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Agriculture Practice

From green ammonia to lower-carbon foods

A sample consumer basket shows that employing green fertilizer could reduce greenhouse-gas emissions from agricultural end products by about 5 percent.

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Agriculture is one of the primary contributors to greenhouse-gas emissions (GHG) and climate change. Agriculture is responsible for about 24 percent of global emission, making agricultural emissions a major focus of decarbonization efforts. Unless addressed, emissions from agriculture production and land use are likely to grow by 15 to 20 percent by 2050.[1] Limiting the impact of climate change to 1.5°C will be difficult without cutting agricultural emissions substantially.

Reducing GHG emissions fast and effectively may be more challenging for agriculture than for other sectors.[2] While other sectors have a set of technologies through which they can choose to substantially reduce emissions, such options are less available in agriculture, and most known levers could disrupt existing production processes. In this article, however, we focus on one decarbonization lever that has great potential: replacing fossil-fuel-based ammonia (so-called gray ammonia) with green ammonia for fertilizer production. Fertilizer is the main application of ammonia; about 70 percent of global ammonia is used in its production.

Ammonia production from fossil fuels is a sizable emissions contributor because the conventional gray ammonia production process generates carbon dioxide as a byproduct. Between 1.9 and 2.6 metric tons (t) of carbon dioxide are generated for every t of ammonia produced.[3] In 2020, global ammonia production accounted for about 450 million metric tons (Mt) of carbon dioxide emissions—about 1.2 percent of global emissions—which is about 37 metric gigatons (Gt) of CO_2 equivalents. In comparison, crop and livestock rearing generate about 5.3 $GtCO_2$ per year.[4] Eliminating those emissions would contribute substantially to GHG reduction, equivalent in size to 1.5 times France's fossil-fuel emissions, or two-thirds that of international shipping (about 700 $MtCO_2$ in 2021).[5]

The good news is that ammonia production can be almost fully decarbonized by switching to green ammonia. To understand this potential impact for producers and consumers of food products, we analyzed ten agricultural end products that may be in a typical consumer basket in Europe. We found that changing the production method from gray to green ammonia can reduce carbon emissions by an average of 5 percent, which is a substantial share of the emissions that are addressable in food products. Green ammonia is a direct replacement for gray ammonia, and the technology to realize these reductions is available today. But making the switch financially attractive will require most actors in the food industry value chain, from fertilizer producers to consumer goods companies, to increase collaboration, adjust buying models, and rethink pricing and premium distribution.

Importantly, transitioning to green ammonia and fertilizer is only one step in reducing agriculture's GHG emissions. It will require actions beyond the farm and throughout the agriculture value chain, making this an "all hands on deck" moment for the industry to transform and move in parallel on a range of decarbonization efforts.[6]

Potential impact of green ammonia in food products

Agricultural-product value chains and their associated emission footprints are complicated, especially given the distributed nature of the

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1. Robbie Andrew et al., "A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018," *Environmental Research Letters,* June 2021, Volume 16, Number 7; Food and Agriculture Oganization, 2022; Robbie M. Andrew et al., "Global carbon budget 2020," *Earth System Science Data,* December 2020, Volume 12, Number 4; Climate Watch; Sustainability Insights EMIT database; Nico Bauer et al., *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA,* Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2019.
2. "Reducing agriculture emissions through improved farming practices," McKinsey, May 6, 2020.
3. Amgad Elgowainya, Xinyu Liu, and Michael Wanga, "Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products," *Green Chemistry,* 2020, Number 17; Bianca Lehmann, "Energy efficiency improvements in ammonia production—perspectives and uncertainties," *Energy,* October 2005, Volume 30, Number 13.
4. "Ammonia technology roadmap: Towards more sustainable nitrogen fertilizer production," International Energy Agency, October 2021; *Emissions due to agriculture: Global, regional and country trends 2000–2018,* Food and Agriculture Organization, 2020.
5. *CO_2 emissions of all world countries,* Emissions Database for Global Atmospheric Research, 2022.
6. "The agricultural transition: Building a sustainable future," McKinsey, June 27, 2023.

sector, including about 570 million farms globally (most of the world's farms are small and family-run, but 16 percent are larger than two hectares, representing 88 percent of the world's farmland).[7] An agricultural product has many potential sources of GHG emissions, such as fertilizer and other input chemicals production, on-farm equipment usage, feed production for livestock, enteric fermentation, transportation, industrial processing, and packaging. Exhibit 1 shows the distribution of emissions along the value chain for a package of potatoes. Ammonia production is found at the start of the value chain; in this example, it accounts for about 6 percent of the total emissions associated with the product.

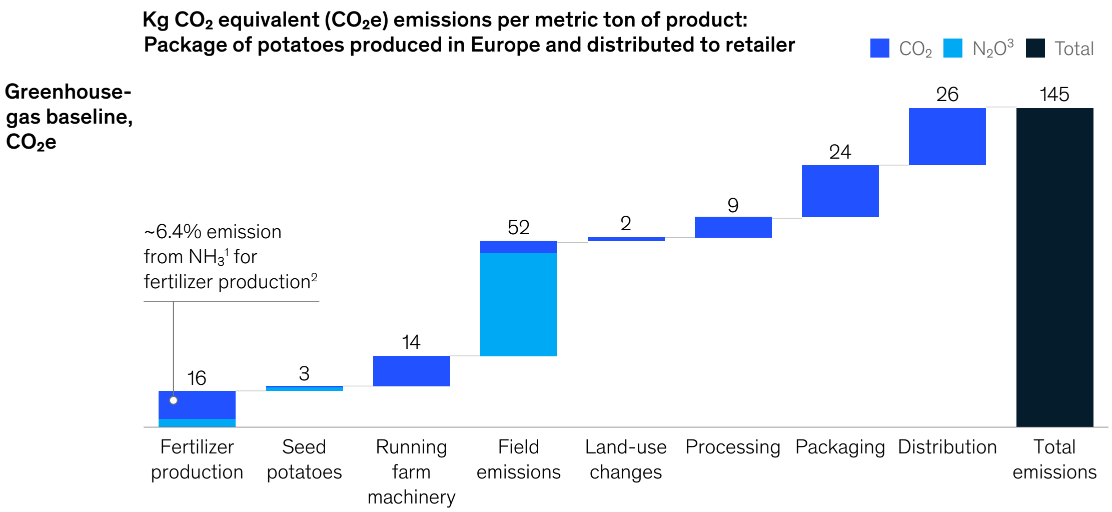
But a change in the production process can make ammonia virtually free of carbon dioxide. Renewable power, for example, can be used in electrolysis to create green hydrogen. In turn, the Haber-Bosch process converts hydrogen and nitrogen into ammonia (Exhibit 2).

[7] Our World in Data; Sarah K. Lowder, Jakob Skoet, and Terri Raney, "The number, size, and distribution of farms, smallholder farms, and family farms worldwide," *World Development,* November 2016, Volume 87.

Exhibit 1

Ammonia production contributes to greenhouse-gas emissions for a package of potatoes in the early stages of the value chain.

Value chain	**Agriculture input** →	**Agriculture production** →	**Processing** →	**Transport**
Description	Producing fertilizers, seed potatoes, and capital goods for agricultural production	Producing potatoes on farm using agricultural inputs	Storing potatoes in a cool environment and packaging them	Transporting packaged potatoes to retailer



Note: Figures do not sum to total, because of rounding.
[1]Ammonia.
[2]Relative emissions from fertilizer production is 11.1%, of which 58.0% is due to ammonia production.
[3]Nitrous oxide.

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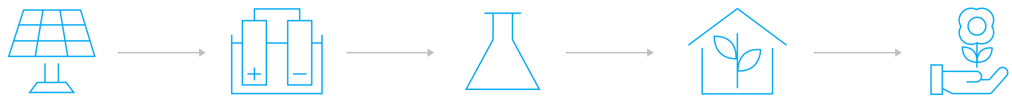
Exhibit 2

Electrolysis powered by renewables can create green hydrogen, with green ammonia and fertilizer to follow.



Renewable energy
Wind, solar, and hydro power

H_2 from electrolysis
Renewable power is converted to H_2 through water electrolysis

Green ammonia (NH_3)[1]
Hydrogen and nitrogen from the air are converted to NH_3 through synthesis using a Haber-Bosch loop powered by sustainable electricity

Agricultural fertilizer production
Including production of nitrates, DAP,[2] and MAP[3]

Application to crops or fertilizer blends

[1]About 0 metric tons of CO_2 are produced per metric ton of ammonia produced.
[2]Diammonium phosphate.
[3]Monoammonium phosphate.
Source: McKinsey Hydrogen Insights

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Replacing gray ammonia with green ammonia has big implications for the chemical industry involved in ammonia production. Green-hydrogen and green-ammonia projects are being announced worldwide, spurred by favorable governmental policies and climate commitments. In fact, more than 1,000 hydrogen projects larger than one megawatt have been announced, of which more than 400 are for large-scale industrial use, including ammonia production.[8]

Several fertilizer producers are starting to experiment with lower carbon production, targeting 20 percent to 50 percent reductions in their Scope 1 and 2 GHG emissions and moving toward fossil-free fertilizers. A recent example is the fertilizer producer Yara and Swedish agricultural cooperative Lantmännen, which have signed a world-first commercial agreement to produce green fertilizer.[9] In Denmark, an industry consortium of the country's four largest agricultural companies are exploring whether more sustainable fertilizer can be produced in Denmark. In the US state of Iowa, Greenfield Nitrogen, a green-hydrogen and green-ammonia company, is developing a $400 million green-ammonia plant to produce 96,000 t of zero-carbon fertilizer.[10]

For the consumer and the world at large, the impact of green ammonia could be sizable, although it is one of many actions that will be necessary to decarbonize agriculture. We estimate that green ammonia for fertilizer production could decarbonize 3 percent to 8 percent of emissions associated with a range of consumer food product emissions. This means that for a representative consumer basket illustrated in Exhibit 3, emissions of about 0.6 kilograms of carbon dioxide could be reduced, or an average reduction of 5 percent, which is a substantial reduction compared to other levers and how much of the emissions that can be addressed.

For most products in our analysis, green ammonia would reduce a meaningful share of emissions but add a relatively low share of cost to the full production

[8] *Hydrogen insights 2023,* a joint report from the Hydrogen Council and McKinsey, May 2023.
[9] "Yara and Lantmännen sign first commercial agreement for fossil free fertilizers," Yara, January 13, 2022; Julian Atchison, "Yara and Lantmännen sign first commercial agreement for fossil free fertilizers," Ammonia Energy Association, February 9, 2022.
[10] Keith Schneider, "A push to turn farm waste into fuel," *New York Times,* April 4, 2023.

Exhibit 3

In this example, green ammonia for fertilizer production can reduce emissions by about 5 percent.

Product category	Selected products	Share of ammonia[1] emissions in the product, %	Additional production cost due to use of green ammonia,[2] %
Sugar	White sugar	6	~1–2
	Chocolate bar	3	<1
Wheat	White bread	8	<1
Potatoes	Potatoes	6	<1
Milk	Milk	4	<1
	Cheese	4	<1
Eggs	Eggs	6	<1
Chicken	Chicken	6	<1
Pork	Ham	6	<1
Beef	Minced beef	3	<1

Example consumer basket[3] (5.2 kg)

13.3 kg CO_2e[4] baseline

0.6 kg CO_2e[4] reduction if using green fertilizer from green ammonia

~5% reduction per consumer basket, or **~8%** of abatable emissions[5]

[1]Only emissions associated with the fertilizer production, not in-field emissions.
[2]Calculation example takes a starting point for gray cost of ~€480/metric ton and a green cost of ~€740/metric ton of ammonia.
[3]For simplicity, assumes 1 kg of each product except for chocolate, where 200 grams is used.
[4]Kilograms of CO_2 equivalent.
[5]For the products assessed, known levers by 2030 results in an average abateability of ~60% (sugar: ~80%; chocolate: ~70%; bread: ~70%; potatoes: ~50%; milk: ~50%; cheese: ~50%; eggs: ~50%; chicken: ~60%; ham: ~50%; beef: ~40%).

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cost. Notably, this cost analysis is highly sensitive to the future cost of green ammonia compared to gray ammonia (for a breakdown of the costs considered in our analysis, see sidebar, "Getting to green ammonia"), and there is no industry consensus on the size of the cost gap between gray and green production in different parts of the world. However, green ammonia may become increasingly attractive by 2030 at least in Europe and the United States, as the European Union tightens policies and requirements on carbon credits and the US Inflation Reduction Act offers incentives for green-hydrogen production.

There are compelling reasons to move toward green ammonia in fertilizer besides the size of the impact (about 315 $MtCO_2$, because about 70 percent of ammonia is used for fertilizer application). First, there is less implementation complexity compared to other levers because reductions can be achieved without changes in farming or production practices (green-ammonia fertilizer is chemically identical to the conventional product). In contrast, we recently identified 28 other levers at the farm level that have major impact potential but largely require changes to the process and ways of working.[11] Second, there are relatively few fertilizer producers, which makes it easier to achieve emissions reductions compared with trying to encourage millions of farmers to take action. Last, green ammonia offers a relatively high abatement level relative to costs, and the costs are expected to decrease in the coming years.

[11] "The agricultural transition," June 27, 2023.

Getting to green ammonia

A prerequisite for producing green ammonia is scaling up green-hydrogen production and the associated equipment. Green hydrogen has attracted a lot of interest in recent years because it is one of the only applicable levers for a range of so-called hard-to-abate sectors, including ammonia. In fact, we estimate that in 2050, green hydrogen could contribute to more than 20 percent of annual global emission reductions.[1]

For fertilizer producers, it will be an option to source green (or blue) hydrogen from third parties. Additionally, some producers are exploring opportunities to produce their own green hydrogen. Yara is an example of the latter,[2] while other companies are negotiating offtake agreements with stand-alone green-ammonia projects. Location will likely be a key consideration for companies pursuing both strategies, because producing green ammonia requires large amounts of energy from renewable sources such as solar and wind. Hydrogen and ammonia producers are thus considering putting their plants close to renewables installations.

Cost is top of mind for prospective producers and buyers of green ammonia, as is the price of gray ammonia, which has been volatile in recent years. In our analysis, we offer a scenario in which green ammonia is more expensive to produce than gray ammonia in the short term to midterm. We then assess the carbon and production cost impact.

The cost gap between green and gray ammonia depends on the price of natural gas—the main driver of gray ammonia costs—and the cost of renewable power. Increased gas prices raised the cost of gray ammonia to more than €900 per metric ton (t) in the spring of 2021, up from about €270 to €450 per t between 2015 and 2020. As of May 2023, prices have dropped to about €400 per t.

We aimed to compare green-ammonia costs to gray-ammonia costs by 2030 in Europe. We estimated the cost of gray ammonia at about €480 per t compared with an estimated green-ammonia cost of about €740 per t in 2030, based on a range of assumptions about power prices and plant costs. Our estimates are illustrative, and the actual numbers will depend on a range of assumptions and geopolitical factors.

In Europe, part of the cost gap may be closed by the impact of changes in the European Union's Emissions Trading System (ETS). Ammonia producers will start to feel the changes from 2025 on as their allowances to emit carbon are gradually phased out toward 2035. Under the EU ETS, regulated entities buy or receive emissions allowances, which they can trade with one another as needed. At the end of each year, regulated entities must surrender enough allowances to cover all of their emissions. The ETS price for one tCO_2 emitted rose to more than €100 for the first time in February 2023, indicating that the potential cost impact on gray-ammonia producers could be about €200 per t in this decade.

In the United States, the Inflation Reduction Act will likely provide subsidies for green-hydrogen production through production tax credits of more than €2 per kilogram (kg). Because production of one t of ammonia requires about 180 kg of hydrogen, a potential subsidy effect of more than €360 per t of green ammonia could be realized—matching or surpassing the ETS effect in Europe.

[1] Bernd Heid, Alma Sator, Maurits Waardenburg, and Markus Wilthaner, "Five charts on hydrogen's role in a net-zero future," McKinsey, October 25, 2022.
[2] "Yara and Linde Engineering agree to build a 24 MW green hydrogen demonstration plant in Norway. Both companies aim to achieve a significant carbon dioxide reduction in the production of fertilizers in Norway," Yara, January 28, 2022.

Making green ammonia for fertilizer a reality

Market demand for materials that are more sustainable is clear. For example, recycled plastics command price premiums of up to 60 percent[12] because demand exceeds supply. Consumer goods companies are committing to increasingly ambitious Scope 3 (purchased goods and services) emission-reduction targets, with leading confectionery brands, for example, aiming for cuts of more than 40 percent

[12] Marcelo Azevedo, Anna Moore, Caroline Van den Heuvel, and Michel Van Hoey, "Capturing the green-premium value from sustainable materials," McKinsey, October 28, 2022.

by 2030. Consumers are also demonstrating a willingness to pay for sustainable products.[13]

Despite the advantages of green ammonia, work still needs to be done to realize its potential at scale and at pace. Prerequisites include the following:

— Because green-ammonia plants are capital-spending-intensive, developers of green ammonia could benefit from increased access to green financing. As we highlight in a recent article, climate capital deployment will require a collaborative effort among stakeholders—alongside dedicated fiscal and regulatory tools and risk-sharing financial mechanisms, such as blended finance—but it also offers massive opportunities.[14] For green ammonia, it is clear that the sector requires investors with a long-term horizon and risk appetite.

— Green-ammonia production requires a massive capacity expansion in renewable power such as solar and wind to ensure there is enough green power available at an economical price. Governments and companies around the world are accelerating their commitments for renewables, but there are still substantial gaps to close.

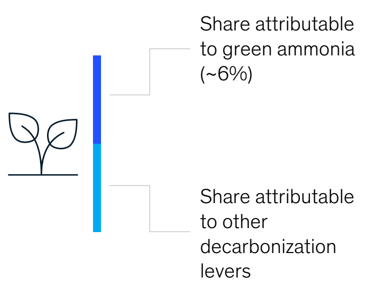
— Prospective producers are facing uncertainty about future prices of green ammonia, raising questions about how long it would take to make projects financially sound. It is clear that the higher cost of green ammonia must be absorbed throughout the value chain until it can become more competitive with gray ammonia. Farmers alone cannot bear the higher costs. As we note in a recent report,[15] a range of barriers are preventing farmers from adopting decarbonization solutions at scale. Farmers, who are key to the sustainability transition, lack incentives to adopt new methods and technologies. Measures to encourage farmers to decarbonize could include green premiums, subsidies, rebates, or other incentive mechanisms.

13 "Consumers care about sustainability—and back it up with their wallets," McKinsey, February 6, 2023.
14 "Financing the net-zero transition: From planning to practice, McKinsey, January 13, 2023.
15 The agricultural transition," June 27, 2023.

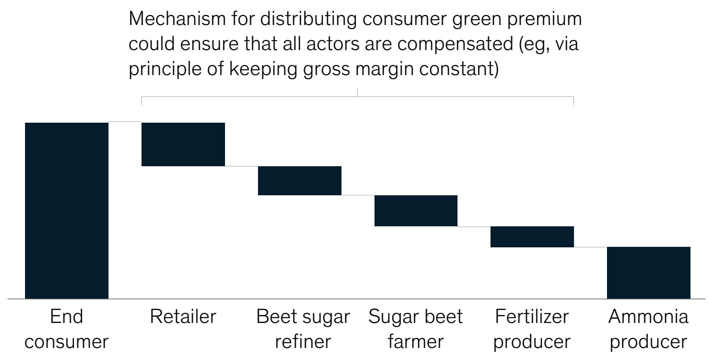
Exhibit 4

Consumers' willingness to pay for more-sustainable products can create an opportunity that maintains gross margins and benefits the entire value chain.

Green premium on end product



Premium division across the value chain (white sugar illustration)



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Using green premiums as an example, one way to think about this is to start from the consumer level and work back in the value chain to explore the economic impact for different players. In Exhibit 4, we illustrate that even a premium of 10 percent could provide sufficient premiums per t of green ammonia to finance higher production costs. Such premiums could encourage large-scale green-ammonia production and green fertilizer application when distributed fairly throughout the product value chain to avoid margin loss. To do this, offtakers (food companies) could contract directly with growers on their farming practices and green price incentives. Increased understanding of and commitment to green fertilizer targets in the industry will also be essential.

Creating functional offtake markets for green ammonia will be key to taking advantage of this decarbonization opportunity. Agriculture could even lead the way as other industrial sectors start to address their ammonia needs and carbon emissions. We see a clear opportunity for players in the agriculture value chain to forge new partnerships and to rethink collaboration and purchasing models to make the use of green ammonia for green fertilizer a reality within the decade.

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