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Low-Emission Production Methods for Nitrogen Fertilizer

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Table of Contents

Executive Summary 3

Notation 4

1. Introduction: Fertilizer and Its Emissions 5

2. System-Level View of Nitrogen Fertilizer 6

2.1 Why Is a Systemic Approach Helpful? 6

2.2 How Could the Model of the Nitrogen Fertilizer System Be Structured? 6

2.3 What Are the Four Levers along the Value Chain? 7

2.4 How Do These Levers Interact with One Another? 8

2.5 Why Do Lever Sequencing and Systemic Trade-Offs Matter? 9

3. European Fertilizer Industry 10

4. Incumbent Production Methods 11

4.1 Urea from Natural Gas 12

4.2 Nitrate Fertilizer from Natural Gas 13

4.3 Future Fertilizers Will Shift to Nitrates over Urea 15

4.4 Section Summary 15

5. Low-Emission Production Methods 15

5.1 Option 1: Electrolytic Hydrogen with Upgraded Haber-Bosch 16

5.2 Option 2: Plasma-Based Route 18

5.3 Option 3: Electrochemical Ammonia Synthesis 19

5.4 Option 4: Haber-Bosch with Carbon Capture and Storage 20

6. Comparison of Pathways 22

6.1 Energy Intensity 22

6.2 Technology Readiness Level 23

6.3 Emissions 24

6.4 Cost and Flexibility 25

7. Policy Recommendations and Conclusions 27

References 29



Executive Summary

Synthetic nitrogen fertilizers feed around half of the world's population but cause 2.5% of global greenhouse gas emissions. Roughly 40% of these emissions stem from production, while 60% are released during field application, primarily as nitrous oxide. Production relies mainly on natural gas, used both as feedstock and as fuel for high-temperature heat. While Europe seeks to reduce its reliance on imported natural gas, its nitrogen fertilizer supply becomes more dependent on imports from regions with cheap and abundant gas. Natural gas can account for up to 90% of the variable cost of ammonia production. Since 2022, gas prices have remained around 160% above the pre-war average, and EU production has fallen by ~12%. This also raises costs for agriculture and food production, exposing Europe's vulnerability along the food value chain.

Effective strategies for a resilient, affordable, innovative low-emission fertilizer value chain therefore diversify feedstocks and energy sources, reduce reliance on natural gas, and lower overall fertilizer use. This requires close coordination across four levers: pivot to low-emission production technologies (the focus of this report), improve nutrient management, reduce and shift demand, and recover nutrients and carbon.

Low-emission routes shift production from natural gas to electricity. Four routes are discussed:

Renewable hydrogen with upgraded Haber-Bosch: mature and ready for commercialization, with an energy intensity comparable to the incumbent (43-50 GJ/tN and 35-48 GJ/tN, respectively).

Plasma-based route: produces nitric acid directly from the air. Currently 3-4 times more energy-intensive (130-180 GJ/tN) but with a theoretical minimum below that of any other route, and modular, suited to flexible operation, and moving toward first-of-a-kind plants.

Electrochemical ammonia synthesis: produces ammonia directly from nitrogen and water, but is currently at laboratory scale and energy-intensive (111-172 GJ/tN).

Carbon capture and storage: retains natural gas as a feedstock and captures the pure process CO_2 stream, but its added costs mean it cannot compete without regulation, and it would require storing 22-25 Mt of CO_2 per year in Europe, a scale-up that remains uncertain.

Europe is well placed to lead the development of these low-emission fertilizer production routes. Every major method of industrial nitrogen fixation and its downstream processing (Haber-Bosch, Ostwald and Birkeland-Eyde) was developed in Europe, and it currently hosts more low-emission nitrogen innovators than any other region.

Importantly, the cost of electricity is decisive. The more energy-intensive a route, the more it gains from flexible operation during low-price hours. In Sweden, renewable hydrogen with Haber-Bosch already reaches the market price of natural-gas-based nitrogen fertilizer, and future plasma plants could too; in Germany, grid fees, levies and taxes keep both routes above it.

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Recommendations

The transition to low-emission nitrogen production will not happen through market forces alone and requires supportive public policy. The EU should accelerate access to affordable, clean, and reliable electricity. This report sets out the following recommendations:

1. **The overarching goal:** Build a resilient, innovative, and affordable fertilizer value chain.
2. **The underlying factor:** Accelerate the build-out of and access to affordable, clean, and reliable electricity.
3. **The technology push:** Provide CAPEX support for innovative low-emission nitrogen fertilizer production.
4. **The market pull:** Provide OPEX support and create demand for low-emission nitrogen fertilizer.
5. **The system perspective:** Take a system-level view of nitrogen fertilizers.



Notation

Chemical	Name	Notes
N_2	Nitrogen (dinitrogen)	78% of air. Triple bond makes it unavailable to crops
NH_3	Ammonia	Chemical building block
HNO_3	Nitric Acid	Chemical building block of nitrate fertilizers
N_2O	Nitrous Oxide	Greenhouse gas. 273× the warming effect of CO_2
NO_x	Nitrogen Oxides	Collective term for NO and NO_2
$CO(NH_2)_2$	Urea	46% nitrogen. Most widely used nitrogen fertilizer
NH_4NO_3	Ammonium Nitrate (AN)	33.5% nitrogen. Most widely used in Europe
$Ca(NO_3)_2$	Calcium Nitrate (CN)	15.5% nitrogen. “Premium” fertilizer, needs no liming
$CaCO_3$	Calcium Carbonate	Limestone; liming material to offset soil acidity

Process	Name	Notes
SMR	Steam Methane Reforming	Reacts methane with water to produce hydrogen
HB	Haber-Bosch	Produces ammonia from hydrogen and nitrogen from the air
BM	Bosch-Meiser	Combines ammonia with carbon dioxide to produce urea
Ost.	Ostwald	Produces nitric acid from ammonia
EAS	Electrochemical Ammonia Synthesis	Produces ammonia directly from nitrogen and water in an electrolyzer
DAC	Direct Air Capture	Extracts CO_2 from the atmosphere

1. Introduction: Fertilizer and Its Emissions

For the vast majority of human history, wild land mammals have far outweighed the biomass of humans [1], [2]. The human population was limited by the natural rate of nitrogen provided by the nitrogen cycle. Nitrogen is essential for plant growth but, although it makes up 78% of the air, plants can only use it once it has been "fixed" into a usable form, which only occurs in limited amounts in nature. However, in the 20th century these natural limits were overcome with the invention of the Haber-Bosch process, which made it possible to turn large quantities of atmospheric nitrogen into fertilizers [3], [4]. This enabled significant population growth; today, humans outweigh wild land mammals by roughly twenty to one [1], [2], and **synthetic nitrogen fertilizers feed approximately half of the world's population [5].**

As a globally interconnected sector, the modern agricultural industry is vital to the food security of billions of people and serves as the major consumer of fertilizers, most notably synthetic nitrogen. Fertilizers enhance soil nutrient availability to enable efficient, high-yield crop production [3]. Crops require three key macronutrients, each categorized by its main element. Nitrogen is needed in the largest quantity and serves as a building block for proteins and chlorophyll. Phosphorus supports energy transfer within the plant and the development of roots and seeds, while potassium regulates water use and strengthens resistance to stress and disease.

Nitrogen fertilizers are the most emissions-intensive type of fertilizer. As shown in Figure 1, they are responsible for 5% of global emissions [5]. Half of this is due to the application and management of on-farm nitrogen-rich manure, and the other half is due to synthetic nitrogen fertilizers. Notably, only 40% of emissions from synthetic nitrogen fertilizers can be attributed to their fossil-intensive production methods. The remaining 60% is caused by the release of potent greenhouse gases when the nitrogen fertilizers are applied to the field. These are primarily in the form of nitrous oxide (N_2O) and occur due to soil bacteria modifying the nitrogen molecules before they are taken up by the plant. Specifically in the EU, the production and application of synthetic nitrogen fertilizer emits around 100-115 Mt CO_2eq annually; this is the fourth-largest globally after China, India, and the United States [5], [6]

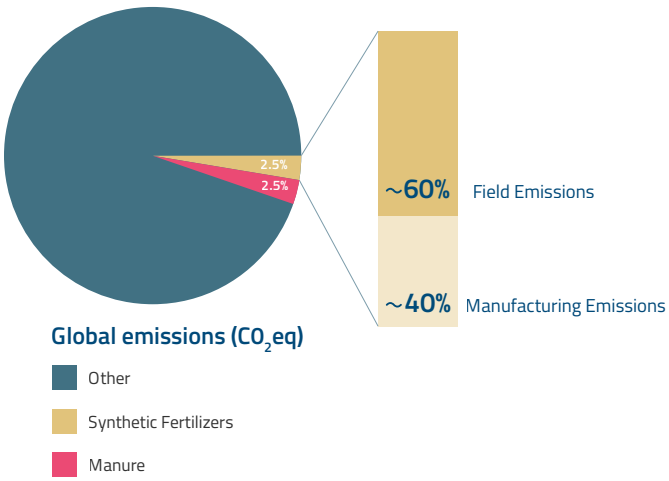


Figure 1: Global emissions caused by the production and application of synthetic fertilizers and manure [5].

Figure 2 provides an overview of the fertilizer process. During production, hydrocarbons are consumed both as a chemical feedstock and as a fuel to generate high-temperature heat up to 900°C [7]. As a rule of thumb (discussed in more detail later), roughly two-thirds is used as feedstock and one-third as fuel. Production occurs in large chemical plants, in which the nitrogen fertilizer is created through a series of steps, each producing a chemical building block for the next (an overview of the European industry and detailed process information is given later). Nitrogen fertilizer is then applied to the fields to ensure nutrient-rich and high-quality soil for crop growth. The minerals contained in the nitrogen fertilizer are taken up by the crops and ultimately consumed by humans. Note, fertilizer is often applied together with calcium carbonate, in a process known as "liming", to counteract the soil acidity that would otherwise occur from the fertilizer.

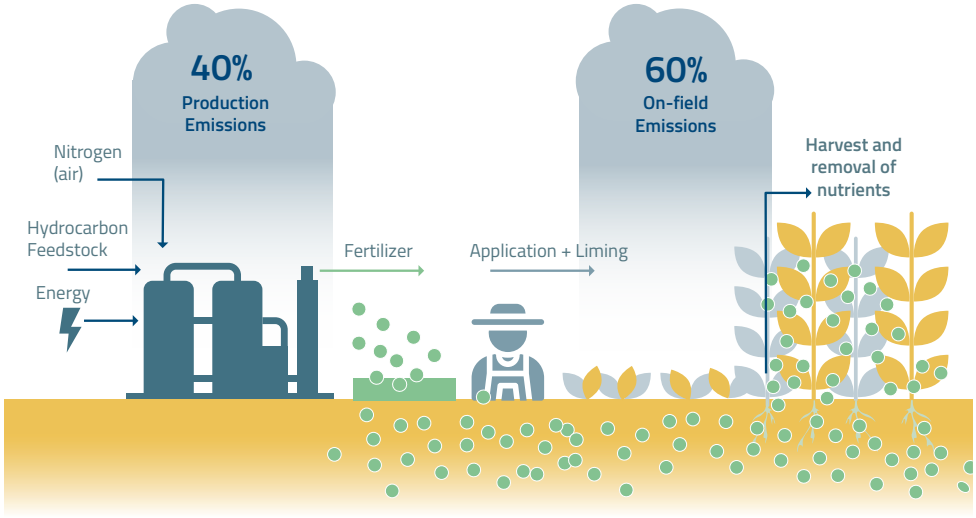


Figure 2: The process for nitrogen fertilizer production and field application, and associated emissions [5], [6].

With around 40% of these emissions arising from the production of nitrogen fertilizer and 60% from its application, pivoting to low-emission production technologies alone is not enough. The system boundary must therefore include agriculture, where application emissions occur, and can extend to downstream sectors that indirectly influence how much fertilizer is needed.

Chapter 2 sets out this system-level view in more detail.

The specific scope of this report is on ways to reduce the emissions from the production of synthetic nitrogen fertilizers.

2. System-Level View of Nitrogen Fertilizer

2.1 Why Is a Systemic Approach Helpful?

Chapter 1 showed that a large portion of nitrogen emissions occurs downstream of the fertilizer supply chain. Only 40% of the emissions from synthetic nitrogen fertilizers can be attributed to the first stage, namely, nitrogen fertilizer production. The remaining 60% result from the release of potent greenhouse gases when these nitrogen fertilizers are applied to the fields [5].

What follows is that a meaningful system boundary must include agriculture, where application emissions occur. The system boundary can also extend further downstream to sectors that are not directly involved in producing or applying fertilizer but indirectly influence how much of it the system requires, thereby reducing overall dependence on nitrogen fertilizers and their associated emissions. These include demand-side sectors such as food and bioenergy, as well as the circular economy, which recycles nutrients and carbon along the fertilizer value chain.

Studies covering both production and field application show that tackling the two together has the greatest potential, whereas isolated approaches deliver smaller reductions or can even increase emissions. For example, switching the hydrogen source for ammonia production from steam methane reforming (SMR) to renewable-powered water electrolysis could cut production emissions by 75% by 2050, yet would reduce total global emissions from nitrogen fertilizers by only 27% [5].

Addressing field emissions alone, through nutrient-efficient practices such as improved fertilizer management, efficient irrigation expansion and improved crop varieties, could reduce global emissions from nitrogen fertilizers by 48% [5]. The most effective strategies therefore combine measures along the entire nitrogen fertilizer supply chain [8].

Systemic thinking about nitrogen is not new to EU policymakers. The Fertilizer Action Plan (COM(2026) 310) frames the problem along the value chain, calling for an EU fertilizer value chain partnership. In addition, it emphasizes the need for nutrient-efficient practices on farms [9]. The current green architecture of the Common Agricultural Policy (CAP), on which the Action Plan builds, ties direct payments to nutrient-relevant standards and tracks performance through the result indicator "improved nutrient management" [10]. And the European Innovation Council's Pathfinder has designed a CO_2 and Nitrogen Portfolio, bundling eight projects as part of an interconnected system of nitrogen and carbon flows [11]. Earlier EU instruments such as the Integrated Nutrient Management Action Plan, which drew on an analysis by the Joint Research Centre, intended to manage "nitrogen and phosphorus better throughout their lifecycle," spanning agriculture, food processing, consumption, disposal, and recycling. However, it was never implemented [12].

2.2 How Could the Model of the Nitrogen Fertilizer System Be Structured?

The first step in a systemic analysis of nitrogen fertilizer emissions reductions is to define the system boundary. This boundary determines which sectors along the supply chain are included, which flows are tracked, and what the objective of the assessment is. Moreover, it shapes every subsequent analytical decision [13], [14].

The system boundary used here encompasses five interconnected sectors: the production of synthetic nitrogen fertilizers, agriculture, food, bioenergy/biomass industry, and the circular economy sector, the latter being defined as the recovery and recycling of nitrogen and carbon from waste & residue streams. Figure 3 illustrates a simplified and conceptual version of the synthetic nitrogen fertilizer supply chain encompassing these five sectors.

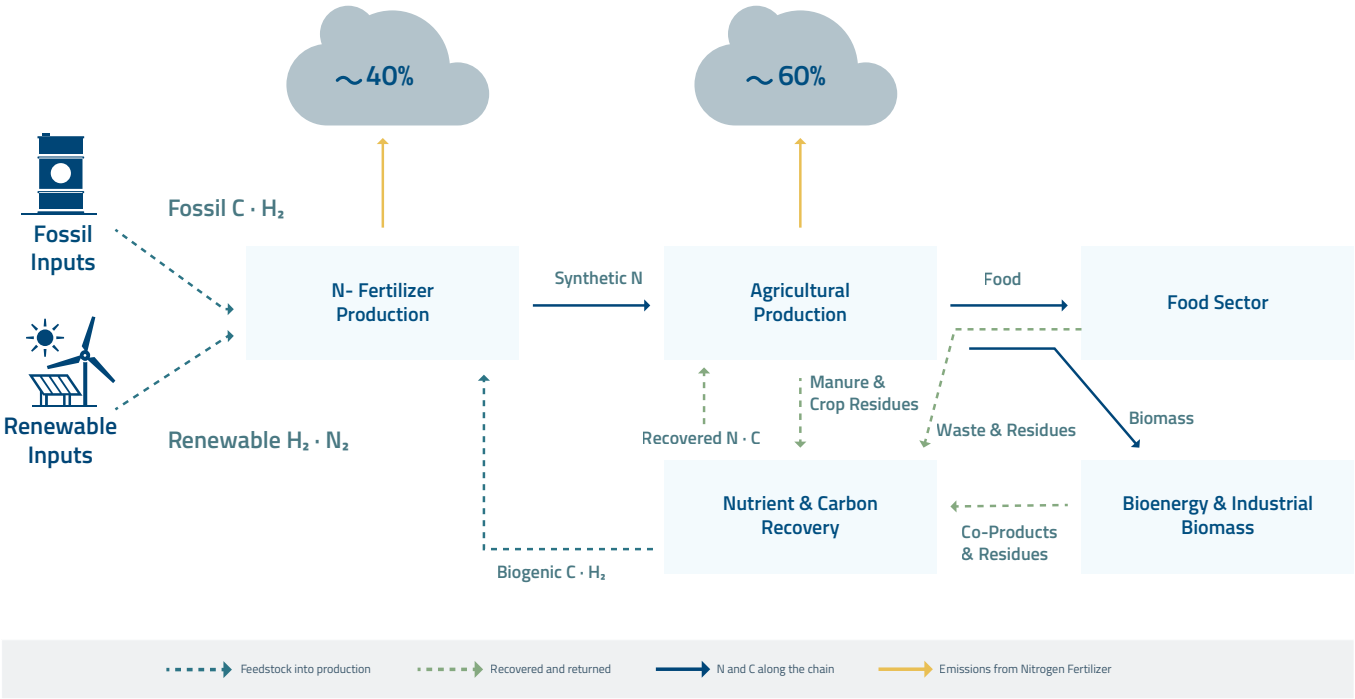


Figure 3: The nitrogen fertilizer supply chain.

These sectors are linked by physical flows of nitrogen, carbon, energy sources, and biomass. Synthetic nitrogen fertilizer production serves as the starting point, where renewable and/or non-renewable feedstocks are converted into synthetic nitrogen fertilizers, which are then supplied to the agricultural sector. Agricultural production supplies crops to the sectors food, bioenergy & industrial biomass. Those sectors mark the end of this linear, simplified representation, generating demand that influences the volume of synthetic nitrogen fertilizer that must be produced. Beyond this linear flow, a fifth sector introduces the circular economy: nutrient and carbon recovery. This sector uses byproducts, waste, and residual streams from all sectors, thereby partially replacing synthetic fertilizers with biogenic fertilizers. Including all five sectors in the scope ensures that the emissions reductions which recovery and demand-side measures deliver on the production side, by displacing synthetic fertilizer, are captured rather than treated as external and invisible.

Within this boundary, the analysis focuses on material flows of nitrogen, carbon, and the energy carriers and biomass that transport or transform them. Price and market feedback loops are deliberately excluded. The aim is to track how physical interventions along the value chain affect the amount of nitrogen and carbon flowing through the system, and how these changes impact other parts of the chain. Economic effects, such as higher production costs for low-emission fertilizer dampening demand, are not considered, as they require a different analytical approach and lie beyond the scope of this simplified analysis [15].

The goal of the model is to provide a qualitative illustration of how greenhouse gas emissions associated with nitrogen fertilizers, from production to field application to subsequent losses, can be reduced. Therefore, the orange arrows in Figure 3 indicate only those emissions. At the same time, it is important to maintain the functions of the system (nutrition, bioenergy & biomaterials). Hence, any quantitative assessment based on the model should define its objective under specific constraints. Emissions are minimized while ensuring that food security and bioenergy & biomaterials supply security are maintained.

Several emission sources also lie deliberately outside the system boundary and are not shown in Figure 3. First, upstream emissions are excluded. These include methane leakage and other emissions from the extraction, processing and transport of natural gas and other feedstocks, as well as the embodied emissions of plant equipment, renewable generation assets and electrolyzers. Second, emissions from the nutrient and carbon recovery sector itself, such as those from anaerobic digestion, composting, nitrogen stripping, biochar production and crop residue removal, are not quantified. Third, emissions from fertilizer transport and distribution, land-use change, and the downstream processing of food, bioenergy and biomaterials are not included. The net emissions benefit of each lever therefore also depends on flows outside this boundary and should be confirmed through a full life-cycle assessment before drawing quantitative conclusions.

This approach is consistent with established methods in the literature on integrated nitrogen management and the modeling of food systems.[1] However, while each of these studies models a part of the system, none of them captures the entire value chain as a single, interconnected system in which measures in the individual phases interact with one another.

A meaningful reduction in emissions requires a holistic approach across the entire supply chain, encompassing fertilizer production, agricultural practices, and the end use of food, energy, and biomass, and it requires an analytical framework that makes the interactions between these domains explicit.

2.3 What Are the Four Levers along the Value Chain?

The framework adopted categorizes four strategic levers for emissions reduction along the nitrogen fertilizer supply chain and maps the coupling between them. The following section describes these levers in detail and the section after that examines how they interact.

Lever 1 – Synthetic Nitrogen Fertilizer Production: Shift to low-emission technologies (core report focus – Chapters 5 and 6). Low-emission production methods include renewable hydrogen with an upgraded Haber-Bosch loop, plasma-based nitrogen, Direct Electrochemical Ammonia synthesis, and Carbon Capture and Storage on conventional steam methane reforming. Chapters 5 and 6 provide in-depth details on technical specifications and comparisons of energy intensities, technological readiness levels, greenhouse gas emissions, and production costs.

Lever 2 – Agricultural Production: Improve nutrient management and retain nitrogen & carbon in soils. This lever encompasses various measures, including the implementation of efficient management practices in arable farming, such as fertilizer management (e.g., precision application, inhibitors, and deeper incorporation), organic fertilization, the cultivation of legumes, soil analysis & liming, and irrigation management. Where jurisdictions permit it, the lever could also include genetic modification, either of crops to improve their nitrogen use or of the soil microbes that fix nitrogen for them. Scenarios show that, independent of the specific method, improving nitrogen use efficiency alone could reduce global greenhouse gas emissions from nitrogen fertilizers by 61-72% by 2050 [5]. The EU Fertilizer Action Plan likewise identifies better nutrient management and nutrient-efficient farming practices as key actions to support farmers [9]. Importantly, the effectiveness of this lever depends on regional contexts, as varying soil and climate conditions dictate which specific measures can be successfully deployed.

Lever 3 – Food, Bioenergy & Industrial Biomass Sector: Reduce and shift demand. More plant-rich diets, food-waste reduction, feed-conversion, post-harvest efficiency, and alternative proteins lower the nitrogen the system needs in the first place. Studies on food consumption project that halving the consumption of meat, dairy and eggs across the EU would cut agricultural nitrogen emissions by around 40% and greenhouse gas emissions by 25-40%. Furthermore, this shift would require 23% less cropland per capita and raising the nitrogen use efficiency of the EU food system from 18% to 41-47% [16].

In bioenergy, two shifts have the same effect: phasing out or capping biofuel mandates for food and feed crops, and moving the remaining feedstock to wastes and residues. Because these fuels are scarce, they should be prioritized for aviation and shipping, where few alternatives exist. Reducing the biomass drawn into bio-based materials and chemicals pulls in the same direction. Together, these measures free up both land and nutrients for food production. A 2026 analysis estimates that roughly 8% of fertilizer nutrients used in the EU and UK go to crop biofuel production [17].

[1] Similar approaches are: Knowledge for Integrated Nutrient Management Action Plan by the JRC (2023), Material flow analysis of nitrogen and phosphorus by Zoboli et al., 2018.; Agent-based model of local agricultural and food networks by Fernandez-Mena et al., 2020; Global land-use model showing trade-off between food availability and nitrogen pollution by Bodirsky et al., 2014; Study by Springmann et al., 2018, using the planetary boundaries framework to model impacts of the global food system.
The European Nitrogen Assessment has argued that integrated approaches to nitrogen management, which encompass the vertical dimension of cause-and-effect relationships between nitrogen species, the horizontal dimension of all nitrogen forms in a balance, and the cross-element dimension linking nitrogen to carbon and phosphorus, are essential to avoid the inefficiencies and inconsistencies that arise when measures are designed in isolation at the sectoral level (Oenema et al., 2011; Sutton et al., 2011).

Lever 4 – Circular Economy: Recover and substitute nutrient & carbon. Manure treatment and processing, food-waste digestion, and wastewater and urine recovery each return nitrogen that has already been fixed once on the field. Composting and biochar return carbon and improve the soil's capacity to hold nitrogen. Every tonne recovered this way is a tonne that does not have to be fixed from air again. The lever works by displacing virgin synthetic nitrogen rather than by abating the emissions from making it. Nitrogen recovered from source-separated human urine, for example, is estimated to cover around 19% of global synthetic nitrogen fertilizer demand [18].

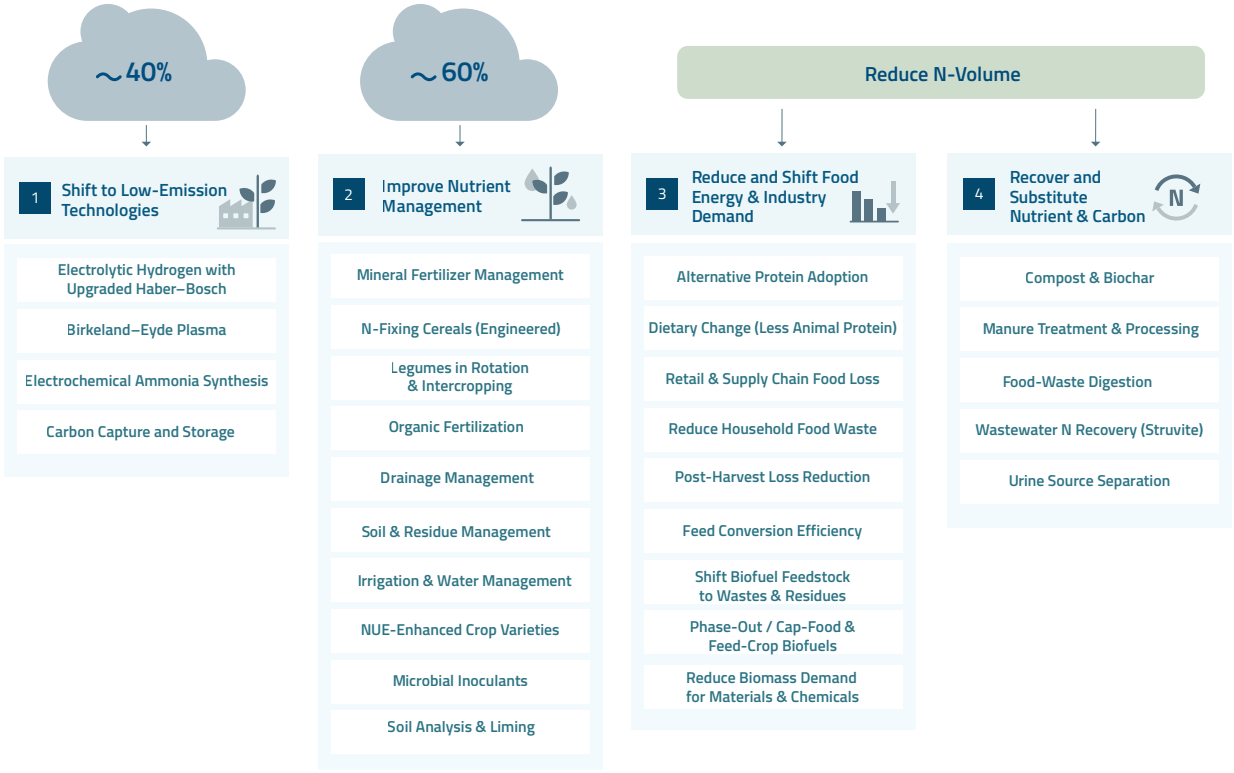


Figure 4: Four levers to reduce nitrogen fertilizer emissions (comprehensive but simplified and non-exhaustive).

2.4 How Do These Levers Interact with One Another?

The previous two parts showed why a systemic view is needed and which levers exist. The following analysis examines how these levers interact, including how nutrient recovery and demand-side measures displace synthetic fertilizer production and thereby reduce production-side emissions. Figure 5 shows a simplified, isolated, model-based representation of the interactions between the individual levers along the supply chain and illustrates their interdependencies.

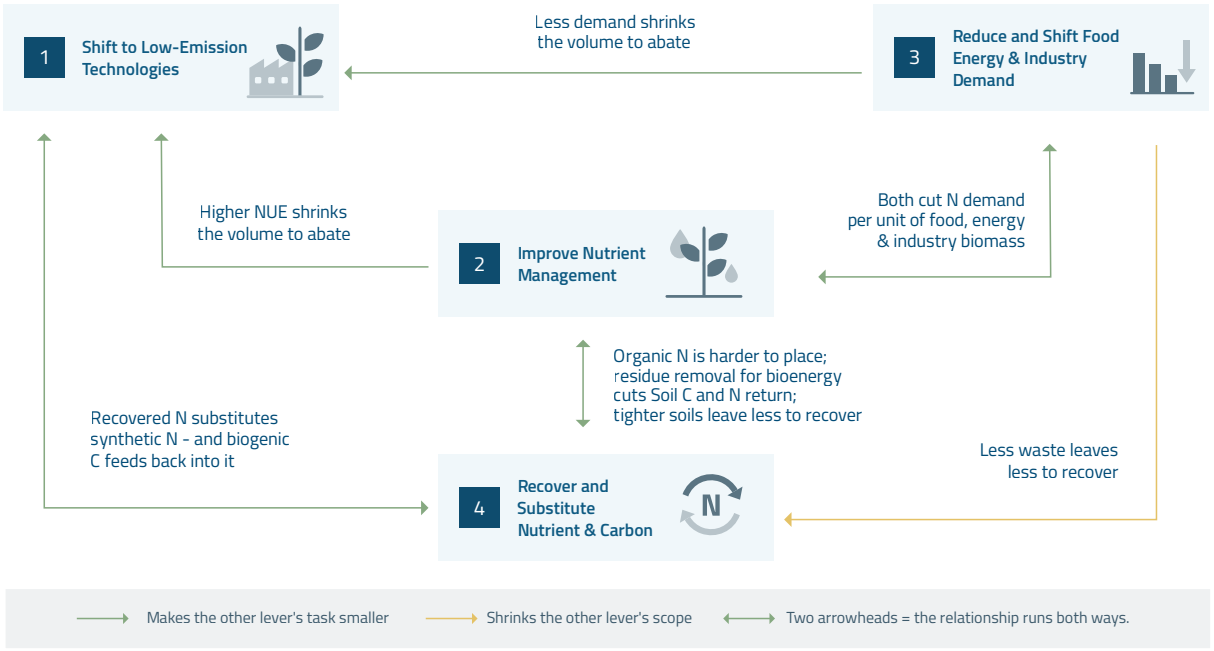


Figure 5: Interaction of the four levers.

Using the example of lever 4 "Recover and substitute nutrient & carbon", Figure 5 illustrates how biogenic waste streams from agriculture are recycled and feed back into the system. The analysis focuses on how recovering these streams affects other levers, in particular the emissions reductions of the synthetic fertilizer industry (lever 1). In this example, assuming all other system factors remain constant, the recycling of biogenic waste streams leads to nitrogen being returned to the agricultural production system in the form of biogenic fertilizer and replacing synthetic nitrogen fertilizer. Conversely, for a given crop nitrogen demand, a larger supply of synthetic nitrogen fertilizer leaves less demand for recovered nutrients. The two levers thus reduce each other's impact [19].

In practice, this physical link is moderated by prices and regulation, which are outside the scope of this analysis (see Section 2.2). For example, binding recovery targets could keep recovery rates high regardless of synthetic supply.

A second example is how declining or shifting demand for food, bioenergy and industrial biomass affects emission reduction efforts in the synthetic fertilizer industry. The chain of effects runs as follows: Assuming all other system factors remain constant, growing less agricultural biomass for bioenergy lowers demand for synthetic nitrogen fertilizer, and with it the production volume whose emissions need to be reduced. Unlike the previous example, this relationship runs in one direction only. Reducing emissions from synthetic nitrogen fertilizer production does not itself change demand behavior [20].

Both examples are purely bilateral and illustrate the interaction based on the assumption that other system factors remain constant. In reality, the entire system of levers interacts simultaneously and exhibits highly interconnected dynamics [8].

2.5 Why Do Lever Sequencing and Systemic Trade-Offs Matter?

At its core, the model demonstrates that synthetic nitrogen (lever 1) continues to play a central role in food and bioenergy security [5]. However, its emission reduction target cannot be set in isolation. Shifts in levers 2, 3, and 4 reduce or increase both the capacity lever 1 must provide [5], [21] and the amount of feedstocks (e.g., renewable electricity and clean hydrogen) needed [22]. Furthermore, the model shows that some levers constrain one another. For example, less food waste means fewer feedstocks are available for recovery. Stricter nutrient retention results in less nitrogen remaining in usable streams [23]. And plant residues can either be harvested for bioenergy production or left in the field to return carbon and nutrients to the soil, not both. The order and scope of the levers are therefore just as important as the further development of each individual lever [21].

Finally, no single lever can deliver transformation independently [8]. Unlocking these solutions requires cross-cutting system enablers, including: robust policy and regulatory standards, certification for biological, low-carbon and recycled inputs, scaled clean energy, transport and waste treatment infrastructure, and integrated supply chain partnerships from energy providers, fertilizer producers, farmers, food retailers to public infrastructure services [21]. But integrative approaches come with caveats. The European Nitrogen Assessment cautions that coordinated strategies are harder to agree on than single-sector ones and can delay adoption [24]. Effective implementation strategies therefore require close coordination across the four levers: emission reduction in synthetic nitrogen fertilizer production, improve nutrient management and retain nitrogen, reduce and shift food, energy and industrial biomass demand, and nutrient and carbon recovery. Within such strategies, the system enablers serve to reduce trade-offs between the levers and to maximize their combined potential.



3. European Fertilizer Industry

Synthetic nitrogen fertilizer production is an integral part of the chemical industry. Like most bulk chemicals, nitrogen fertilizers are manufactured at large industrial sites through a series of processing steps. The process combines hydrogen (H_2), obtained mainly from natural gas (CH_4), with nitrogen (N_2) from the air to produce ammonia (NH_3), part of which is further converted into nitric acid (HNO_3). These compounds are then used to create larger nitrogen fertilizer molecules. Before analyzing the production processes, it is valuable to understand the current level of nitrogen fertilizer production within, and trade to and from, Europe.

The total mass of nitrogenous fertilizers produced within and traded by the EU, and how these have varied over the last decade, is shown in Figure 6. Prior to Russia's invasion of Ukraine in 2022, the EU produced between 15.9 and 17.4 million tonnes of nitrogen fertilizer each year. This output came from more than 120 production sites, including 30 ammonia plants, sited both close to farmland to shorten delivery distances and close to the European gas grid to secure access to their main feedstock. Note that ammonia capacity is highly concentrated, with Poland, the Netherlands and Germany accounting for approximately half of the EU total [25]. During this pre-war period, Europe imported 7.2-8.1 million tonnes (roughly 45% of the amount it produced) and exported a slightly smaller quantity of 6.8-7.6 million tonnes [26].

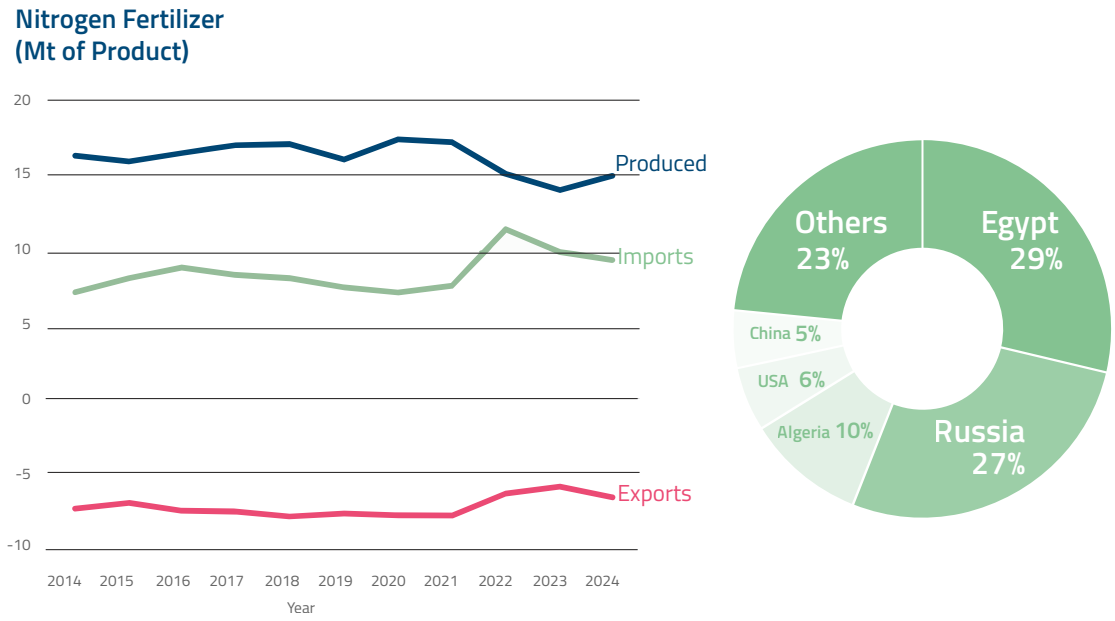


Figure 6: Production and trade of nitrogen fertilizers in the EU [27].



Following the invasion, EU production fell by ~12% to 14.5-15 million tonnes per year and has yet to recover. The production deficit was met by increasing imports and reducing exports. In 2024, European imports of nitrogenous fertilizers were dominated by Egypt (29%), Russia (27%) and Algeria (10%), primarily due to the lower natural gas costs in those countries [26].

Figure 7 shows the monthly cost of fertilizer and natural gas since 2019. The two are closely correlated, which is unsurprising given that natural gas can account for up to 90% of the variable cost of ammonia production. Wholesale gas prices rose tenfold in 2022 and have since remained at approximately 40 €/MWh, which is approximately 160% above the pre-war average of 15 €/MWh. At these levels, the business case for European production is significantly weakened. In May 2026, CEFIC (the European chemical industry's trade association) reported aggregate EU27 plant capacity utilization rates remained at historically low levels, around 74%, well below its long-term average [28]. This is significantly below the 80% threshold generally considered necessary for chemical plants to remain profitable.

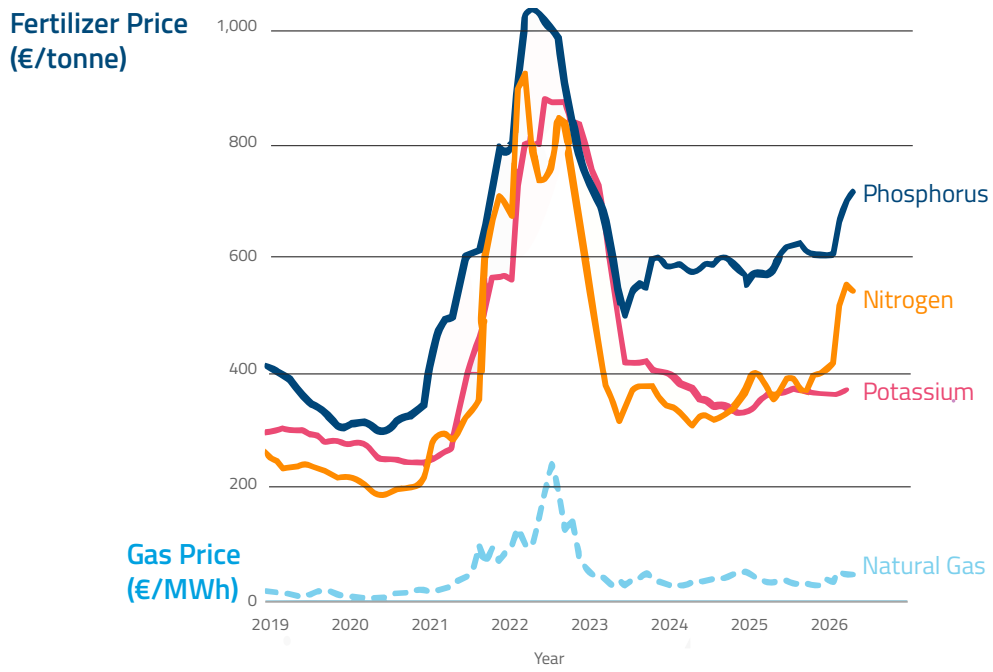


Figure 7: Fertilizer and wholesale natural gas prices [29], [30]. Fertilizer prices are given per tonne of product.

Nitrogen fertilizer prices have risen across two successive shocks. Before the war in Ukraine, the average price was 230 €/tonne. Between the onset of that conflict and the start of the US-Iran war, it was approximately 400 €/tonne. As of May 2026, following the second shock, the price is 550 €/tonne. This range, roughly 400-550 €/tonne, is crucial as it sets the threshold that low-emission production methods must compete with.

European nitrogen fertilizer producers are unable to pass these cost increases on to consumers (i.e., farmers), because they compete against fertilizer imports, which are manufactured in regions with cheaper natural gas prices. Thus, while Europe seeks to reduce its reliance on imported fossil fuels, its nitrogen fertilizer supply becomes more dependent on imports from regions with cheap and abundant gas.

4. Incumbent Production Methods

Roughly 78% of Earth's atmosphere is nitrogen; however, this nitrogen exists in the form N_2, in which two nitrogen atoms are held together by a very strong triple bond. This bond makes atmospheric nitrogen unusable by crops. Synthetic fertilizer production therefore works by breaking this bond and converting atmospheric nitrogen into a usable, bioavailable form (this is known as nitrogen fixation). However, since the triple bond is very strong, breaking it requires substantial amounts of energy.

This section details the incumbent natural-gas-based production methods for (i) urea and (ii) nitrate-based fertilizers. Figure 8 compares the most popular type of nitrogen fertilizer product used globally and in Europe. Globally, urea and nitrate-based fertilizers are the most common products and supply 53% and 8.3% of the nitrogen delivered to the soil, respectively [31]. In Europe this trend is reversed, with urea supplying only 23% and nitrates 37% [31]. This is primarily due to historical investment in nitrate production capacity, and to agronomic conditions that favor nitrate over urea. Nitrate is immediately available for uptake, while urea must first be converted in the soil, a process that occurs slowly in cool, acidic conditions [25]. Approximately 20-25% of global fertilizer is delivered in compound form, which combines nitrogen with phosphorus and potassium into a single product [31]. The nitrogen in these compound products is also typically in the form of urea or nitrate.

Note, for the remainder of this report, values are given per tonne of nitrogen delivered to the soil, rather than per tonne of product. This allows for a fair comparison between fertilizers of different nitrogen content. For instance, on a unit weight basis, one tonne of urea is 46% nitrogen while one tonne of calcium nitrate is only 15.5%.

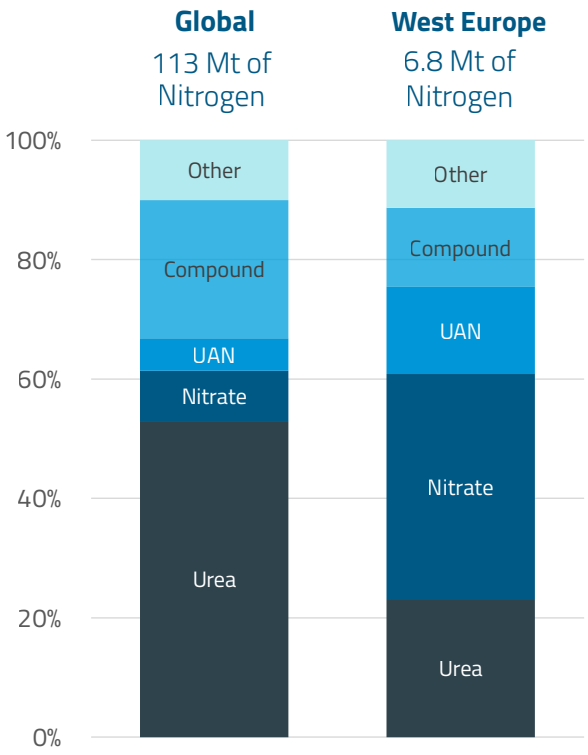


Figure 8: Nitrogen fertilizer use by product type, globally and in Europe [31]. UAN = urea ammonium nitrate.

4.1 Urea from Natural Gas

Description: Figure 9 shows the process for producing urea from natural gas. The production process can be split into three steps:

- **Steam reforming:** methane and water are reacted to produce separate streams of hydrogen and carbon dioxide.[2]
- **Haber-Bosch**: hydrogen is combined with nitrogen from the air in a pressurized reactor at high temperature to synthesize ammonia.
- **Bosch-Meiser:** ammonia is combined with a portion of the CO_2 produced earlier in the process and converted into urea.

These processes usually take place on the same industrial chemical site, with the output from one process directly feeding the next. Colloquially, it is common for this whole process to be referred to as a "Haber-Bosch plant", even though the term technically refers only to the ammonia synthesis step.

Haber-Bosch plants are large chemical facilities, which produce approximately 1,000-3,000 tonnes of ammonia per day [22]. They have lifetimes of 60+ years and capital costs in the billions of euros. Haber-Bosch plants operate continuously at maximum rated output; this inflexibility is due to both technical and economic reasons.

Ammonia synthesis is exothermic and occurs at high temperature (400-500°C) over an iron catalyst [32]. Exothermic means the chemical reaction that produces ammonia generates its own heat. Thus, when production stops, the reaction no longer supplies heat, and since the catalyst is inactive below around 400°C, it cannot restart itself. The plant must be slowly reheated externally, which is why a cold start takes 1-2 days [32], [33]. The iron catalyst must also be held within a narrow temperature range, and ramping too quickly risks thermal damage. In addition, the steam methane reforming loop and Haber-Bosch loop are tightly coupled, since hydrogen is difficult to store. Thus, once hydrogen is generated it is typically consumed immediately and continuously with minimal buffer.

From an economic perspective, even if flexible operation were technically feasible, it would not be cost-effective to run the plant intermittently, given the high initial capital costs required. Traditionally this has not been a problem, since there is no need to operate flexibly as natural gas prices do not fluctuate on an hourly basis like electricity prices, and fixed rates are typically agreed in advance.



[2] This is a simplified description of what happens. In reality, steam reforming produces syngas, a mixture of hydrogen and carbon monoxide. A second reaction called the 'water-gas shift' reacts the carbon monoxide with more steam into additional hydrogen and carbon dioxide. The two steps are treated together here for simplicity. Importantly, syngas is itself a platform chemical with industrial uses beyond ammonia production.

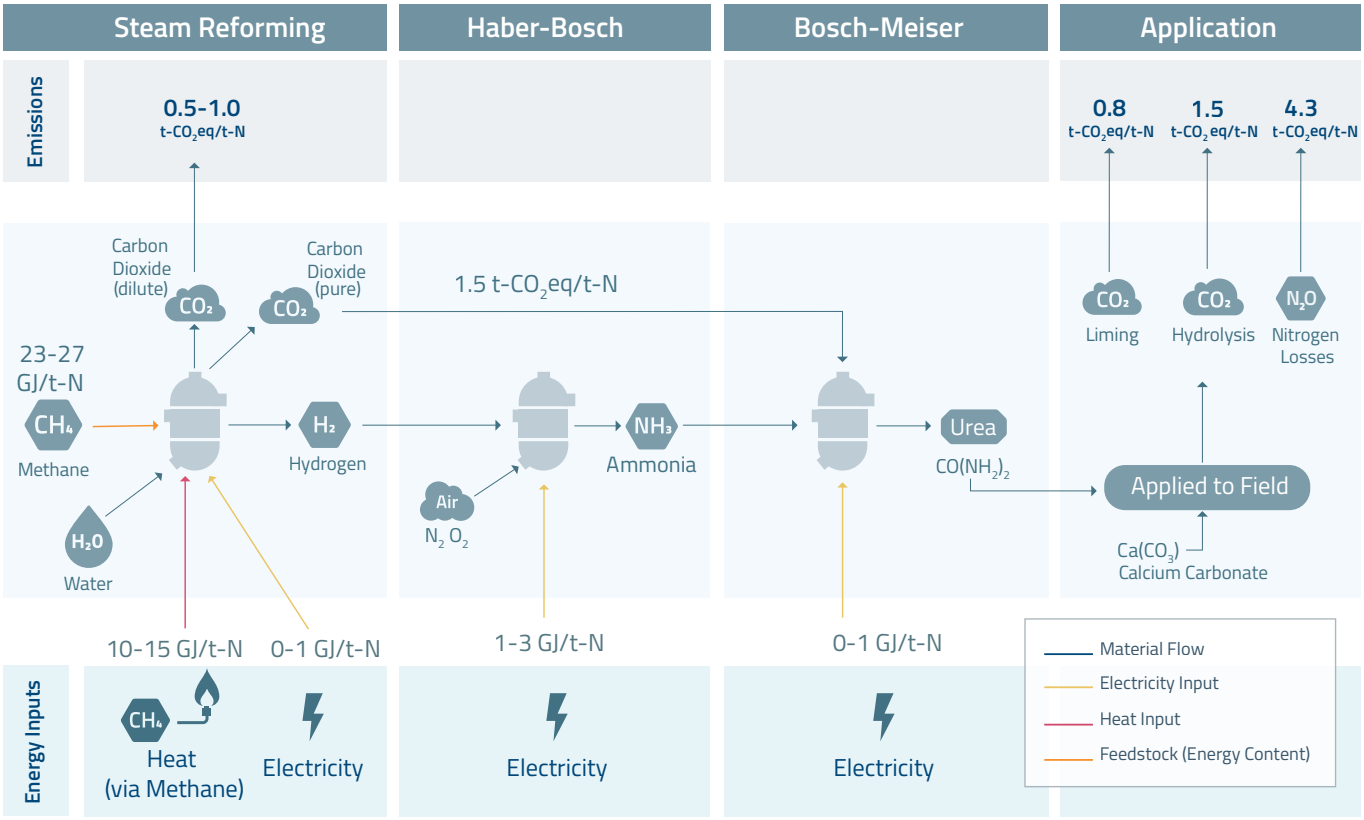


Figure 9: Production and application of urea fertilizer from natural gas. Globally, this is the most widely used nitrogen fertilizer production process. Note that values are gross, and heat recovery and internal energy flows are not explicitly drawn. References for energy and emissions values: SMR: Table 1.2 in [22], Table 3 in [7], Table 3.1 in [34], pg. 152 in [35], pg. 5 in [36]. Haber-Bosch: pg. 36 in [22], pg. 10 in [7]. Field Application: Table 11.1 in [37], pg. 27-34 in [38], Figure 1 in [5], pg. 1 in [39].

Energy: The majority of energy input into a urea plant comes from natural gas. 67% of the gas is consumed as feedstock during the steam reforming process to produce the hydrogen, while 33% is burned to supply the heat that the reforming reaction requires. These two processes are physically separated within the reformer; the reforming reaction takes place inside catalyst-filled tubes, while the fuel is burned in a furnace which surrounds them.[3] This means the CO_2 from the feedstock and the CO_2 from the fuel leave the reformer as two distinct streams. The downstream Haber-Bosch and Bosch-Meiser steps require relatively little energy input, as both of these reactions are exothermic. The electricity input to these steps is mainly used for control systems and to drive the compressors which raise the synthesis gases to operating pressure. (Note, often these compressors are driven by steam turbines using steam generated from waste heat from the reforming process.)

Emissions: Urea is a highly transportable and stable form of nitrogen ready for agricultural use. It is very nitrogen-dense, with every 1,000 kg of urea containing 460 kg of nitrogen. Of all the mainstream nitrogen fertilizers in use, urea is the most nitrogen-dense, which reduces its shipping and transport costs per unit of nitrogen delivered.

Due to the acidifying effect of urea on soil, it is typically applied alongside a liming material, which is slightly basic. This counteracts the acidity of the urea and means the net effect on soil pH is broadly neutral. The most common liming material is calcium carbonate, also known as limestone.

Recall from Figure 2 that approximately 60% of total fertilizer emissions arise from on-field emissions. These on-field emissions come from three main pathways:

- **Liming -** application of calcium carbonate neutralizes soil acidity but releases the CO_2 held in the carbonate. This carbon was initially geologically sequestered in the earth, so it causes a net addition of CO_2 to the atmosphere.
- **Hydrolysis -** urea reacts with water in the soil and is broken down. It releases the CO_2 that was incorporated into the molecule during the Bosch-Meiser process. This CO_2 was originally a byproduct from the steam reforming process which was reused.
- **Nitrogen losses - N**itrogen from the fertilizer is lost to the atmosphere through several routes. Microbes in the soil produce nitrous oxide, through processes known as nitrification and denitrification. Nitrous oxide is a highly potent greenhouse gas with a warming effect roughly 273 times that of CO_2 [37]. In addition, the breakdown of urea in the soil can lead to the release of ammonia. Ammonia is not a greenhouse gas; however, once it returns to the ground it can be decomposed and is an indirect source of nitrous oxide.

4.2 Nitrate Fertilizer from Natural Gas

Description: In Europe, the most widely applied form of nitrogen fertilizer is nitrate-based. This means that the nitrogen is delivered to the soil as a "nitrate", which can easily be taken up by the plant. Nitrate-based fertilizers use nitric acid as the main building block during the production process. Figure 10 shows the production of ammonium nitrate, as it is one of the most widely used nitrate fertilizers (others include calcium nitrate, potassium nitrate, etc.).

[3] An alternative to this steam reforming process is autothermal reforming (ATR). In the ATR process the feedstock and fuel are not physically separated. Pure oxygen is fed directly into the reactor and a portion of the natural gas is burned within the same vessel, supplying the heat internally. This yields a single concentrated CO_2 stream, however it requires an air separation unit to supply the oxygen.

The largest change from the urea manufacturing process is the replacement of the Bosch-Meiser process by the Ostwald process, which uses ammonia and air to produce nitric acid. This is performed in a reactor which uses a platinum-rhodium catalyst to turn the ammonia first to nitric oxide (NO) and then into nitrogen dioxide (NO_2). This process happens at 850-950°C and 5-10 bar; however, it does not require an external heat input, as the reaction heats itself (exothermic) [40]. The nitrogen dioxide is then absorbed in water to form nitric acid. The production is finalized by mixing the nitric acid with ammonia from the previous step to form ammonium nitrate.

Energy: The insertion of the Ostwald process does not change the energy input requirements. The reaction is exothermic, and the recovered heat is used to evaporate water from the ammonium nitrate solution.

Emissions: An important caveat for the Ostwald process is the unwanted formation of nitrous oxide (N_2O); recall N_2O is a potent GHG with a warming potential 273 times that of CO_2 [37]. Although very similar in name and symbol, nitrous oxide is very different from the NO and NO_2 gases which the plasma-based process wants to create. Nitric acid plants are consequently a significant source of process N_2O and are estimated to account for 6.5% of total global nitrogen fertilizer emissions [5].

During nitric acid production, the CO_2 byproduct is managed very differently than for urea. First, the CO_2 produced during the steam methane reforming step is emitted directly into the atmosphere. It is not captured and added back to the fertilizer molecule. Thus, ammonium nitrate may seem like a more emission-intensive fertilizer; however, this is not the case. Ammonium nitrate does not contain carbon. When it is applied to the soil and comes into contact with water it does not undergo hydrolysis or release CO_2. This is unlike urea. The CO_2 that urea appeared to "lock up" during production is captured only temporarily as it is ultimately re-released in the field during hydrolysis.

Therefore, when considering both production and application of urea and ammonium nitrate, the total CO_2 emitted is roughly comparable. Importantly, in both cases the dominant greenhouse gas is not CO_2 from production but N_2O from field emissions.

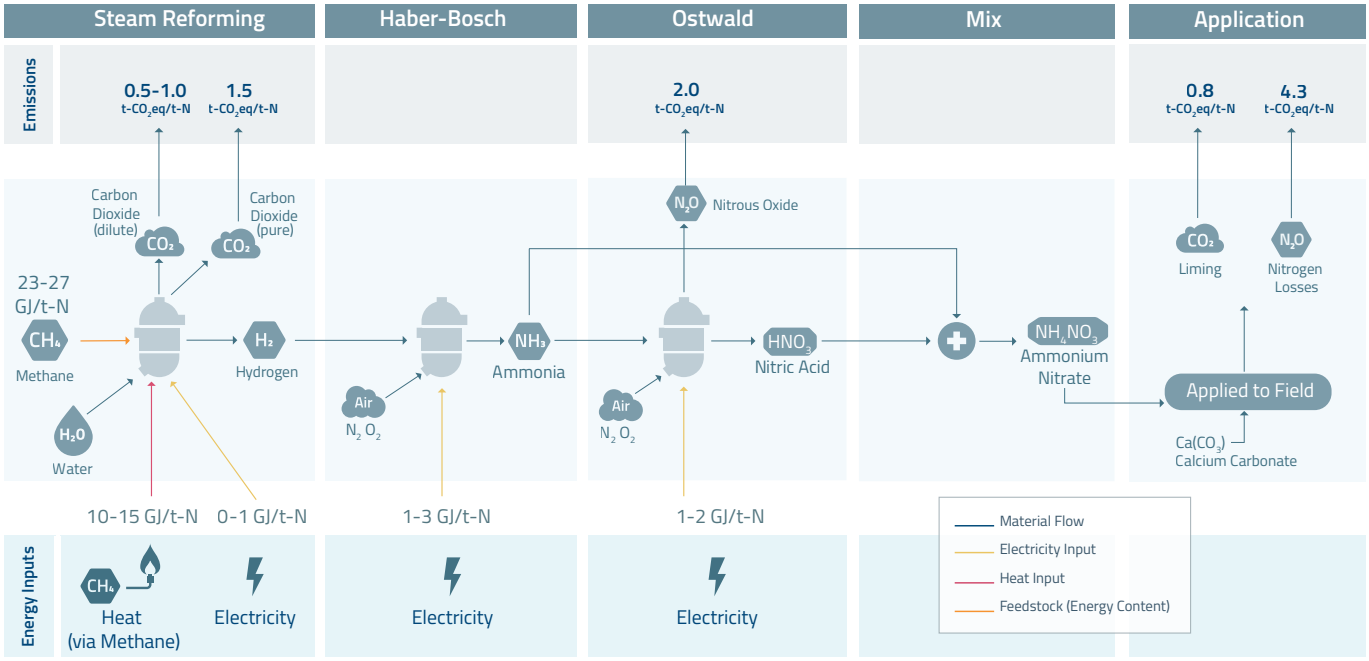


Figure 10: Production and application of ammonium nitrate fertilizer from natural gas. Note that values are gross, and heat recovery and internal energy flows are not explicitly drawn. References for energy and emissions values: SMR: Table 1.2 in [22], Table 3 in [7], Table 3.1 in [34], pg. 152 in [35], pg. 5 in [36]. Haber-Bosch: pg. 36 in [22], pg. 10 in [7]. Ostwald: Table 3.3 in [34]; Table 3.6 in [41] Field Application: Table 11.1 in [37], pg. 27-34 in [38], Figure 1 in [5], pg. 1 in [39].

The Ostwald Process and Reducing its Climate Impact

Box 1

The production of nitric acid from ammonia was developed by Wilhelm Ostwald in 1902. The so-called Ostwald process still underpins all commercial nitric acid production. The same reaction also forms nitrous oxide, and because N_2O is so potent a greenhouse gas, even small quantities matter. It is estimated that nitric acid plants account for 6.5% of all GHG emissions from fertilizer production and application [5], [42].

These emissions can be abated by fitting catalysts in the reactor, which prevent the release of N_2O. The cost of this abatement is estimated to be 0.5-5 € per tonne CO_2eq [43], which is one of the most cost-effective emission reduction options available today. Unabated plants emit 6-9 kg N_2O per tonne of nitric acid (7-11 tCO_2eq/tN), while with the catalysts widely used in Europe today, this falls to 0.12-0.6 kg/t (0.2-0.7 tCO_2eq/tN) [41]. However, because abatement does not bring a yield or energy benefit, it is used only where regulation pays for it (in Europe, nitric acid plants fall within the EU ETS). The Nitric Acid Climate Action Group puts the remaining global potential above 100 $MtCO_2$eq/yr. A global average of 2 tCO_2eq/tN is assumed here [43].

4.3 Future Fertilizers Will Shift to Nitrates over Urea

The production of urea requires 1.3 tonnes of CO_2 feedstock for every tonne of ammonia [7], [22]. The CO_2 binds with the ammonia produced in the Haber-Bosch process to produce the nitrogen-dense urea molecule. In the incumbent natural-gas-based process, the CO_2 used is actually a byproduct of the initial steam reforming reaction used to make hydrogen.

For electrified fertilizer production pathways, a reforming reaction does not take place and thus this source of CO_2 is no longer available. The two main alternatives for this CO_2 (direct air capture (DAC) and CO_2 recovered from biomass) are both energy-intensive. The energy requirement of current DAC is estimated at approximately 8-14 GJ/tonne CO_2, which corresponds to an energy intensity of 13-23 GJ/tN [44]. As will be shown in the following section, this will add 30-50% to the total energy demand of the electrified production routes, for carbon that is ultimately released back to the atmosphere when the urea is applied to the field.

Importantly, this CO_2-supply issue occurs for all low-emission ammonia production pathways. The availability of a cost-effective and sustainable CO_2 feedstock is therefore a major barrier to sustainable urea production. One way around this is a greater production of nitrate fertilizers, as is already done in Europe. Instead of binding ammonia with CO_2, the ammonia is converted to nitric acid, which is then combined with other, easier-to-acquire molecules.

4.4 Section Summary

The incumbent production pathways operate at enormous scale. They produce thousands of tonnes of fertilizer per day in capital-intensive and long-life chemical plants, which have been optimized over a century of operation. They are also inflexible, continuously consuming large amounts of natural gas both as a feedstock and as a source of heat.

Urea and nitrate-based fertilizers are the dominant forms on the global market. They are derived from two main building blocks: ammonia and nitric acid. In the incumbent method, hydrogen is used to produce ammonia, which then serves as the basis for nitric acid.

When comparing the energy and emissions of different fertilizers, the production and field-application stages must be considered together. Looking at only one is inaccurate and can distort emission calculations, since emissions may simply be shifted between stages. Urea, for instance, may appear to have lower production emissions only because the carbon diverted from steam reforming is released later, during field application.

5. Low-Emission Production Methods

Ammonia and nitric acid are the chemical building blocks from which all synthetic nitrogen fertilizers are derived. As such, low-emission fertilizer production hinges on producing these molecules sustainably. Several routes to produce these building blocks from electricity are considered in this section:

- **Renewable hydrogen with upgraded Haber-Bosch:** renewable hydrogen is produced from the electrolysis of water and then synthesized with nitrogen in a flexible Haber-Bosch process to produce ammonia. Nitric acid is then produced via the Ostwald process.
- **Plasma-based:** nitric acid is synthesized directly using an electrically powered plasma to fix nitrogen from the air. This bypasses the ammonia step entirely.
- **Electrochemical ammonia synthesis:** ammonia is produced directly from nitrogen and water in an electrochemical cell, bypassing both the hydrogen production and Haber-Bosch steps. Nitric acid is then produced via the Ostwald process.
- **Carbon Capture and Storage:** natural gas is maintained as the feedstock, but the concentrated process CO_2 stream is captured. The reforming heat is supplied by electricity rather than by burning natural gas, removing the diluted combustion stream. Capturing both streams instead is also possible, and is discussed later.

Figure 11 shows these production pathways and the molecules they create, in addition to the incumbent natural-gas-based process.



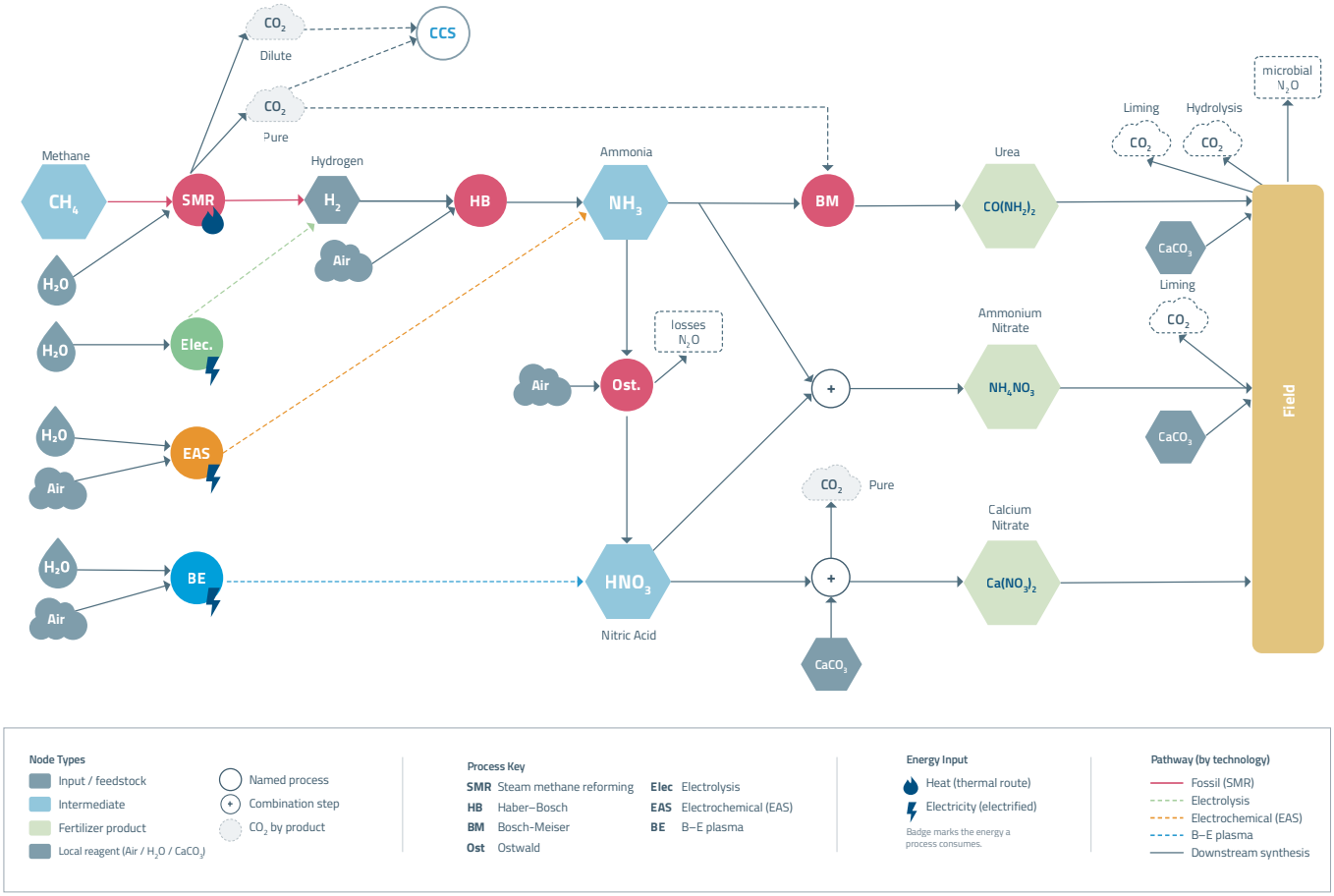


Figure 11: Overview of production methods and their intermediate molecules.

5.1 Option 1: Electrolytic Hydrogen with Upgraded Haber-Bosch

Description: The most energy- and emissions-intensive step of the incumbent fossil production method is the steam methane reforming process used to produce hydrogen. The production of "green" hydrogen from the electrolysis of water is one way to reduce emissions from this step.

Figure 12 shows the production of ammonium nitrate from this method. In the first step, an electrolyzer powered by electricity is used to split purified water into hydrogen and oxygen. The hydrogen is then fed into an "upgraded" Haber-Bosch process and the oxygen is typically vented into the atmosphere, although it can be utilized as a byproduct. The ammonia synthesis loop itself remains largely unchanged, since the same reaction of hydrogen and nitrogen over an iron catalyst is used.

In this context, "upgraded" refers to two required modifications: the addition of an air separation unit, and improved flexibility.

An air separation unit is needed to supply a nitrogen-rich flow to the Haber-Bosch reactor. In the incumbent process, a nitrogen-rich stream is created by feeding air into the final part of the steam reforming reaction, where the oxygen in that air is consumed during the combustion of natural gas. This conveniently removes the oxygen and leaves a nitrogen-rich flow for the synthesis loop. Since the electrolysis route involves no combustion, a dedicated air separation unit is required instead, splitting air into its nitrogen and oxygen components.

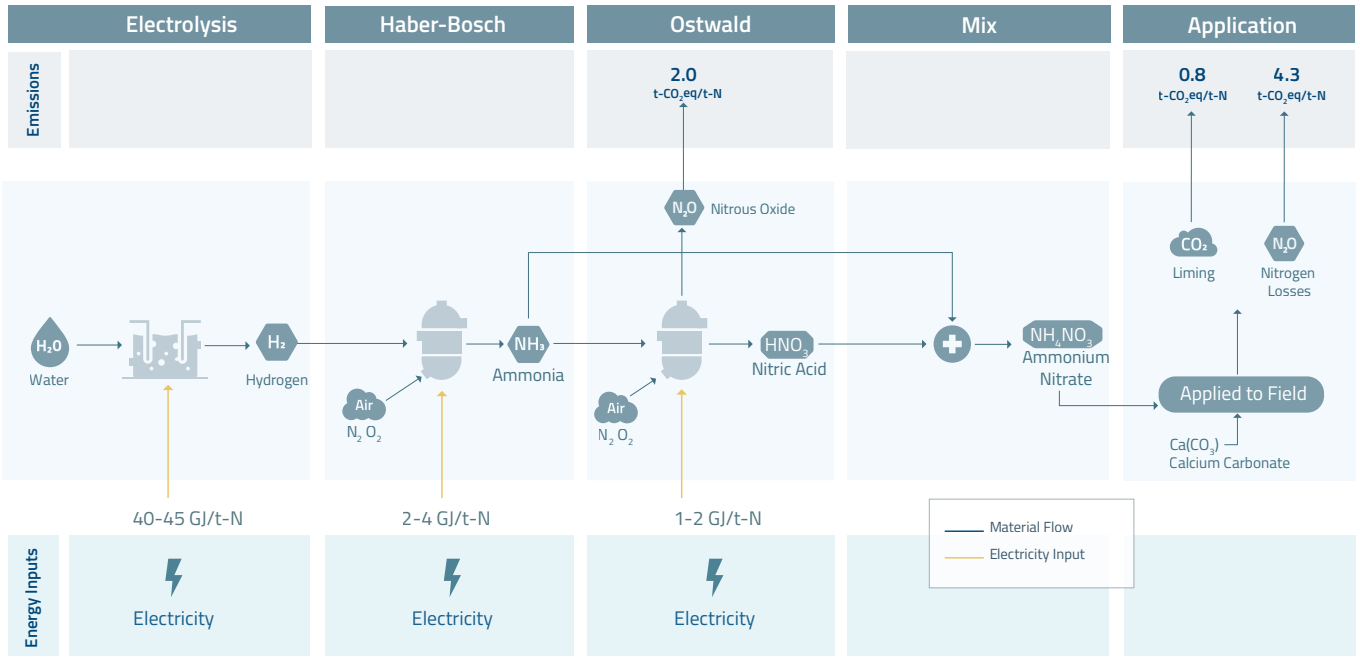


Figure 12: Production and application of ammonium nitrate fertilizer from electrolytic hydrogen and an upgraded Haber-Bosch process. Note that values are gross, and heat recovery and internal energy flows are not explicitly drawn. References for energy and emissions values: Electrolysis: Table 1.2 in [22], Table 5 in [7], pg. 152 in [35]. Haber-Bosch: pg. 36 in [22], pg. 10 in [7]. Ostwald: Table 3.3 in [34]; Table 3.6 in [41] Field Application: Table 11.1 in [37], pg. 27-34 in [38], Figure 1 in [5], pg. 1 in [39].

The second "upgrade" is flexibility. Incumbent Haber-Bosch plants are optimized for a fossil-based energy system, in which the objective is to produce as much fertilizer as possible, at the lowest cost. This favors large plants running continuously, so that capital is fully utilized and the component wear associated with repeated ramping is avoided. Continuous operation is straightforward when the plant is fed by a steady stream of hydrogen from steam reforming, but not when the hydrogen comes from electrolysis powered by intermittent renewable electricity. Matching a variable hydrogen supply with a synthesis loop that requires steady operation is the central engineering challenge of this route; the synthesis loop is a small share of total plant cost, but its limited flexibility is the main bottleneck [33]. Two approaches are being pursued. The first is to make the synthesis loop itself more flexible, through the design of reactors and catalysts able to tolerate variable operation [32]. This is an active area of research and commercial development, although the level of flexibility remains uncertain [33]. The second is to keep the loop running continuously and provide flexibility upstream, through hydrogen storage between the electrolyzer and the synthesis loop, or battery storage to smooth the electricity supply to the electrolyzer. Thermal storage can also offer an intermediate option where it stores heat to keep the reactor at temperature during low-load or standby periods [45]. One study from the UK found that a flexible system, made by combining parallel reactors with thermal storage, was cheaper than either storage option (however this was at 2022 battery prices) [45].

Energy: The main change in energy input to the process occurs during the electrolysis step, which requires 40-45 GJ/tN of electricity (refer to Figure 12). The net heat input to the process is close to zero, as the exothermic Haber-Bosch and Ostwald reactions generate enough heat for themselves. Recall that the natural-gas route has two separate input streams of methane: 23-27 GJ/tN as feedstock and 10-15 GJ/tN as a fuel to generate high-temperature heat (required in the endothermic steam reforming reaction). This means the incumbent energy intensity of hydrogen production of 33-42 GJ/tN is close to the renewable hydrogen option. The significant change is therefore not necessarily the quantity of energy required, but the shift from fossil fuels to electricity, and the associated difference in costs. For reference, electricity is on average almost three times more expensive than gas for EU companies, with only Finland and Sweden below a ratio of two [46]. That shift replaces imported natural gas with electricity that is, in large part, domestically generated, and does so at comparable total energy demand.

Emissions: Production emissions can be lower than the incumbent, but the extent depends on the carbon intensity of the electricity consumed. When powered by renewable, low-carbon electricity, emissions from the electrolysis, air separation and synthesis steps are negligible. Below a grid carbon intensity of approximately 190 gCO_2/kWh, this route emits less than the incumbent steam methane reforming pathway; above it, the electrolytic route emits more (FCA analysis based on Figure 10 and Figure 12).

Importantly, emissions from nitrous oxide (N_2O) formed as a byproduct in the Ostwald process remain. In Europe, however, there is widespread use of catalysts which can minimize the release of N_2O to less than 10% of an unabated plant [41].

Emissions from field application also remain, at approximately 4 tCO_2eq/tN due to nitrogen losses typically in the form of N_2O, and a further 0.8 tCO_2eq/tN from liming.

5.2 Option 2: Plasma-Based Route

Description: The objective of fertilizer production is to deliver nitrogen to plants in a usable form. The use of ammonia and hydrogen is not actually required, but rather they serve as convenient and well-established intermediates. The Birkeland-Eyde process is distinct from the other methods in that it produces nitric acid directly from air using electricity, thereby bypassing the conventional Haber-Bosch and Ostwald synthesis steps.

Figure 13 shows the production of calcium nitrate fertilizer using this method. The Birkeland-Eyde process was developed in Norway in the early 1900s. It works by applying a high voltage across a gap through which air is passed. This causes the air to break down and become electrically conductive, forming a plasma (the same phenomenon as lightning). A plasma is a highly energized gas in which electrons separate from their atoms, producing a mixture of positively charged ions and "free" electrons. Under these conditions the atmospheric nitrogen N_2 can be separated into its individual nitrogen atoms. This allows nitrogen and oxygen to recombine and form nitrogen oxides. The nitrogen oxides are then absorbed in water to form nitric acid.

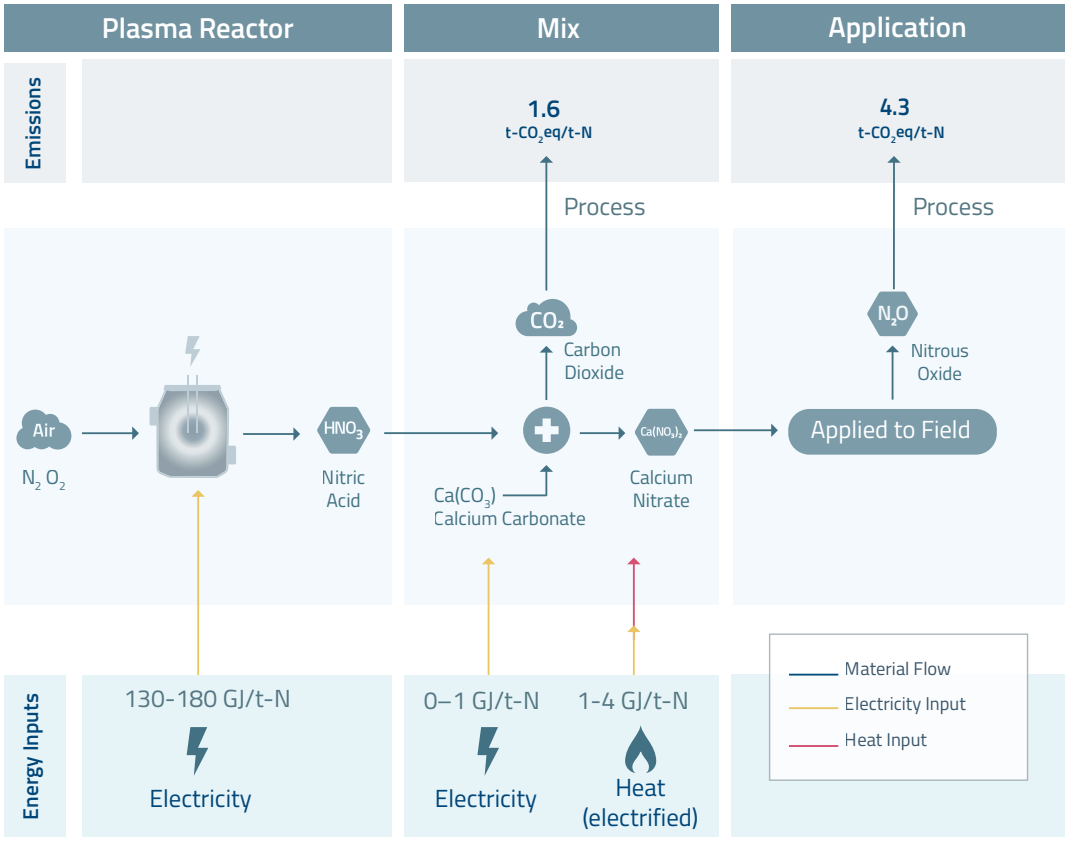


Figure 13: Production and application of calcium nitrate fertilizer from the Birkeland-Eyde process. Note that values are gross, and heat recovery and internal energy flows are not explicitly drawn. References for energy and emissions values: Plasma: [47], [48], [49],[50], [51], [52], [53]; Mixing: values are estimated and are stoichiometric, and the heat input is used for drying; Field Application: Table 11.1 in [37], pg. 27-34 in [38], Figure 1 in [5], pg. 1 in [39]. Note, where soils require routine liming, the mildly alkalizing effect of calcium nitrate can offset up to ~0.8 tCO_2/tN of field liming [54].

It is important to distinguish between thermal and non-thermal plasma. In a thermal plasma, the entire gas is heated to several thousand degrees. This requires significant amounts of energy and is how the historical Birkeland-Eyde process operated, in what was called an electric arc reactor. In a non-thermal plasma, however, energy is used to only heat the electrons while the bulk of the gas remains relatively cool. The chemistry is the same and the product is the same nitric acid. The aim is that less energy is spent heating gas that does not need to be hot. Non-thermal plasma is one of the main focus areas of current research and start-ups in the plasma-based fertilizer space.

The nitric acid is then neutralized by combining it with a base. Calcium carbonate is a common base used for this purpose, and results in calcium nitrate (CN) fertilizer. Unlike ammonium-based fertilizers, calcium nitrate does not acidify the soil and even has a slight pH-increasing effect. Thus, no liming is required at application and other sources of soil acidification are reduced. There is a trade-off, however, as the inclusion of calcium carbonate to neutralize the nitric acid reduces the nitrogen density of the final product. Commercial calcium nitrate is approximately 15.5% nitrogen, which is roughly half the nitrogen density of ammonium nitrate at 33.5%. This means that roughly twice the mass of product must be transported for the same quantity of nitrogen delivered.

Energy: The most challenging aspect for commercialization of the Birkeland-Eyde process is the significant electricity consumption of the plasma reactor. The early 1900s production sites, which operated at large industrial scale, consumed approximately 165-220 GJ/tN [47]. Recall that the incumbent natural gas route requires approximately 35-48 GJ/tN for the entire process. Reducing the energy intensity of the plasma reactor is an active area of research, with breakthroughs including optimization of reactor pressure, microwave energy input, and oxygen partial pressure. Nevertheless, when compared to the renewable hydrogen route, the plasma-based route currently requires 3-4 times as much electricity.

There is significant research interest in flexible operation of plasma reactors, which would allow production to follow periods of low or zero electricity prices. This is the principal argument for the route in a renewables-dominated system and is discussed later.

Emissions: Emissions from the Birkeland-Eyde process depend entirely on the carbon intensity of the input electricity. Since the electricity demand is roughly three times that of the electrolytic hydrogen route, the requirement for low carbon intensity is very important (on a fossil-heavy grid this method would likely be worse than natural gas Haber-Bosch).

The neutralization step is not carbon-free. Reacting calcium carbonate with nitric acid releases approximately 1.6 tonnes of CO_2 for every tonne of nitrogen in the fertilizer. Calcium carbonate is a geological carbon source, and so this represents a net addition to the atmosphere. However, the CO_2 is released as a pure stream, making it easier to capture.

Initially this makes CO_2 emissions from calcium nitrate appear greater than those from ammonium nitrate. Ammonium nitrate is neutralized with ammonia, which releases no CO_2; its carbonate emissions instead occur in the field, where around 0.8 tCO_2/tN is released from the lime applied to counteract its acidifying effect on soil. Calcium nitrate, however, is slightly alkalizing and has the opposite effect on soil. Where soils require routine liming, it therefore reduces the lime needed by a similar amount, avoiding ~0.8 tCO_2/tN. Its net carbonate emissions are therefore ~0.8 tCO_2/tN (1.6 at the plant minus 0.8 avoided in the field), effectively the same as ammonium nitrate [54]. The difference is simply where the CO_2 is released.

5.3 Option 3: Electrochemical Ammonia Synthesis

Description: An electrolyzer is a device which uses electricity to drive a chemical reaction that would not occur on its own without an energy input. Electrolyzers are most commonly discussed in the context of hydrogen, where electricity is used to split water into hydrogen and oxygen. The same principle can be applied to produce other substances, including ammonia directly.

In electrochemical ammonia synthesis, nitrogen from the air is fed into the cell alongside water, and ammonia is produced directly. In doing so, the route replaces both the steam methane reforming and Haber-Bosch steps of the incumbent process with a single electrically driven reaction. The route to produce ammonium nitrate via this method is shown in Figure 14.

Several approaches to electrochemical ammonia synthesis are being developed, differing primarily in the chemistry by which nitrogen is reduced within the cell. So-called "lithium-mediated" systems are currently the most advanced, although "direct" and other routes remain active areas of research. The technology remains at an early stage of development, with a technology readiness level (TRL) of approximately 3-4. Demonstrations are primarily at laboratory scale, although there are a few commercial developers.

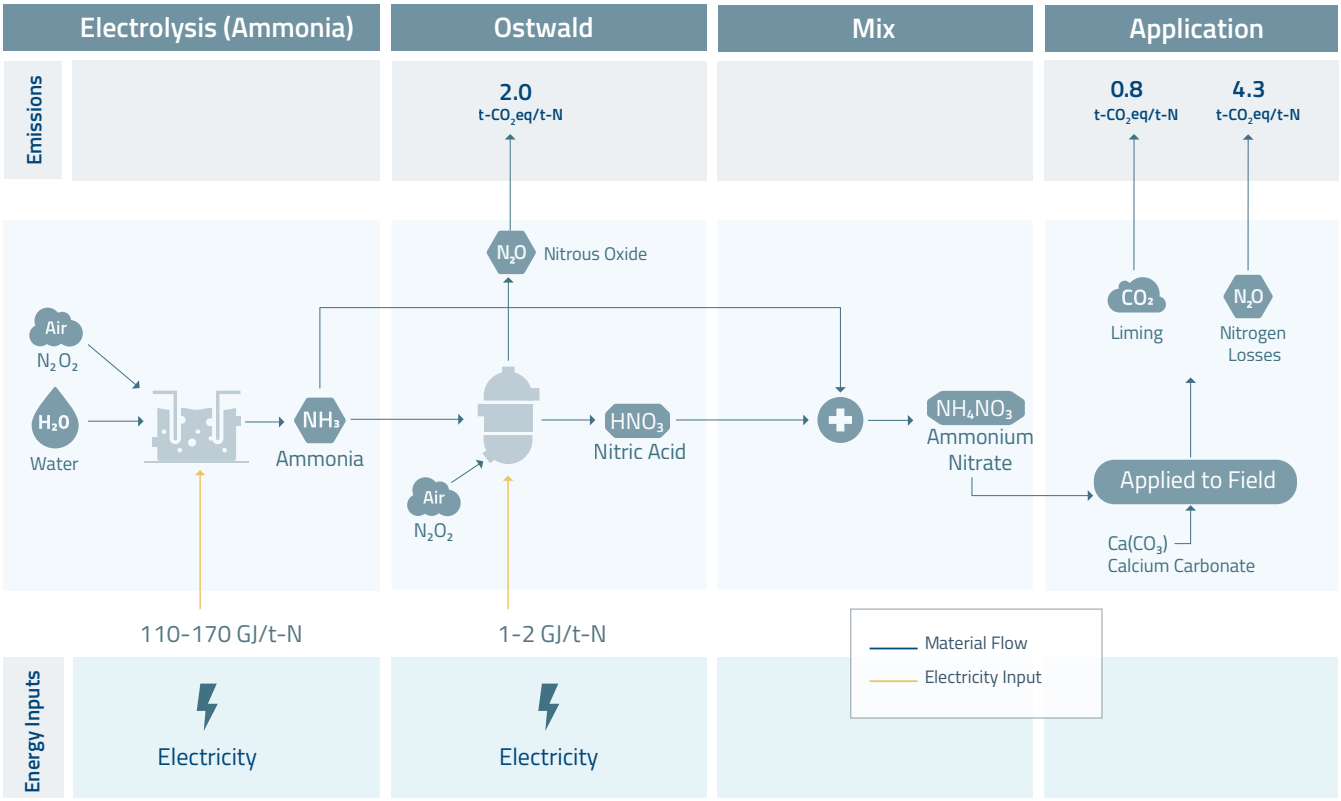


Figure 14: Production and application of ammonium nitrate fertilizer from electrochemical ammonia synthesis. Note that values are gross, and heat recovery and internal energy flows are not explicitly drawn. References for energy and emissions values: Ammonia Electrolyzer: [55], [56], [57]. Ostwald: Table 3.3 in [34]; Table 3.6 in [41] Field Application: Table 11.1 in [37], pg. 27-34 in [38], Figure 1 in [5], pg. 1 in [39].

Energy: The energy consumption of the electrolysis step is one of the main barriers to commercialization, with current laboratory demonstrators requiring 111-172 GJ/tN (recall the incumbent natural gas route only requires approximately 35-48 GJ/tN for the entire process). There are two reasons for this high energy intensity. First, in an aqueous cell it is easier to reduce protons to hydrogen than to reduce nitrogen to ammonia. Thus, a significant fraction of the electricity supplied actually produces hydrogen gas rather than ammonia as intended. The second reason is due to "overpotential" since the electrolyzer must be driven at a voltage well above the thermodynamic minimum in order to achieve a useful rate of production.

After the ammonia has been produced, the remainder of the route is unchanged from the electrolytic hydrogen pathway, with nitric acid produced via the Ostwald process and neutralized to form ammonium nitrate.

It is worth noting that bypassing Haber-Bosch offers no thermodynamic advantage over the electrolytic hydrogen route. Both begin with nitrogen and water and end with ammonia, so both share the same theoretical minimum of approximately 24 GJ/tN. Almost all of this is the cost of separating hydrogen from oxygen in water. The case for electrochemical synthesis therefore rests entirely on whether its single step can approach the minimum energy intensity more closely than the other methods.

Emissions: When powered by renewable electricity, production emissions arise only from the nitrous oxide formed during the synthesis of nitric acid from ammonia. The use of abatement catalysts to minimize N_2O formation is commonplace in Europe and can reduce emissions to below 0.5 tCO_2eq/tN.

5.4 Option 4: Haber-Bosch with Carbon Capture and Storage

Description: Virtually all carbon dioxide emissions are created during the steam methane reforming stage. Thus, the use of carbon capture and storage is also widely promoted as a means of reducing emissions from nitrogen fertilizer manufacturing.

Steam reforming consists of two parts. In the first, natural gas is reacted with steam to produce hydrogen. This releases a pure stream of CO_2, roughly 1.5 tCO_2/tN, **which is separated from the hydrogen as a standard part of ammonia production**. The second is the combustion of natural gas to produce the high-temperature heat required for the reforming reaction to take place. This produces a diluted stream of CO_2 within a flue gas, roughly 0.5-1.0 tCO_2/tN.

Carbon capture can be applied in two ways:

- (1) Capture of both the pure CO_2 stream and the dilute flue gas stream.
- (2) Capture of the pure stream only, with electrification of the reformer heat to remove the dilute stream.

Note that capturing only the pure stream does not require electrification. Plants can retain the conventional gas-fired reformer, exhaust the dilute combustion stream to the atmosphere, and then capture only the pure stream. This would still reduce production emissions by ~1.5 tCO_2/tN (roughly 60-75%). The two options above differ only in how these heat-related emissions are addressed.

Both options involve trade-offs. Electrification of the reformer heat is possible but will require plant retrofit, whereas capturing both streams is more readily attached to an existing plant. However, capturing the diluted stream requires a scrubbing process (typically using an amine solvent), which in practice struggles to capture more than 85-90% of the CO_2 in the flue [22]. Electrification removes the diluted stream altogether rather than treating it. In this analysis, only the second option is considered, in which the pure stream is captured and the heat is electrified. Figure 15 shows this process for the production and application of ammonium nitrate fertilizer.

It is worth noting that, compared with other industrial processes, carbon capture is technically far easier for ammonia production, since roughly 66% of the carbon dioxide is already emitted as a pure process stream. For this fraction a separate capture step is unnecessary, with only compression and storage required. These simplicities mean that ammonia production often ranks as one of the least expensive sectors for CCS [58].

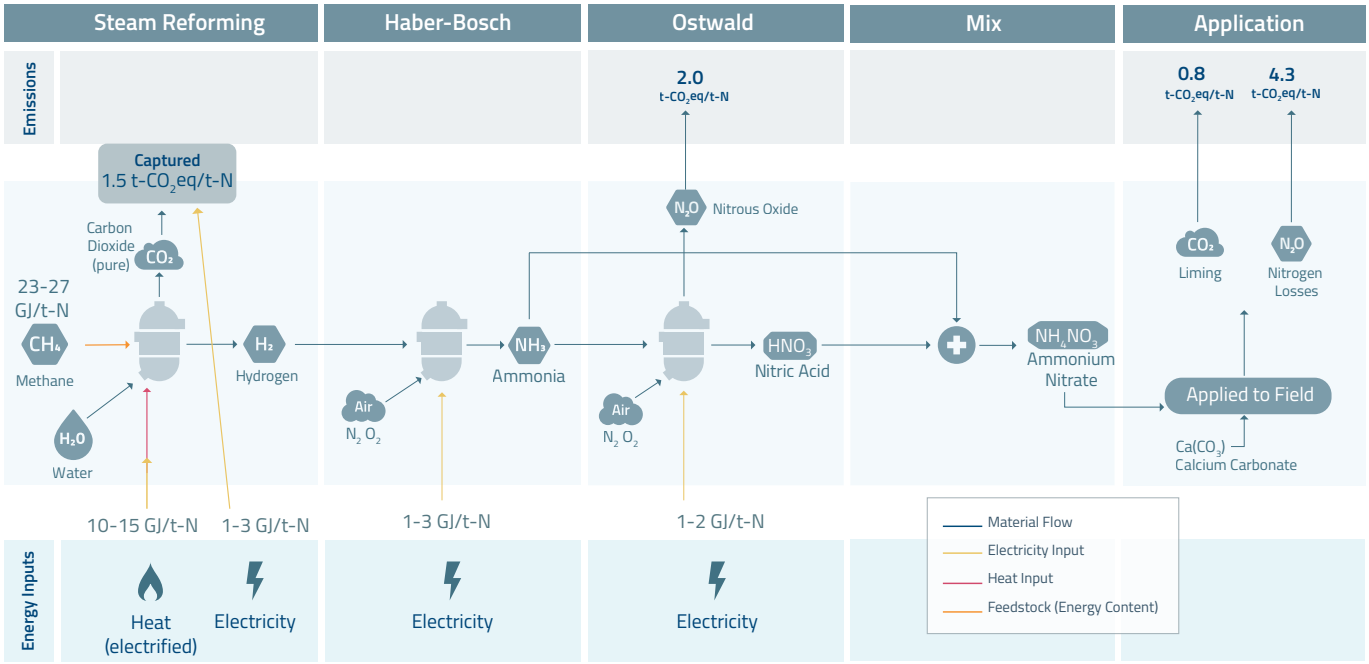


Figure 15: Production and application of ammonium nitrate using carbon capture and storage combined with electric steam methane reforming. Note that values are gross, and heat recovery and internal energy flows are not explicitly drawn. References for energy and emissions values: CCS: Table 1.2 in [22], [59]. SMR: Table 1.2 in [22], Table 3 in [7], Table 3.1 in [34], pg. 152 in [35], pg. 5 in [36]. Haber-Bosch: pg. 36 in [22], pg. 10 in [7]. Ostwald: Table 3.3 in [34]; Table 3.6 in [41] Field Application: Table 11.1 in [37], pg. 27-34 in [38], Figure 1 in [5], pg. 1 in [39].

Energy: Compared to the incumbent method, the methane used as feedstock remains the same at 23-27 GJ/tN. However, the 10-15 GJ/tN of heat previously supplied by burning natural gas is instead supplied as electricity. This route is therefore partially electrified, shifting roughly a third of the plant's energy demand to electricity.

Electrified steam methane reforming is an active area of research and demonstration, at a technology readiness level of approximately 6-7. This approach was first demonstrated in 2019 and has been deployed at a pilot plant in Denmark [60]. The pilot produces methanol rather than ammonia and operates at a fraction of the throughput of a commercial fertilizer plant.

A benefit noted from the pilot is that electrical heating is more flexible than a gas-fired furnace, with the reactor able to ramp considerably faster. For instance, a “cold start” in under three hours was demonstrated, which contrasts with the multi-day start-up of a conventional reformer.

Finally, the pure CO_2 stream requires a further 0-2 GJ/tN of electricity to compress the gas for transport. No separation step is needed, as the stream is already close to pure.

Emissions: The combination of electrified heating and capture of the pure stream eliminates production CO_2 almost entirely. All of the carbon entering the plant does so as feedstock methane, and almost all of that carbon leaves as the concentrated process stream, which is stored. Electrifying the reformer removes the dilute combustion stream that would otherwise be difficult and expensive to treat.

As with the other routes, nitrous oxide formed during the synthesis of nitric acid from ammonia is unaffected. Abatement catalysts are commonplace in Europe and reduce this to below 0.5 tCO_2eq/tN, though a global average of 2 tCO_2eq/tN is used in this analysis.

However, this route ties production to a natural gas system, in which methane leaks directly to the atmosphere during extraction, processing and transport. These emissions fall outside the production boundary used in this section, but a 1% leak rate would add in the region of 0.2 tCO_2eq/tN [61]. The electrified routes avoid this exposure entirely.

Carbon capture also depends on effective long-term sequestration. The CO_2 must be transported to suitable geological sites, and those sites must retain it permanently. The scale involved is substantial. European nitrogen fertilizer production of roughly 15 Mt per year implies the storage of 22-25 Mt of CO_2 annually, ideally close to existing production sites to limit transport costs. In Europe, such storage currently operates only at the scale of individual projects of a few million tonnes per year, and its scale-up remains uncertain.

Low-Emission Nitrogen Fertilizer Innovators

Box 2

The landscape maps the emerging field of low-emission nitrogen fixation across three technology families. The 18 entries span the full innovation pipeline, but the distribution is heavily weighted toward the middle: only three reach TRL 7-8 (Vitalfluid in Europe; Nitricity and TalusAg in the US), while 14 sit at pilot or demonstration stage (TRL 4-6) and one remains at fundamental research level (TRL 1-3).

Europe’s position differs sharply by family. In plasma technology, Europe is leading, having four of six entries (Sweden, the Netherlands, Norway and the United Kingdom), and European groups hold two of four places in electrochemical ammonia synthesis (Iceland and Denmark). In upgraded Haber-Bosch, the United States leads with four of eight entries; the remaining four are based in Canada, Japan, New Zealand and the United Kingdom. Across all three technologies, Europe (including Iceland and the United Kingdom) hosts the most innovators (seven), followed by the United States (five) and Australia (two).

Plasma (Birkeland–Eyde)

NITRIC ACID / NITRATE

US	Nitricity	7
AU	PlasmaLeap	5
SE	NitroCapt	6
NO	N2 Applied	6
UK	Plasma2X	3

FERTIGATION

NL	VitalFluid	8

Electrochemical (EAS)

DIRECT N_2 REDUCTION

IS	Atmonia	4
IL	NitroFix	4

LITHIUM-MEDIATED REDUCTION

AU	Jupiter Ionics	4
DK	NitroVolt	4

Upgraded Haber-Bosch

NEW CATALYST DESIGN

JP	Tsubame BHB	6
NZ	Liquium	4
GB	Nium	4
US	Copernic Catalysts	4

PROCESS ENGINEERING

US	ReMo Energy	5
US	Ammobia	6

DISTRIBUTED HABER–BOSCH

US	TalusAg	7
CA	FuelPositive	6

READINESS

1–3 4–6 7+

Technology readiness level, best available estimate per entry.

ENTRY TYPE

Flag = headquarters country.

EU PUBLIC FUNDING

6. Comparison of Pathways

This section compares the technologies mentioned above. All quantities are presented per tonne of nitrogen delivered, to allow fair comparison between routes producing different fertilizer products.

6.1 Energy Intensity

Figure 16 compares the energy intensity. The incumbent natural gas Haber-Bosch process has the lowest energy intensity at 35-48 GJ/tN. This is the result of continuous refinement of the technology over many decades. Coal-based production in the 1920s consumed 115-120 GJ/tN, and successive generations of gas-based plants have reduced this by roughly two-thirds [35], [47]. The process now operates at approximately twice its thermodynamic minimum of 24 GJ/tN. This is a considerable achievement but also an indication that the remaining room for improvement is limited.

The electrolytic hydrogen route is currently comparable at 43-50 GJ/tN. It is worth noting that this is not a new technology. Electrolysis-based ammonia synthesis was the most energy-efficient route available in the 1920s, consuming roughly 58-61 GJ/tN compared to 115-120 GJ/tN for coal [35], [47]. Despite this, coal and gas were favored due to their low cost and availability, rather than efficiency. This is a key conclusion: energy intensity considered in isolation is misleading. What matters is the combination of energy intensity, the cost of the energy consumed, and the capital cost of the facility. Importantly, the cost of energy can be reduced through flexible operation, which favors routes able to follow periods of low electricity prices.

Birkeland-Eyde and electrochemical ammonia synthesis are far more energy-intensive today than the incumbent, so the important question is how much of that gap can be closed. Electrochemical ammonia synthesis currently requires 111-172 GJ/tN, and Birkeland-Eyde requires 130-180 GJ/tN, down from 165-220 GJ/tN for its historical plants [47], [62], [63]. The two routes face different thermodynamic limits, depending on whether nitrogen is reduced to ammonia or oxidized to nitric acid. Electrochemical synthesis has a minimum of 24 GJ/tN, the same as the electrolytic route, against 51 GJ/tN for a thermal plasma and 14 GJ/tN for a non-thermal one [47].

Haber-Bosch reduced its energy intensity through scale and heat recovery. Plasma reactors and electrochemical cells are instead modular manufactured units and should see cost reductions as production volumes increase. This is an opposite method for improvement: mass manufacturing rather than large, optimized plants.

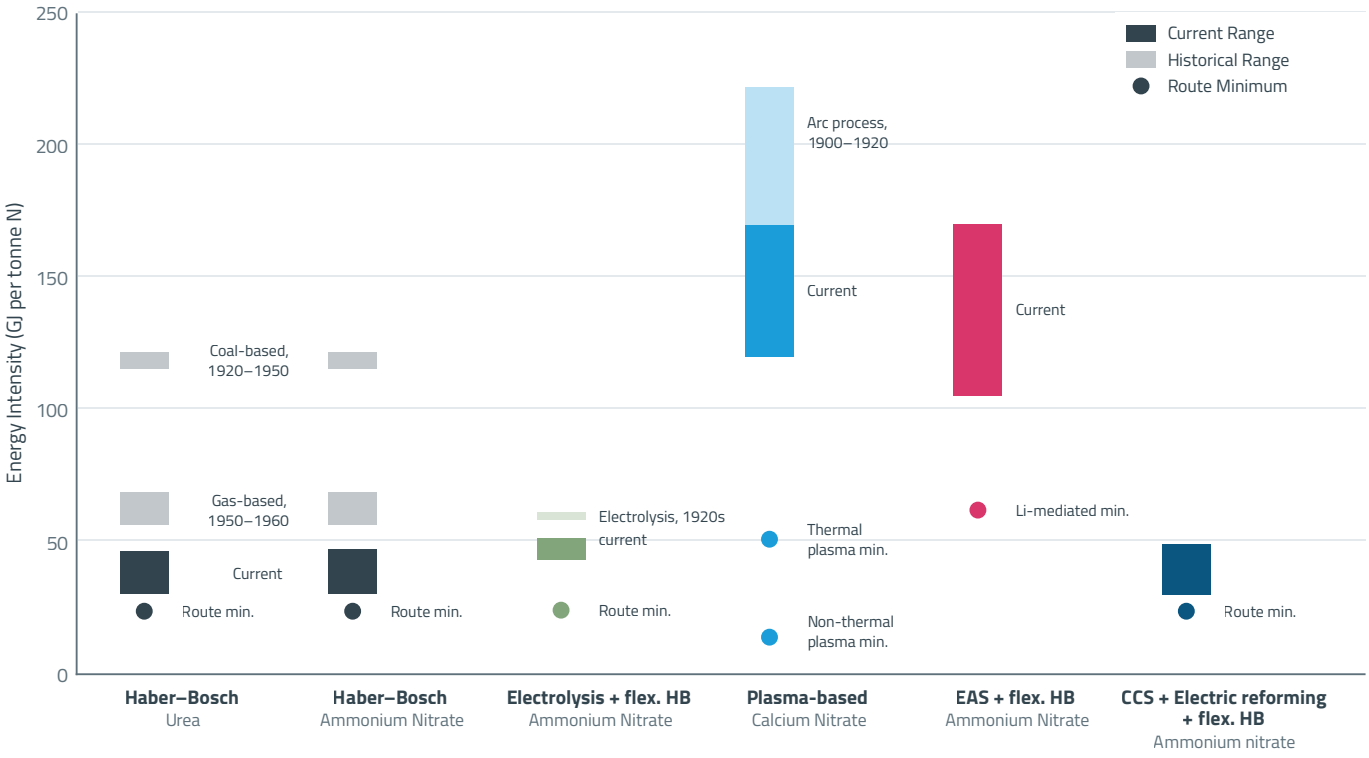


Figure 16: Comparison of energy intensity. Route minima refer to the minimum energy intensity achievable by each route. These are path-dependent and sit above the true thermodynamic minimum given by the Gibbs free energy, which is independent of the production route. For example, all ammonium nitrate routes using Haber–Bosch must first reduce the nitrogen to ammonia before oxidising half of it back to nitrate, which sets a floor of approximately 24 GJ/tN. References are listed in the captions of Figure 9 to Figure 15.

Modular Plants to Scale Up

Box 3

Incumbent Haber-Bosch facilities are the result of 100 years of technological refinement. At the start of this period these plants were smaller in size, but gradually "economies of scale", efficiency measures, and waste heat recovery were implemented, resulting in large billion-euro facilities. This is what has delivered the lowest levelized cost of fertilizer today and enabled widespread global use (and dependency).

However, the future may look different, because, for an unproven technology, going straight to a large first-of-a-kind plant is unrealistic (even if already proven at pilot or demo scale). A billion-euro first plant is well beyond the scale and budget for venture capital and too unproven for traditional project finance. Smaller modular units change the business case and offer a way to scale and ramp production, while increasing confidence (repeatable designs, availability of supply chain actors, feedstocks and off takers) along the way [32]. Building many identical units also allows costs to fall through manufacturing learning. Importantly, each unit is more financeable for early investors and offers the ability to ramp up production and deploy more units quickly.

6.2 Technology Readiness Level

Figure 17 shows the technology readiness level (TRL) for each method. Note that technology readiness is not a quantitative grouping. Each production method spans several sub-technologies at differing stages of development, which is why the routes are shown as ranges rather than single values. The TRL metric also does not account for past deployment - e.g., Birkeland-Eyde operated at commercial scale in the early twentieth century, which would place it at the highest readiness level, yet the plasma systems currently under development are considerably less mature.

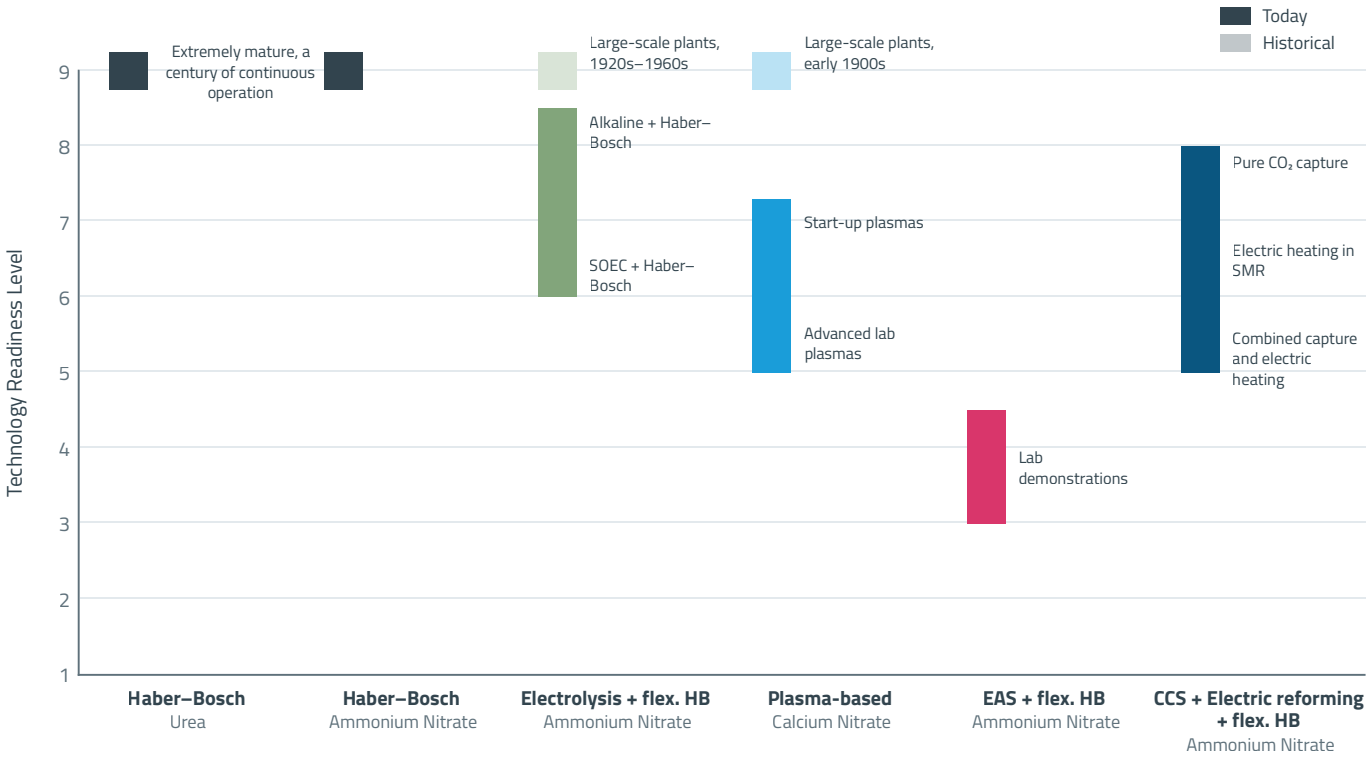


Figure 17: Comparison of technology readiness level (TRL).

6.3 Emissions

Figure 18 shows the greenhouse gas emissions of each production route. It is clear that production and on-field emissions cannot be considered in isolation. Urea carries 1.5 tCO_2eq/tN out of the plant embedded in the molecule itself. This is released only when the fertilizer hydrolyzes in the soil. Calcium nitrate works in the opposite direction, consuming limestone at the plant.

Field nitrous oxide is common to every route and is the dominant emission. Importantly, it varies by a factor of three between dry and wet soils. In wet soils the water stops oxygen in the air from reaching the soil bacteria. The bacteria then switch to using nitrate to breathe and release nitrous oxide in the process.

For the natural gas routes, when upstream methane leaks are assumed to be 1%, the emissions increase is small at 0.2 tCO_2eq/tN. Throughout this analysis, electricity is assumed to be zero-carbon.

The incumbent method of ammonium nitrate production is the most emissions-intensive, at 9.5 tCO_2eq/tN, while current urea is 7.5 tCO_2eq/tN. These are plant-to-field figures for natural-gas-based production.

For ammonium nitrate, around 4.5 tCO_2eq/tN arises at the plant, with the remainder from field nitrous oxide and liming; for urea, plant emissions are only ~1 tCO_2eq/tN, as its process CO_2 is carried out in the product and released in the field. Production emissions can also vary widely. In Europe, plants with nitrous oxide abatement report around 3.6-3.8 tCO_2eq/tN for ammonium nitrate [64], while coal-based production, still common in China, is substantially higher. Almost all of this difference is due to the unwanted nitrous oxide byproduct from nitric acid manufacturing.

As mentioned previously, since green urea requires a carbon source, and this is difficult without costly direct air capture or biogenic CO_2, decarbonization may favor a shift toward nitrate fertilizers [5]. However, this shift will be difficult, as urea is the cheapest and most widely traded nitrogen fertilizer and is embedded in current farming practice. If such a shift does occur, guardrails should be put in place to ensure that it deploys the abatement technology already standard in Europe, where best-available plants emit around 0.5 tCO_2eq/tN against 7-11 tCO_2eq/tN unabated. The technology is mature, and ensuring new capacity worldwide is built to that standard is among the cheapest emissions reductions available in the sector.

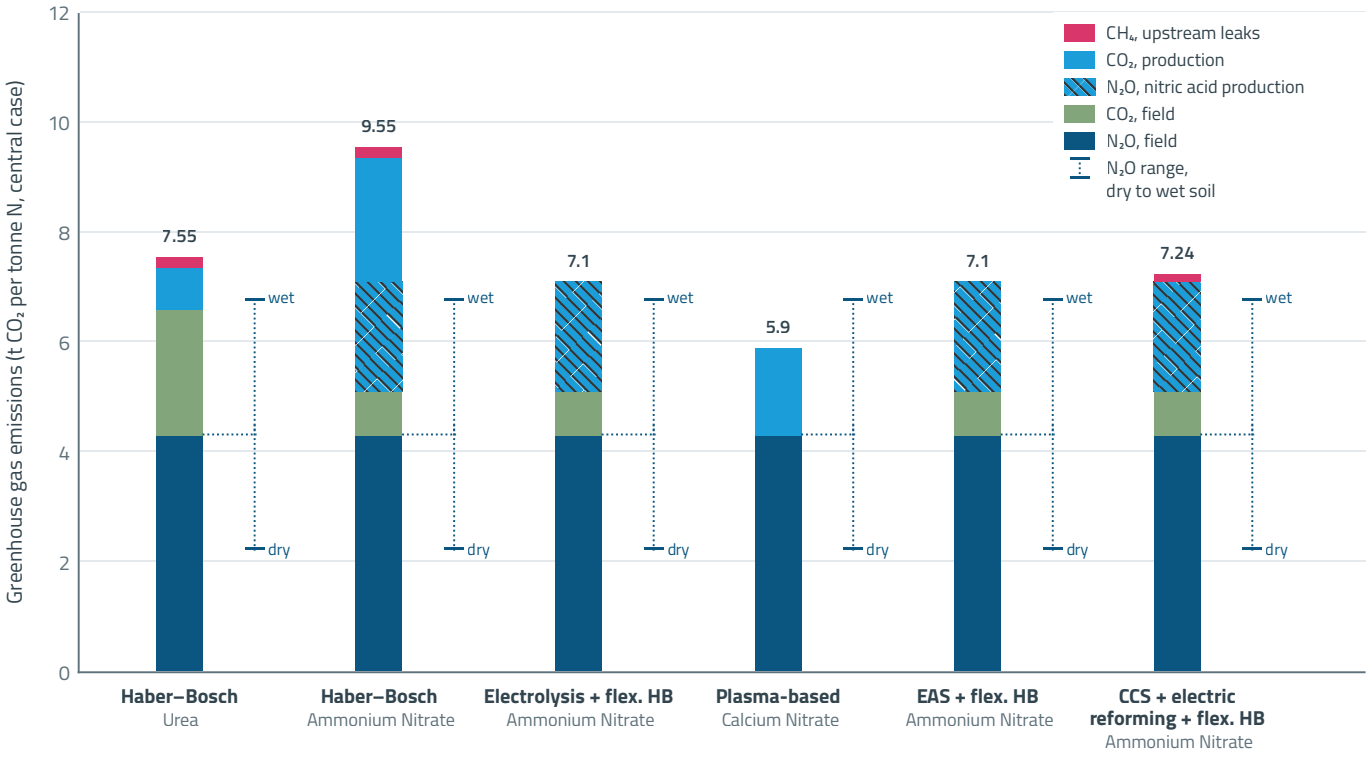


Figure 18: Comparison of emissions. References are listed in the captions of Figure 9 to Figure 15.

Precision Application to Reduce Field Emissions

Box 4

Field nitrous oxide is the largest emission for every route, and is driven by nitrogen that is not taken up by the crop. Specifically matching nitrogen supply to crop demand can reduce this surplus (e.g. the "4R" principle of right source, rate, time and place [5]). Practical measures include smaller and more frequent applications timed to align with crop growth, variable-rate application guided by sensors measuring local soil conditions, and placement of fertilizer below the soil surface. So-called nitrification and urease inhibitors can also cut direct N_2O by around half and ammonia volatilization by around 70% [5]. These measures reduce emissions mainly by lowering the nitrogen required per tonne of crop, rather than per tonne of nitrogen applied. Pairing the specific fertilizer product with method of application is also very important. For instance, the benefit of readily available nitrate fertilizers such as calcium nitrate is greatest when applications are precisely timed.

6.4 Cost and Flexibility

Figure 19 shows the levelized cost of nitrogen for plasma and renewable hydrogen production facilities located in Germany (top row) and south-central Sweden (bottom row). The left subplots show how the levelized cost varies with the fraction of the year that the plant operates. Hours are ranked from cheapest to most expensive, so moving from left to right represents operating over a progressively larger share of the year, at a progressively higher average wholesale electricity price (red line). The shaded band is the current European market price of nitrogen fertilizer. Points on the curves mark the cost-optimal operating point, where the saving from cheaper electricity is offset by the capital cost being spread across less output. Note, each route is drawn twice. The dark curves are the cost if it were built today, and the light curves are with grid costs removed and lower CAPEX due to plant build-out and learning. The right subplots show the same comparison but separate the cost components in more detail.

These are the dominating factors which shape the curve: running for more hours in the year allows the capital expenditure to be spread over more hours and thus units of production; however, operating for more hours means that the cost of energy increases. The minimum occurs at the balance between these. Since cost is approximately energy intensity multiplied by energy price, the more energy-intensive a route, the more it gains from flexible, selective operation. High energy intensity is therefore not disqualifying, provided the electricity is cheap enough. Where a curve is flat around its optimum, the plant can operate across a wide range of hours without significant cost penalties, allowing it to follow grid conditions rather than a fixed schedule.

The scope for improvement differs between the routes. In Germany, once grid costs are removed, the plasma-based levelized cost falls from 3,800 €/tN to 1,250 €/tN between the current and future cases, a reduction of two-thirds. The electrolytic Haber-Bosch route experiences a reduction of one-fifth due to the extensive learning which has occurred in the past century. This occurs because in the renewable hydrogen route only the electrolyzer improves, while the Haber-Bosch loop, air separation unit and Ostwald plant downstream are mature technologies that will not change substantially. Note, changes will occur, but these will be limited to flexible operation and similar improvements. In the plasma route the reactor is essentially the whole plant, so gains directly affect the entire cost basis.

The two locations differ in both price level and price variability. Swedish wholesale prices are roughly half the German level. This lowers costs for all routes. Current electrolytic Haber-Bosch already sits inside the market band and future plasma also reaches it, whereas in Germany both future cases remain above it. German prices are also more variable, reflecting a larger share of variable renewable generation. This widens the gap between the cheapest hours and the annual average, pushing the cost-optimal operating point to fewer hours. Plasma optimizes at 35% of the year in Germany against 62% in Sweden (3,100 and 5,400 hours, respectively). Greater variability therefore rewards flexibility more but does so by requiring the plant to stand idle for longer, worsening capital recovery. Sweden's advantage comes from cheaper power overall rather than from the flexibility.

Grid costs are the largest single component in Germany. Network charges, levies and tax add around 71 €/MWh there, against roughly 17 €/MWh for Swedish industry. For a German plasma plant this corresponds to about 3,100 €/tN. Because the charge is "volumetric", it scales with energy intensity, so plasma carries over three times the burden of the hydrogen route. This means that on current charges neither German route reaches the market band, while in Sweden both do. A flat per-MWh charge shifts the curve upward without moving the optimum, whereas capacity-based charges behave like capital cost and push plants toward baseload, penalizing the flexibility the system needs. A fertilizer plant supplied by on-site renewables can avoid many of these charges. However, on-site generation and batteries carry their own capital cost, so even if they allow access to lower-price hours (OPEX) there is a trade-off (this is beyond the scope of this report).

Note that several limitations apply to this methodology. The analysis covers only two bidding zones in 2025, whereas wholesale prices and their distribution change from year to year. Levelized cost also omits financing terms, project risk and the differing value of the products made. Despite this, one conclusion is clear: all of the low-emission production methods require a significant amount of electricity, and reducing the delivered cost of that electricity (wholesale plus fees) should be one of the main goals.



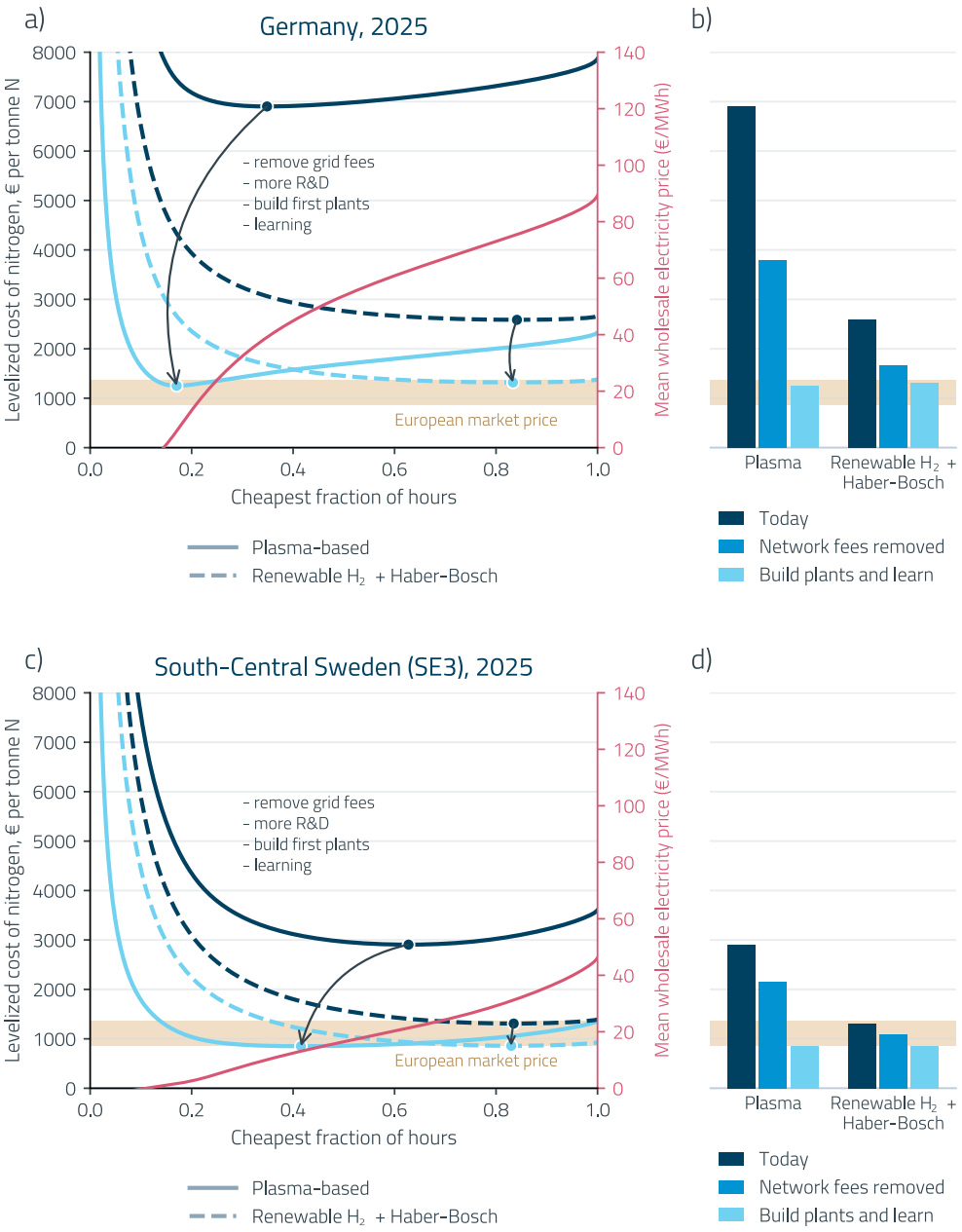


Figure 19: Levelized cost analysis for Germany and south-central Sweden. (a) and (c): levelized cost against the share of the year operated. (b) and (d): cost components of each route as built today and with fees removed and CAPEX learning. Current case: plasma reactor at 900 €/kW and 155 GJ/tN and electrolyzer at 1,000 €/kW and 42.5 GJ/tN. Future case: plasma reactor at 100 €/kW and 77.5 GJ/tN and electrolyzer at 300 €/kW and 33.3 GJ/tN [47], [52]. Grid costs of 71 €/MWh in Germany and 17 €/MWh in Sweden [65]. Wholesale prices from [66].



7. Policy Recommendations and Conclusions

The previous chapters, in particular the comparison of incumbent and low-emission production methods in Chapter 6, showed that low-emission technologies can become an economically viable alternative to incumbent natural-gas-based production. Three technologies stand out: renewable hydrogen with upgraded Haber-Bosch, the plasma-based route, and electrochemical ammonia synthesis (EAS). Each brings its own strengths, but all share one dependency. They rely on low-cost, abundant, and clean electricity as a key input to compete economically with the incumbent method. The main difference between them is technological maturity, which shapes their available cash flow and funding requirements.

Figure 20 shows where each of the three technologies stands across four development phases: research, pilot and demonstration, first-of-a-kind (FOAK), and mass roll-out. EAS, currently at TRL 3-4, is in the research phase and relies on public funding to reach the maturity required for pilot and demonstration plants. Plasma-based innovators are one phase further, moving from pilot and demonstration units to their first FOAK plants. This transition is held back by a lack of financing for the capital expenditure (CAPEX) these plants require. CAPEX support is therefore essential to bridge this funding gap, often called the "valley of death" because many companies fail before reaching the next stage. Finally, renewable hydrogen with Haber-Bosch has already passed this stage. The technology is mature and ready for large-scale commercialization. For mass roll-out, it mainly needs operational expenditure (OPEX) support, above all related to the access to affordable, clean, and reliable electricity, which is the underlying enabler for all three technologies.

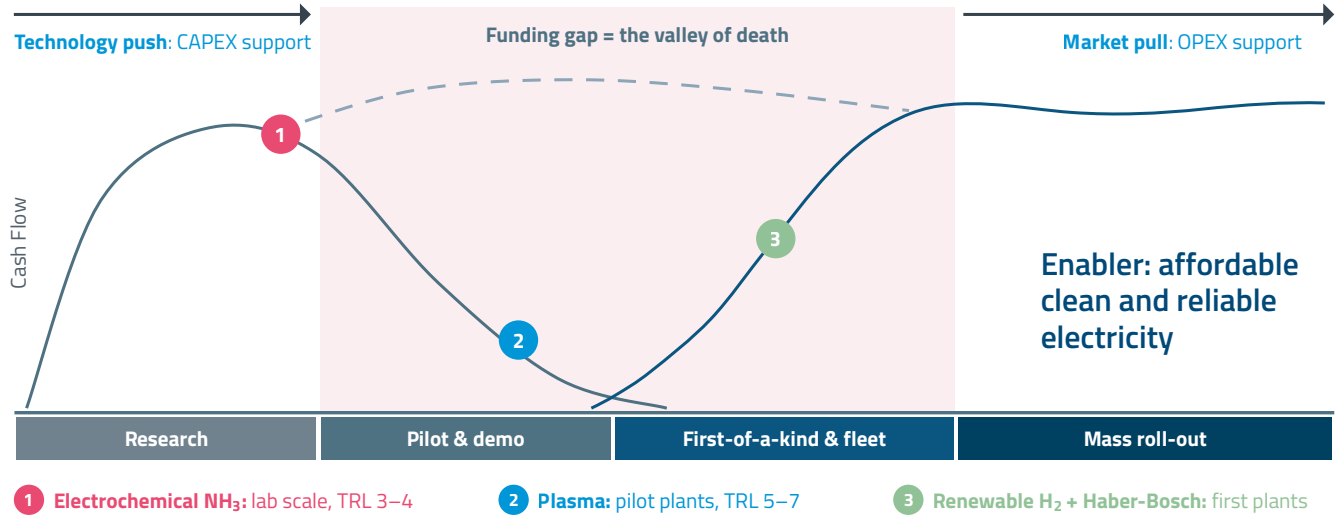


Figure 20: Development phase, technology readiness level (TRL) and funding needs of the three low-emission technologies. Source: FCA.

However, technologies do not evolve in a vacuum. They are shaped by market forces and by the financial and regulatory environment around them. Which pathways materialize at scale, how quickly, and at what production volumes will depend on more than technical feasibility. Market push and pull signals, together with policy at every stage of the supply chain, determine demand volumes, where capital flows, which feedstocks are prioritized, and whether EU domestic production can compete with imports.

Crucially, the three technologies are complementary rather than competing, and all depend strongly on electricity prices. Cultivating an ecosystem for all three enables Europe to pursue the overarching goal of building a resilient, innovative and affordable fertilizer value chain that is independent of natural gas as feedstock.

The following high-level recommendations set out EU policy directions to accelerate the development and scale-up of all three technologies:

1. The overarching goal: Build a resilient, innovative, and affordable fertilizer value chain

The EU should build a diversified, resilient, domestic production base for nitrogen fertilizers by accelerating the development, demonstration, and commercialization of multiple low-emission nitrogen production pathways. Such a system would:

- Reduce exposure to geopolitical shocks by diversifying feedstocks and energy sources, reducing reliance on imported fossil fuels and limiting EU vulnerability to disruption in international gas markets and fertilizer supply chains.
- Improve price stability and affordability by decoupling fertilizer production costs from natural gas prices and enabling the development of alternative production pathways with competitive long-term costs.
- Scale up low-emission production routes in Europe such as renewable hydrogen with upgraded Haber-Bosch, plasma-based nitrogen, and electrochemical ammonia synthesis.

2. The underlying factor: Accelerate the build-out of and access to affordable, clean, and reliable electricity

This means securing low-cost, low-carbon power at scale and enabling flexible operation of electrified fertilizer plants. All major low-emission production routes are electricity-intensive, so the cost of electricity is a central determinant of competitiveness. Policy can lower electricity costs and improve access by:

- Building out renewable generation and storage.

- Expanding and optimizing grids and fast-tracking connections for first-of-a-kind plants.
- Reducing non-energy charges such as grid fees and levies, including for plants co-located with renewable hydrogen and/or electricity generation.

3. The technology push: Provide CAPEX support for innovative low-emission nitrogen fertilizer production

Innovative nitrogen production pathways face different financing barriers depending on their technological maturity. This matters most for the EAS and plasma-based routes. EAS needs support to build pilot and demonstration plants, while plasma-based routes need capital for first-of-a-kind (FOAK) plants to demonstrate technical and commercial viability. EU policy should tailor funding to these distinct needs by:

- Strengthening EU-level funding for research, pilot and demonstration phases for EAS and plasma-based routes (e.g., Horizon Europe, European Innovation Council).
- Mobilizing capital for a first wave of industrial plasma-based FOAK plants through EU-level industrial financing instruments (e.g., Innovation Fund, Industrial Decarbonization Bank), with support linked to clearly defined technical and deployment milestones.
- Enabling regional FOAK deployment of decentralized plasma units through farmer–agricultural cooperative–innovator/technology developer partnerships.
- Funding independent field trials to validate product performance and build farmers' confidence and facilitate market uptake.

4. The market pull: Provide OPEX support and create demand for low-emission nitrogen fertilizer

In the short to medium term, low-emission fertilizers are likely to remain more expensive than their natural-gas-based alternatives. Demand-side measures and lead markets are therefore essential to help reduce investment risks and help early projects reach commercial scale. Policy can close this cost gap by:

- Introducing product carbon footprint (PCF) targets in fertilizer end markets, supported by a harmonized methodology for verifying emissions across production pathways.
- Fixing prices and volumes upfront through advance market commitments and long-term offtake agreements between producers and downstream buyers, for revenue visibility.
- Topping up revenues to a strike price through contracts for difference.

5. The system perspective: Take a system-level view of nitrogen fertilizers

The fertilizer supply chain, from production through to consumption, is a far-reaching system of global importance. As Chapter 2 showed, this interconnectedness calls for an approach that pulls several levers at once. Policy can enable this by:

- Assessing the potential of each of the four levers, from low-emission nitrogen fertilizer production and better nutrient management to lower biomass demand and nutrient recovery.
- Establishing cross-cutting enablers, such as shared data, nitrogen accounting and integrated supply chain partnerships from energy providers, fertilizer producers, farmers, food retailers to public infrastructure services.
- Sequencing and coordinating the levers so that they reinforce each other.

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