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Breaking new ground: decentralised renewable nitrogen fertilisers

Exploring opportunities and barriers



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Preface

Dear reader,

Fertiliser production and supply have become a focus of policymaking as countries seek to secure critical industrial supply chains. Today, global fertiliser production is unevenly distributed and heavily reliant on fossil fuels. Many Global South countries depend on imports, exposing them to volatile markets shaped by geopolitical tensions. This leads to high transport and distribution costs, further raising the retail price for farmers.

Conventional synthetic nitrogen fertiliser makes an important contribution to increasing agricultural yields. However, its use causes environmental damage, in addition to greenhouse gas emissions from their fossil-based production. Nitrogen fertiliser should thus be used as efficiently as possible to align its application with climate and other biodiversity goals. Decentralised renewable-based production might serve as a complementary strategy to wider decarbonisation plans in the

sector. At the same time, bringing fertiliser production closer to end users can contribute to local value creation and strengthening domestic supply chains. Pilot projects, often led by start-ups, are already underway in North America and East Africa.

This report aims to inform discussions on adopting decentralised renewable ammonia and fertiliser production in Global South countries. It scopes competitiveness, environmental impact and social implications, and outlines practical considerations for safe and effective deployment, including the careful management of ammonia when used directly as a fertiliser. We hope this report contributes to a better understanding of how this emerging technology could support a low-carbon and resilient fertiliser supply.

I wish you an insightful read!

Julia Metz
Director, Agora Industry

→ Key findings at a glance

- 1 **Transitioning from fossil-based ammonia and nitrogen fertiliser to renewables-based production has significant potential to reduce emissions and enhance global supply chain resilience.** Replacing coal and fossil gas with renewables could eliminate emissions from production, which currently account for around 30 to 40 percent of the fertiliser sector's total greenhouse gas output. It would also enable decentralised supply, strengthening supply security and lowering exposure to global fertiliser price volatility.
- 2 **Decentralised nitrogen fertiliser production can complement existing supply chains to help decarbonise the sector, particularly in locations heavily reliant on imports.** Driven primarily by renewable energy-based technologies, decentralised systems also reduce transport and distribution barriers where access to production hubs or import ports is limited, particularly in Global South countries.
- 3 **Locations with cheap renewable energy and large-scale agriculture have good conditions in place for decentralised fertiliser production.** While still about twice as expensive as centralised renewable options, cost parity with retail prices is possible by 2035 in selected areas. Policies promoting renewable energy, de-risking mechanisms and financial support for both supply and demand are essential to making decentralised technologies more competitive.
- 4 **While decentralised renewable ammonia offers important climate benefits, its direct use as fertiliser requires thoughtful management.** Proactively addressing ammonia's toxicity is critical to ensuring environmental protection and user safety, through clear regulations, robust safety standards and comprehensive training. These are key prerequisites for responsible integration of decentralised production technologies into fertiliser and agricultural development strategies.

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1 Nitrogen fertilisers: trends and perspectives

Emissions from the current production of ammonia and nitrogen fertilisers account for around 1.3% of global emissions (Menegat et al., 2022). This is becoming increasingly relevant given that the global demand for fertilisers is on the rise, driven by population and economic growth in countries of the Global South, where the availability and use of fertilisers can still be limited. However, if low-carbon technologies are not adopted in the production process, the future supply of fertilisers could become more dependent on fossil fuels, resulting in higher carbon emissions.

Mitigating emissions in the production of fertilisers is essential to achieving climate neutrality by mid-century. As presented in our Global Green Fertiliser Tracker (Agora Industry, 2024a), technology is now available for the low-carbon production of ammonia and fertilisers. Moreover, innovative strategies for improving fertiliser supply chains can bring climate benefits and have a positive impact on supply chain diversity, food security, and local development.

Industrialised fertiliser production has allowed humans to increase agricultural productivity tremendously. It has made these nutrients available on a large scale, becoming a major traded commodity globally. The current fertiliser market encompasses a wide range of end products, mainly based on the chemical concentration of important crop nutrients such as nitrogen (N), phosphorus (P) and potassium (K). Among those, nitrogen is the most widely used crop nutrient, coming mainly from synthetic industrial production of fertilisers (67%) and manure (33%) (Gao et al., 2023). Current industrial production of nitrogen fertilisers is at about 130 million tonnes per year (Mt/y); this number is projected to go up to about 165 Mt/y by 2050 (FAO, 2022; FAO, 2024).

Nitrogen fertilisers are manufactured in around 400 centralised large-scale production plants worldwide (Mingolla et al., 2025). Their production depends on ammonia made through the Haber-Bosch process (see Infobox 1), an industrial method developed over

a century ago. Because it relies on fossil fuels, ammonia production is both highly energy and carbon-intensive (see Section 4). The current centralised production model can require long-distance transport to reach farmers, which can be critical in large countries with inadequate transport infrastructure. This can lead to higher fertiliser costs and lock farmers into dependency on the global fertiliser market (Rosa et al., 2022).

However, nitrogen fertilisers can also be produced with novel and renewable technologies in decentralised locations in countries highly dependent on fertiliser imports. As shown in Figure 1, these decentralised, small-scale strategies can bypass central fertiliser markets to provide fertilisers directly in areas of demand, which is crucial for locations where transport and distribution logistics can strongly influence the retail price of these products. Decentralisation helps lower geopolitical dependency and serves as a complementary strategy to the development of centralised domestic production of green nitrogen fertilisers. The production of such fertilisers can reduce emissions when renewable electricity and hydrogen are used in the production process.

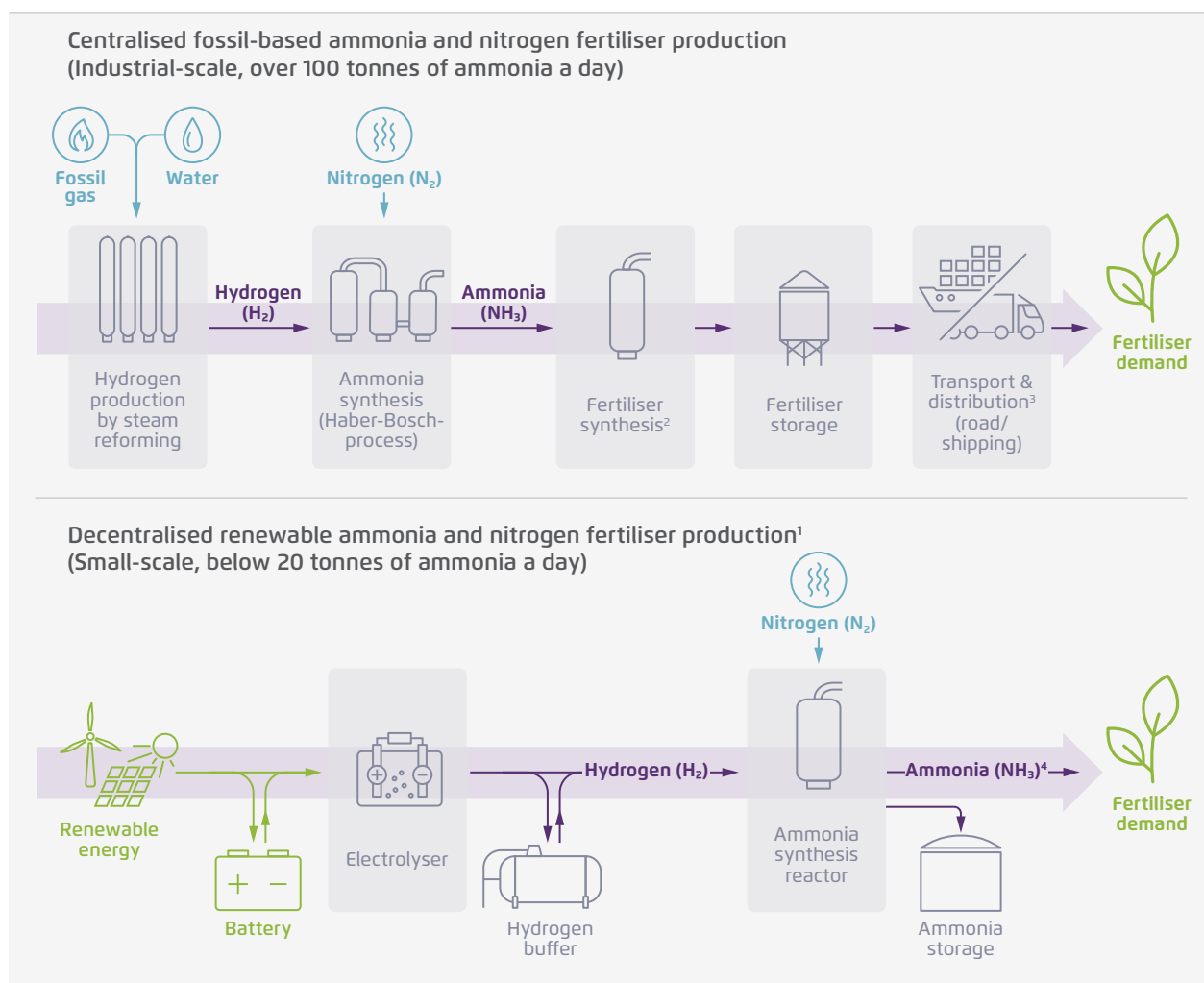
This study presents the decentralised production of renewable ammonia and nitrogen fertilisers as a complementary strategy to accelerating the decarbonisation of the ammonia and fertiliser industry. A decentralised approach has the potential to disrupt the fertiliser supply chain, reducing its dependence on fossil fuels and enhancing the security of supply to agricultural communities. Locations that are vulnerable to fertiliser imports and have good renewable resources are ideal hosts for this approach. However, current decentralised technologies mainly produce anhydrous ammonia as the final fertiliser, which requires great caution due to its high toxicity to humans and ecosystems. This fertiliser should only be used in agricultural settings that meet the highest health and safety standards to protect farmers and the environment. In addition, the high cost of

these technologies affects their competitiveness in the short and medium term, so policy support is required to accelerate their development and adoption. We present policy recommendations to provide

decision-makers and policy experts in relevant countries with a basis to consider adopting the renewable, decentralised production of ammonia and nitrogen fertilisers.

Comparison between centralised vs decentralised ammonia and nitrogen fertiliser production

→ Fig. 1



Agora Industry (2025).

Notes: ¹This scheme only presents one potential technology for decentralised production (electric Haber-Bosch). Electric Haber-Bosch technology can also be scaled up to reach industrial production levels and is a low-carbon option for centralised ammonia production.

²This depends on the final nitrogen fertiliser to be used.

³Depending on the location of the farming community, this section can include transport from the production plant to the export port, shipping to the import port, and transport from the port to the local distribution centre for the final user.

⁴Ammonia can be used directly as fertiliser or transformed into other nitrogen fertilisers.

→ Infobox 1: Ammonia vs other nitrogen fertilisers: why should direct fertilisation with ammonia be the last resort?

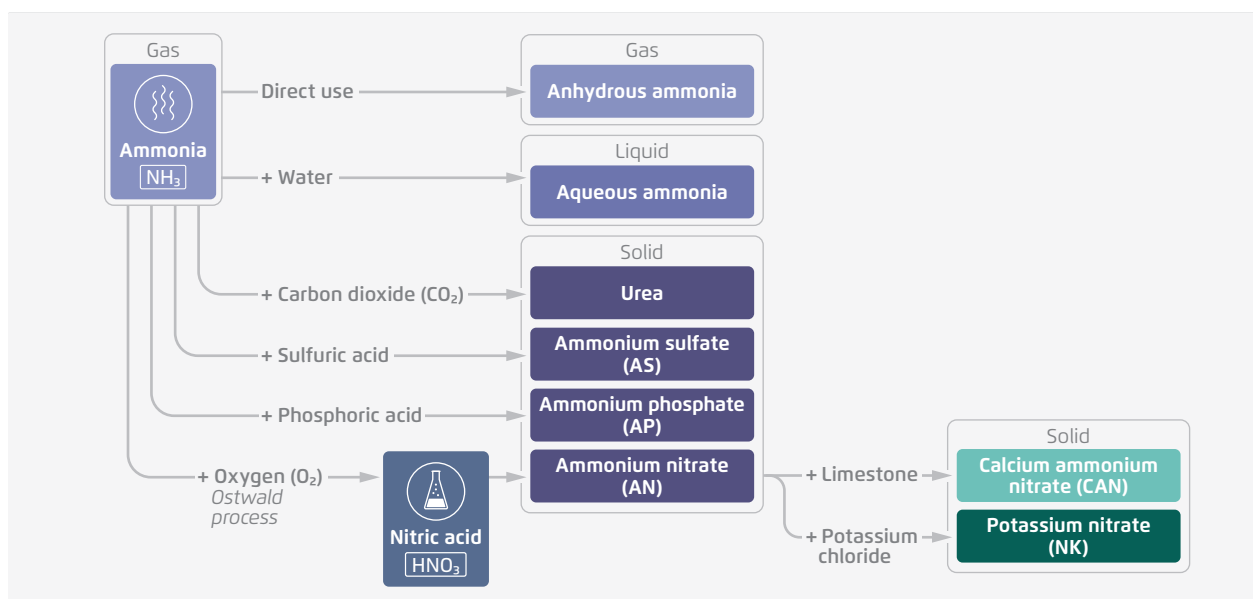
For health and safety reasons, nitrogen fertilisers in the form of ammonium nitrates, NPK or urea are preferable to direct fertilisation with ammonia.

Pure gaseous ammonia accounts for only 3% of the nitrogen supplied. Using ammonia as a nitrogen fertiliser is common in the United States (Mingolla et al., 2025) and to a lesser extent in Kenya and South Africa (PtX Hub, 2025). Gaseous at room temperature, ammonia is injected into soils in a compressed form to minimise volatilisation. Specialised equipment and farmer knowledge are needed for this. Ammonia is a toxic chemical which can cause severe injuries, depending on concentration, when it comes into contact with humans or animals. Because of its toxic, caustic, explosive and flammable nature, technical equipment needs to fulfil the highest safety requirements, and strict safeguards need to be in place for any procedures related to handling, storing, transporting and applying ammonia to fields.

Figure 2 shows the various forms of nitrogen fertilisers. Apart from anhydrous ammonia, all other nitrogen fertilisers are applied to soils either as granules or solutions, making their application comparably less prone to injury and risks (see also 3.3. Health and safety). All are based on ammonia as an intermediate product generated by the Haber–Bosch process. It converts inert nitrogen gas from atmospheric air (N_2) into a compound capable of releasing reactive nitrogen into the soil, facilitating its uptake by crops. Urea is the most widely used nitrogen fertiliser, accounting for about 50% of the nitrogen applied to crops with synthetic fertilisers worldwide (Gao et al., 2023; Mingolla et al., 2025). Other commonly used nitrogen fertilisers are nitrogen, phosphorus and potassium (NPK), compounds supplying 17% nitrogen; ammonium nitrate and urea ammonium nitrate (UAN), both with 12% of nitrogen supplied; and calcium ammonium nitrate (CAN) and potassium nitrate (NK), derived from ammonium nitrate (AN), with only 3% of nitrogen supplied.

Overview of the conversion steps from ammonia into other nitrogen fertilisers

→ Fig. 2



Agora Industry (2025)

1.1 Centralised nitrogen fertiliser production and geopolitics

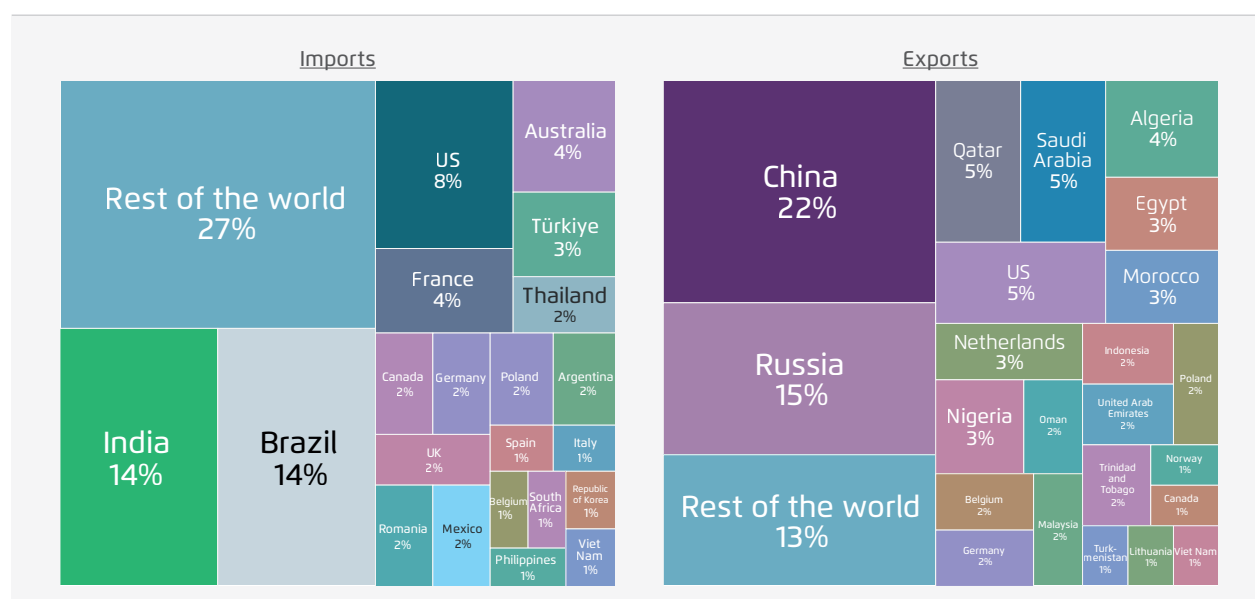
There is an imbalance in the market for ammonia and nitrogen fertilisers, as many countries in the Global South lack production facilities to meet current and future demand. The mismatch between current producers and consumers, as well as the location of future demand, could lead to more dependence on fossil fuels, thus increasing emissions. Countries in the Global South that do not produce ammonia and nitrogen fertilisers domestically but have a growing demand for them are increasingly exposed to the global market. Currently, only 61 countries host ammonia production facilities, making ammonia and nitrogen fertilisers important globally traded commodities, accounting for about 49 Mt of nitrogen traded globally each year (Mingolla et al., 2025). Most ammonia production facilities are concentrated in a few regions, with China, India, the Middle East, the US, and Europe having the highest concentration. Other regions, such as Latin America and Africa, have relatively few ammonia production facilities, despite having large agricultural producers such as Brazil and Argentina. It is also important to consider that African countries are forecast to be the driver of nitrogen

fertiliser demand, given the development of the agricultural sector, highlighting the need to increase fertiliser supply in the region.

Geopolitical tensions and fossil gas prices affect the global trade in nitrogen fertilisers. With many countries producing locally to supply their domestic demand, the global supply chain of these commodities lacks diversification. Figure 3 shows the most relevant countries in the global trade of nitrogen fertilisers. Russia and China are the most important exporters globally, and seven countries account for over 50% of global exports. Given the importance of fossil gas in the production of nitrogen fertilisers, most of the exporting countries have fossil fuel resources for the production of ammonia and nitrogen fertilisers. On the other hand, Brazil, India and the US are the largest importers of nitrogen fertilisers. This is despite having domestic ammonia production plants. This makes the global supply chain for ammonia and nitrogen fertilisers vulnerable to different factors, including geopolitical turbulence. For example, heavy reliance on fossil fuels for ammonia and fertiliser production has resulted in fossil gas costs accounting for up to 90% of ammonia production costs (Kenkel P., 2017). As shown in Figure 4,

Top importers and exporters of nitrogen fertilisers in 2022

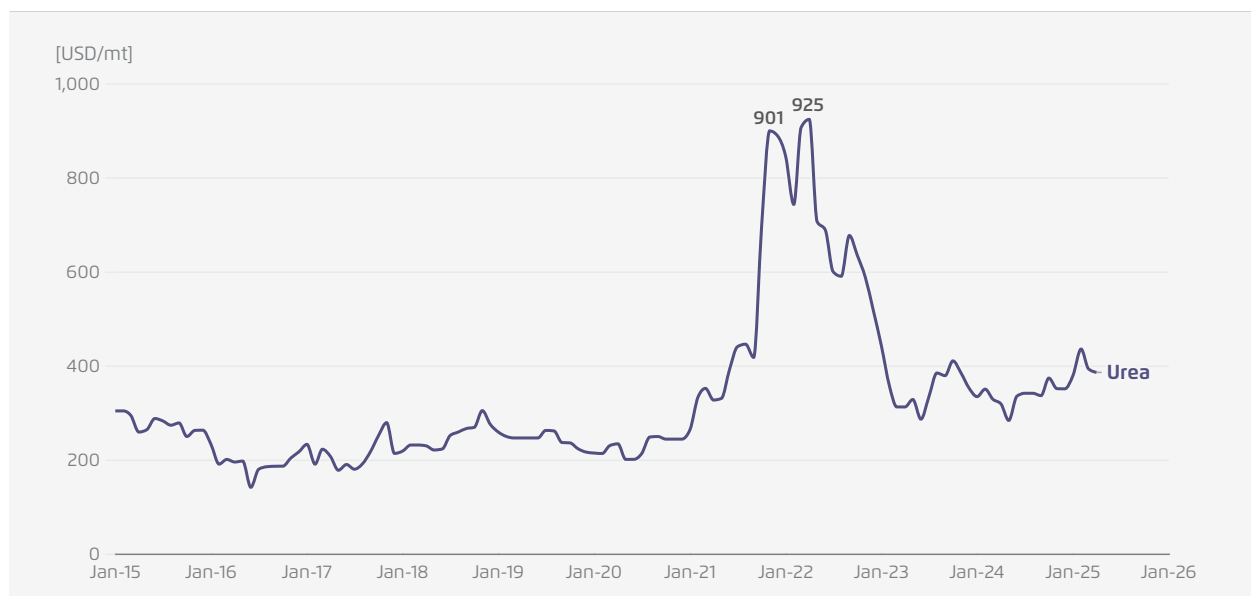
→ Fig. 3



FAOSTAT (2025). Note: Global demand of 49Mt N per year

Variation in the cost of urea from 2015 to 2025

→ Fig. 4



Urea, (Ukraine), prill spot f.o.b. Middle East, beginning March 2022; previously, f.o.b. Black Sea.

the disruption of global fossil gas markets following Russia's invasion of Ukraine in 2022 caused the price of nitrogen fertilisers to triple (IEA, 2022a), which also propagated to the costs of the fertiliser industry and subsequently to food prices (Agora Industry and Agora Energiewende, 2023). Although the price of ammonia and nitrogen fertilisers has been more stable since 2023, new geopolitical tensions in the Middle East are threatening the global supply chain of fossil fuels and fertilisers produced and commercialised via that region, potentially creating new price fluctuations.

Countries seek more domestic fertiliser production and less dependence on the global market. Trade and market disruptions in the global supply of fertilisers have led countries to develop policies to support the domestic production of fertilisers, especially nitrogen fertilisers, to reduce their exposure to price volatility in the global market. Brazil's National Fertiliser Plan is one example (see Section 1.3). Countries are also looking at more sustainable alternatives for the production of ammonia and nitrogen fertilisers, mitigating reliance on fossil fuels, and reducing carbon emissions associated with their production. Carbon tariffs and policy frameworks in leading markets are pushing fertiliser producers to scale up

their decarbonisation efforts. Renewables-based hydrogen has become a key driver in the decarbonisation of ammonia production due to the flexibility of the Haber-Bosch process in terms of gas mixtures. Using renewables-based hydrogen in the production process – whether partially or fully – can greatly cut carbon emissions. However, the production of more traditional fertilisers like urea presents other challenges, such as the need for a CO₂ source for its synthesis. Producing the hydrogen needed for ammonia synthesis involves steam reforming fossil gas, and the resulting carbon emissions are used for the production of the final nitrogen fertiliser. Therefore, the use of renewable-based hydrogen, which does not produce CO₂ emissions, requires a new carbon source to convert ammonia to urea. Biogenic sources of CO₂ may be available at agricultural sites where crop fermentation also takes place, for example, in Brazil for the production of bioethanol. Another option is expensive direct air capture (DAC) of CO₂. An early assessment of this technology puts the current cost of DAC at USD 125–335/tCO₂, a figure that could fall to an optimistic value of around USD 100/tCO₂ by 2030 in locations with high renewable energy potential (IEA, 2022b).

The current centralised nitrogen market has important inefficiencies that need addressing. The challenges of the current global supply of ammonia and nitrogen fertilisers have exacerbated other major inefficiencies of the current model of centralised production. Many countries are dependent on imports, yet the intensifying agricultural sector will require greater amounts of synthetic fertiliser, making it important for them to secure the supply and avoid price volatility in global markets. However, the lack of fossil fuel endowments in many countries makes them vulnerable to an international fossil gas market, limiting their capability to begin producing their nitrogen fertilisers. At the same time, the centralised production of nitrogen fertilisers is often far from main users, creating a need to develop infrastructure to supply these commodities in rural areas, as users pay a high price for the transport and distribution of their fertilisers.

The production of ammonia and nitrogen fertilisers provides an opportunity for renewable-rich countries in the Global South to develop a low-carbon industry, create local value chains, and mitigate their dependence on fossil fuels and the volatile global fertiliser market. A more diversified supply chain for ammonia and nitrogen fertilisers, based on renewable energy and renewable-based hydrogen, can address some of the inefficiencies of the current production and trade model. Centralised production facilities in countries with a growing demand for nitrogen fertilisers could generate new opportunities for green industrialisation and economic development. Decentralised ammonia and nitrogen fertiliser production could also complement these strategies by reducing the risk of increased emissions from fertiliser production. This could enhance local value chains in agricultural areas distant from industrial hubs.

1.2 Decentralised green ammonia and nitrogen fertiliser production

Decentralised green ammonia and nitrogen fertiliser production can complement other decarbonisation strategies focusing on the large-scale, renewable production of these products. Countries looking to

promote the domestic production of ammonia and nitrogen fertilisers should choose renewable-based production technologies to mitigate their dependence on fossil fuels and limit emissions from the industry. Decentralised technologies use renewable energy to produce ammonia and nitrogen fertilisers, which also contributes to the low-carbon production of these commodities. Due to the small-scale production of these systems, they are primarily employed as supplementary strategies. Decentralised ammonia and nitrogen fertiliser production might not fulfil all domestic demand for these products; however, it can complement other strategies that aim to enhance local supply and decarbonise this industry.

Decentralised strategies could improve the regional supply of fertiliser, particularly in areas heavily dependent on imports and market and price fluctuations. Several companies are beginning small-scale production of ammonia and nitrogen fertilisers using low-carbon technologies as units that can be easily installed in remote areas. This business model offers an alternative for improving the supply of fertilisers to agricultural centres that are not well connected to centralised ammonia and fertiliser production or ports. Producing fertiliser closer to agricultural areas can mitigate price volatility from fossil fuels and the global supply chain, as well as extra transport and distribution costs for ammonia and fertilisers from centralised industrial hubs.

New business models are developing for decentralised ammonia and nitrogen fertilisers, but they are still at an early stage. Private companies are increasingly pursuing decentralised strategies located closer to farmers, which in turn opens up opportunities for socio-economic development. These decentralised initiatives have technological innovation at the core of their business model, seeking climate-resilient solutions for alternative ammonia and nitrogen fertiliser production through renewable energy, electrolysis and other low-carbon technologies (see Section 2). Start-ups have been the leading providers promoting decentralised nitrogen fertiliser production with technological development stages ranging from R&D, pilot and even operational phases. According to the Global Green Fertiliser Tracker (Agora

Industry, 2024a), the global market for decentralised systems is still in its infancy. In early 2025, only one company was producing renewable ammonia via decentralised systems on a commercial scale in two locations: Naivasha, Kenya (one tonne a day, operational since 2023) and Iowa, US (20 tonnes a day, operational since February 2025) (TalusAg, 2025; Landus and TalusAg, 2025).

1.3 Geographical scope of the study

This study provides a comprehensive overview of the status quo of decentralised ammonia and fertiliser technologies and their economics and gives a broader assessment of socio-economic considerations and environmental challenges. Site-specific conditions will strongly influence the adoption of decentralised

ammonia and nitrogen fertiliser production. This, among other factors, includes:

- linkage to global markets,
- the availability and cost of renewable energy sources,
- the demand and capabilities of agribusinesses to advance renewable nitrogen fertilisers, and
- a supportive policy and regulatory framework.

To assess the techno-economic aspects of different renewable fertiliser production technologies (see Section 2), we use site-specific data and assumptions with a clear geographical scope. Based on current trends, policy support, agricultural development, and the fertiliser market, we have identified four countries with strong potential for deploying decentralised technologies: Brazil, Kenya, Thailand and the United States (see Table 1).

Country conditions for potential adoption of decentralised production of renewable ammonia and nitrogen fertilisers at a glance

→ Table 1

 Brazil	 Kenya	 Thailand	 US
1. Fertiliser demand and renewable share			
Demand¹			
6.7 Mt/year (6.2% of total global demand)	0.2 Mt/year (0.2% of total global demand)	1.4 Mt/year (1.3% of total global demand)	11.9 Mt/year (10.9% of total global demand)
Share of renewable electricity generation			
88% in 2022 ²	86% in 2022 ¹⁰	20% in 2022 ¹⁷	21% in 2022 ²⁰
2. Fertiliser production			
Production¹			
0.70 Mt/year	no domestic production	no domestic production	12.7 Mt/year
Central production			
Four ammonia plants cover ~15% of demand ¹	None	None	32 industrial ammonia plants ²¹ .
Decentralised production			
Not operational. Only one agreement to start project in Goiás ³	One pilot project to produce decentralised ammonia as fertiliser	None	Decentralised pilots in the Midwest ²¹
3. Import dependency and demand			
→ Largest fertiliser importer in the world ¹ . → Imports worth USD 15.8 billion in 2023 ⁵ ~7% of agricultural export value ⁴ .	→ Fully import-dependent ¹	→ Fully import-dependent ¹	→ Imports still needed despite domestic capacity ²¹ . Midwest transport distances drive decentralised innovation.

Country conditions for potential adoption of decentralised production of renewable ammonia and nitrogen fertilisers at a glance

→ Table 1

 Brazil	 Kenya	 Thailand	 US
4. Overview agricultural sector			
→ Farm size in Brazil is diverse, but large commercial farms are a major feature: 77% of rural establishments in Brazil were household farms, occupying 80.9 million hectares or 23% of the country's rural agricultural land⁶. → Brazil is a global leader in agricultural trade, ranking as the top producer of sugarcane, coffee, tropical fruits, orange juice, and cattle, with primary outputs of soybeans, corn, cotton, and more, driven by decades of strong growth⁷.	→ Mostly smallholder farms, typically less than 2 hectares. → Kenya has 28 million hectares of agricultural land (48% of total land area), only 16% suitable for rain-fed farming due to arid conditions¹². → Agriculture contributes 33% to GDP, employs 40% of Kenyans, and generates 65% of export earnings¹³.	→ Small-scale and family-run, centred on rice, with limited irrigation, low incomes, and 30% of the population working on farms averaging just four hectares¹⁸.	→ Dominated by large, high-tech farms with corn, soy and wheat covering most cropland, especially in the Corn Belt. → Average farm size was 187.36 hectares in 2022, with a clear trend toward fewer but larger farms^{21, 22}.
5. Fertiliser policies			
→ Nova Indústria Brasil policy: promotes industrial development based on renewable resources, including the fertiliser sector⁸. → National Fertiliser Plan (2022): to boost local production to 55% by 2050⁹. However, there is no clear framework for implementation in place.	→ Industrial policy aims to reduce fertiliser imports by 20% by 2027 and by 50% by 2032¹⁴. → National Fertiliser Subsidy Programme (2022): to mitigate rising food prices by offering fertiliser at half the commercial price, with a total subsidy budget of USD 23 million¹⁵.	→ Fertiliser subsidies (2019): new incentives to offer cheap fertilisers to farmers¹⁹. → Fertilisers price cap (2022): to control rising costs and maintain agricultural stability¹⁹	→ Clean hydrogen policy: tax credits in the Inflation Reduction Act, which indirectly supports the development of decentralised ammonia systems²¹. However, the current government in the process of repealing many of the act's provisions (as of now). → Regional policies (Minnesota).
Specific policies for decentralised fertiliser production			
→ No specific policies for decentralised fertiliser production.	→ Nairobi declaration from the African Soil Health Summit (2024): to leverage opportunities of domestic, decentralised and low-carbon fertiliser production to improve access and affordability for smallholder farmers¹⁶.	→ No specific policies for decentralised fertiliser production.	→ Distributed ammonia production: research funding, tax incentives, and infrastructure investments focused on renewable-based hydrogen technologies for ammonia synthesis^{21, 23}. → Renewable fertiliser initiative (Minnesota): USD 7 million grant programme for development of decentralised renewable fertiliser production²⁴.

¹Mingolla et al. (2025); ²IRENA (2025); ³Ammonia Energy Association (2023); ⁴Agora Industry and Agora Energiewende (2023); ⁵OEC (2025); OEC (2023); ⁶Arré et al. (2024); ⁷Arias et al. (2017); ⁸Gov.br (2024); ⁹MAPA (2022); Gov.br (2022); ¹⁰IRENA (2025b); ¹¹TalusAg (2025); Landus and TalusAg (2025); ¹²Kamau et al. (2025); ¹³FAO (2024) ¹⁴Dekeyser et al. (2024); ¹⁵IFPRI (2023); ¹⁶African Union (2024); ¹⁷IRENA (2025c); ¹⁸FAO (2025); ¹⁹Research & Markets (2024); ²⁰IRENA (2025d); ²¹Schueler et al. (2024); ²²USDA NASS (2024); ²³U.S. DOE (2023); ²⁴Minnesota AG Connection (2024); Minnesota Department of Agriculture (2024)

2 Analysis of technology and competitiveness

As shown in Figure 5, there are various technological pathways for producing ammonia and nitrogen fertilisers. In addition to the most common fossil-based method, renewable technologies could produce renewable ammonia and fertilisers while reducing process emissions. Small-scale decentralised technologies in particular offer a wide range of options for innovating the traditional Haber-Bosch process. However, many aspects of this new approach should be considered to understand its competitiveness, especially when compared with traditional centralised industrial fertiliser production. This section provides an overview of the technologies currently under consideration for decentralised renewable nitrogen fertiliser production. It assesses key techno-economic components such as technology-specific capital and operating costs, site-specific renewable resources, and operational configurations, among others, to show the factors influencing decentralised nitrogen fertiliser costs compared with the traditional centralised model. The analysis here is applied

to the four identified countries with significant potential for adoption of these technologies: Brazil, Kenya, Thailand and the US.

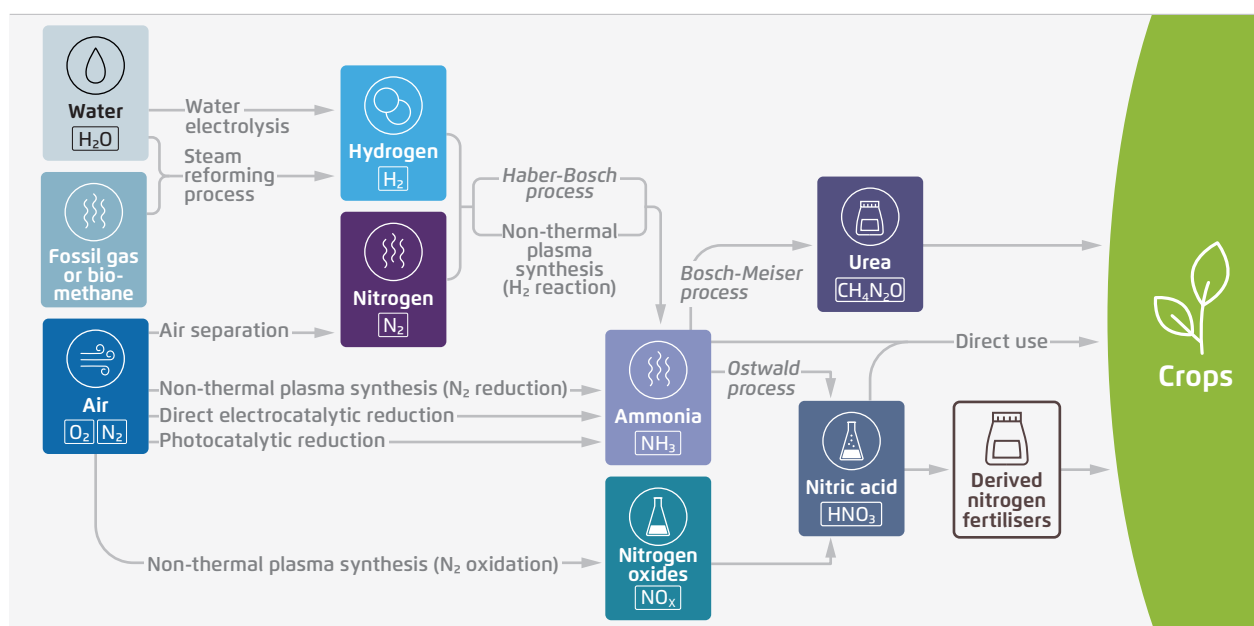
2.1 Overview of production technologies

Here we give an overview of the main low-carbon technologies being developed for the production of less carbon-intensive ammonia and nitrogen fertiliser, including their approach to decentralised production systems. A summary is presented in Table 2.

Current producers of decentralised technologies are targeting anhydrous ammonia as the main fertiliser, yet it poses serious health and environmental risks. Other products are AN, CAN and aqueous ammonia (see Figure 5 and Appendix 1). Anhydrous ammonia is not the most widely used nitrogen fertiliser due to its significant environmental, health and social risks (analysed in Sections 3 and 4). However, as

Nitrogen fertiliser production routes

→ Fig. 5



Agora Industry (2025)

Overview of current decentralised renewable ammonia and fertiliser technologies → Table 2

 Electric Haber-Bosch	 Direct electrocatalytic nitrogen reduction	 Non-thermal plasma synthesis	 Photocatalytic nitrogen reduction
Description			
Closely resembles current industrial ammonia production methods, but is adapted for small-scale, decentralised systems. Two-step production: → Step 1: hydrogen is produced through electrolysis. → Step 2: hydrogen reacts with nitrogen in the air within a modified Haber-Bosch reactor to produce ammonia.	Converts nitrogen into ammonia directly. A catalyst activates the nitrogen molecule, facilitating its reaction to ammonia.	Technology activates nitrogen using an electric field, enabling conversion via two production pathways: Pathway 1: activated nitrogen reacts with hydrogen, which is produced via electrolysis, resulting in ammonia. Using a catalyst enables the process to be conducted at atmospheric pressure and low temperature. Pathway 2: activated nitrogen reacts with oxygen to produce nitric acid, which is used in the synthesis of NPK fertilisers. This option bypasses the production of ammonia.	Mimics the natural photosynthesis process, artificially activating nitrogen and causing it to react with water molecules to produce ammonia. This process operates at ambient temperature and pressure.
Opportunities and challenges			
Advantages: operates under milder conditions compared with traditional large-scale ammonia production. Drawbacks: not flexible to operate with variable power supply.	Advantages: → Bypasses hydrogen production, eliminating the need for storage. → Mild operating temperature, enabling the system to adapt to variable power input. Drawbacks: → Still in the early stages of development. → Noble metal materials are required for the catalyst.	Advantages: → Flexibility in the desired final fertiliser. → Allows the ammonia conversion step to be avoided, thus mitigating the risks associated with handling ammonia. Drawbacks: → Still in the early stages of development. → It is an energy-intensive process because of the production of the electric field.	Advantages: → Operates at ambient temperature and pressure. → Bypasses hydrogen production, avoiding the need for its storage. Drawbacks: → It is still under development and is only available at laboratory-scale. → The catalyst requires further development because of its currently low conversion efficiency.
Final product			
Anhydrous ammonia	Anhydrous ammonia	Depends on production pathway: → Option 1: anhydrous ammonia → Option 2: nitric acid, CAN, AN, soluble nitrates or NPK compounds	Anhydrous ammonia
TRL			
→ Step 1 (depends on electrolyser type): 7–9 (Alkaline/PEM); 3–5 (SOEC) → Step 2: 1–7	1–3	1–3	1–3

this process produces ammonia as an end product, it could also give manufacturers other applications as a decarbonised option, such as for internal combustion engines and fuel cells. This can further support the business model of decentralised fertiliser systems and provide low-carbon options for local communities.

2.1.1 Electric Haber–Bosch



The electric Haber–Bosch technology leads in decentralised fertiliser production

technologies due to its adaptability to small-scale production (see Appendix 1). This technology is also the closest to today's large-scale, centralised production technology for nitrogen fertilisers, as it uses the same chemical reactions. This technology is based on two steps:

(1) the production of hydrogen, and (2) the synthesis of ammonia via the Haber–Bosch process (see Figure 5). Decentralised electrified Haber–Bosch technology relies on hydrogen production from water electrolysis fed with renewable electricity, which splits water molecules to produce hydrogen and oxygen. Current large-scale centralised ammonia synthesis relies on the reaction of nitrogen (N_2) with hydrogen (H_2) over an iron-based catalyst at a high temperature (300–500°C) and high pressure (200–300 bar) (Izelaar et al., 2024). By contrast, decentralised electric Haber–Bosch technologies need milder operating conditions, with operating pressures between 20 and 80 bar (see Table 2). The Technology Readiness Level (TRL) of the technology depends on the reaction steps: step 1 highly depends on the electrolyser, with alkaline and proton exchange membrane electrolysers having a TRL of around 7–9, while solid oxide electrolysers have a lower TRL of around 3–5. Step 2, including Haber–Bosch reactors, has been reported to be between 1 and 7, depending on the process (IEA, 2025).

A central challenge of the electric Haber–Bosch is its inflexibility to operate with variable power output from solar or wind technologies, given the slower dynamics of the ammonia synthesis reactor. This means that the process requires power and hydrogen

storage systems that guarantee a constant flow of energy and feedstock. This is particularly true of decentralised systems, where batteries for power storage and tanks for hydrogen storage can significantly impact the system's cost. Still, the commercial availability of small-scale electrolysers does make the process adaptable to small-scale production.

2.1.2 Direct electrocatalytic nitrogen reduction



Direct electrocatalytic nitrogen reduction is attractive for avoiding intermediate

hydrogen production, but it is still at an early stage of development. By bypassing the intermediate production and storage of hydrogen, no additional equipment is required. The electrocatalyst operates under mild pressure and temperatures. The nitrogen reduction reaction typically involves four steps: adsorption, activation, protonation, and dissociation (Wang et al., 2021). During the first step, a catalyst adsorbs air and ionises the nitrogen molecule (N_2), activating it in the process. The activated nitrogen is then progressively converted to ammonia, which is finally released from the catalyst as the end product of the process. Direct electrocatalytic nitrogen reduction can adapt to intermittent power supply, such as variable renewable energy, given the mild operating temperature of this technology. Noble metal¹ materials are the most widely studied catalysts for electrocatalysis, but non-noble transition metals² represent a cost-effective alternative with promising catalytic activity (see Appendix 1). However, these technologies currently have a low TRL, reported to be between 1 and 3 (Wang et al., 2021).

1 Noble metals refer to ruthenium (Ru), rhodium (Rh), palladium (Pd), silver (Ag), osmium (Os), iridium (Ir), platinum (Pt), and gold (Au). Except for Ag and Au, the metals are collectively called platinum metals. Noble metals are widely used in the petroleum, chemical, electronic, electrical, marine, and aviation industries (Wang, 2017).

2 A non-noble metal catalyst refers to an alternative material, such as transition metal oxides or metal-organic frameworks, that is cost-effective and abundantly available compared with noble metals. These catalysts offer tailored reactivity and can be customised to enhance activity, selectivity and stability in various catalytic processes (ScienceDirect Topics, 2025).

2.1.3 Non-thermal plasma synthesis



Non-thermal plasma synthesis could bypass ammonia production altogether and yield nitric acid directly, but the early understanding of the plasma process limits its development.

Plasma-based processes can create ammonia synthesis via two methods, as shown in Figure 5. The first method activates nitrogen from air without the presence of a catalyst by gas excitation and ionisation in an electric field at atmospheric pressure (Winter et al., 2021), resulting in ammonia as the main product. This process is similar to the conversion that takes place when lightning strikes. To enhance the reaction, a solid catalyst can be used, allowing the reaction to take place at atmospheric pressure and a low temperature. This technology is usually called non-thermal because only a limited amount of the energy is dissipated as heat, making it more flexible than the traditional Haber-Bosch process. The second method is a two-step reaction: 1) producing hydrogen by electrolysis and 2) creating a reaction between the hydrogen and activated nitrogen in the non-thermal plasma reactor to produce ammonia.

This technology also enables an alternative production method without ammonia as an intermediate product. Here, nitrogen from the air is activated in the non-thermal plasma reactor and reacts with oxygen from the air to produce various forms of nitrogen oxides (NO_x). This produces nitric acid (HNO₃), which can be used directly as a fertiliser or converted into other nitrogen fertilisers such as NPK formulations. The Birkeland-Eyde process was the first industrial method of producing nitric acid (Winter et al., 2021), but it has been gradually replaced by the more efficient catalytic oxidation of ammonia via the Ostwald process (Figure 5), which is now the most widely used method.

Non-thermal plasma synthesis is an attractive technology for electrifying and potentially decarbonising nitrogen fertiliser production, but it requires a significant power supply to generate the plasma discharge, resulting in high energy consumption. The TRL for this technology is low, with an indicative value of 1–3 (Smith et al., 2020).

2.1.4 Photocatalytic nitrogen reduction



Photocatalytic nitrogen reduction is still limited to the laboratory due to its low conversion efficiency. This technology mimics the natural

process of photosynthesis by artificially using solar radiation to generate electrons and holes³, thus facilitating the reduction of nitrogen under ambient conditions (Huang et al., 2022). Similar to electrocatalytic nitrogen reduction, this technology relies only on the raw materials water and air (see Figure 5) and uses solar light instead of electricity as the energy source. Artificial photosynthesis on semiconductor-based photocatalysts consists of three steps: (1) the photo-excitation of electrons creating holes, (2) the dissociation of electrons and holes, and (3) the diffusion of electrons and holes on the photocatalyst surface to react with the hydrogen and water molecules (Li, 2018), resulting in ammonia as the end product of the process. Although various materials have been successfully used in photocatalysis, the efficiency of solar-to-chemical conversion (SCC) remains unsatisfactory. Reliable and repeatable photocatalytic performance generally has an SCC < 0.05%, while commercial use of synthetic ammonia would require an SCC > 0.1% (Zhao et al., 2022). Despite its positioning as an interesting alternative, the low conversion efficiency and the required advances in catalyst design and light absorption limits its development with an indicative TRL reported between 1 and 3 (Smith et al., 2020).

2.2 Techno-economic assessment

Assessing the competitiveness of decentralised ammonia and nitrogen fertilisers should consider a comparison with large-scale centralised green ammonia production. This can provide an understanding of the different components that influence the competitiveness of decentralised technologies

³ Positively charged vacancies left behind when electrons are excited during the photocatalytic process.

and indicate which countries have better conditions for adoption. The assumptions used in this assessment are summarised in Appendix 2.

The levelised cost of nitrogen (LCON)⁴ is used here as a comparative measure, regardless of the final nitrogen fertiliser. This metric enables results that are comparable to the retail price for decentralised technologies. LCON is also more easily comparable with the current retail prices of fossil-based nitrogen fertiliser. The more common metric, the levelised cost of ammonia (LCOA), is usually more applicable to large-scale production, where ammonia is the main component of the production process as an intermediate product. The LCON calculations cover centralised nitrogen fertilisers using the Haber–Bosch production process with renewable hydrogen as feedstock to produce green ammonia. For decentralised nitrogen fertilisers, the LCON covers the electric Haber–Bosch and electrocatalysis technologies. No information on the capital and operating costs (CAPEX and OPEX) is yet publicly available for the other technologies, making it difficult to assess their competitiveness.

The downstream transport and distribution costs, which can represent a significant fraction of a farmer's retail price, are not included in the LCON of centralised industrial plants here. While the LCON of decentralised technologies can be seen as the retail price at the farm, the LCON of centralised industrial plants only represents the cost of production. The techno-economic analysis also includes a comparison of verified retail prices for fossil-based nitrogen fertilisers in different locations. This makes it easier to compare the competitiveness of decentralised technologies with current centralised/import-based models.

Two different operating configurations are compared for electric Haber–Bosch and electrocatalysis below:

1. **Autonomous system:** this configuration uses variable renewable energy (solar PV and wind) to supply the system. It is necessary to consider the storage systems for electricity and hydrogen (battery and hydrogen buffer), the curtailment of electricity, and the oversizing of the installed renewable energy capacity to guarantee a constant power supply, all of which influence the final LCON and therefore the competitiveness of the technologies⁵. However, the cost calculation includes the optimisation of the system based on the renewable potential of the site (generation intermittency) to determine the optimal installed renewable power capacity.
2. **Grid-connected system:** this configuration assumes the availability of the electricity grid at the farm site in all evaluated countries and allows continuous operation of the system with a capacity factor of up to 100%, as electricity can be purchased from the grid as needed. The grid-connected system is strongly influenced by the cost of electricity in the country, as this directly impacts the system's operating costs; no storage for electricity or hydrogen is required. Another important aspect is the sustainability and carbon intensity of the fertiliser when using grid electricity. In many cases, the share of renewable energy in the country's electricity system is not high enough to ensure a low-carbon electricity supply to the decentralised system. This is particularly relevant for Thailand and the US, where electricity is still mainly generated from fossil fuels (renewable power generation in 2022 reached only 20% in Thailand and 21% in the US) (IRENA, 2024). The high share of renewables in Brazil's and Kenya's power systems (88% and 86%, respectively) increases the potential for this configuration to significantly reduce carbon emissions from ammonia and nitrogen fertiliser production in these countries (IRENA, 2024). It can be assumed that the long-term decarbonisation policies for the power sector in the four countries will contribute to integrating more renewable energy sources, thus

⁴ Levelised Cost of Nitrogen (LCON) is preferred over the more common Levelised Cost of Ammonia (LCOA) as this metric is independent of specific fertiliser products, including ammonia. The LCOA (USD per tonne of ammonia) can be derived from the LCON (USD per tonne of nitrogen) by dividing the LCON by 0.82 (tonnes of nitrogen per tonne of ammonia).

⁵ The sizing and operation of each system's component is obtained through an optimisation model based on the hourly local production profiles of solar and wind technologies.

ensuring the sustainability of this configuration in the long term, when the supply of renewable energy from the grid can be guaranteed.

While the total yearly demand influences the overall system scale, it is the timing and profile of that demand – such as seasonality and peak loads – that can significantly affect system design, including storage and curtailment, and thus the LCON. At the same time, the size of the decentralised system is expected to face technical constraints regarding equipment size. For example, it would be challenging to have electrolyzers with capacities below 1 MW, given the manufacturing size of the stacks offered by manufacturers (Nel, 2025; John Cockerill, 2025; Sunfire, 2024). This means that a decentralised fertiliser project could meet the fertiliser needs of many large-scale surrounding farms. For the techno-economic assessment, a nitrogen demand of 20 tonnes per year (t/y) is considered here to be representative of an average farm in the US, and a demand of 70 t/y and 5 t/y to be representative of medium commercial and small farms in Brazil. Both Thailand and Kenya have smallholder farms, for which an estimate of

0.3 t/y and 0.03 t/y of nitrogen is assumed as indicative demand; areas of relevant agricultural activity have been identified in each country. These specific locations are important for assessing the renewable resources available at a given site. This is an important factor affecting the LCON through the capacity factor of renewable technologies.

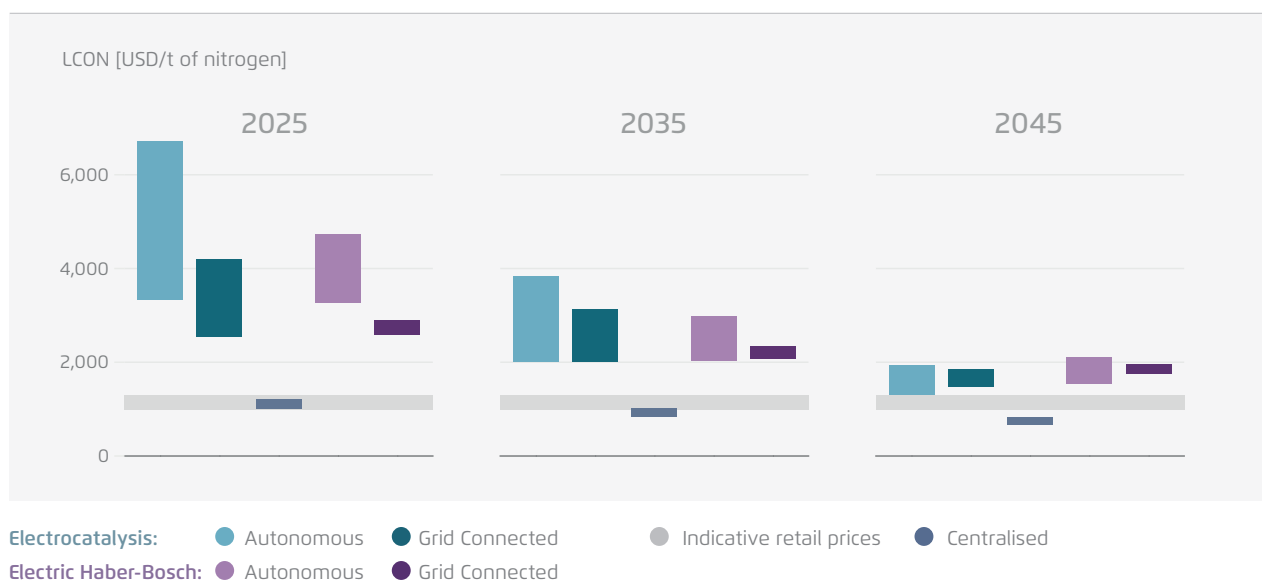
Brazil⁶

Brazil has good conditions for implementing decentralised renewable ammonia and nitrogen fertiliser technologies, but policy support would be required to close the price gap quickly with current retail prices for fossil fertilisers in locations like Mato Grosso.

Sorriso in Mato Grosso was chosen as a reference location in Brazil because of its important agricultural

⁶ Brazil has significant potential to produce fertilisers using biomass and/or biogas-based technologies; however, this is beyond the scope of this analysis. This report focuses on technologies currently being developed and piloted in different regions, thanks to the widespread availability of solar and wind resources. These technologies have greater scalability potential in different regions, as is described in the policy recommendations below.

Levelised cost of nitrogen (LCON) for renewable-based technology configurations compared with indicative retail prices in Brazil (Mato Grosso) → Fig. 6



Agora Industry (2025). Note: For centralised production, results are derived from Öko-Institut, Agora Industry and Agora Energiewende (2024): PTX Business Opportunity Analyser 2.1.1. Any policy support schemes at the national level are not included in the modelling analysis of this study. The modelling results for different business cases do not include ammonia storage.

economy and its distance from the Brazilian coastline, where the country's most important trade ports are located. Brazil's well-developed renewable market and large-scale commercial farms offer the technological conditions that make decentralised technologies more competitive.

A grid-connected configuration for decentralised renewable ammonia and nitrogen fertiliser technologies in Brazil would offer the fastest decrease in costs and the most competitive values in the short term. However, this competitiveness is limited by unfavourable wind generation conditions in Mato Grosso. As shown in Figure 6, the grid-connected configuration is more competitive for both technologies in the short to medium term. In the most optimistic scenario for 2025, the grid-connected configuration will cost roughly twice as much as the centralised configuration, with an LCON of about USD 2,600/t N for electric Haber-Bosch and USD 2,500/t N for electrocatalysis. In contrast, decentralised technologies with an autonomous configuration could be around three times more expensive for electric Haber-Bosch and between four and eight times more than centralised production for electrocatalysis in 2025. In 2045,

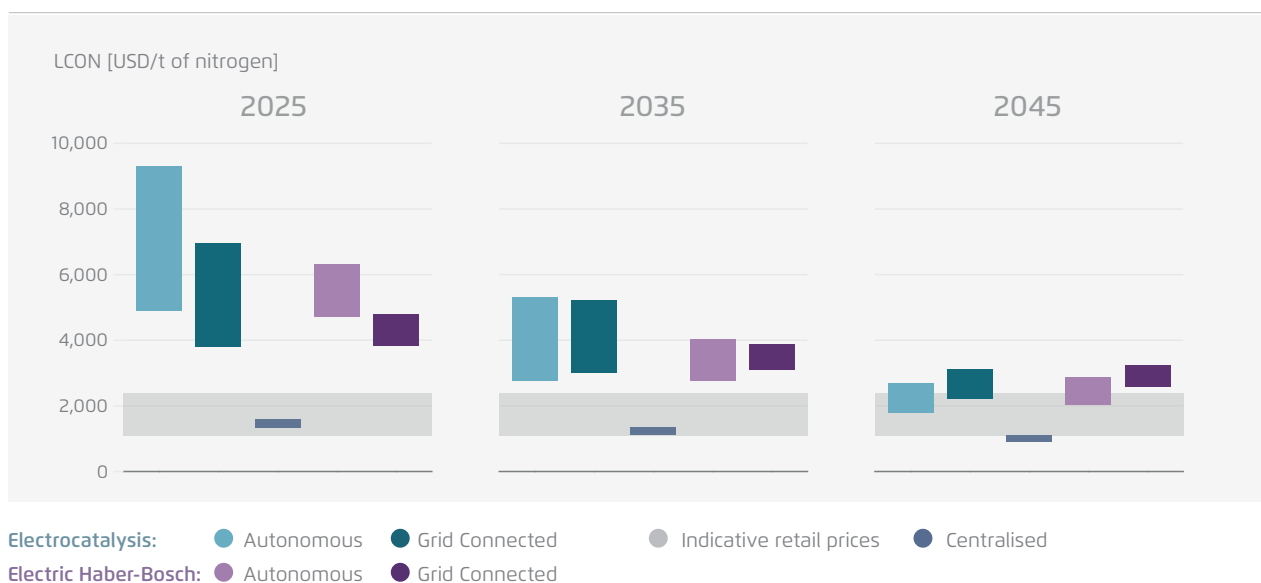
decentralised technologies in both configurations would still be twice as expensive as centralised production, with LCON values as low as 1,500 USD/t of N.

When comparing the LCON for decentralised technologies in Mato Grosso with the current retail price of fossil nitrogen fertiliser, cost parity can be reached by 2045 without policy support. In 2024, the retail price of fossil nitrogen fertiliser in Mato Grosso was between 1,000 and 1,300 USD/t of N (Veloso, 2024; Veloso, 2024b). The price gap here is much smaller and comparable because both values already consider the transport and distribution of the products. With appropriate policy support (see Section 5), decentralised technologies could achieve cost parity more quickly and become more competitive in Brazil.

Kenya

The competitiveness of decentralised renewable ammonia and nitrogen fertiliser technologies in Kenya is strongly affected by the country's investment risk. However, other conditions, such as full import dependency and favourable renewable energy resources, favour the competitiveness of

Levelised cost of nitrogen (LCON) for renewable-based technology configurations compared with indicative retail prices in Kenya (Naivasha) → Fig. 7



Agora Industry (2025). Note: For centralised production, results are derived from Öko-Institut, Agora Industry and Agora Energiewende (2024): PTX Business Opportunity Analyser 2.1.1. Any policy support schemes at the national level are not included in the modelling analysis of this study. The modelling results for different business cases do not include ammonia storage.

these technologies. The techno-economic assessment in Kenya is strongly influenced by the Weighted Average Cost of Capital (WACC) (see Infobox 2), a metric that reflects the risk of investing in a particular country. WACC estimates are influenced by contractual, country and technology risk (Agora Industry and Agora Energiewende, 2024). In Kenya, WACC has been estimated at around 14%, which is the highest among the countries considered in this assessment (compared with Brazil (9%), Thailand (7%) and the US (5%)) (see Appendix 2). Naivasha was selected as the region for this assessment due to its agricultural activity and the development of a pilot project for decentralised ammonia production in the area.

Decentralised technologies in Kenya incur high costs in the short term compared with centralised renewable production, with autonomous systems offering the greater cost reduction over the long term. By 2025, decentralised technologies can cost between four and six times more than centralised production, which has an LCON between 1,350 and 1,600 USD/t N (see Figure 7). In an optimistic scenario for autonomous systems in 2045, this cost difference will be lower, with electric Haber–Bosch reaching a cost of around 2,000 USD/t N and electrocatalysis around 1,800 USD/t N (both of which are twice as expensive as centralised production). Grid-connected systems would have higher LCON values in 2045, with electrocatalysis as low as 2,200 USD/t N and electric Haber–Bosch around 2,600 USD/t N.

Current retail prices of fossil nitrogen fertilisers in Naivasha can be high, creating better opportunities for decentralised technologies. In 2025, the Naivasha region saw retail prices for fossil fertilisers ranging from 1,100 to 2,400 USD/t N, with the lowest values benefiting from government subsidies (Argus Media, 2024; Jiji Kenya, 2025). These high retail prices reflect inefficiencies in the nitrogen fertiliser supply chain. If price trends remain the same, decentralised technologies could achieve cost parity by 2045 despite the high investment risk. Risk mitigation mechanisms and other policies (see Section 5) could significantly enhance the competitiveness of decentralised technologies in the region.

Thailand

In Thailand, the slow adoption of renewables – along with a still-developing renewable market and a low share of renewables in power generation – reduces the competitiveness of decentralised renewable ammonia and nitrogen fertiliser technologies. For autonomous systems, the cost of renewables plays an important role, especially in the short term. At the same time, for grid-connected configurations, the carbon content of the electricity that could power these technologies is still high, limiting their potential to reduce emissions. The Lopburi region in Thailand was identified due to its significant agricultural activity; it is also interesting because it lies in the centre of the country, far from ports where fertilisers are usually imported.

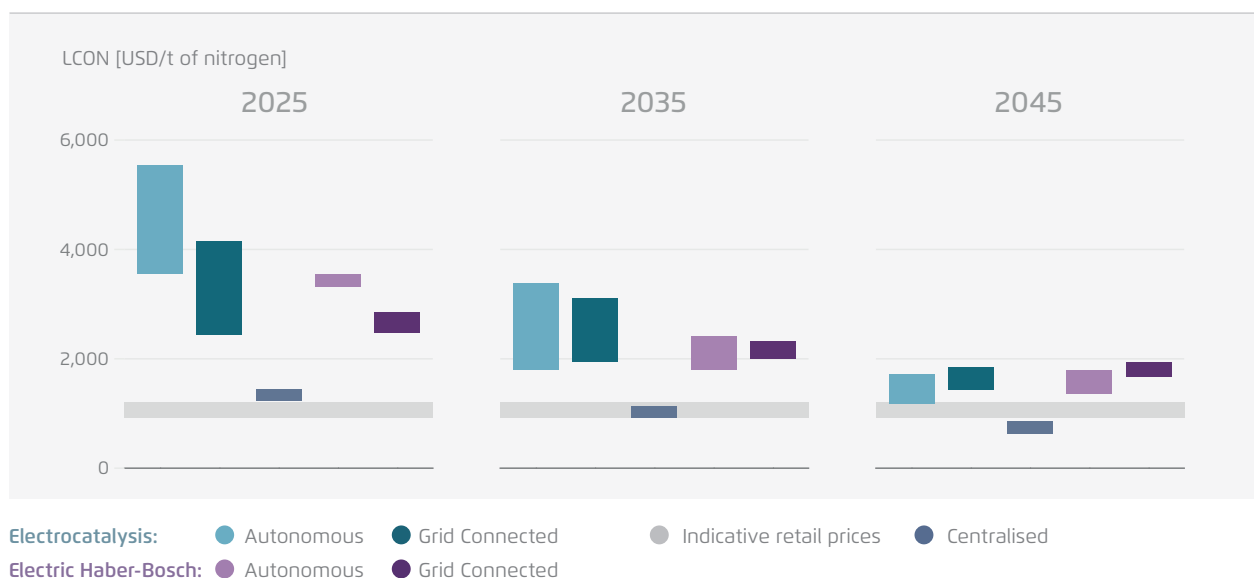


Infobox 2: Equity Risk Premium (ERP) and Weighted Average Cost of Capital (WACC)

The project-specific WACC captures the blended cost of both equity and debt financing and is tailored to the unique financial structure and risk profile of individual projects. For hydrogen production, known for its capital-intensive and innovative nature, equity investments typically comprise the majority of project financing. This makes using the Equity Risk Premium (ERP), which focuses only on equity, a pragmatic and simpler approach to estimating the “Country WACC” for hydrogen projects. In this study, the country-specific ERP is used as a proxy for the WACC based on the database developed by Damodaran (2024).

Agora Industry (2024b)

Levelised cost of nitrogen (LCON) for renewable-based technology configurations compared with indicative retail prices in Thailand (Lopburi) → Fig. 8



Agora Industry (2025). Note: For centralised production, results are derived from Öko-Institut, Agora Industry and Agora Energiewende (2024): PTX Business Opportunity Analyser 2.1.1. Any policy support schemes at the national level are not included in the modelling analysis of this study. The modelling results for different business cases do not include ammonia storage.

A grid-connected configuration for decentralised technologies could be more competitive in Thailand in the short term, but renewables have significant potential to reduce costs in the long term. Figure 8 shows that, in the short term, the grid-connected configuration could be more cost-effective for both technologies, with LCON values of around 2,500 USD/t N, twice the cost of centralised production. However, cost reductions in renewables will make autonomous configurations more competitive in the long term. In the most optimistic scenario, costs would be around 1,350 USD/t N for electric Haber-Bosch and 1,200 USD/t N for electrocatalysis in 2045.

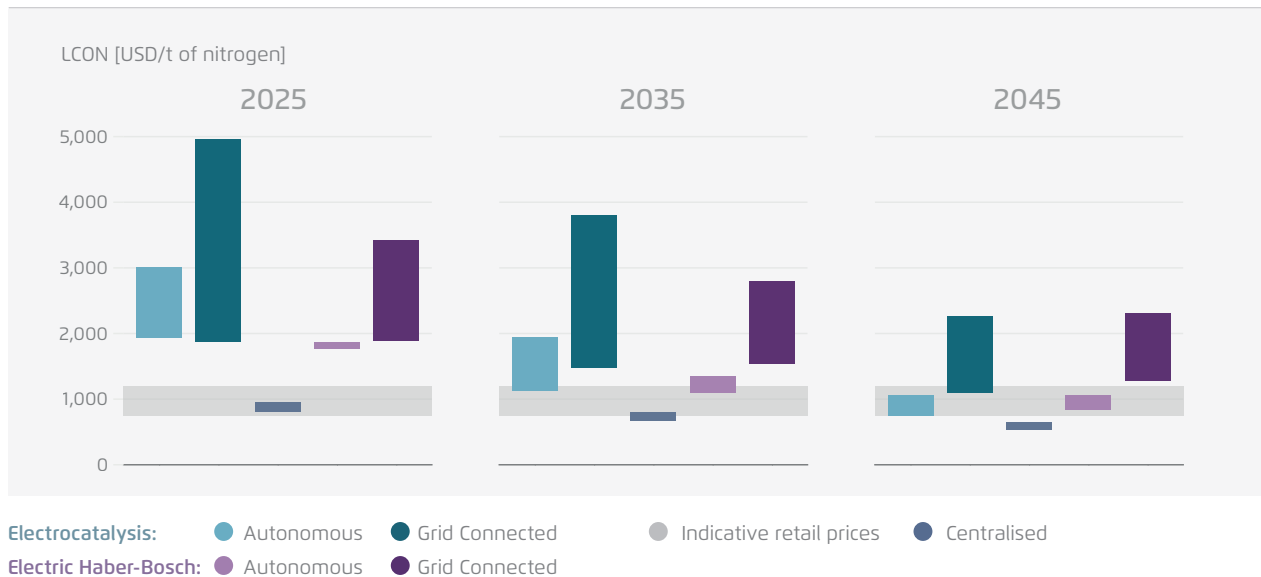
Even without policy support, autonomous decentralised nitrogen fertilisers could catch up with current retail prices for fossil fertilisers in Lopburi by 2045. Retail prices for nitrogen fertilisers in Thailand are reported to be around 920 and 1,200 USD/t N in 2025 (OAE, 2024). This price range would achieve cost parity with centralised green nitrogen fertilisers by 2035. If this trend continues, decentralised technologies could even achieve cost parity in the long term without policy support.

United States

There is significant potential for decentralising the production of renewable ammonia and nitrogen fertiliser in the Corn Belt region of the US, thanks to favourable renewable energy resources and large-scale agricultural practices. The favourable wind and solar resources in this region make decentralised technologies attractive, particularly in an autonomous configuration. Omaha, Nebraska was selected as a representative example of the region, where commercial agricultural production takes place and ammonia is already used as a fertiliser. Omaha is also far from industrial fertiliser production hubs and ports. Pilot projects for decentralised renewable ammonia production are already underway.

Employing decentralised technologies with autonomous configuration could reduce costs significantly, leading to parity with centralised technologies in the long term. In 2025, decentralised technologies with autonomous and grid-connected configurations in Nebraska are two to three times more expensive, with electric Haber-Bosch having the lowest values of around 1,750 USD/t N; however, costs could be

Levelised cost of nitrogen (LCON) for renewable-based technology configurations compared with indicative retail prices in the US (Nebraska) → Fig. 9



Agora Industry (2025). Note: For centralised production, results are derived from Öko-Institut, Agora Industry and Agora Energiewende (2024): PTX Business Opportunity Analyser 2.1.1. Any policy support schemes at the national level are not included in the modelling analysis of this study. The modelling results for different business cases do not include ammonia storage.

reduced in Omaha due to good solar and wind resources, low WACC and competitive renewable energy costs (see Figure 9). In the most optimistic scenario, decentralised technologies could almost achieve cost parity with centralised production by 2045 without policy support, with the LCON reaching around 800 USD/t N for autonomous electric Haber-Bosch and 750 USD/t N for autonomous electrocatalysis.

When compared with fossil-based fertilisers, decentralised technologies could achieve cost parity in Omaha as early as 2035, even without policy support.

In 2024, retail prices for fossil nitrogen fertiliser in Nebraska were between 750 and 1,200 USD/t N (Quinn, 2025). Decentralised technologies in Omaha reach values below 1,200 USD/t N already by 2035, making them attractive in locations such as Nebraska where the commercial size of farms, distance to ports, and experience with using anhydrous ammonia favour their adoption.

3 Socio-economic factors influencing adoption

Several factors influence the adoption of decentralised fertiliser production. Here, we examine these from economic and farming perspectives and dive deeper into the following questions:

- What are the implications of actual supply and demand in terms of time and location?
- Which farmers will adopt fertilisers produced locally? How should farmers be equipped with the necessary machinery, knowledge and skills?
- How do different types of nitrogen fertilisers compare in terms of their health and safety implications? How should toxic ammonia be handled?
- What socio-economic benefits, such as job creation, are generated by decentralised renewable fertiliser production?

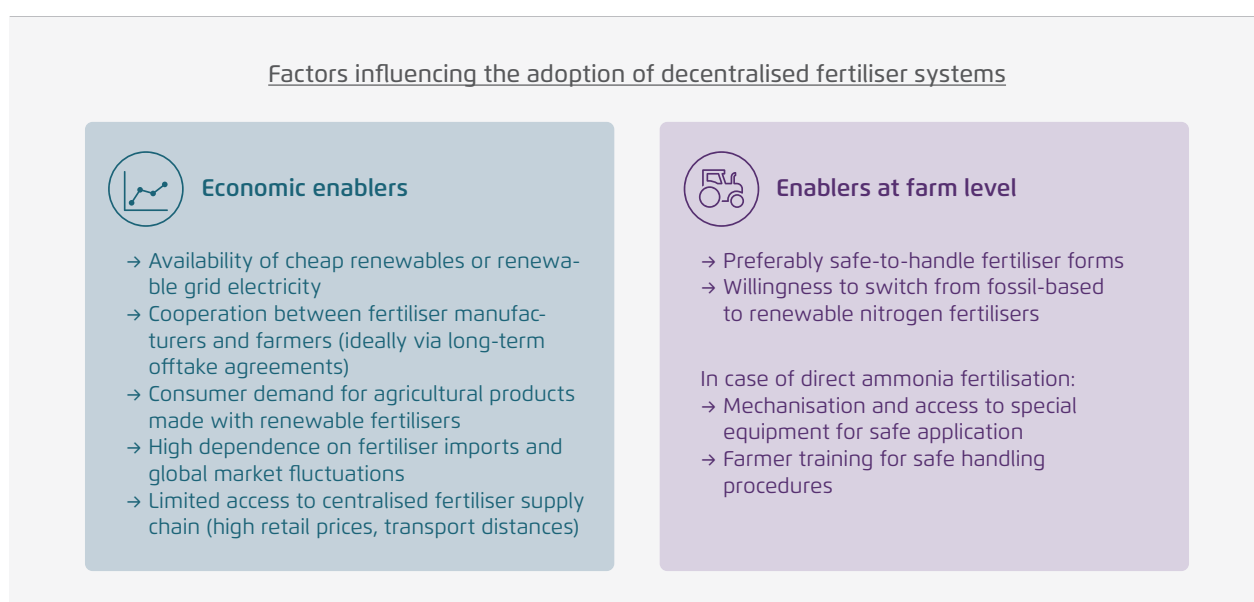
These factors must be understood to create an enabling environment that maximises local value creation while strictly adhering to safety precautions and minimising human and environmental risks.

Figure 10 summarises the economic and agricultural enablers crucial for the adoption of decentralised fertilisers.

3.1 Demand and supply of decentralised fertilisers

Decentralised systems are desirable in regions where centralised fertiliser plants are distant or where the transport infrastructure is weak. This is especially true for many countries in the Global South, particularly in Latin America and Africa, where domestic fertiliser production is limited or absent. The decentralised fertiliser business model is driven by the private sector in places with a strong agricultural sector, abundant renewables, and sometimes distant from fertiliser markets. Frontrunner projects that meet these criteria are found in Iowa (US), Naivasha (Kenya) and Manitoba (Canada).

Enablers for adoption of decentralised ammonia and nitrogen fertiliser production → Fig. 10



Decentralised systems have the potential to reduce the need for extensive shipping/transport and minimise the associated costs. Distance to centralised fertiliser plants, the role of intermediaries in cost markup, and transport costs all play a role when choosing the production site. In areas with limited access to key industrial inputs or where traditional supply chains are prone to disruptions, decentralised production systems can offer a more resilient and cost-effective alternative (Tonelli et al., 2024a).

Matching seasonal and geographical supply and demand remains a challenge. The production of one or more tonnes of ammonia a day is many times greater than the consumption of even large-scale farms. To compare, we assume an annual demand of between 24 and 85 tonnes of ammonia for average farms in Brazil and the US, but small decentralised systems produce as much as one tonne of ammonia a day (see Appendix 2). This means that operators of decentralised ammonia plants (sellers) will have to look for buyers in the greater geographical vicinity, ideally contracted via long-term offtake agreements to provide economic security. Depending on traded volumes, this could create new regional fertiliser hubs; moreover, alternative buyers from other industries requiring ammonia (for example, the mining or chemical industry) could increase local demand and stabilise offtake additionally.

To ensure the steady production of nitrogen fertiliser throughout the year by electric Haber-Bosch systems, storage will have to match varying agricultural demand. We assume that production must be maximised throughout the year to become economical. However, crop demand follows a particular pattern during the growing season, sometimes resulting in peak demands, a phenomenon also seen in conventional fertiliser markets. For this reason, storage systems will probably play an important role in decentralised fertiliser markets. Compared with conventional nitrogen fertilisers (sold as granules or solutions), storing anhydrous and aqueous ammonia presents greater challenges (see Section 3.3 Health and safety). If anhydrous or aqueous ammonia is used as a fertiliser, its storage system must account for

its toxicity and its chemical and physical properties. Farmers should also carefully weigh the costs and risks of implementing such systems.

Long-term partnership agreements between the operators of decentralised ammonia and fertiliser plants and farmers secure a steady offtake⁷ and reduce financial risk. Currently, manufacturers of decentralised ammonia and fertiliser plants own and run the production facilities. In theory, decentralised plants could also be owned by financially sound and large agribusinesses, as large and highly industrialised farms are more inclined to have the economic resources and operational scale to benefit from decentralised nitrogen fertiliser production systems⁸ than small-scale farms. This could lead to a more direct supply chain, with farmers producing their nitrogen fertiliser and becoming self-sufficient. However, this model does not yet exist, most likely because of the significant upfront investment needed, the lack of operational experience, and potential technical risks. Policy support and innovative strategies are needed to facilitate the wider adoption of decentralised ammonia and fertiliser systems, while mitigating the risks associated with the high upfront costs of these technologies.

3.2 End-users of decentralised nitrogen fertilisers

The safe handling of ammonia as a fertiliser requires specialist knowledge, machinery and training; this limits its use to highly industrialised farming systems. Directly applying anhydrous ammonia is a relatively complex operation (see Infobox 3). It can only be carried out by farmers with expertise in this type of fertilisation, and the farm must be highly mechanised. Large farms are the most likely to employ the

⁷ Kenya Nut Company, for example, has signed a 15-year offtake agreement with TalusAg in the first operational decentralised ammonia and fertiliser plant (Talus Renewables, 2023).

⁸ See for example: <https://fuelpositive.com/fuelpositive-completes-on-farm-commissioning-of-the-first-scale-able-green-ammonia-production-system-and-announces-new-manitoba-based-partnerships>

→ Infobox 3: Direct use of ammonia as fertiliser

Anhydrous ammonia is a gas that must be pressurised for storage in its liquid form. It does not contain water. Even small concentrations of ammonia in the air can be detected due to its characteristic, unpleasant scent. To apply it as a fertiliser, a special harrow cuts the soil with a disc and injects the anhydrous ammonia 10–20cm below the soil surface. The (pressurised) ammonia tank is towed on-field behind application devices. In the soil, anhydrous ammonia reacts with soil water to form ammonium. In this form, it can easily be adsorbed by charged soil particles via cation exchange.

Ammonia can also be dissolved in water to form **aqueous ammonia**. Aqueous ammonia can be both injected (though not as deeply as anhydrous) or added to irrigation water. When a nutrient is added to irrigation water, the process is called **fertigation**. Ammonia can also be used for crops requiring flooding, such as wetland rice (Mosaic Crop Nutrition, 2025). When adding ammonia to irrigation water, special attention needs to be given to its caustic nature: contact with skin must be avoided (see Section 3.3).

practice as they typically employ skilled labour and have access to technical expertise. Years of experience with anhydrous ammonia fertilisation certainly increases the acceptance and upscaling of decentralised systems. In the US, where direct ammonia fertilisation is a common practice, (large-scale) farms train employees and collaborate with experts such as agronomists and consultants to ensure safety and efficiency. In the case of aqueous ammonia, safe handling and storage remain important despite different application techniques (see Infobox 3).

For small and medium-sized farms, the level of mechanisation can be a barrier to using anhydrous ammonia as a fertiliser. Medium-scale producers lack the necessary infrastructure and equipment for the storage and application of ammonia, as well as the operational expertise, making these fertilisers less viable for them. Agricultural cooperatives present an alternative: beyond shared technical resources, they could leverage training opportunities to pool knowledge and upskill farmers for safety measures, thus tackling the lack of skilled labour among medium and small-scale farmers.

3.3 Health and safety aspects for different forms of nitrogen fertilisers

Anhydrous and aqueous ammonia are hazardous substances; other nitrogen fertilisers (for example, ammonium nitrates or urea) should be preferred.

Risks must be carefully assessed when setting up new decentralised fertiliser facilities in farming systems lacking experience, particularly in countries of the Global South. Fertilisers in the form of granules or solutions are less hazardous to handle. Of the decentralised technologies examined in Section 2.1, only non-thermal plasma (see Section 2.1.3) directly yields nitric acid, a precursor of ammonium nitrates and NPK fertilisers. However, the technology is still in its infancy as compared with electric Haber-Bosch. Other decentralised technologies would include an extra step – the conversion of ammonia to NPK fertilisers – which could increase the system's costs. Research efforts should specifically focus on technologies able to yield ammonium nitrates and scale the conversion of ammonia into nitrogen fertiliser forms that are safer to apply via additional technological add-ons. In this respect, non-thermal plasma technologies that produce ammonium nitrates have a comparative advantage over electric Haber-Bosch. Given their lower technological maturity, anhydrous or aqueous ammonia products are likely to see faster

Health and safety risks for humans and management options of anhydrous ammonia

→ Table 3

Risk	What can happen?	Safety measures
Toxic and caustic nature	Anhydrous ammonia is drawn to moist body parts (eyes, lungs, nose, etc). Exposure results in instant chemical burning of living tissue with disfiguring and potentially fatal results (depending on concentration and exposure).	Wearing protective equipment when handling ammonia, including gloves and eye protection, with respirators for high exposure.
Frostbite explosions	Sudden releases of pressurised ammonia cause temperatures to drop from 38°C to -33°C, resulting in instant freeze burns to the skin.	Flushing affected body parts with large amounts of water continuously can neutralise caustic effects. Carrying emergency water tanks in tractors is advised. In bulk facilities, water tanks must be close by. Regular monitoring of technical storage and refilling equipment, such as tanks, seals, valves, etc.
Flammability	Under exceptional circumstances (in closed and insufficiently ventilated areas), leaked ammonia can ignite and explode, but only when reaching minimum concentration levels of 16% of ambient air.	Safety monitoring of storage vessels (see above).

Agora Industry (2025) based on Nowatzki (2021)

market growth, highlighting the urgency of adequate health and safety measures for farmers unfamiliar with them.

Safe handling and application measures are crucial for ensuring farmers' health and safety. Compared with nitrates, anhydrous ammonia requires special storage, handling and training to mitigate environmental and safety impacts when used directly as a fertiliser. Significant risks of handling anhydrous ammonia are summarised in Table 3.

Ammonia's toxicity and explosive potential pose additional safety risks during storage and use. Mis-handling can lead to serious hazards, including leaks and explosions, resulting in serious health effects, ranging from severe damage to the respiratory tract if inhaled, burns and irritation of the skin, and frostbite from direct contact with liquefied ammonia. Road accidents with ammonia tanks have resulted in fatalities (Hydrogen Insight, 2023).

Regulatory health and safety measures must cover the entire supply chain from production to on-site application to minimise the risks associated with ammonia handling. Brazil, Kenya and the US have regulations in place to ensure proper handling, storage and transport at the national and state levels

(only in the US). In the US and Kenya, where direct ammonia fertilisation is already practised, specific standards are in place.

Countries interested in developing new decentralised fertiliser markets must ensure that regulatory structures and inspection bodies are in place to guarantee health and safety on farms. As this is a new practice for many farmers, extensive technical training will be needed to ensure that safety protocols are known and followed. Local authorities can support these systems by providing training through agricultural extension services and compliance with (new) standards. Research in the study countries revealed that in the US and Kenya, where decentralised fertiliser production has already begun, several policies at the national level regulate the handling of hazardous anhydrous ammonia for agricultural use (see Table 4). In the US, the agricultural departments of the Corn Belt states have enacted special regulations for anhydrous ammonia handling on farms, such as risk management plans (Missouri and North Dakota) and certified grower training (Illinois), in addition to national regulations.

Health and safety regulations for ammonia handling on farms¹

→ Table 4

	Kenya	US
Health and safety regulations	→ Technical standard for ensuring safety of anhydrous ammonia application for tractors and agricultural/forest machinery (KS ISO 4254-2:1986) → Anhydrous ammonia storage and handling standard (KS 2865:2019) → Storage and handling of the toxic substance (KS 2866:2019)	National standard (OSHA 1910.111 2024): → The Occupational Safety and Health Administration (OSHA) imposes process safety management standards for ammonia and training for workers in contact with ammonia, including the use of personal protective equipment. → Guidelines for transporting ammonia and risk management programmes in place
Farmer experience in handling ammonia	Currently, at least one farm processes ammonia directly; application method and farming equipment are not known.	Specialised farms in the US use application equipment designed for safely handling anhydrous ammonia, following strict safety protocols outlined by the USDA and OSHA. These include using proper personal protective equipment, ensuring precise application.

Energy and Petroleum Regulatory Authority (2024), OSHA (2024); ¹Although there is a national regulation in place for the safe transportation, storage and handling of anhydrous ammonia in Brazil, there is no standard for the agricultural sector. No specific information was found for Thailand.

3.4 Jobs as additional local socio-economic opportunities

Cooperation between operators of decentralised systems and agribusinesses should maximise local value. Besides gaining more strategic autonomy for a basic commodity needed for food production, projects should be steered towards additional socio-economic benefits for local communities. This is particularly important given that it is mainly North American and European companies and start-ups that initiate expansion into new markets in the Global South.

Socio-economic benefits linked to the uptake of decentralised production systems across different sectors include the creation of new jobs and a wider range of employment opportunities. While little

information is available on the exact number of jobs created in this industry, values can be derived from the literature. Decentralised fertiliser plants create jobs in manufacturing, construction and operation; jobs could also be created in constructing (additional) renewable parks, ideally next to the plants. In both cases, construction jobs outnumber operation jobs by far, but only the latter are long-term. Assuming an electrolyser capacity of 1 MW (in line with actual production capacity described in Section 2.2), a decentralised plant would result in a rather small additional employment opportunity of only 0.1 full-time equivalents per year and per fertiliser plant. This is mirrored by one operator indicating that their system runs entirely autonomously and can be monitored remotely (Talus Renewables, 2023).

Employment factors associated with decentralised fertilisers

→ Table 5

	Manufacturing [jobs per year and MW]	Construction and installation [jobs per year and MW]	Operation and maintenance [jobs per year and MW]
PV utility scale	6.5	13	0.7
Water electrolysis	Around 1	1.3	Around 0.1

Agora Industry (2025) based on Ram et al. (2022a) and Ram et al. (2022b)

4 Agri-environmental assessment

Decentralised nitrogen fertilisers powered by renewable energy deliver substantial emissions reductions compared with their fossil fuel-based counterparts. This chapter discusses the potential savings in emissions at different stages of the fertiliser production and use, as well as other environmental impacts. In a nutshell, fertiliser emissions stem from the following processes:

- **Soil-related emissions after fertiliser application:** the bulk of all fertiliser-related emissions come from soils and account for 50–60% of total emissions (Menegat et al., 2022). Emissions mainly refer to nitrous oxide, but carbon emissions can also be released by nitrogen fertilisers such as urea.
- **Production:** for centrally produced nitrogen fertilisers, most emissions arise during production, which relies heavily on fossil fuels for heat and feedstock – primarily fossil gas (72%), followed by coal (22%) and heavy oil (3%) (IRENA et al., 2022). Using fossil fuels in ammonia production has a

carbon intensity of around 1.8 tonnes of CO₂ per tonne of ammonia (Agora et al., 2023), resulting in 438 Mt CO₂-eq in 2018, around 1.3% of global emissions in that year (Menegat et al., 2022).

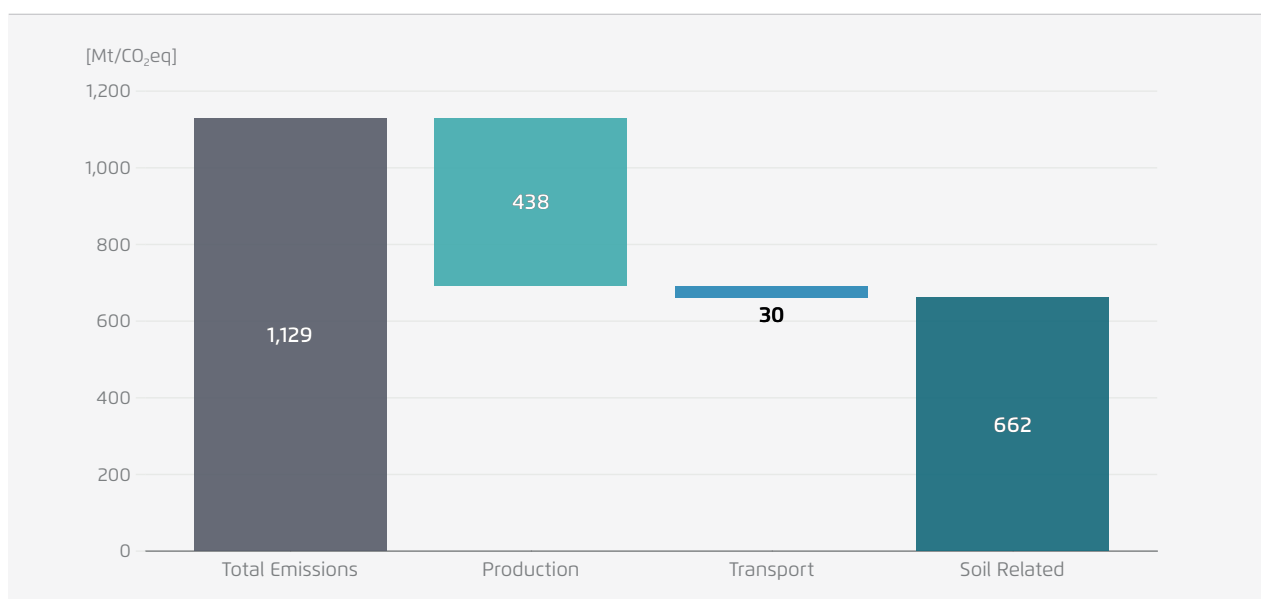
→ **Transport:** currently about 3% of total emissions.

4.1 Emissions from decentralised fertilisers

Emission reductions from production: where dedicated and additional renewable energy is the primary source of electricity, decentralised nitrogen fertiliser technologies significantly reduce emissions compared with centralised production based on fossil energy sources. As shown in Figure 11, actual emissions savings from a carbon-neutral production method make up 30–40% of the total emissions from fertiliser use. Where grid electricity is used, the overall carbon impact depends on the amount of carbon produced during electricity generation. It is crucial

Global GHG emissions related to nitrogen fertiliser production, transport and use

→ Fig. 11



Agora Industry (2024a) based on Menegat et al. (2022). Note: Reference year 2018. Emissions from urea are accounted for in column Soil Related. According to IEA (2021), demand for nitrogen-based fertiliser (excluding urea) is expected to almost double in the net-zero scenario.

to ensure that emissions are reduced and that the potential abatement from grid-connected systems is not overestimated.

Emission reductions from transport: by bringing fertiliser production closer to the points of use, decentralised systems reduce transport emissions to a minimum. This could also lead to significant cost reductions in regions with long distances to centralised plants, such as in many countries of the Global South (Srivastava et al., 2023), but also in landlocked areas with long distances to import terminals. Typically, the share of transport costs in retail prices is more significant in remote areas.

Unchanged high share of soil-related emissions: the application of renewable nitrogen fertiliser produced by decentralised technologies does not change greenhouse gas emissions from fields, which already account for the largest share of total fertiliser emissions, at around 60% of the entire value chain (see Figure 11). Adding nitrogen to soils causes soil microbial nitrification and denitrification processes that naturally release NOx into the atmosphere. About one percent of the total nitrogen applied to soils results in direct NOx emissions (IPCC et al., 2019). While the default value is applied regardless of the nitrogen source (synthetic/organic fertilisers, crop residues, or anhydrous ammonia), under the assumption of no significant differences in emissions, empirical studies have demonstrated that fertiliser types can have

different effects. Although higher NOx emissions were observed following the application of anhydrous ammonia (Zhu-Barker et al., 2015), studies on this topic are currently too scarce to make conclusive statements about the impact of anhydrous ammonia on soil-related emissions. Similarly, any changes in secondary nitrous oxide emissions (occurring after nitrogen re-deposition, for example, after leaching) cannot be adequately evaluated in the context of direct ammonia application.

Direct ammonia emissions from direct ammonia application: because ammonia is gaseous, it is prone to volatilisation, leading to atmospheric losses and contributing to particulate matter formation, particularly where anhydrous ammonia is applied directly. Weather conditions and soil moisture at the time of fertilisation strongly influence the amount of ammonia emissions, with dry soils showing increased volatilisation through soil pores during or even some time after application (Roth et al., 2024). In addition, once volatilised in its gaseous form, ammonia is re-deposited on nearby soils, subsequently undergoing nitrification and denitrification processes, which yield NOx emissions.

To conclude, improving nitrogen use efficiency is a key measure to drive down soil-related emissions. The 4R nutrient stewardship guideline (see Table 6) summarises all levers to reduce emissions.

Improving nitrogen use efficiency and reducing emissions → Table 6

Right source → Emissions per fertiliser type differ → Nitrification inhibitors can slow the nitrification process and reduce soil emissions → Urease inhibitors can reduce ammonia emissions	Right rate → Avoid overapplication of fertiliser → Use precision agriculture
Right time → Aligning application with crop demand → For dry soils, application after precipitation is recommended as it decreases volatilisation losses	Right place → Adding fertiliser where plant roots can efficiently access it

University of Missouri (2025)

4.2 Environmental impacts of applying ammonia and fertiliser

Although proper agricultural practices can mitigate environmental risks such as air and water pollution and soil degradation, the overapplication of fertilisers can cause major environmental problems.

Overuse of fertilisers risks acidifying soils, reducing soil health, and microbial diversity. Excess nitrogen is released into the atmosphere as nitrous oxide and ammonia, and into water as nitrate. Nitrate is produced by ammonia in a microbial process called nitrification. Nitrogen is available for plant uptake in this form, but it is also highly susceptible to loss through leaching. The leaching of nitrate into surface water and groundwater can have an adverse effect on water quality and increase eutrophication. The focus here is on nitrogen surplus, the part of the fertiliser that is not taken up by the plants and is removed with the harvest. One of the most important agri-environmental measures is to avoid nitrogen surpluses and emissions of reactive nitrogen (N) compounds. Best management practices, as described in Table 6, are essential to optimise nitrogen use and minimise these impacts.

Effects of anhydrous ammonia injection in soils: the direct injection of ammonia causes a sudden increase in pH, which can kill soil microbes near the injection point. This pH shock can pose an additional environmental risk for soil microbial biodiversity, although the effects are only expected close to the injection lines. When ammonia is injected in its gaseous form, it reacts quickly with water to form ammonium, which is less susceptible to leaching than nitrates.

However, when higher soil moisture increases ammonium formation in drier soils, ammonia is lost through soil pores. To avoid this, anhydrous ammonia should ideally be injected into slightly moist soils; this should be done at the correct depth, and the slits should be sealed during application (Roth et al., 2024).

Air pollution: in addition to direct ammonia losses, the direct application of ammonia can cause significant temporary air pollution due to its characteristic, unpleasant odour.

Fertiliser overuse: many countries are struggling with the consequences of fertiliser overuse outlined above. The priority here is to increase the efficiency of nutrient use through modern technology, knowledge and policy reform, not increased fertiliser use. The risk that a greater nitrogen fertiliser supply could intensify agriculture through higher fertiliser use must be carefully assessed to avoid worsening emissions and other environmental impacts. To this end, it is important to ensure that decentralised nitrogen fertiliser production does not increase nitrogen application in regions already overusing fertilisers. Accelerated nitrogen loss and increased environmental degradation should be avoided (Zhang et al., 2024).

All these environmental challenges highlight the need to apply ammonia and fertiliser properly, combined with supportive policies to minimise environmental impacts and maximise the benefits of renewable nitrogen fertilisers.

5 Policy recommendations

The decentralised production of renewable ammonia and fertiliser can help to mitigate emissions from production and enhance domestic supply, but targeted policy support is essential to improve its competitiveness. Decentralised initiatives can complement larger strategies focused on centralised production, aiming to reduce reliance on fossil fuels and ammonia and fertiliser imports, particularly in vulnerable locations. However, these technologies require policy support to accelerate their adoption

and make them more competitive in the short and medium term. Beyond economic factors, this section presents several policy recommendations for governments, industry and civil society to promote decentralised renewable ammonia and fertiliser production while ensuring the proper use of technology and the integration of local value chains. These policies should maximise the potential benefits of decentralised fertiliser production and mitigate risks. A summary of the policy recommendations is presented in Table 7.

Summary of policy recommendations for the promotion of decentralised renewable ammonia and nitrogen fertiliser production

→ Table 7

Policy recommendation	Objective	Country example ¹
Promote a policy framework for low-carbon domestic production of fertilisers, including decentralised nitrogen fertilisers.	Create a policy framework for implementing policy instruments that support the competitiveness of decentralised technologies, such as tax incentives and a carbon tax.	→ Brazil – National Fertiliser Plan to reduce dependency on imports → US – targeted policy for decentralised ammonia production
Implement decarbonisation strategies in the power and industrial sectors to favour decentralised nitrogen fertiliser production.	Align energy and industrial sector policies to benefit the competitiveness of decentralised technologies.	→ Brazil – industrial policy focusing on developing industries based on renewable energy and green manufacturing → Kenya – industrial policy with targets for domestic fertiliser production → US – tax credits for low-carbon hydrogen production
Introduce de-risking instruments and financial mechanisms to cover the green premium, as they will be key to upscaling decentralised nitrogen fertiliser technologies.	Implement instruments that mitigate the risk of investment, especially in countries of the Global South, and create favourable investment conditions.	
Establish clear regulations and safety measures, especially when ammonia is the main fertiliser.	Mitigate the environmental and health risks of using ammonia directly as a fertiliser while creating a framework to train agricultural communities in its use.	→ Kenya and US – comprehensive set of standards, guidelines and regulations for the production, storage and field application of ammonia as fertiliser.
Support R&D, piloting and capacity building for producing and using decentralised nitrogen fertilisers.	Test new technologies and open up opportunities for innovative business models. Create programmes that develop technical capacities in agricultural communities.	→ Kenya and US – pilot projects are in place for decentralised renewable ammonia and nitrogen fertiliser production.
Integrate the production of decentralised renewable ammonia and nitrogen fertiliser into agricultural and rural development policies.	Maximise local value creation by promoting agricultural cooperatives and rural entrepreneurship to integrate the decentralised production of ammonia and fertilisers.	

Agora Industry (2025). ¹ Considering only the countries in the scope of this paper: Brazil, Kenya, Thailand and the US.

1. Promote a policy framework for low-carbon domestic production of fertilisers, including decentralised nitrogen fertilisers.

A national policy to promote the domestic production of renewable nitrogen fertilisers is a sound instrument for setting an overarching framework that maximises emissions savings and local added value while considering national circumstances. National fertiliser policy, in the framework of a fertiliser plan, for example, should mention decentralised strategies as complementary efforts to achieve domestic production targets and mitigate emissions from the sector. According to national circumstances, fertiliser policy can define support mechanisms for green centralised and decentralised production, such as subsidies, tax incentives and carbon benefits. For instance, the US has a clear and specific policy to support the decentralised production of green ammonia, together with research funding, tax incentives and infrastructure investment, creating a friendly environment for the private sector to explore this production approach. As a result, several start-ups have emerged to exploit this new technological approach, providing a good example of how a clear long-term policy framework can stimulate private sector initiatives in countries. Similarly, Kenya has set a target to replace 20% of current fertiliser imports by 2027 and 50% by 2032 with domestically produced fertiliser derived from hydrogen produced from renewable energy. However, there is no explicit mention of a decentralised system to achieve these targets (Dekeyser et al., 2024). In Brazil, the country's National Fertiliser Plan, with a clear target to achieve 55% domestic production of the country's fertiliser needs by 2050, opens up the possibility of exploring new approaches to achieving such targets, as is the case with decentralised strategies.

2. Implement decarbonisation strategies in the power and industrial sectors to favour decentralised nitrogen fertiliser production.

Decarbonisation strategies that promote the use of renewable energy in the power sector and low-carbon technologies in the industrial sector can also benefit the uptake of decentralised fertiliser

technologies. Lower capital costs for renewable energy make decentralised nitrogen fertiliser production more competitive. At the same time, a highly decarbonised power sector can facilitate the grid-connected approach for decentralised technologies, providing real emission reduction benefits in the production process. Brazil and Kenya have achieved competitive renewable energy costs and over 85% renewable electricity generation, which in the short term favours the cost of grid-connected configuration for decentralised fertilisers. Industrial decarbonisation policies can also accelerate the deployment of decentralised technologies as an alternative to mitigating emissions in the ammonia and nitrogen fertiliser production process. This can open up new policy support mechanisms that can mitigate capital, electricity and other costs. The Inflation Reduction Act in the US, designed to advance low-carbon hydrogen production, can indirectly support decentralised ammonia systems (Schueler et al., 2024) by offering tax credits to project developers and improving project economics. In Brazil, project developers can take advantage of the Nova Indústria Brasil policy, which aims to develop industries based on renewable energy and green manufacturing, and provides tax exemptions, price support mechanisms and other financial support that could benefit decentralised nitrogen fertiliser technology, especially given the importance of reducing the country's dependence on fertiliser imports.

3. Introduce de-risking instruments and financial mechanisms to cover the green premium, as they will be key to upscaling decentralised nitrogen fertiliser technologies.

As reflected in the WACC, countries in the Global South have higher investment risks, and these directly impact the competitiveness of decentralised technologies. For example, our analysis shows that Kenya has a WACC of around 14.1%, resulting in capital costs that are 33% higher than in the US, which has a WACC of 4.5% (see Appendix 2). De-risking mechanisms, such as credit guarantees, can make markets in the Global South more attractive to private investors. These financing mechanisms can come from private or government initiatives in the form

of sovereign guarantees, facilitating access to other financing mechanisms. In addition, our techno-economic assessment found that decentralised nitrogen fertilisers can be more expensive than centralised technologies in the short to medium term. For this reason, financing mechanisms need to address the supply and demand in the value chain. Dedicated funding for project developers to make decentralised nitrogen fertiliser technologies more competitive by reducing capital costs can help scale up this approach and improve inefficiencies in the centralised nitrogen fertiliser supply chain. Financial mechanisms should also be directed at the point of demand to help farmers purchase low-carbon products, especially when competing with fossil-based alternatives. The US IRA is a clear example of financial support that can stimulate the development of low-carbon technologies; although it does not explicitly aim to support decentralised nitrogen fertiliser technologies, it can help such technologies to become more competitive when accessing financial support. Most countries analysed here have provided subsidies to farmers to purchase fertiliser at peak costs, mainly driven by the fossil gas market. These subsidies can be re-directed to support green fertiliser use and be regularly reduced as the technology and market become more competitive.

4. Establish clear regulations and safety measures, especially when ammonia is the main fertiliser.

The decentralised production of ammonia and nitrogen fertilisers has the advantage that it brings these industrial products closer to their main users, farmers, but it presents significant safety and regulatory challenges. Given the toxicity of ammonia – particularly in its aqueous and anhydrous forms – clear, enforceable safety regulations are essential for production, storage and distribution near communities and agricultural users to ensure the safety of farmers and the protection of the environment. Clear regulations will also open opportunities for capacity building and training to users of nitrogen fertilisers in the proper use, storage and handling of these chemicals, especially anhydrous ammonia, whose toxicity can pose a significant safety and health risk. This training could be offered through existing

agricultural cooperatives in each location, creating more trust and ownership in the local communities to adopt decentralised fertiliser production. The US, currently the largest user of ammonia, has a comprehensive set of standards, guidelines and regulations for the production, storage and field application of these fertilisers. Similarly, Kenya has developed a set of regulations for ammonia-based products. As both countries are running pilot projects for decentralised nitrogen fertiliser production, these regulations are crucial to preventing major incidents that could affect the local population.

5. Support R&D, piloting and capacity building for producing and using decentralised nitrogen fertilisers.

The development of innovative technologies for decentralised nitrogen fertilisers has been driven mainly by research institutions and start-ups. These institutions have developed important technological approaches capable of competing with traditional ammonia production via the Haber-Bosch process, which has been the main approach used by the chemical sector for a century. However, low-carbon technologies will need continued support to provide new solutions to innovate the fertiliser supply chain. This is particularly important for technologies that can produce nitrogen fertilisers directly in the form of NPK or nitric acid, as these are a safer alternative for farmers (see Sections 3 and 4). Testing these innovative technologies and business models through pilot projects is a good practice as this serves as a learning experience for agricultural sites on how the technology works, involving local communities, and addressing environmental, safety and health risks. In the US, programmes prioritise the development of small-scale, modular ammonia synthesis technologies powered by green hydrogen. Such initiatives can influence the growing number of small companies seeking to develop new technologies for decentralised ammonia and nitrogen fertiliser production in the country, spurring pilot projects across diverse agricultural regions. In addition, it is important to create socio-economic benefits for local communities (by maximising local labour and keeping revenues in the regions). Providing potentially low-cost and

resilient fertilisers for agricultural production is not enough; workers will need to be integrated into the production process so that these technologies can be easily adopted as a new local economic activity for communities. To make this possible, it is necessary to build capacity and train members of local communities in the new processes and technologies, as well as to employ those with academic backgrounds in business-related areas, such as management, logistics, accounting, etc. Pilot projects in Kenya, for instance, are integrating local farmers in fertiliser production. These projects could be improved on and replicated in other locations in the country as more pilot projects are implemented.

6. Integrate the production of decentralised renewable ammonia and nitrogen fertiliser into agricultural and rural development policies.

It is important to consider the potential for decentralised ammonia and fertiliser production in locations where it could be adopted. This could help to align the development of agricultural and rural areas, making them more receptive to this technology. Development plans could consider the infrastructure required for local fertiliser production and the necessary equipment for using ammonia as fertiliser. Aligning decentralised production with national agricultural strategies could promote agricultural cooperatives, rural entrepreneurship and local supply chains. This will also ensure that the limited number of jobs created by decentralised projects directly impacts local agricultural communities. Agricultural development plans should also incorporate practices that promote the efficient use of fertilisers, even when decentralised production ensures local availability. Overuse can elevate NOx emissions, soil and water contamination, and other environmental risks.

Appendix

1. Overview of current manufacturers of decentralised fertiliser products

Table A.1 provides an overview of the scale-up phase (funds raised), technology adopted for development, and final nitrogen fertiliser products of all the manufacturers with at least one headquarters

registered within EU-27 countries, the United Kingdom, Switzerland, the United States, and Canada. Data was reported from Tonelli et al. (2024b), and last updated in January 2025. Please note that this table is not exhaustive. Given the rapid pace of technological advancement in the field, other manufacturers not listed here also exist.

Overview of current developers of decentralised ammonia and nitrogen fertiliser technologies within EU-27 countries, the United Kingdom, Switzerland, the United States, and Canada.

→ Table A.1

Company	Funds raised [million EUR]	Technology	Product
Atmonia, Iceland (2016), www.atmonia.com	3.3	one-step electrocatalysis	pressurised anhydrous ammonia, aqueous ammonia used through irrigation
Nitrovolt, Denmark (2022), www.nitrovolt.com	3.5	electric Haber–Bosch (patented catalyst)	
NitroCapt, Sweden (2016), www.nitrocapt.com	2.0	non-thermal plasma reactor	nitrate fertilisers
Nium, United Kingdom (2022), www.wearenum.com	3.9	electric Haber–Bosch (patented nanocatalyst)	
PlasmaLeap, Ireland (2017), www.plasmaleap.com	0.4	non-thermal plasma reactor	aqueous solutions of calcium ammonium nitrate (CAN) or ammonium nitrate (AN) applied through spray, knife/injection delivery, or fertigation
Nitricity, California, US (2018), www.nitricity.co	24.9	non-thermal plasma reactor	nitric acid (3% dilution in water), liquid calcium ammonium nitrate, potassium nitrate, intermittent pilot with direct injection in the irrigation system
NTP Technologies, Virginia, US (2021), www.ntptechnologies.com	0.092	non-thermal plasma reactor	nitrates (NO ₃) in soluble in water, NPK compounds derived from nitrate solution
Talus Renewables, Texas, US (2021), production facilities in Iowa, US, and Naivasha, Kenya www.talusag.com	20.3	electric Haber–Bosch	anhydrous ammonia, ammonium nitrate
ReMo Energy Massachusetts, US (2020), www.remo.energy	5.8	electric Haber–Bosch at 80 bar pressure	anhydrous ammonia
Ammobia, California, US (2022) www.ammobia.co	4.6	electric Haber–Bosch at 20 bar pressure	anhydrous ammonia
FuelPositive, Waterloo, Canada (2022), production facility in Manitoba, www.fuelpositive.com	29.6	electric Haber–Bosch	anhydrous ammonia aqueous ammonia (5%–30% concentration)
Ampower, Toronto, Canada (2019), www.iamm.green	9.5	electric Haber–Bosch	anhydrous ammonia
Starfire Energy, Denver, US (2007)	22.2	electric Haber–Bosch	

Tonelli et al. (2024b)

2. Overview of assumptions used in the techno-economic assessment

Technical parameters related to the performance of technologies

→ Table A.2

Technology	Parameter	Year	Low	Medium	High	Unit	Source
Thermodynamic parameters	LHV H ₂	–	33.3	33.3	33.3	MWh/t _{H₂}	The Engineering ToolBox (2003)
	LHV NH ₃	–	5.20	5.20	5.20	MWh/t _{NH₃}	
	mass ratio	–	5.67	5.67	5.67	t _{NH₃} /t _{H₂}	
Electric battery	roundtrip efficiency	–	0.90	0.90	0.90	%	Agora Industry and Umlaut (2023)
	self-discharge rate	–	0.00054	0.00054	0.00054	(-)/h	Terlouw et al. (2022)
	duration at rated power	–	4.00	4.00	4.00	h	NREL (2021a)
Ammonia Storage Unit (ASU)	energy consumption	–	0.30	0.30	0.30	MWh/t _{NH₃}	D'Angelo et al. (2023)
Electrocatalysis	faradaic efficiency	2025	0.60	0.50	0.40	%	Martín et al. (2019)
	faradaic efficiency	2035	0.70	0.60	0.50	%	Martín et al. (2019)
	faradaic efficiency	2045	0.95	0.90	0.85	%	Martín et al. (2019)
	theoretical voltage	2025	1.17	1.17	1.17	V	D'Angelo et al. (2023)
	overpotential	2025	0.70	0.70	0.70	V	D'Angelo et al. (2023)
Electric Haber–Bosch	efficiency electrolyser	2025	0.654	0.654	0.654	%	Agora Industry and Umlaut (2023)
	efficiency electrolyser	2035	0.705	0.705	0.705	–	
	efficiency electrolyser	2045	0.730	0.730	0.730	–	
	energy required HB reactor	2025	5.33	5.33	5.33	MWh/t _{NH₃}	Smith et al. (2020)
	energy required HB reactor	2035	3.43	3.43	3.43	MWh/t _{NH₃}	Smith et al. (2020)
	energy required HB reactor	2045	1.5	1.53	1.5	MWh/t _{NH₃}	Smith et al. (2020)
	efficiency HB reactor	2025	0.88	0.88	0.88	%	Stoichiometric conversion based on LHV
	efficiency HB reactor	2035	0.88	0.88	0.88	%	
	efficiency HB reactor	2045	0.88	0.88	0.88	%	

Cost assumptions for different technologies

→ Table A.3

Technology	Parameter	Year	Low	Medium	High	Unit	Source
Electric battery	CAPEX	2025	498.50	655.00	832.00	USD/kWh	NREL (2021a)
	CAPEX	2035	327.50	521.50	689.00	USD/kWh	
	CAPEX	2045	256.50	452.00	597.00	USD/kWh	
	O&M	–	0.025	0.025	0.025	capex fraction	
Solar PV	lifetime	2025	30	30	30	years	NREL (2021b)
	O&M	2025	14	15	17	USD/kW/year	
	O&M	2035	9	11	15	USD/kW/year	
	O&M	2045	9	10	13	USD/kW/year	
Onshore wind	lifetime	2025	30	30	30	years	NREL (2021c)
	O&M	2025	38	41	43	USD/kW/year	
	O&M	2035	32	37	43	USD/kW/year	
	O&M	2045	27	35	42	USD/kW/year	
Ammonia Storage Unit (ASU)	CAPEX	–	21.65	21.65	21.65	USD/t_NH ₃	Wang et al. (2021)
	O&M	–	0.02	0.02	0.02	capex fraction	Terlouw et al. (2022)
Electrocatalysis	CAPEX electrolyser	2025	2,491	2,491	2,491	USD/kW_el	Agora Industry and Umlaut (2023)
	CAPEX electrolyser	2035	1,500	1,500	1,500	USD/kW_el	
	CAPEX electrolyser	2045	1,257	1,257	1,257	USD/kW_el	
	O&M	2025	0.02	0.02	0.02	capex fraction	Terlouw et al. (2022)
	lifetime	2025	30	30	30	years	Nayak-Luke (2020)
Electric Haber–Bosch	CAPEX electrolyser	2025	2,491	2,491	2,491	USD/kW_el	Agora Industry and Umlaut (2023)
	CAPEX electrolyser	2035	1,500	1,500	1,500	USD/kW_el	
	CAPEX electrolyser	2045	1,257	1,257	1,257	USD/kW_el	
	capex Haber–Bosch normal	2025	40	40	40	USD/t_NH ₃	Wang et al. (2021)
	capex Haber–Bosch normal	2035	40	40	40	USD/t_NH ₃	
	capex Haber–Bosch normal	2045	40	40	40	USD/t_NH ₃	
	O&M capex fraction	–	0.02	0.02	0.02	%	Terlouw et al. (2022)
	lifetime	–	30	30	30	years	Nayak-Luke (2020)
Hydrogen storage	capex	2025	637	653	669	USD/kgH ₂	Terlouw et al. (2022)
	capex	2035	382	426	469	USD/kgH ₂	
	capex	2045	176	241	307	USD/kgH ₂	
	O&M	–	0.01	0.01	0.01	capex fraction	

Techno-economic assumptions used for renewable energy generation

→ Table A.4

Parameter	Location	Year	Low	Medium	High	Unit	Source
Solar PV CAPEX	US	2025	1456	1491	1540	USD/kW	NREL (2024a), NREL (2024b)
Solar PV CAPEX	US	2035	682	895	1189		
Solar PV CAPEX	US	2045	602	753	993		
Solar PV CAPEX	Brazil	2025	797	1491	1540		
Solar PV CAPEX	Brazil	2035	655	895	1189		
Solar PV CAPEX	Brazil	2045	565	753	993		
Solar PV CAPEX	Kenya	2025	948	1491	1540		
Solar PV CAPEX	Kenya	2035	655	895	1189		
Solar PV CAPEX	Kenya	2045	565	753	993		
Solar PV CAPEX	Thailand	2025	1456	1491	1540		
Solar PV CAPEX	Thailand	2035	682	895	1189		
Solar PV CAPEX	Thailand	2045	602	753	993		
Onshore wind CAPEX	US	2025	1544	1569	1632		
Onshore wind CAPEX	US	2035	1258	1334	1522		
Onshore wind CAPEX	US	2045	1093	1188	1411		
Onshore wind CAPEX	Brazil	2025	1035	1569	1632		
Onshore wind CAPEX	Brazil	2035	656	1334	1522		
Onshore wind CAPEX	Brazil	2045	569	1188	1411		
Onshore wind CAPEX	Kenya	2025	1035	1569	1632		
Onshore wind CAPEX	Kenya	2035	656	1334	1522		
Onshore wind CAPEX	Kenya	2045	569	1188	1411		
Onshore wind CAPEX	Thailand	2025	1544	1569	1632		
Onshore wind CAPEX	Thailand	2035	1258	1334	1522		
Onshore wind CAPEX	Thailand	2045	1093	1188	1411		

Location-specific inputs for the model

→ Table A.5

Parameter	Location	Low	Medium	High	Unit	Source
Electricity price (grid)	Brazil	0.11	0.119	0.128	USD/kW	EIA (2025), World Population Review (2024), Global Petrol Prices (2024, Industry)
Electricity price (grid)	Kenya	0.167	0.194	0.221	USD/kW	
Electricity price (grid)	Thailand	0.109	0.119	0.131	USD/kW	
Electricity price (grid)	US	0.082	0.125	0.168	USD/kW	
Nitrogen demand	Brazil	0.55	0.55	0.55	kg_N/h	–
Nitrogen demand	Kenya	0.003	0.003	0.003	kg_N/h	–
Nitrogen demand	Thailand	0.028	0.028	0.028	kg_N/h	–
Nitrogen demand	US	2.14	2.14	2.14	kg_N/h	–
Retail fossil fertiliser price	Brazil	1000	–	1300	USD/t N	Veloso (2024) and Veloso (2024b)
Retail fossil fertiliser price	Kenya	1100	–	2400	USD/t N	Argus Media (2024) and Jiji Kenya (2025)
Retail fossil fertiliser price	Thailand	920	–	1200	USD/t N	OAE (2024)
Retail fossil fertiliser price	US	750	–	1200	USD/t N	Quinn (2025)

Financial inputs for the model

→ Table A.6

Country	Equity Risk Premium (WACC)	Source
Brazil	9.00%	Damodaran (2024)
Kenya	14.10%	
Thailand	6.94%	
US	4.60%	

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About Agora Industry

Agora Industry develops scientifically sound and politically feasible strategies for successful pathways to a climate-neutral industry – in Germany, Europe and internationally. The organisation which is part of the Agora Think Tanks works independently of economic and partisan interests. Its only commitment is to climate action.

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