts to these changes, the role of ammonia in energy systems and agriculture is likely to expand, reinforcing its importance in the global economy.

## 4.3. Ammonia as hydrogen carrier

Since green hydrogen is not easily stored and will likely be produced in places far from centres of consumption, transport becomes an important aspect of its development. Ammonia is being discussed as a promising hydrogen carrier for several reasons:

**High hydrogen ratio:** Ammonia is one of the most efficient hydrogen carriers available. Its high hydrogen density allows for significant amounts of hydrogen to be stored and transported in a relatively compact form (Hu, 2021) (Aligholizadeh, 2023).

**Ease of conditioning for transport:** Ammonia can be easily liquefied at atmospheric pressure and temperatures below -33.4°C. This property facilitates its storage and transport in liquid form, which is advantageous compared to liquid hydrogen, which requires cryogenic conditions of -253°C (Okanishi, 2015).

**Partially existing infrastructure:** The successful implementation of ammonia as a hydrogen carrier requires the development of appropriate infrastructure for storage, transport, and distribution. Existing ammonia transport networks can be leveraged, but additional investments are required to adapt these systems for hydrogen applications (Shi, 2022). This includes the establishment of ammonia cracking facilities in harbour facilities and/or smaller cracking facilities distributed throughout the country and close to the customers, and fuel cell systems compatible with ammonia.

Widespread use of ammonia as a hydrogen carrier will require ammonia cracking facilities to produce pure hydrogen from ammonia at the point of consumption. Harbour-based cracking plants for bulk hydrogen supply and smaller decentralised units for local distribution will play a crucial role. Furthermore, investments in the modification of existing infrastructure and the construction of new facilities will ensure the safe and efficient handling of ammonia on a larger scale. However, ammonia cracking facilities are not yet mature and while some companies (like H2SITE, Starfire Energy, and Amogy) are working on ammonia cracking solutions, widespread commercial deployment is still limited. Moreover, the energy consumption of such a facility is substantial.

Ammonia is a highly promising hydrogen carrier that overcomes many of the challenges associated with hydrogen's storage and transport. Its high hydrogen density, ease of liquefaction, and existing infrastructure make it an efficient and scalable solution for long-distance hydrogen transport. With appropriate investments in cracking facilities, safety measures, and fuel cell technology, ammonia can play a pivotal role in enabling the hydrogen economy and advancing global defossilisation efforts. The carbon-free nature of ammonia is one of its strongest advantages as a hydrogen carrier. Additionally, its transport and storage require less energy-intensive processes compared to liquid hydrogen. While care must be taken to prevent ammonia spills or leaks, the risks are manageable with existing technologies and safety protocols.

# 5 Safety considerations

While ammonia is a viable hydrogen carrier, its toxicity and corrosiveness pose safety challenges. Effective safety protocols and monitoring systems must be implemented to mitigate the risks associated with ammonia transport and use (Rahman, 2023). Research into safer handling practices and materials resistant to the corrosive effects of ammonia is ongoing.

Ammonia is toxic to humans, animals, and aquatic organisms, and its production process carries risks of loss of containment (LoC), explosion, and fire. The handling of large quantities of ammonia in storage systems requires stringent safety measures.

Over the past 100 years, improvements have been made to handle ammonia safely and implement barriers to prevent catastrophic events. Most ammonia-related incidents have occurred during the handling of further processed products, such as ammonium nitrate, rather than ammonia itself (Elishav et al., 2021). While ammonia itself is hazardous, toxic, and flammable, its risks are generally well understood and managed during production, storage, and transport. In contrast, ammonium nitrate is extensively used as a synthetic fertiliser and in explosives. The latter poses significant hazards due to its potential to detonate under certain conditions, such as exposure to heat, shock, or contamination with incompatible substances, and has led to numerous catastrophic incidents in the past.

The following sections outline the potential hazards, risks, and environmental impacts associated with ammonia. It is important to note that this general information does not replace supplier-specific safety measures, regulations, and risk assessments.

## 5.1. Hazards of anhydrous ammonia

### Toxicity and corrosiveness

Ammonia is a colourless, corrosive gas with a pungent odour detectable at concentrations as low as 5 ppm, well below levels that pose a health risk (Crolius S. H., 2020). Despite having low flammability compared to many fuels, its toxicity and reactivity with water make it a significant hazard to human health and the environment.

| Substance | Health | Flammability | Reactivity |
|---|---|---|---|
| Ammonia | 3 | 1 | 0 |
| Hydrogen | 0 | 4 | 0 |
| Gasoline | 1 | 3 | 0 |
| LPG | 1 | 4 | 0 |
| Natural Gas | 1 | 4 | 0 |
| Methanol | 1 | 3 | 0 |

**No hazard = 0** **Severe hazard = 4**

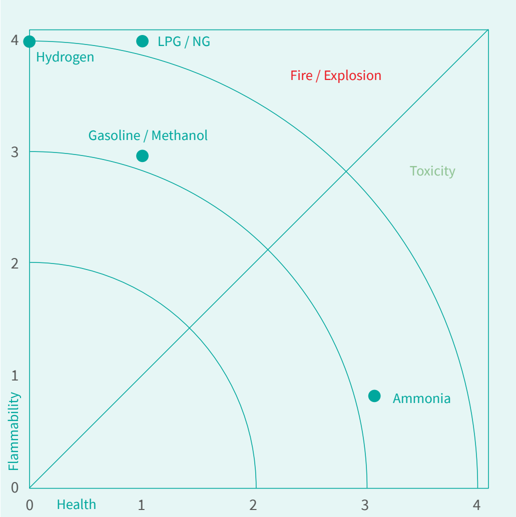


Figure 13: Toxicity and Fire/Explosion comparison of different fuels (Karabeyoglu, 2012).

## Fire and explosion risks

Ammonia is classified as only slightly flammable and requires high temperatures and energy to ignite. The flammability range in air is low (15-28%), making outdoor applications relatively safe (Mengyao et al., 2022). However, in confined spaces, such as refrigeration facilities, the likelihood of ignition increases, requiring careful ventilation and monitoring (Valera-Medinaa et al., 2018).

Compared to other fuels, the low flammability of ammonia is considered a safety advantage, especially in transport applications (Hansen & Han, 2021). Even in the rare event of combustion, ammonia burns at a slow rate, reducing the potential for rapid explosions.

## Loss of Containment (LoC)

Loss of containment, especially of large volumes of ammonia, can pose serious risks to living organisms. Leaks of liquid ammonia under pressure produce dense white aerosol clouds, hazardous to human health. In contrast, leaks at atmospheric pressure generate gaseous ammonia which dissipates rapidly into the atmosphere. Refrigerated storage of ammonia at atmospheric pressure is inherently safer than pressurised storage for large volumes (Rouwenhorst et al., 2019).

Material selection is critical to prevent leaks caused by the corrosive properties of ammonia. Corrosion-resistant materials and effective leak detection and ventilation systems are essential safeguards.

## 5.2. Potential impacts of ammonia

### Human health impacts

Ammonia is highly irritating and corrosive, and exposure by inhalation, ingestion, or skin contact can cause serious injuries. Inhalation of high concentrations leads to respiratory damage, lung failure, and death (Hansen & Han, 2021). Ammonia reacts with body fluids such as sweat and respiratory tract moisture, causing irritation, burns, and possibly blindness (Rouwenhorst et al., 2020).

The IDLH Levels ("Immediately Dangerous To Life or Health") from the National Institute for Occupational Safety and Health (NIOSH) define 300 ppm as the "Immediately Dangerous to Life or Health" level, where exposure for more than 30 minutes poses a risk of irreversible harm (AMMPOWER, 2023).

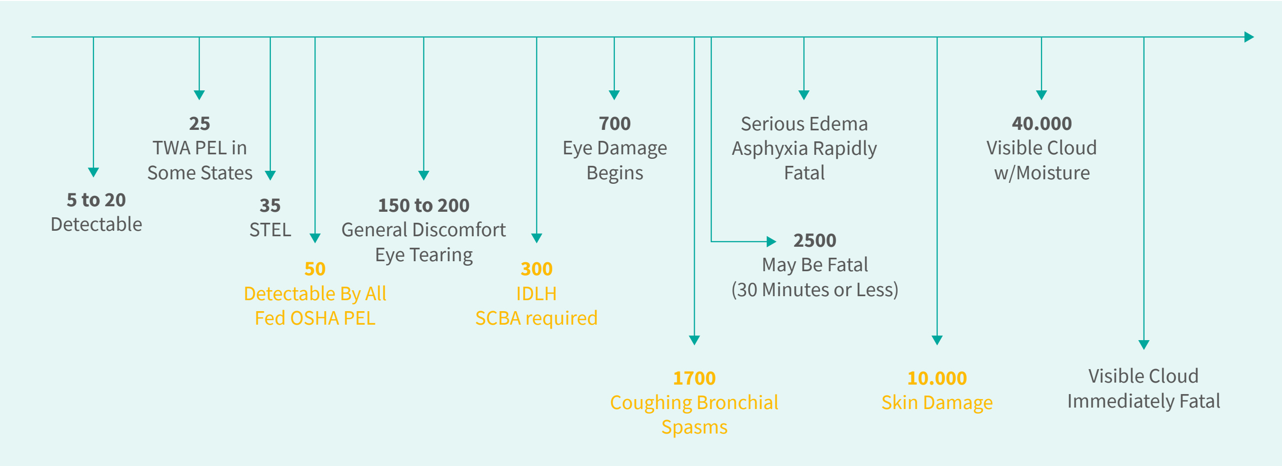


Figure 14: Effect of ammonia exposure on human health. Taken from (Rouwenhorst, Krzywda, Benes, Mul, & Lefferts, 2020).

### Environmental impacts

Ammonia emissions do not cause damage to the ozone layer or contribute directly to climate change. However, ammonia spills in aquatic ecosystems can cause significant damage. Concentrations as low as 0.04 mg/L can be lethal to some marine organisms and freshwater ecosystems are similarly vulnerable (Australian and New Zealand Guidelines for Fresh & Marine Water Quality, 2000). Sensitive ecosystems such as mangroves, estuaries, and wetlands are particularly at risk (IRENA, 2021).

Ammonia has several impacts on aquatic ecosystems. Plants are usually more tolerant to a potential leaks, but are affected by higher pH levels. This can cause a range of issues, from algal growth and oxygen depletion to mortality of aerobic organisms and of fish, as well as changing food chain dynamics, and slower reproductive rates.

Ammonia leaks can contaminate soil and groundwater, affecting agricultural productivity and water quality. The presence of ammonia in the soil can alter microbial communities, reduce soil fertility and disrupt nutrient cycling. Furthermore, ammonia can leach into groundwater, posing risks to drinking water supplies (Gezerman, 2022). This poses a significant threat to human lives and wildlife.

Throughout the ammonia combustion processes, as well as a result of an ammonia leak, emissions of reactive nitrogen compounds can occur. The main difference between reactive nitrogen ($NO_x$ and $N_2O$) and nitrogen ($N_2$) lies in the ability of the reactive form to undergo the process of nitrogen fixation and deposition in the environment. While the process of nitrogen fixation is quintessential for plant health and growth (underlying process in fertilisation), in higher, industrial quantities, it can have adverse environmental consequences. For instance, $NO_x$ emissions can contribute to air pollution through the formation of fine particulate matter (PM2.5). Reactive nitrogen deposition can also disrupt the natural nitrogen cycle, degrading biodiversity in forest ecosystems by favouring nitrogen-efficient plant species over others, thereby reducing species diversity (Bertagni, et al., 2023). The accumulation and deposition of reactive nitrogen in forest ecosystems has been identified as a major risk for plant diversity degradation.

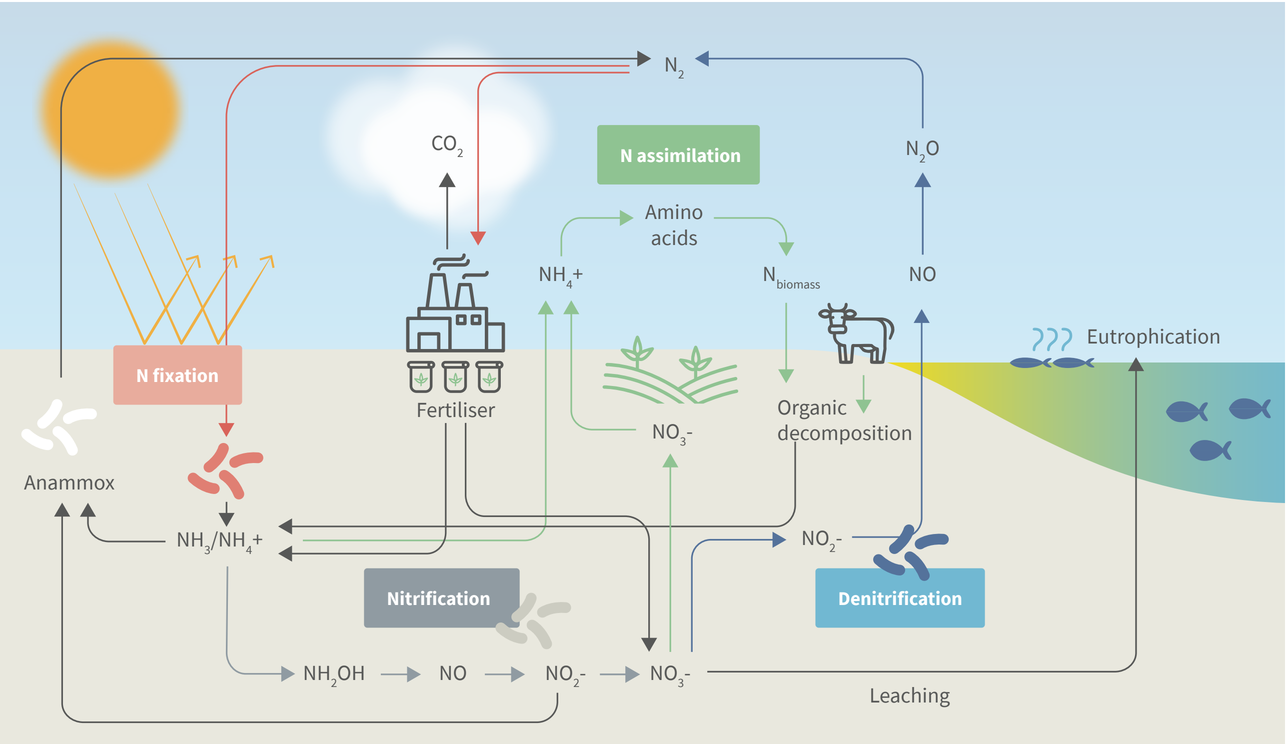


Figure 15: Environmental Impacts of perturbing the nitrogen cycle (Bertagni, et al., 2023).

Adverse environmental effects of reactive nitrogen emissions can however be mitigated. By taking the correct safety precautions to prevent ammonia leaks, and by adopting technologies that limit reactive nitrogen emissions (e.g. ammonia cracking technologies over ammonia combustion ones) can thus minimise environmental impacts.

In addition to the environmental impacts that ammonia can have, it is important to remember that each by-product of ammonia has its own safety considerations that must be adhered to. Two such products are ammonia-based nitrogen fertilisers and ammonia as a fuel.

## Potential safety impacts of synthetic ammonia-based fertilisers

One of the primary risks associated with synthetic ammonia-based fertilisers is their potential for decomposition, particularly in products containing ammonium nitrate. Ammonium nitrate-based fertilisers can be categorised into two groups: those containing pure ammonium nitrate and those formulated as mixtures with other materials, such as NPK (Nitrate-Phosphorus-Potash) fertilisers, which are among the most widely used.

Decomposition in these fertilisers can be triggered by exposure to external heat sources or contamination with substances such as organic matter, copper, and other metals. When exposed to intense heat or confined spaces, ammonium nitrate can undergo a violent reaction, releasing nitrogen, oxygen, and water, along with large amounts of energy. This rapid release of gases can result in a build-up of pressure, leading to explosions. To mitigate these risks, many nitrogen fertilisers are designed with safety features that interrupt decomposition when the heat source is removed. Such products are considered inherently safer. However, during transport, it remains essential that companies are aware of and follow all necessary safety measures to minimise risks.

Key hazards include gas release during decomposition and the release of large quantities of irritating and toxic gases, including nitrogen oxides ($NO_x$) and ammonia vapours, which pose significant risks to human health and the environment. In the event of an explosion, the rapid generation of high-pressure gases can result in catastrophic explosions, as seen in the Beirut port disaster in 2020. In this case, a combination of heat, containment, and contaminants led to the detonation of approximately 2,750 tonnes of improperly stored ammonium nitrate.

To minimise the risks associated with ammonium nitrate decomposition, several strategies are employed as mitigation measures. Certain stabilisers can be added to ammonium nitrate-based fertilisers to reduce their sensitivity to heat and contaminants: so-called safety additives. In addition, ammonium nitrate should be stored in well-ventilated facilities, away from heat sources and incompatible materials such as fuels or metals. Above all, strict adherence to international safety standards and transport regulations is essential to ensure safe handling and storage.

While ammonium nitrate is a valuable component of synthetic fertilisers, its chemical reactivity requires careful handling to prevent decomposition and potential accidents. Understanding the chemical processes involved in its decomposition highlights the importance of strict safety measures, appropriate storage conditions, and effective risk management practices to mitigate hazards. With these precautions, ammonium nitrate-based fertilisers can be used safely and effectively in agriculture.

## Potential impact of ammonia as a shipping fuel

As the maritime industry seeks alternatives to traditional carbon-based fuels, ammonia has emerged as a promising candidate. Its carbon-free nature and potential for zero-emission production align with global decarbonisation targets. However, the use of ammonia as a shipping fuel presents unique challenges, including safety considerations and environmental risks that must be carefully managed.

Exposure to ammonia vapours can cause severe respiratory problems, and leaks pose serious risks to crew, port workers, and nearby communities. Stringent safety protocols, such as leak detection systems and emergency response measures, are essential for safe handling.

Ammonia is also corrosive to certain materials, including copper, brass, and zinc. Ships using ammonia as a fuel will need specific materials and coatings to prevent corrosion in fuel tanks, pipelines, and other components of the fuel system. Potential leaks during storage, bunkering, or operation can result in environmental contamination, posing significant risks to local ecosystems.

Although ammonia is less flammable than conventional marine fuels, it can form explosive mixtures with air under certain conditions. Specialised ventilation systems, inerting protocols (use of inerting gases to prevent explosions when the air or atmosphere is flammable), and fire suppression technologies are necessary to mitigate this risk. Moreover, unburned ammonia escaping into the atmosphere during combustion, referred to as ammonia slip, does not only reduce efficiency, but also poses further risks to humans and ecosystems. Combustion systems must be designed to minimise ammonia slip through precise fuel injection and combustion control. Advanced exhaust gas treatment systems, such as Selective Catalytic Reduction (SCR), are required to minimise improperly combusted nitrogen oxide ($NO_x$) emissions. In addition, nitrous oxide ($N_2O$) emissions can undermine the environmental benefits of using ammonia as a fuel. Ongoing research is focused on reducing $N_2O$ emissions through improved combustion technology and catalysts.

| | |
|---|---|
| Nitrogen Oxide ($NO_x$) | Mainly formed during combustion processes of ammonia production (e.g. burning fuel in reforming furnaces), and during nitric acid production (downstream ammonia synthesis), nitrogen oxides can contribute to air pollution, among other things. |
| Nitrous Oxide ($N_2O$) | Generated as a byproduct in nitric acid production often associated to ammonia plants, as well as catalytic oxidation processes (e.g. ammonia oxidation in nitric acid synthesis), it is a potent greenhouse gas and contributes to ozone layer depletion. |

While it is an interesting development, ammonia combustion in engines is still in its early stages. Dual-fuel engines that can run on both ammonia and conventional fuels are being explored as a transitional solution, but challenges remain in achieving stable combustion, minimising emissions, and optimising engine efficiency.

To unlock the potential of ammonia to defossilise the shipping industry, the industry needs to invest in advanced combustion technologies, robust safety systems, and comprehensive training for personnel. Further collaboration between industry stakeholders, regulators, and researchers will be essential to address technical and operational challenges, paving the way for ammonia to play a central role in the transition to a cleaner, more sustainable shipping sector.

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| Safety Risks | Safety Measures |
| --- | --- |
| Ammonia Toxicity and Corrosiveness | Follow international and national safety regulations for transport and handling<br>Keep human exposure below toxic levels<br>Prevent leaks and adopt technologies that limit environmental damage (e.g. ammonia cracking over ammonia combustion). |
| Ammonia Flammability and Explosiveness | Low risk<br>Careful ventilation and monitoring must be set in place |
| Ammonia Loss of Containment (LoC) | Refrigerated storage of ammonia at atmospheric pressure is safer for large volumes<br>Use of corrosion-resistant materials and effective leak detection and ventilation systems |
| Fertilisers – Decomposition and Explosion Risks (esp. in view of Ammonium Nitrate) | Nitrogen fertilisers designed with features interrupting decomposition. For further precaution, safety additives can be added to reduce sensitivity<br>Additional safety measures need to be implemented in view of transport according to regulation<br>Storage in well-ventilated facilities |
| Marine Fuel – Leak, Explosion, and Ammonia Slip Risks | Leak detection systems and emergency response measures<br>Coating ships in specific materials to prevent corrosion<br>Specialised ventilation systems, inerting protocols, fire suppression technologies<br>Precise fuel injection to minimise ammonia slips, as well as combustion control and exhaust gas treatment systems (e.g. Selective Catalytic Reduction) |

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# 6 Economic considerations for green ammonia production

## 6.1. Economic landscape

The transition from grey to green ammonia presents both challenges and opportunities within the global economic landscape. Green ammonia production entails higher initial capital investment due to the costs associated with renewable energy infrastructure and advanced technologies such as electrolysis (Vinardell, 2023; Saygin et al., 2023). However, as technology matures and economies of scale are achieved, production costs are expected to decrease significantly. By 2030, green ammonia could become cost-competitive with grey ammonia in regions with high natural gas prices (IRENA, AEA, 2022; Wang, 2022). Additionally, growing global demand for sustainable products and increasing regulatory support are likely to further enhance its economic viability (Cesaro, 2021; Salmon, 2021).

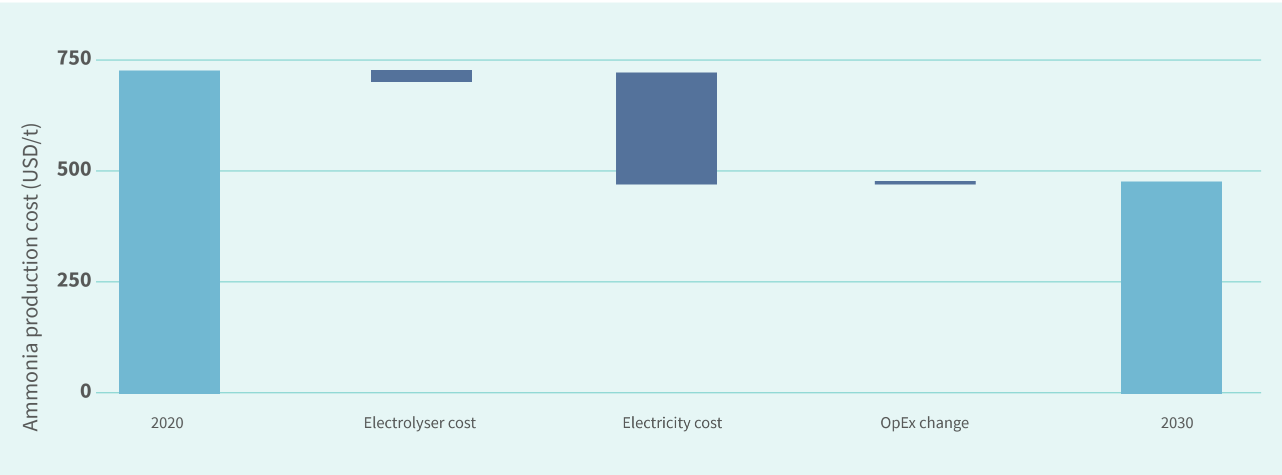


Figure 17: IRENA (2022) Ammonia Energy Association, Innovation Outlook Renewable Ammonia, p.46 f,
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf


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## Levelised Cost of Ammonia (LCOA)

A critical metric for assessing the economic feasibility of green ammonia is the Levelised Cost Of Ammonia (LCOA). Current studies indicate that the LCOA for green ammonia remains significantly higher than that of grey or blue ammonia. This underscores the importance of optimising production processes, selecting favourable locations, and scaling operations to reduce costs.

Integrating renewable energy sources, such as wind and solar, into the production process is essential to minimise costs. By leveraging abundant and low-cost renewable resources, especially in optimal locations, producers can significantly improve the economic competitiveness of green ammonia (Wang & Abild-Pedersen, 2021; Yang, 2024).

## Managing energy supply and demand dynamics

As mentioned in **Chapter 2**, the intermittent nature of renewable energy sources poses a challenge to maintaining consistent ammonia production. Careful planning is required to ensure operational efficiency, which may involve energy storage solutions or hybrid systems combining renewable and traditional energy sources (Sousa, 2022). The use of by-product can offset production costs and improve overall economic performance, for instance, selling oxygen generated from water electrolysis (Tjahjono et al., 2023).

## Market demand for green ammonia

The growing emphasis on decarbonisation across industries is driving demand for green ammonia as a clean energy carrier and e-fertiliser feedstock. The latter regroups all synthetic fertilisers with carbon-free production chains, using green ammonia sourced from green hydrogen instead of grey ammonia. Regions dependent on imported nitrogen fertilisers can particularly benefit from local green ammonia production, reducing carbon footprints and enhancing agricultural and energy resilience (Ofori-Bah, 2023). Building a robust market will depend on strategic partnerships between producers, consumers, and governments, government incentives to support green ammonia adoption and consumer awareness of the environmental benefits of green ammonia.

## Regulatory frameworks and policies

Supportive policies play a pivotal role in shaping the economic landscape of green ammonia production. Key measures include:

**Carbon pricing and taxation:** Imposing taxes on fossil fuel-based ammonia production to level the playing field for green alternatives (Smith, 2020).

**Subsidies and grants:** Encouraging investment in renewable energy projects and electrolysis technologies.

**Research and development funding:** Driving innovation in production technologies and promoting modular approaches such as electrochemical ammonia production (Adeli, 2023).

## Technological advancements and process selection

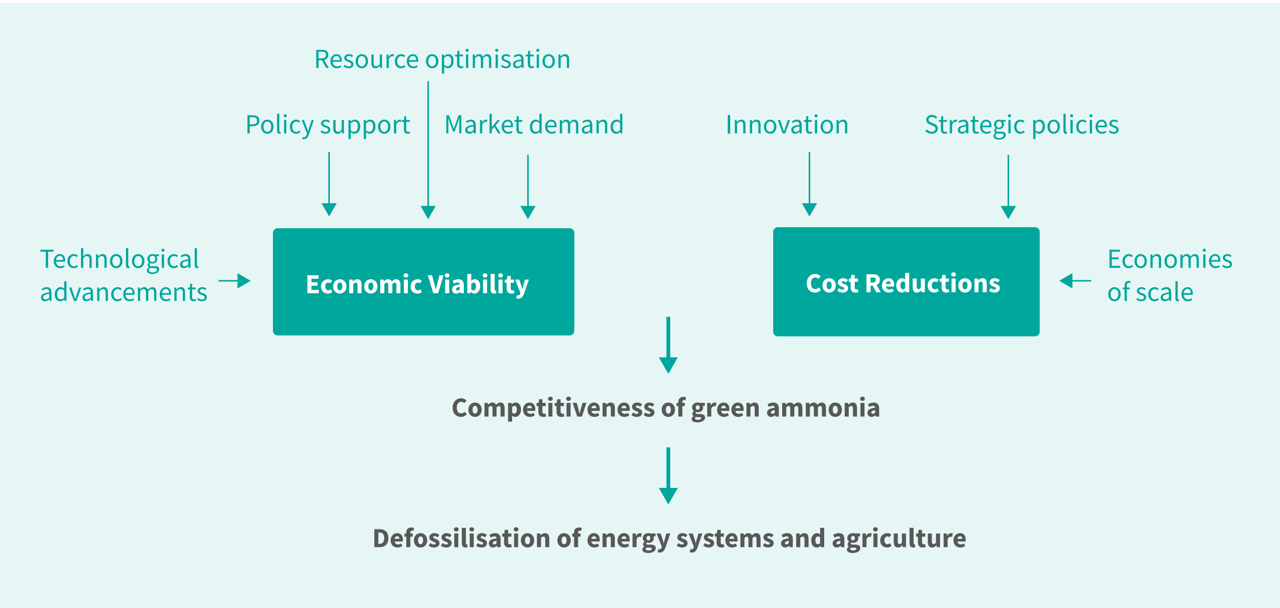
Technological progress is crucial for improving the economic viability of green ammonia production (Saygin et al., 2023). Some examples of research in technological innovation are developing more efficient electrolysers or exploring alternative pathways (e.g. biomass gasification, electrochemical synthesis and plasma-assisted synthesis) to diversify feedstocks and improve sustainability (Perna, 2022; Cardoso, 2021).

## Cost projections

Projections by the International Renewable Energy Agency (IRENA, AEA, 2022) highlight the expected decline in renewable ammonia production costs by about 55%, from USD 720 – 1,400 per tonne (USD 39 – 75 per GJ) today to USD 310–610 per tonne (USD 17 – 33 per GJ) in 2050 (see figure 17). This will be driven by falling prices for renewable electricity and electrolysers, as well as technological advancements and improved utilisation rates.

In optimal locations, green ammonia is projected to achieve cost parity with fossil-based ammonia with carbon capture and storage (CCS) after 2030. For imported green ammonia, shipping costs may add USD 45 – 100 per tonne or USD 2 – 5 per GJ to local production costs (IRENA, AEA, 2022).

Thus, the economic viability of green ammonia production depends on a combination of technological advancements, policy support, market demand, and resource optimisation. While current costs remain higher than those of grey ammonia, the potential for cost reductions through innovation, economies of scale, and strategic policies is significant. As green ammonia becomes more competitive, it is poised to play a critical role in the defossilisation of energy systems and agriculture.



## 6.2. Decoding Green Ammonia Economics

Capital expenditure (CAPEX) and operational expenditure (OPEX) are critical components in evaluating the economics of green ammonia production. Understanding these costs is essential for stakeholders considering investing in this emerging technology. Green ammonia plants, powered by renewable energy, have unique cost structures that differ from conventional ammonia plants due to their reliance on intermittent energy sources and newer technologies.

Understanding these differences is crucial for stakeholders considering investments in green ammonia production technologies. Each plant type has unique characteristics that influence its overall capital costs, including technology, scale, and operational requirements.

Economic optimisation can be reached, e.g. by optimising the renewable power input to the static Haber Bosch process to increase economic and technical viability. However, the intermittent nature of renewable energy requires a decision as to where to "place" the energy sources:

Upstream energy storage: Installing energy storage systems (e.g. batteries) upstream can stabilise power supply and enable continuous plant operation. While this requires significant initial investment, it ensures that the plant operates efficiently without interruption.

Downstream process flexibility: Alternatively, modifying the green ammonia production process to be more flexible can allow operations to adapt to with variable energy input. This approach, while potentially less capital-intensive upfront, introduces technical complexity and may reduce overall efficiency.

Optimisation lies in finding the balance between these options, taking into account local energy profiles, technology costs, and financing conditions.

Additionally, cost parity, i.e., the role of the energy source in the economics of production becomes a critical point: green ammonia is more expensive than conventionally produced ammonia not because renewable electricity is inherently costly, but because the conventional process does not rely primarily on electricity at all, but on natural gas only.

If ammonia production were to be electrified using fossil-based electricity, the cost would be even higher than using renewable energy. This is because electricity as an energy source introduces conversion inefficiencies and higher costs relative to the direct use of fossil fuels – especially under current conditions where carbon prices are non-existent/not high (enough) in many parts of the world. Understanding this distinction is crucial for framing the cost competitiveness of green ammonia. It highlights that the challenge lies in the legacy design of the Haber-Bosch process, not merely in the cost of renewable electricity.

Lastly, it is important to consider market segmentation to enable a technological transition. Innovative technologies often face immense challenges when competing directly with established processes, especially when the product (e.g., ammonia) is identical. For green ammonia to achieve cost parity and scalability, a protected or incentivised market is necessary to allow the technology to advance along its learning curve. Historical examples underscore this principle. In the 1990s, renewable electricity technologies such as wind and solar could not compete with established fossil-based electricity production. Segmented markets and subsidies (e.g. feed-in tariffs) allowed these technologies to mature and achieve economies of scale. Similarly, green ammonia production requires policies such as carbon pricing, green ammonia mandates, or dedicated procurement programmes to offset initial cost disadvantages and foster innovation. Without such mechanisms, new production routes are unlikely to overcome the entrenched advantages of legacy systems, which benefit from decades of optimisation and scale.

## 6.3. CAPEX estimations

CAPEX is a key cost component of green ammonia production but should not be confused with the levelised cost of ammonia (LCOA), which represents the production cost per unit and incorporates CAPEX, operational expenses (OPEX), energy costs, plant efficiency, and financing conditions. While CAPEX is important, the overall cost-effectiveness of green ammonia depends on multiple interrelated factors.

### Conventional ammonia plant CAPEX

For large-scale conventional ammonia plants, CAPEX can vary and includes expenses for equipment, installation, land acquisition, and other associated infrastructure. Large-scale plants can achieve economies of scale, resulting in lower costs per tonne as production capacity increases (Lin, 2020). However, the need for carbon capture technologies (CCS) to mitigate GHG emissions is becoming increasingly relevant, potentially adding to the CAPEX of conventional ammonia plants as regulatory pressure for defossilisation increases (Tanzeem & Al-Thubaiti, 2023).

### Green ammonia plant CAPEX

CAPEX for green ammonia plants is influenced by factors such as plant scale, technology, and location. Current estimates for green hydrogen plants range from 2160 USD/kWe in 2023 to 960 USD/kWe in the IEA's Net Zero Emissions by 2030, estimates include the electrolyser system, electric equipment, gas treatment, plant balancing, and engineering, procurement and construction (EPC) (IEA, 2024). For green ammonia the CAPEX incl. the air separation unit are estimated at 770 USD/(tNH3/y) in 2023, as in the NZE 2030 Scenario (IEA, 2024). Other CAPEX drivers for green ammonia plants include:

**Electrolyser costs:** Electrolysers dominate total investment costs in green ammonia production and are expected to decline significantly by 2030 as technologies mature and economies of scale are achieved.

**Renewable energy integration:** Incorporating renewable energy sources often requires energy storage systems to manage intermittency, further increasing CAPEX (Salmon, 2021).

**Regional variations:** Regions with abundant renewable energy (e.g., the Middle East, North Africa, and Australia) typically have lower CAPEX compared to areas with higher labour or infrastructure costs, such as Europe or Japan.

Larger plants benefit from higher economies of scale, reducing CAPEX per tonne (Fernández C. A., 2020). Advancements in electrolyser efficiency and catalysts for the Haber-Bosch process are expected to further drive down costs, improving the economic feasibility of green ammonia production (Wang & Abild-Pedersen, 2021).

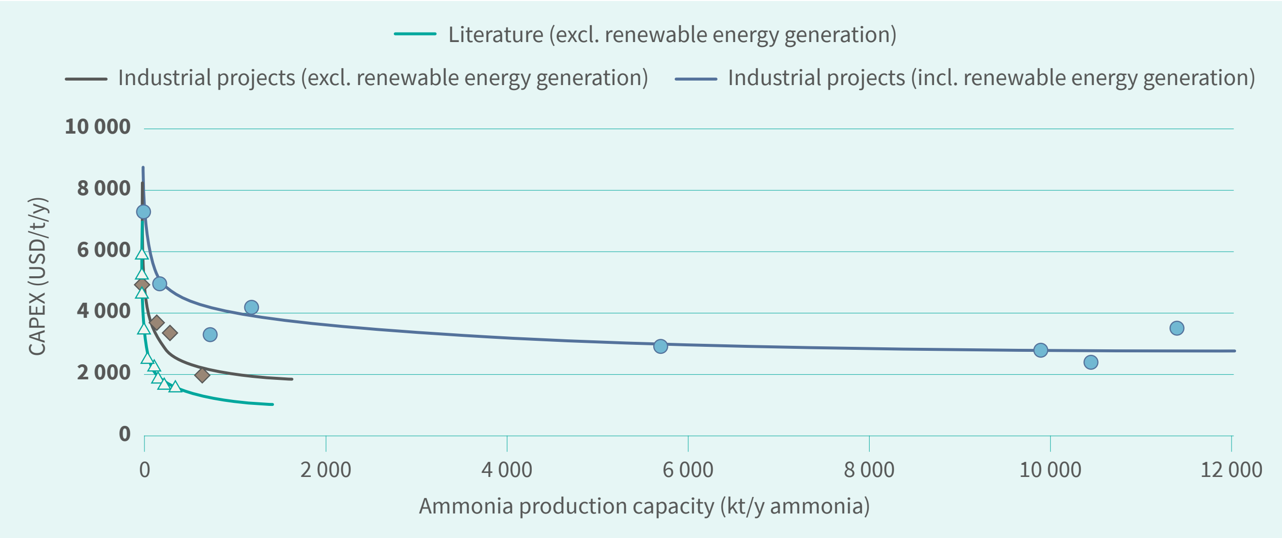



Figure 18: Capital intensity of renewable ammonia synthesis as a function of ammonia production capacity. Taken from (IRENA, AEA, 2022).

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 combined investment cost for nitrogen purification, water desalination and ammonia storage is only around USD 5 – 30 per tonne of ammonia and is lesser compared to the cost of electrolysis and the ammonia synthesis loop (IRENA, AEA, 2022).

Decentralised ammonia plants offer an innovative approach by focusing on smaller-scale facilities located closer to end-users. These ammonia plants can utilise stranded renewable energy installations – e.g. plants that have interrupted production due to lack of investments – reduce transportation costs and improve supply chain resilience (Lin, 2020). CAPEX for decentralised plants ranges from USD 800 to 1,500 per tonne of annual capacity, reflecting reduced transport costs and the ability to leverage local renewable resources (Tonelli et al., 2024). Benefits of decentralised production include flexibility, as smaller-scale plants allow for more adaptive designs, lower investment risks, and greater resilience due to the proximity to end users, mitigating logistical challenges. Further along the green ammonia value chain, decentralised production also has a significant impact on reducing exposure to agricultural commodity price volatility, as mineral fertilisers are less dependent on import markets or volatile fossil fuel prices and provision (Fernández & Chapman, 2024).

Production costs for new green ammonia plants are estimated to be in the range of USD 720 and USD 1,400 per tonne, falling to USD 310 to 610 per tonne by 2050 (IRENA, AEA, 2022).

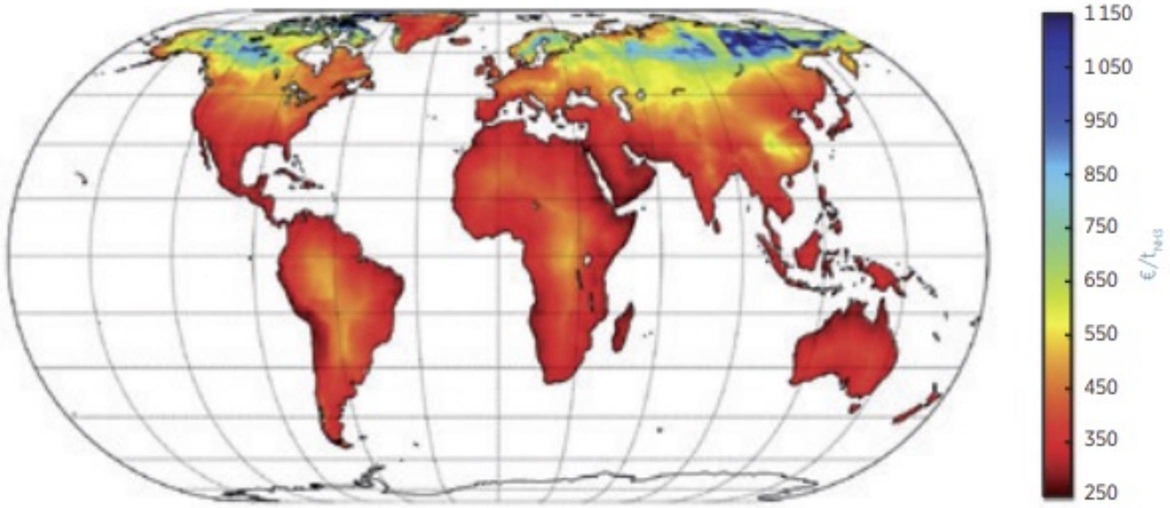



Figure 19: Heat map for the production cost of renewable ammonia by 2050. Reproduced from Fasihi et al. (IRENA, AEA, 2021).

The capacity factor plays a crucial role in determining the investment cost of electrolysis-based ammonia production. Renewable energy sources such as solar and wind are inherently variable, and without adequate buffering or storage, annual ammonia output may fall below the plant's capacity. As a result, stand-alone („islanded“) green ammonia plants are often oversized to compensate for lower productivity, resulting in increased capital intensity. Achieving a high capacity factor, such as combining solar and wind resources to reach around 70%, is essential to minimise these costs (Armijo & Philibert, 2020; Tancock, 2020).

While conventional ammonia plants remain less expensive upfront, they face increasing OPEX pressures due to carbon regulations and rising natural gas prices. Green ammonia plants, while initially more capital-intensive, align with global sustainability goals and benefit from declining renewable energy costs and technological advancements. Key influences on CAPEX reduction are:

**Technology maturation:** Continued progress in electrolysis and renewable energy technologies will significantly lower CAPEX over the next decade.

**Carbon pricing:** As carbon taxes are implemented and natural gas prices rise, green ammonia will become increasingly competitive.

**Market expansion:** Growing demand for green ammonia will drive competition, fostering innovation and cost reductions.

A key distinction between fossil and green ammonia production is that for the former, feedstock is purchased as an ongoing operational expense, while upfront capital is primarily allocated to hydrogen and ammonia plants (e.g., SMR or gasification units). In contrast, green ammonia production requires the upfront construction of all assets, including electricity generation infrastructure. Consequently, the cost of green ammonia is heavily influenced by capital investment, and the weighted average cost of capital (WACC) – the average after-tax cost of capital that a company has to pay to finance its business – significantly impacts its overall economic feasibility. This implies that green ammonia production is capital intensive, but its economic viability is steadily improving due to advancements in technology, increasing fossil fuel prices, and regulatory support for sustainable alternatives. The potential for decentralised, modular production and the integration of stranded renewable energy further bolsters its appeal as a solution for meeting future needs sustainably. With continued policy support and technological innovation, green ammonia could emerge as a critical pillar in global efforts to defossilise agriculture and industry.

## 6.4. Rethinking OPEX and CAPEX for green ammonia production

The operational expenditure (OPEX) for ammonia production varies significantly between conventional and green ammonia plants, due to differences in energy sources, maintenance needs, and regulatory setups. While conventional ammonia plants have historically had lower operational costs, the landscape is shifting as green ammonia production becomes more viable due to advancements in renewable energy and global defossilisation efforts. A critical consideration in this transition is the need to reframe electricity costs from an operational to a capital expenditure for green ammonia production.

This strategic reallocation of electricity costs (CAPEX) has to do with renewable electricity being the primary energy source for green hydrogen production via electrolysis, representing the largest component of – conventionally viewed as – operational costs. However, this dependence on electricity can be mitigated by embedding energy generation infrastructure directly into the plant’s CAPEX. By integrating on-site renewable energy systems, such as solar panels or wind turbines, the plant can effectively stabilise its energy supply costs, insulating itself from market volatility and reducing its reliance on external electricity procurement.

This strategic shift offers several benefits:

- **Cost stabilisation:** Upfront investment in renewable energy infrastructure minimises exposure to fluctuating electricity prices. This predictability of energy costs enables better long-term financial planning and reduces OPEX.
- **Operational autonomy:** On-site energy generation allows green ammonia plants to operate independently of external grid constraints, enhancing reliability and minimising disruptions caused by grid instability or supply shortages.
- **Efficiency gains:** Embedding energy production within the plant’s design eliminates transmission losses associated with external electricity procurement, improving overall energy efficiency.
- **Regulatory compliance:** Investing in renewable energy systems aligns with global sustainability targets and reduces the facility’s carbon footprint, potentially qualifying it for green incentives and subsidies such as the EU’s Renewable Energy Directive (RED II).
- **Near-Zero RE costs:** Once the debt for the initial investment in electricity generation is paid off, the cost factor for the green hydrogen production is reduced to almost nothing.

## 6.5. OPEX Estimations

Even with a significant portion of energy costs shifted to CAPEX, green ammonia plants face higher OPEX compared to conventional plants. This is primarily due to the advanced technologies required for green ammonia production and their associated maintenance and operational challenges. Key OPEX drivers include:

- **Electrolyser maintenance**, which is critical for green hydrogen production. Electrolysers are subject to wear and degradation over time. Regular inspections, component replacements (e.g., membranes and electrodes), and efficiency optimisations contribute significantly to OPEX.
- **Ammonia synthesis reactors**, designed to handle variable renewable energy inputs, and requiring specialised maintenance protocols, add complexity and cost.
- **Labour and skilled workforce**, required by plants. Highly trained technicians familiar with advanced equipment add to labour costs compared to conventional plants.
- **Energy storage and ancillary systems** to accommodate intermittent renewable energy sources which often require energy storage or buffering systems with ongoing maintenance and monitoring costs.

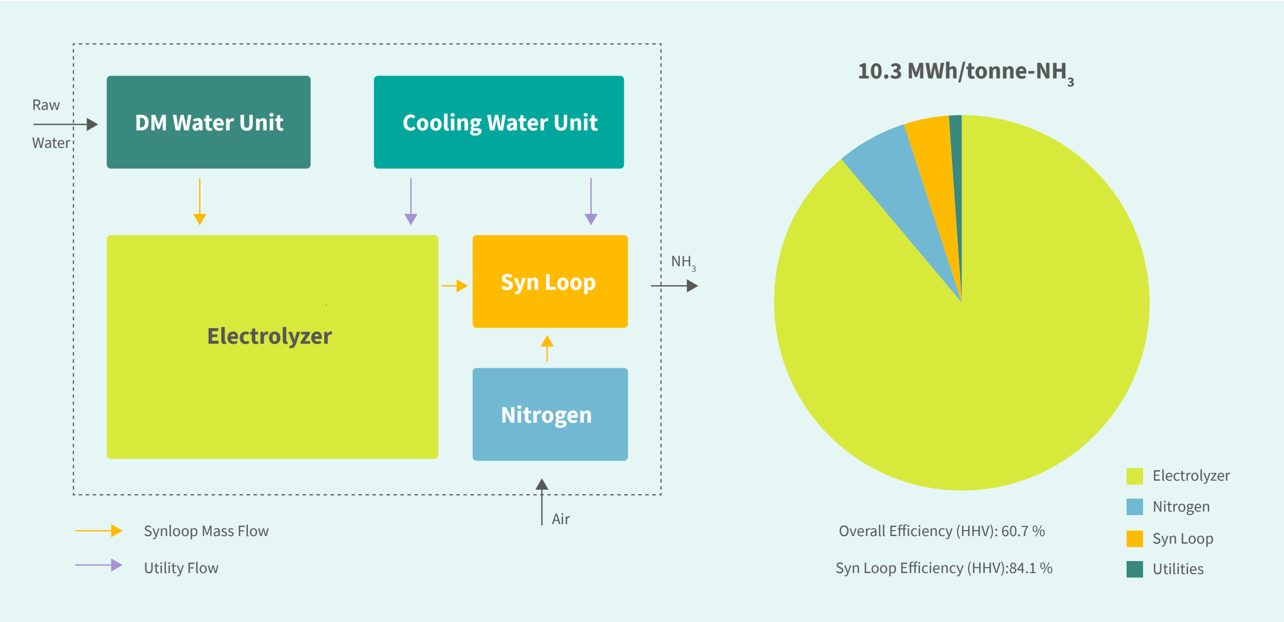



Figure 20: Distribution of energy demand in a green ammonia plant. Taken from (AMMPOWER, 2022) .

Conventional plants, while initially less expensive in terms of OPEX, face increasing pressures from regulatory frameworks and fluctuating fossil fuel prices. Green ammonia plants, despite their higher operational costs, align with global sustainability goals and may benefit from future cost reductions in renewable energy technologies. Decentralised plants offer a middle ground, providing flexibility and lower transportation costs, but may struggle with achieving competitive production costs due to their smaller scale.

In conclusion, the economic considerations for establishing a green ammonia plant encompasses a wide range of factors, including production costs, market demand, regulatory frameworks, technological advancements, and logistical challenges. A thorough understanding of these elements is crucial for stakeholders wishing to capitalise on the potential of green ammonia as a sustainable energy carrier and e-fertiliser feedstock. As the global economy increasingly shifts towards defossilisation and sustainability, green ammonia production will play a pivotal role in addressing the challenges of climate change while providing economic opportunities across various sectors.

Government intervention is crucial to de-risk the operational phase of green ammonia plants and can use certain instruments to do so:

**Contracts for Difference (CfDs)**: Government-issued CfDs aim to compensate renewable energy producers and consumers in view of price fluctuations. With a set price for the trade of renewable energy per plant, if the price were to exceed the pre-established threshold, the buying counterpart would pay the difference, offsetting higher production costs. Vice versa, if the price were to be lower, the producer would pay the difference to the buyer.

**Green premiums**: Seeing as many technologies required for the defossilisation of industries are expensive, setting up green premiums compensates for additional costs. These costs are measured by calculating the price difference between green and fossil-based products, and can be covered by the government, companies and investors, or individuals.

**Renewable energy mandates and procurement contracts**: Renewable energy mandates are the targets set by governments and institutions for a progressive green transition. Setting these in place allows to direct efforts towards renewable energy adoption. In addition, government-backed procurement programmes can stimulate demand, lowering OPEX through economies of scale (IRENA, AEA, 2022).

Despite higher OPEX, green ammonia plants represent a decisive step towards the defossilisation of the ammonia industry. Advanced automation, predictive maintenance systems, and economies of scale promise to reduce OPEX over time. Decentralised plants, while offering logistical advantages, may struggle with higher unit costs due to smaller production scales. However, continued innovation and supportive policies can bridge this gap, making green ammonia production a cost-competitive and sustainable alternative to conventional methods.

It is important to reiterate that green ammonia is currently more expensive than its conventionally produced grey ammonia, not because renewable electricity is inherently costlier, but due to the fundamental differences in energy sourcing. The Haber-Bosch process, optimised over decades, uses the chemical energy of natural gas directly, bypassing the need for electricity. Electrifying this process with fossil-based electricity would result in even higher costs due to inefficiencies and the high price of electricity as an energy carrier. This highlights a key challenge: the legacy design of conventional ammonia production systems, i.e. centralised, large-scale Haber-Bosch processes. Without significant carbon pricing or policy interventions, the economic advantages of these systems remain entrenched, without pricing the true cost of carbon emissions, leading to high external costs such as soil and health damage.

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# 7 Summary and outlook

Green ammonia holds immense potential to contribute to the achievement of the Sustainable Development Goals (SDGs), climate change mitigation, and the transition to a more resilient, efficient and sustainable energy system. By harnessing renewable energy, driving technological innovation, and fostering supportive policy environments, green ammonia can address critical global challenges such as food security, energy security, and environmental sustainability. As the global economy moves towards defossilisation, integrating green ammonia into the energy and agricultural sectors will be instrumental in building resilience and fostering a sustainable future.

## The role of green ammonia in resilience and sovereignty

While climate change mitigation remains a key driver, the transition to green ammonia also offers a pathway to increased resilience and sovereignty. For countries with economies significantly structured around agriculture, such as Ethiopia, reliance on imported mineral fertilisers exposes them to market and price volatility, geopolitical disruptions, and rising costs tied to fossil fuel dependencies. By leveraging decentralised green ammonia production, countries can reduce logistical challenges, secure steady synthetic fertiliser availability, and insulate their agricultural systems from global shocks. Specifically, in Ethiopia, decentralised green ammonia plants could support rural communities by ensuring a steady supply of synthetic fertiliser, reducing dependence on imports, and fostering local economic development while avoiding costly transport. In Brazil, a leading agricultural exporter, domestic green ammonia production could strengthen supply chains, stabilise costs, and improve global competitiveness. Finally, in Kenya, a country where food systems are highly climate-sensitive, green ammonia offers a renewable solution to secure inputs in a variety of supply chains (e.g. fertilisers, chemicals, plastics, textiles, etc.) while supporting climate adaptation efforts.

Resilience, based on by local renewable energy resources and reduced dependence on fossil fuels, not only enhances food and energy security but also contributes to economic growth, enabling countries to prioritise sovereignty and self-reliance while promoting job creation in future-oriented professions.

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The path forward lies in policies, investments, and collaboration. To unlock the full potential of green ammonia, strong policy support and targeted investments are essential. Governments, international organisations, and private stakeholders must collaborate to create an enabling environment for green ammonia production. Key priorities include:

**Research and Development (R&D):** Funding innovation in electrolysis, ammonia synthesis, and energy storage technologies to reduce costs and improve efficiency.

**Infrastructure investments:** Building scalable and decentralised green ammonia production facilities, including renewable energy integration and distribution networks.

**Market incentives:** Implementing policies such as carbon pricing, green ammonia mandates, procurement programmes, and Contracts for Difference (CfD) to offset initial cost disadvantages and drive adoption.

**Public-Private Partnerships:** Encouraging collaboration between governments, industries, and financial institutions to accelerate deployment and foster innovation.

By following this path, green ammonia can become a cornerstone of climate action and economic growth. As countries commit to ambitious climate targets under international frameworks such as the Paris Agreement, green ammonia offers a dual solution: enabling defossilisation while driving sustainable economic development. It can serve as a key component of the energy transition, providing clean energy storage, fuelling sustainable transport, and supporting agricultural systems with carbon-neutral fertiliser production.

The transition to green ammonia production is not without challenges, including high initial CAPEX, operational complexities, and competition with established legacy systems. However, these obstacles can be overcome through continued technological advancements, declining renewable energy costs, and coordinated policy action.

Green ammonia represents more than a technological innovation – it is a transformative opportunity to redefine energy and agricultural systems for a more equitable and sustainable future. By addressing critical challenges with resilience-focused solutions, countries can secure their energy and food systems, reduce environmental impacts, and achieve long-term economic growth. With bold commitments, innovative partnerships, and global cooperation, green ammonia can become a cornerstone of the sustainable economy, bridging the gap between climate ambition and actionable progress.

Supportive policies and investments are essential to realise the full potential of green ammonia. Governments and international organisations must prioritise funding for research and development, infrastructure, and market incentives to encourage the adoption of green ammonia technologies. Collaborative efforts between public and private sectors can accelerate the deployment of green ammonia solutions, fostering innovation and creating new economic opportunities in the renewable energy sector. As countries commit to ambitious climate change targets, green ammonia can serve as a cornerstone for achieving these goals while promoting sustainable economic growth.

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