

## Decarbonizing Ammonia and Nitrogen Fertilizers with Clean Hydrogen

**The bottom line.** Synthetic fertilizers are essential to sustaining the world's population, but their production is responsible for 1.8–2.4 percent of global greenhouse gas emissions. Clean hydrogen holds growing potential (amid falling costs) to decarbonize fertilizer production. Hydrogen is used to produce synthetic ammonia, a building block of most fertilizers. With the fertilizer market as a reliable offtaker, this shift could support the expansion of clean hydrogen overall even as it boosts global food security. But this transition may require adjustments, including changes in fertilizer types, and modifications to existing subsidy schemes.

### What is the best way to decarbonize fertilizer production?

*By replacing fossil fuels with clean sources of hydrogen in the synthesis of ammonia*

The fertilizer industry plays a crucial role in global agriculture, ensuring food security for billions by enhancing crop yields and soil fertility. However, traditional fertilizer production is energy-intensive and relies on fossil fuels, particularly natural gas, leading to substantial greenhouse gas emissions. By replacing fossil fuels with clean hydrogen sources, the carbon intensity of fertilizer production can be reduced, thereby advancing global climate change goals, such as those set by the Paris Agreement, aiming to limit global warming to well below 2°C.

The production of fertilizer ingredients such as urea, ammonium nitrates, and ammonium phosphates requires ammonia, over 85 percent of whose production is specifically for fertilizers. Fertilizer production can thus be made greener by decarbonizing ammonia synthesis using clean hydrogen.

Clean hydrogen can be generated using renewable power or produced from so-called low-carbon hydrogen, which itself is produced from fossil fuels combined with carbon capture and storage (CCS). Beyond shrinking the carbon footprint of fertilizer production, clean hydrogen can drive innovation and economic growth, create market opportunities, and make the agricultural supply chain more resilient.

Renewable hydrogen is produced using renewable electricity sources like solar and wind (see examples in figure 1). This hydrogen is then combined with nitrogen, obtained from an electrically powered air separation process, to synthesize ammonia using the Haber-Bosch process. Ammonia production in most Haber-Bosch plants releases significant GHG emissions since natural gas is used as a feedstock to

This Live Wire was prepared by the Energy Sector Management Assistance Program at the World Bank in support of the Hydrogen for Development Partnership. H4D consists of nearly 50 partner organizations around the world. It assists countries that have included low-emissions hydrogen in their long-term decarbonization strategies.

Preparation of the Live Wire was coordinated by Rafael Ben, an energy specialist at ESMAP, and Dolf Gielen, ESMAP's hydrogen lead.

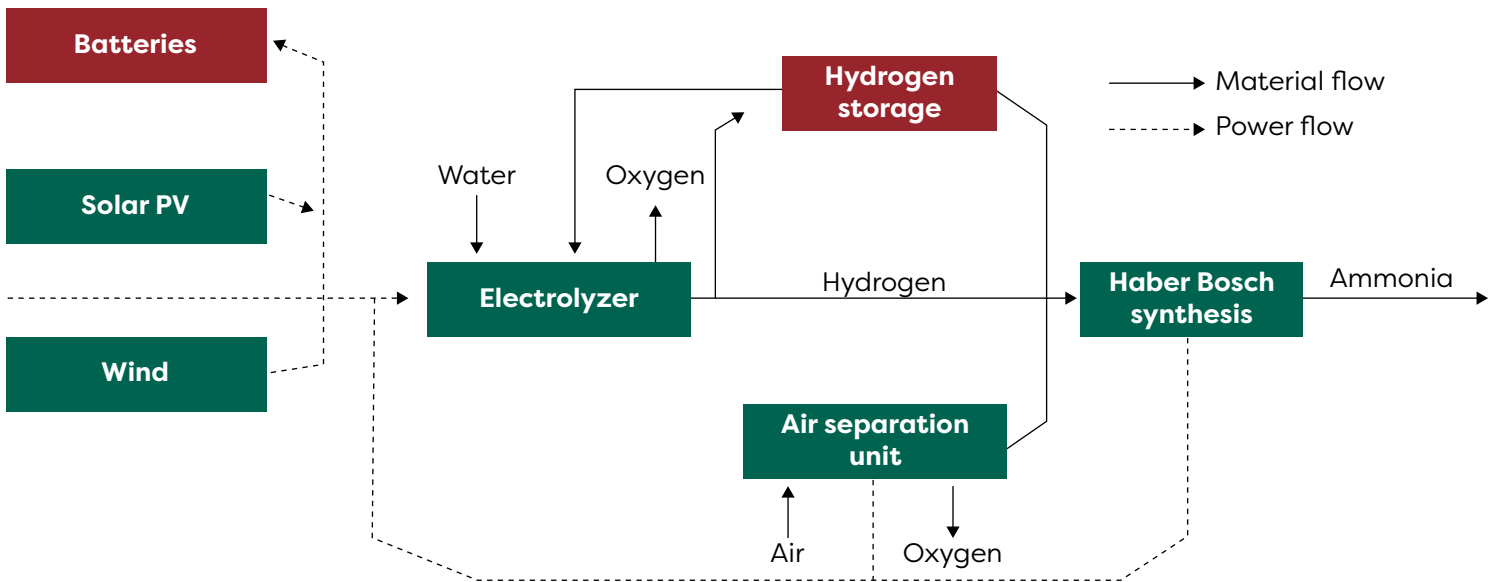


THE WORLD BANK  
IBRD • IDA



ESMAP  
Energy Sector Management  
Assistance Program

**Figure 1. Basic concepts underlying renewable ammonia production**



Note: Energy storage and backup power are shown in red. These are required in the absence of a grid connection or access to so-called baseload renewables—consistent, reliable energy sources like geothermal or hydropower that provide a continuous supply of electricity. PV = photovoltaic.

produce hydrogen. Parts of the production process are driven with steam produced as a by-product of the exothermic (heat-releasing) ammonia synthesis reaction. But renewable ammonia plants will rely minimally on fossil fuels and emit significantly less because renewable hydrogen will replace hydrogen derived from natural gas reforming. Also, renewables-based electricity will replace steam, even though it will still be produced in the ammonia synthesis reaction (MacFarlane et al. 2020).

A major challenge in renewable ammonia production is the flexibility of the Haber-Bosch process to match the variability of renewable energy sources. Ideally, plants' operation would be fully dynamic, matching fluctuations in resource variability through real-time adjustments. But such full flexibility is generally not feasible due to the high temperatures and pressures involved. Nevertheless, recent efforts, particularly by Danish researchers and companies, are showcasing advancements in this area. For example, partial flexibility allows plants to operate at a fraction of their design rate. The degree of flexibility possible varies depending on the equipment design and manufacturer. An innovation of this

kind is a promising step toward integrating ammonia synthesis with variable renewable energy sources (Boyles 2023; Rouwenhorst 2023a).

Renewable ammonia production therefore requires:

- ✓ A stable renewable power source such as hydro, or a combination of variable renewable sources, such as solar and wind;
- ✓ A connection to a low-carbon electricity grid, although this may not be practical during periods of peak demand; or
- ✓ On-site energy storage, from hydrogen storage or pipeline delivery of hydrogen, or a combination of the two.

These requirements could drive up costs, given the high costs of stable renewables and hydrogen storage. But partial flexibility is a significant technological advance, the alternative being to provide a fixed, constant flow of hydrogen at very high costs, as in the steel industry (Aagaard et al. 2023).

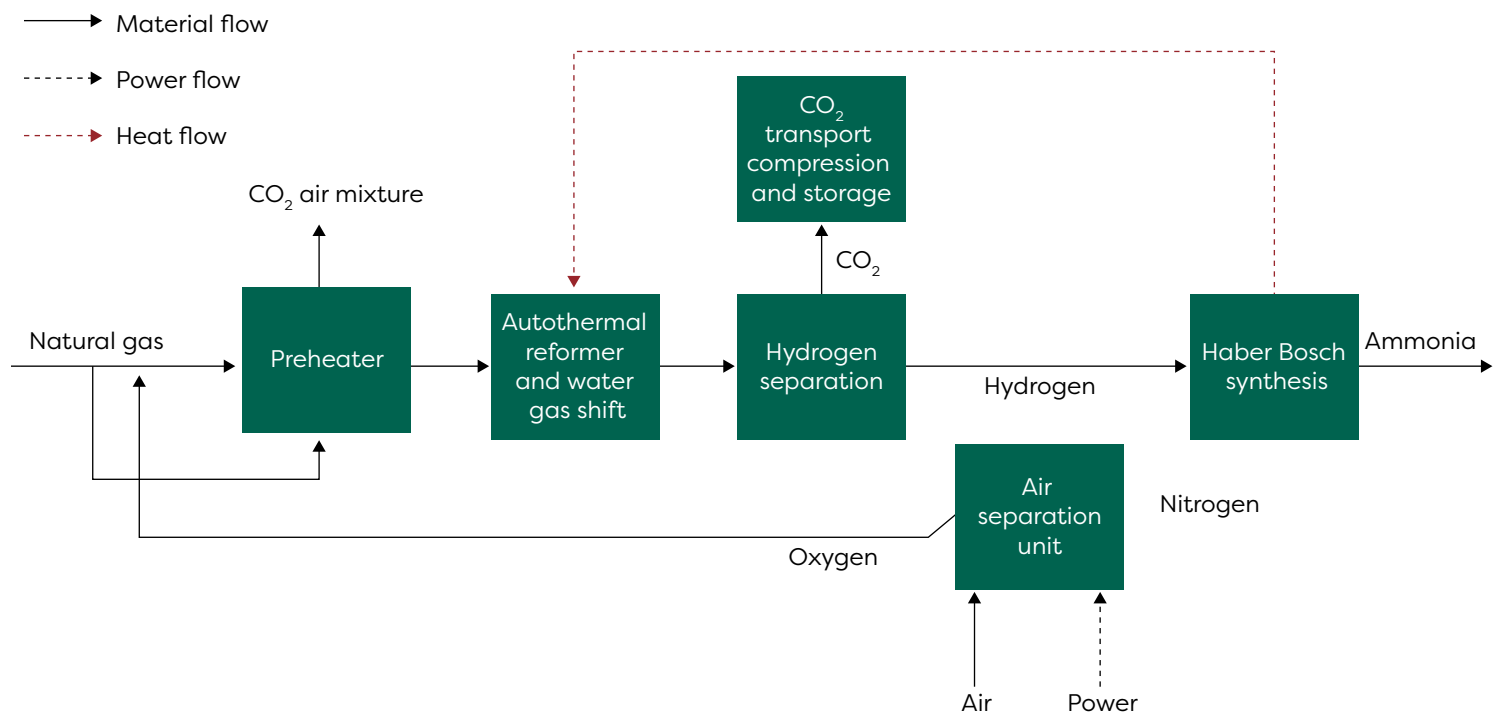
Uncertainty around equipment costs, especially for new technologies like electrolyzers, makes it hard to predict the costs of renewable ammonia. Current estimates are \$794–\$1,543 per ton—significantly higher than the cost of grey ammonia, \$121–\$518 per ton, depending on natural gas prices (Boyles 2023; Aagaard and others 2023). Efforts are being made to reduce costs through government subsidies and improved production technologies, with expectations of a significant cost decline by 2050 (Fasihi and others 2020), supported by the falling costs of renewable hydrogen. Moving toward renewable ammonia can prevent assets from becoming stranded; it is also a useful option for short-term emission reductions and for developing operator skills and practices.

For low-carbon ammonia, hydrogen is still produced most commonly from natural gas via steam methane reforming (SMR) with CCS. However, a newer alternative process, autothermal reforming (ATR), could make low-carbon hydrogen, and thus low-carbon ammonia, less costly by improving

carbon capture efficiency. Approximately two-thirds of carbon emissions can be captured relatively easily in SMR, but the remaining third is more challenging and costly to capture. By contrast, up to 99 percent of emissions can be captured in ATR, which is potentially more economical and environmentally friendly for low-carbon hydrogen production (Salmon and Bañares-Alcántara 2021a and 2021b).

The higher capture rate in ATR is achievable because partial oxidation and steam reforming are integrated, and, thus, external heating, which produces low-concentration flue gases, as in SMR, is not needed. But ATR uses more energy than SMR, even though it offers ease of capture and has added operational flexibility since a wider range of hydrocarbon feedstocks can be used. These advantages make ATR a promising alternative to SMR for low-carbon hydrogen and ammonia production. The process of low-carbon ammonia production is summarized in figure 2.

**Figure 2. Low-carbon ammonia production using autothermal reforming**



Note: Depending on the level of heat integration, the preheater may not be required. CO<sub>2</sub> = carbon dioxide.

ATR partially oxidizes the natural gas feed. This partial oxidation means that the heat requirement for natural gas cracking is mostly delivered inside the reactor, and only a small amount of natural gas combustion is required outside it to produce low-carbon hydrogen. Delivering heat inside the reactor in a controlled environment ensures that the waste stream is nearly pure carbon dioxide (CO<sub>2</sub>), which then becomes easier (and cheaper) to sequester because no separation is needed. For ammonia production, integrating heat with the energy produced by the Haber-Bosch synthesis reactor could further reduce or even eliminate the natural gas combustion required by the preheater (which produces CO<sub>2</sub> that is considerably more difficult to sequester).

The capture of concentrated CO<sub>2</sub> streams is already quite common in the ammonia industry, regardless of the hydrogen production process, SMR or ATR. But this cannot be considered a carbon abatement approach, since the carbon reacts with ammonia to produce urea for agricultural use, and the carbon in the urea will be quickly released into the atmosphere.<sup>1</sup>

### “High-quality renewable energy enables lower-cost ammonia production by lowering electricity costs.”

Because using urea emits carbon, agriculture will need help switching from urea, which is simple to apply, because it is solid, to other low- or no-carbon fertilizers that can be produced from ammonia alone, often in the form of ammonium nitrate, or with other inputs, such as ammonium phosphates or calcium ammonium nitrates. Some of these fertilizers

<sup>1</sup> True abatement would require the captured carbon to be stored either geologically or in a mineral deposit where it cannot enter the atmospheric carbon cycle in the short term. Alternatively, the carbon for urea could be extracted from the atmosphere or from biomass (agricultural residues, forestry by-products, dedicated energy, organic waste materials), but the costs of extracting it from the atmosphere are much too high. Direct air capture and biomass with carbon capture and storage, respectively, cost \$125–\$335 and \$40–\$120 per ton of CO<sub>2</sub> (IEA 2020). Moreover, the availability of biomass is much too low given the global scale of fertilizer production.

must be applied as a liquid, which can be more costly and time-consuming to use (Vogl, Åhman, and Nilsson 2018). The transition will require adjusting subsidy regimes to support other forms of fertilizers (Oni and others 2022).

### What role do subsidies play in fertilizer markets—and how is that likely to change?

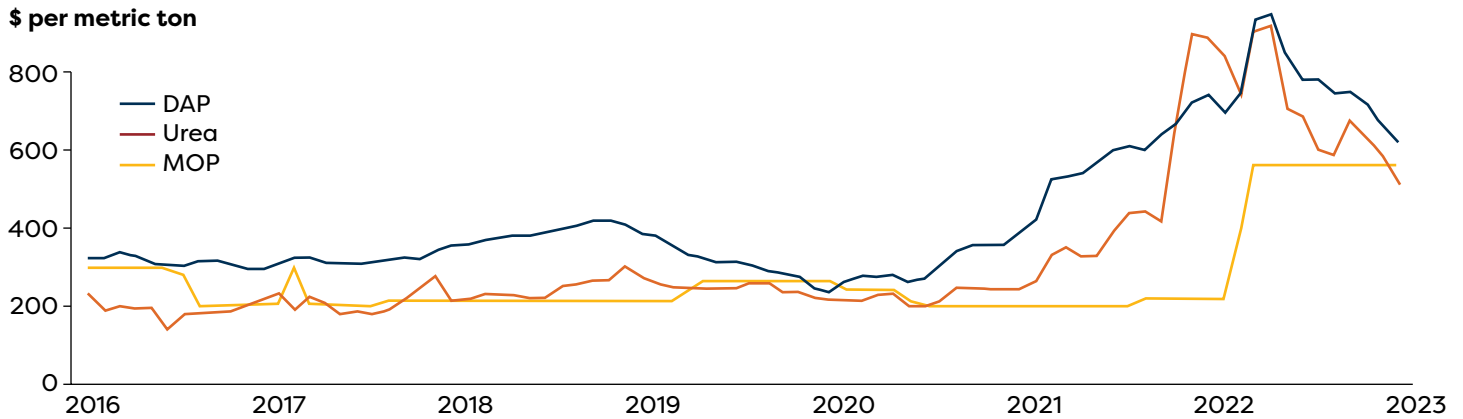
#### *Subsidies interact with natural gas prices and other factors to shape prices, supply chains, and choices of fertilizers*

About 200 million metric tons (MMT) of ammonia are produced globally per year, of which 170–180 MMT go into agricultural fertilizers. The remaining 20 MMT are used in various industrial applications, including the production of explosives, plastics, and other chemicals. Every year, about 20 MMT of ammonia are shipped globally. Transporting ammonia is feasible as well as cost-effective—and important to sustain its global supply chain—given the similarity of its properties with liquified petroleum gas.

Fertilizer types vary by region. Direct application of ammonia is common in the United States, urea is common in India, and nitrate is predominant in Europe. While renewable hydrogen will make the production of renewable ammonia affordable in the medium to long term, producing derivatives like urea remains a challenge.

As noted earlier, the prices of natural gas—a feedstock and energy source in the Haber-Bosch process—primarily drive the cost of ammonia production. The high natural gas prices during the winter of 2022/23 led to the temporary closure of several European ammonia production facilities (Unkovich and others 2020) (figure 3). Price volatility strongly influences the economics of ammonia production, particularly for low-carbon ammonia projects. Given these cost dynamics, the most advanced low-carbon ammonia projects are concentrated in regions where natural gas is affordable, such as the Gulf Coast of the United States.

The quality of renewable energy sources heavily influences the cost of renewable ammonia. High-quality renewable energy enables lower-cost ammonia production by lowering electricity costs. Consistent power production, often achieved by combining wind and solar resources, minimizes

**Figure 3. Fertilizer prices over time, showing a spike coincident with high natural gas prices**

Source: Bloomberg; World Bank.

Note: Last observation is December 2022.

DAP = diammonium phosphate; MOP = muriate of potash.

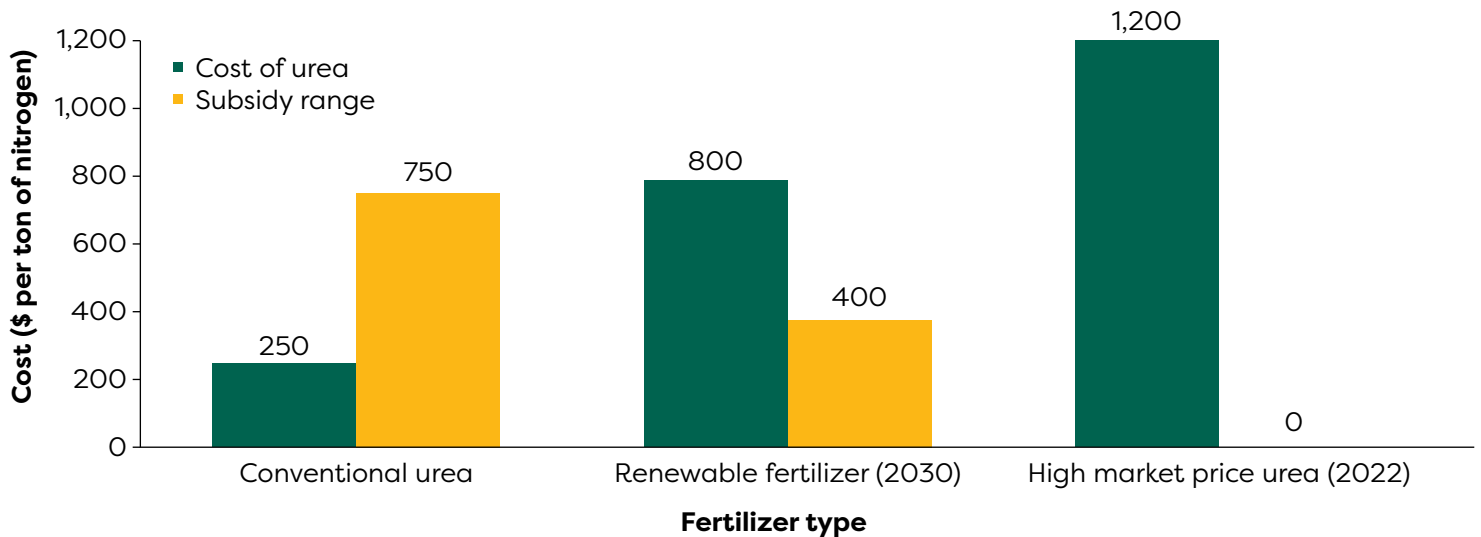
the need for seasonal energy storage. Fertilizer production costs are therefore lowest in countries with favorable renewable energy profiles, making them ideal as fertilizer exporters. Developing countries with limited access to fertilizers thus have a significant opportunity to not only produce and consume fertilizers locally but also export the excess. For instance, fertilizer consumption in Kenya is only a third of the global average per hectare, but the country has a promising profile for the renewable production of fertilizer. Renewable ammonia production in Kenya and other similar economies therefore offers opportunities for both the domestic and export markets (Nayak-Luke and others 2022).

Although ammonia's primary use has historically been as fertilizer, its role is likely to change in a decarbonized economy, for example, as a marine fuel, a long-term energy storage medium, or a hydrogen carrier. This potential for sector coupling may create cost-saving efficiencies but may also introduce competition that could drive up prices in some industries (Terazono, Pickard, and Evans 2022).

While switching to zero-carbon fertilizer production presents a viable opportunity to use clean hydrogen, it is hindered by a low willingness to pay unless production is supported by carbon taxation or government subsidies.

Figure 4 shows the cost structure for different types of fertilizers, using India as an example. The green bars represent the production cost of fertilizers; the yellow bars represent the estimated subsidy to make fertilizers affordable for farmers. Conventional urea benefits from heavy government subsidies, which significantly reduce its costs for farmers. In contrast, the predicted costs for renewable ammonia in 2030 are higher than the lowest-cost conventional urea (but lower than the high market prices observed during price spikes in 2022). This highlights the potential for renewable ammonia to provide price stability and protection against market volatility, though it will still require subsidies to compete with conventional urea.

The figure highlights the significant role of subsidies in determining fertilizer affordability in India. While renewable ammonia will likely require \$500–\$1,200 in subsidies per metric ton to compete with conventional urea in 2030, it is projected to offer price stability. However, widespread adoption of renewable fertilizers may need additional incentives and policy measures such as support for switching from urea to alternative fertilizers. These measures are not considered in the current analysis.

**Figure 4. Role of subsidies in determining fertilizer costs in India**

Source: NEDO 2024.

Note: The green bars represent production costs and the yellow bars indicate the subsidy range required to bridge the gap between market price and subsidized price. Costs are normalized per metric ton of nitrogen to enable a fair comparison across different fertilizer types. The figure illustrates the cost of conventional urea (with subsidies), predicted costs for renewable fertilizers in 2030, and the high market price of urea observed during the 2022 price spikes.

Advancements in solar and electrolysis technology are expected to lower the cost of renewable ammonia, making it a viable, competitive option in agriculture by reducing fertilizer cost. However, careful regulation is necessary to avoid excessive application and the associated environmental risks, such as nitrogen oxides emissions. Strategic government policies can help balance economic gains with environmental protection (Müller et al. 2023).

## What is the status of clean ammonia production?

*Important projects are already operational, and many case studies and pilot projects have begun*

Box 1 highlights a few of the most visible renewable and low-carbon ammonia projects in emerging markets and developing economies.

Renewable ammonia production is making significant progress in India. Major projects are spearheading the green transition in fertilizers. One of the flagship projects is a facility being developed by AM Green in Kakinada, Andhra Pradesh, expected to have a production capacity of 1 MMT

of renewable ammonia annually and projected to begin operations in the second half of 2026. The final investment decision for the project, which represents a major milestone in India's National Green Hydrogen Mission, was reached in August 2024. The project will leverage locally available renewable energy sources to help India achieve decarbonization and rely less on fossil-fuel based ammonia production (NS Energy 2024). The project will provide a low-carbon alternative to conventional, carbon-intensive ammonia production methods. Its renewable hydrogen will be produced using 640 megawatts of advanced pressurized alkaline electrolyzers capable of producing hydrogen from solar and wind energy (supplied to AM Green by John Cockerill under their partnership). This renewable hydrogen will be synthesized into renewable ammonia, which the fertilizer industry can utilize further. This large-scale project underlines India's commitment to sustainable agriculture and positions the country as a leader in global progress toward net zero (Bailey 2024).

Chile has initiated several renewable energy projects that are advancing the production of renewable ammonia for the fertilizer industry. One of the most notable is the HyEx

## Box 1. Selected renewable and low-carbon ammonia projects

Globally, there are many renewable and low-carbon ammonia projects. Most have not announced the intended use of their product, but for many, fertilizers are an offtake case. Table B1.1 offers key statistics of four visible projects.

**Table B1.1 Selected renewable and low-carbon ammonia projects**

Project name	Project owners	Notable for	Approximate ammonia capacity (million metric tons per year)
Australian Renewable Energy Hub	BP, InterContinental Energy, and CWP Global	Scale	9 (Phase 2 of the project)
Neom	Air Products	Reached final investment decision and is under construction	1
Green Energy Oman	Intercontinental Energy, OU, EnerTech, Shell	Scale	10
Fertiberia	Fertiberia	Already operational	0.017

Note: For a comprehensive list of relevant projects, see Argus Media (<https://view.argusmedia.com/nh3-2023.html>).

Project, a collaboration between Enaex and Engie. This project utilizes solar power from northern Chile to produce renewable hydrogen, which is then synthesized into renewable ammonia. The renewable ammonia will be used to produce ammonium nitrate, a vital component in fertilizers and explosives, particularly for the mining sector (Rouwenhorst 2023b). Another such project is the HNH Project in the Magallanes region, involving AustriaEnergy, Ökowind, and Copenhagen Infrastructure Partners. That project is designed to produce approximately 1.35 MMT of renewable ammonia annually using 3.5 gigawatts (GW) of wind power and 3 GW of electrolyzer capacity (Copenhagen Infrastructure Partners 2024). While primarily focused on exports, this renewable ammonia also has potential applications in decarbonizing global fertilizer production.

Morocco's OCP Group-led Tarfaya Green Ammonia Project, a \$7 billion initiative producing renewable ammonia to support sustainable fertilizer production, was in the front-end engineering design phase with Worley as of August 2024. The project will harness Morocco's solar and wind resources

to generate 1 MMT of renewable ammonia annually by 2027, with plans to expand to 3 MMT by 2032 (ESG News 2024). The Tarfaya project, which integrates renewable energy into ammonia production, aligns with Morocco's 2040 carbon neutrality goals. It will help Morocco rely less on fossil fuels and provide a low-carbon input for the fertilizer industry.

Brazil's Rio de Janeiro-based Port of Açú Blue Ammonia Project is advancing the production of low-carbon ammonia, with applications in fertilizers. The \$3 billion initiative, developed in collaboration with Toyo Engineering, will use natural gas with CCS to produce an estimated 1 MMT of low-carbon ammonia annually, for domestic use as well as for export. Located near gas pipelines and fertilizer distribution routes, the project benefits from logistical efficiency and supports Brazil's agricultural and industrial sectors. Future plans include transitioning to renewable ammonia as renewable energy sources become more viable (H2 Bulletin 2024).

Nigeria's Brass Fertilizer and Petrochemical Company project in Bayelsa state is a major low-carbon ammonia initiative

focused on the fertilizer industry. This \$3.5 billion facility, developed in partnership with Shell, TotalEnergies, and Eni, will receive 270 million cubic feet of natural gas daily and integrate CCS technology to lower emissions. The project is expected to produce 1.66 MMT of ammonia annually. It aims to reduce Nigeria's fertilizer imports by 30 percent, saving approximately \$200 million in foreign exchange each year. The project taps into Nigeria's 200 trillion cubic feet of gas reserves, advancing sustainable fertilizer production by utilizing domestic resources and advanced CCS (Eboh 2024).

These case studies from South Asia, Latin America, and Africa illustrate the diverse approaches and significant potential for renewable and low-carbon ammonia production in emerging markets and developing economies. While renewable ammonia projects demonstrate the feasibility and sustainability of utilizing renewable resources, low-carbon ammonia projects leverage existing natural gas infrastructure.

### Are policy and regulatory frameworks conducive?

*In developing countries, policies supporting the use of hydrogen and ammonia in agriculture are gradually evolving to address the need for low-carbon solutions*

To facilitate the transition to clean hydrogen, policy changes must focus on creating an enabling environment that supports investment in clean technologies. Governments should consider implementing robust carbon pricing mechanisms to make renewable hydrogen more competitive relative to conventional fossil fuels. Clear regulations and standards for the production and use of clean hydrogen will help ensure consistency and build investors' confidence.

**“To facilitate the transition to clean hydrogen, policy changes must focus on creating an enabling environment that supports investment in clean technologies.”**

India's National Hydrogen Mission, launched in 2021, targets the production of 5 MMT of renewable hydrogen by 2030; the aim is to decarbonize fertilizer and other industries. Similarly, Brazil's national hydrogen strategy aims to foster a market for clean hydrogen production, despite economic constraints.

Subsidies and incentives will play a critical role in lowering the financial barriers to adopting clean ammonia. Today, conventional fertilizers are heavily subsidized in many countries. For example, India's budget for fertilizer subsidies was \$25.5 billion for the fiscal year 2023–24. A transition to clean ammonia and hydrogen-based fertilizers will require similar or higher levels of subsidies. This could include direct subsidies for renewable hydrogen production, tax incentives for the purchase of hydrogen production equipment, and grants for research and development projects.

However, regulatory hurdles such as bureaucratic delays and lack of infrastructure will have to be addressed. Streamlining regulatory processes and developing infrastructure for hydrogen distribution and storage are critical in supporting the growth of a clean hydrogen economy. Further, international cooperation and financial aid from donor countries can help overcome challenges.

### What are the next steps?

*Takeaways and recommendations for governments and international donor organizations may be grouped into five categories*

- ✓ **Address the price gap through offtake agreements.** The transition to clean hydrogen and fertilizers requires mechanisms to address the price disparity between conventional fertilizers and clean alternatives. Governments and donor organizations should facilitate long-term offtake agreements in which buyers commit to purchasing clean fertilizers at a predetermined price. These agreements reduce the financial risk for producers and signal market stability, thereby encouraging investment in clean production technologies.

✓ **Consider the cost of financing and access to capital.**

Financing remains a significant barrier to the adoption of clean fertilizers. Dedicated green finance instruments, such as low-interest loans or green bonds, can alleviate the up-front capital costs for producers and distributors. International financial institutions and donor organizations should prioritize concessional loans and risk-sharing mechanisms to encourage the private sector to invest in clean ammonia and hydrogen projects.

✓ **Adjust to new nitrogen fertilizers.** Transitioning from urea to alternative nitrogen fertilizers, such as ammonium nitrates or ammonium phosphates, requires significant shifts in agricultural practices. Governments should provide farmer-focused subsidies or incentives to promote the purchase of these otherwise costlier new fertilizers. Also, investment in farmer training and awareness campaigns can help ensure social acceptance and the use of appropriate application methods to maximize benefits.

✓ **Identify and develop niche markets.** Clean fertilizers can command a premium in sustainability-focused markets, such as organic farming or export-oriented agriculture with stringent carbon standards. These niche markets must be identified and developed. Governments and industry stakeholders should collaborate to establish certification schemes and eco-labels that differentiate clean fertilizers so that producers can access higher price points and attract early adopters.

✓ **Leverage consumers' willingness to pay higher prices.** While niche markets offer opportunities, the widespread adoption of clean fertilizers hinges on consumers' and end users' willingness to pay higher prices. Governments and international organizations should invest in public awareness campaigns highlighting the environmental and social benefits of clean fertilizers, such as reduced GHG emissions and improved long-term soil health. These campaigns can help build consumer demand for low-carbon products, despite their higher costs, by highlighting that sustainable practices advance global food security goals.

\* \* \*

**“Decarbonizing fertilizer production is essential for not only environmental sustainability but also greater global food security.”**

Decarbonizing fertilizer production is essential for not only environmental sustainability but also greater global food security. Using clean hydrogen allows the industry to meet the growing demand for fertilizers while significantly reducing its climate impact. Continued commitment and proactive steps to support this transition will ensure a resilient, sustainable agricultural future for emerging markets and developing countries.

Renewables-based hydrogen represents the most sustainable long-term solution, despite the higher production costs and technological challenges. Low-carbon hydrogen, produced from natural gas with CCS, provides a more immediate, cost-effective alternative, albeit with some emissions.

The World Bank sees significant potential for clean hydrogen and ammonia to accelerate the clean energy transition, particularly in countries with substantial renewable energy resources. The Bank's involvement in clean ammonia projects in emerging markets highlights their strategic importance for reducing carbon emissions and promoting sustainable agricultural practices. Such projects can transform energy-intensive industries, enhance food security, and further global climate goals.

The transition to decarbonized hydrogen for fertilizer production presents a transformative opportunity to reduce greenhouse gas emissions while advancing global food security.

## References and additional resources

- Aagaard, P., J. R. Andersen, K. Wedege, T. Nauclér, and P. Prabhala. 2023. "From Green Ammonia to Low-Carbon Foods." McKinsey, December 11, 2023.
- Bailey, M. 2024. "John Cockerill to Supply Electrolyzers for One of the World's Largest Green-Ammonia Complexes." Chemical Engineering, November 5, 2024.
- Boyles, H. 2023. "Climate-Tech to Watch: Green Ammonia." Information Technology & Innovation Foundation, April 17, 2023.
- Copenhagen Infrastructure Partners. 2024. "HNH Project Chile."
- Eboh, C. 2024. "Nigeria Signs Deal to Supply Gas to Proposed \$3.5 Billion Petrochemical Plant." Reuters, October 11, 2024.
- ESG News. 2024. "Worley to Begin Key Phase of \$7 Billion Green Ammonia Project in Morocco." ESG News, August 28, 2024.
- Fasihi, M., R. Weiss, J. Savolainen, and C. Breyer. 2021. "Global Potential of Green Ammonia Based on Hybrid PV-Wind Power Plants." *Applied Energy* 294 (July): 116170.
- H2 Bulletin. 2024. "Prumo and Fuella AS Secured Its First Contract for the Newly Licensed Low-Carbon Hydrogen in Brazil." H2 Bulletin, August 16, 2024.
- IEA (International Energy Agency). 2020. "Current Cost of CO<sub>2</sub> Capture for Carbon Removal Technologies by Sector." IEA, Paris. Last updated September 24, 2020.
- IEA. 2021. *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production*. Paris: IEA.
- IRENA (International Renewable Energy Agency). 2022. *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I: Trade Outlook for 2050 and Way Forward*. Abu Dhabi: IRENA.
- MacFarlane, D. R., P. V. Cherepanov, J. Choi, B. H. R. Suryanto, R. Y. Hodgetts, J. M. Bakker, F. M. Ferrero Vallana, and A. N. Simonov. 2020. "A Roadmap to the Ammonia Economy." *Joule* 4 (6): 1186–205.
- Müller, L. A., A. Leonard, P. A. Trotter, and S. Hirmer. 2023. "Green Hydrogen Production and Use in Low- and Middle-Income Countries: A Least-Cost Geospatial Modelling Approach Applied to Kenya." *Applied Energy* 343 (August): 121219.
- Nayak-Luke, R. M., L. Hatton, Z. Cesaro, and R. Bañares-Alcántara. 2022. "Assessing the Viability of Decarbonising India's Nitrogenous Fertiliser Consumption." *Journal of Cleaner Production* 366 (September): 132462.
- NS Energy. 2024. "AM Green Ammonia Project, Kakinada, India." NS Energy, October 10, 2024.
- Oni, A. O., K. Anaya, T. Giwa, G. Di Lullo, and A. Kumar. 2022. "Comparative Assessment of Blue Hydrogen from Steam Methane Reforming, Autothermal Reforming, and Natural Gas Decomposition Technologies for Natural Gas-Producing Regions." *Energy Conversion and Management* 254 (February): 115245.
- Ritchie, Hannah, and Max Roser. 2024. "Greenhouse Gas Emissions by Sector." Our World in Data.
- Rouwenhorst, K. 2023a. "Flexible Ammonia Synthesis: Shifting the Narrative Around Hydrogen Storage." Ammonia Energy Association, April 27, 2023.
- Rouwenhorst, K. 2023b. "HyEx: Ammonia from the Chilean Desert." Ammonia Energy Association, March 8, 2023.
- Salmon, N., and R. Bañares-Alcántara. 2021a. "Impact of Grid Connectivity on Cost and Location of Green Ammonia Production: Australia as a Case Study." *Energy & Environmental Science* 14 (12): 6655–71.
- Salmon, N., and R. Bañares-Alcántara. 2021b. "Green Ammonia as a Spatial Energy Vector: A Review." *Sustainable Energy & Fuels* 5 (11): 2814–39.
- Terazono, Emiko, Jim Pickard, and Judith Evans. 2022. "UK Meat and Drinks Sectors in Turmoil as CO<sub>2</sub> Production Halted." *Financial Times*, August 25, 2022.

Unkovich, M. J., D. F. Herridge, M. D. Denton, G. K. McDonald, A. M. McNeill, W. Long, R. Farquharson, and B. Malcolm. 2020. *A Nitrogen Reference Manual for the Southern Cropping Region*. Revised edition, August 2020. Kingston, ACT, Australia: Grains Research and Development Corporation (GRDC).

Vogl, V., M. Åhman, and L. J. Nilsson. 2018. "Assessment of Hydrogen Direct Reduction for Fossil-Free Steelmaking." *Journal of Cleaner Production* 203 (December): 736–45.

Wolfram, P., P. Kyle, X. Zhang, S. Gkantonas, and S. Smith. 2022. "Using Ammonia as a Shipping Fuel Could Disturb the Nitrogen Cycle." *Nature Energy* 7 (October): 1112–14.

# Get Connected to liveWire

The *Live Wire* series of online knowledge notes, an initiative of the World Bank Group's Energy and Extractives Global Practice, offers rich insights from project and analytical work done by the World Bank Group.

Every day, Bank Group experts apply their knowledge and expertise to solve practical problems in client countries. *Live Wire* captures the rich insights gained in the field, allowing authors to share their findings with other practitioners, policy makers, and planners.

## **Shouldn't you be connected to Live Wire?**

Since 2014, the 120 briefs in the series have dealt with vital topics such as energy demand and supply; renewable energy; energy efficiency; energy policy; economic growth; environmental protection; climate change mitigation; power systems; rural and urban development; access to energy; infrastructure economics; private sector participation; access to finance; and regulation.

- ✓ **Topic briefs** offer technical knowledge on key energy issues.
- ✓ **Case studies** highlight lessons from experience in implementation, often with insights from private sector engagement.
- ✓ Briefs on **global trends** provide analytical overviews of key energy data and developments.
- ✓ **Bank views** portray the Bank Group's energy and extractives sector activities.

The format is accessible, rigorous, and concise enough to be easily shared. The 6–12 pages of each brief make ample use of graphics. Briefs are peer-reviewed by seasoned practitioners within the World Bank Group and professionally edited and produced. While their main channel of dissemination is online, Live Wires are available in print-ready files for specific client needs.

**“Live Wire is designed for practitioners, policy makers, and planners inside and outside the World Bank Group. It is a resource to share with clients, colleagues, and counterparts.”**

Live Wire briefs are designed for easy reading on the screen and for downloading and self-printing in color or black and white.

**For World Bank Group employees:** Professional printing can be done on a customized basis for meetings and events by contacting GSDPM Customer Service Center at (202) 458-7479, or sending a written request to [cgsdpm@worldbank.org](mailto:cgsdpm@worldbank.org).



Please visit the World Bank Group's Open Knowledge Repository to browse the Live Wire collection and download the issues important to you: [www.worldbank.org/energy/livewire](http://www.worldbank.org/energy/livewire)

