Roadmap for Distributed Green Ammonia in Minnesota

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Introduction

Ammonia (NH_3) accounts for over 1% of global greenhouse gas (GHG) emissions, and with a production scale of around 185 million tons per annum (tpa), it is an essential commodity in fertilizer production and contributor to climate change.[1] Ammonia production is currently concentrated in low-cost natural gas and coal regions such as the US Gulf, China, and Russia. Present-day ammonia supply chains involve complex, multistep processes spanning thousands of miles, as production is often far removed from consumption. During periods of low fossil fuel prices and efficient transportation by ship, pipeline, and truck, the existing supply chain structure adequately ensures fertilizer production, purchase, and application in the quantities needed. However, the stability of such supply chains and low pricing are not guaranteed. Geopolitical factors and extreme weather events have exposed the vulnerabilities of the current centralized system and fossil fuel dependence of existing supply chains, all of which directly affect fertilizer consumers.

Russia's invasion of Ukraine highlighted several weaknesses of highly centralized fertilizer supply chains and natural gas–based production processes. The war disrupted both ammonia and natural gas production, resulting in limited supply and elevated prices. Reduced supply of natural gas from Russia led to high-priced domestic natural gas feedstocks in Europe and the United States. Because natural gas is a primary feedstock for ammonia production, high natural gas prices drove ammonia to cost points producers could not justify, reducing ammonia supply by 70% in Europe and more than tripling prices in the immediate aftermath of the Russian invasion to over $\$1,600/tNH_3$ from the historic market average of $\$516/tNH_3$ in the United States.[2]

The compounding challenges of high carbon intensity, centralized production, and feedstock price variability suggest the need for a complementary ammonia production system that is founded on a low-carbon, decentralized processes — that is, distributed green ammonia (DGA) deployed near consumption centers.

In the United States, Minnesota is a prime candidate for initiating the inaugural wave of distributed ammonia projects. The state is a major consumer of fertilizer, yet Minnesota's agricultural sector faces higher fertilizer costs compared with the national average due to higher transportation costs. This underscores the urgency and potential positive impact of localized ammonia production. Minnesota has also demonstrated robust policy backing with dedicated grants for localized fertilizer production, setting the stage for innovative ventures in the ammonia sector. With these factors in alignment, Minnesota stands poised to spearhead the advancement of distributed ammonia projects, heralding a paradigm shift in the Midwest and, potentially, in other regions of the United States.

This roadmap for advancing DGA in Minnesota focuses on the decarbonization of ammonia production and the direct application of ammonia as a fertilizer in the state. There are significant emissions associated with the use of fertilizers, but that issue is beyond the scope of this report. This roadmap includes an evaluation of business models, techno-economic dynamics, and necessary policy frameworks essential for translating these aspirations into actionable projects in Minnesota, a state that well understands the benefits of local, carbon-free fertilizer production. Key analytical elements include:

- Assessment of the enabling environment of Minnesota, including a high-level market analysis, demand profile, emissions intensity, renewable energy capacity and potential, techno-economic analysis, and available policy support

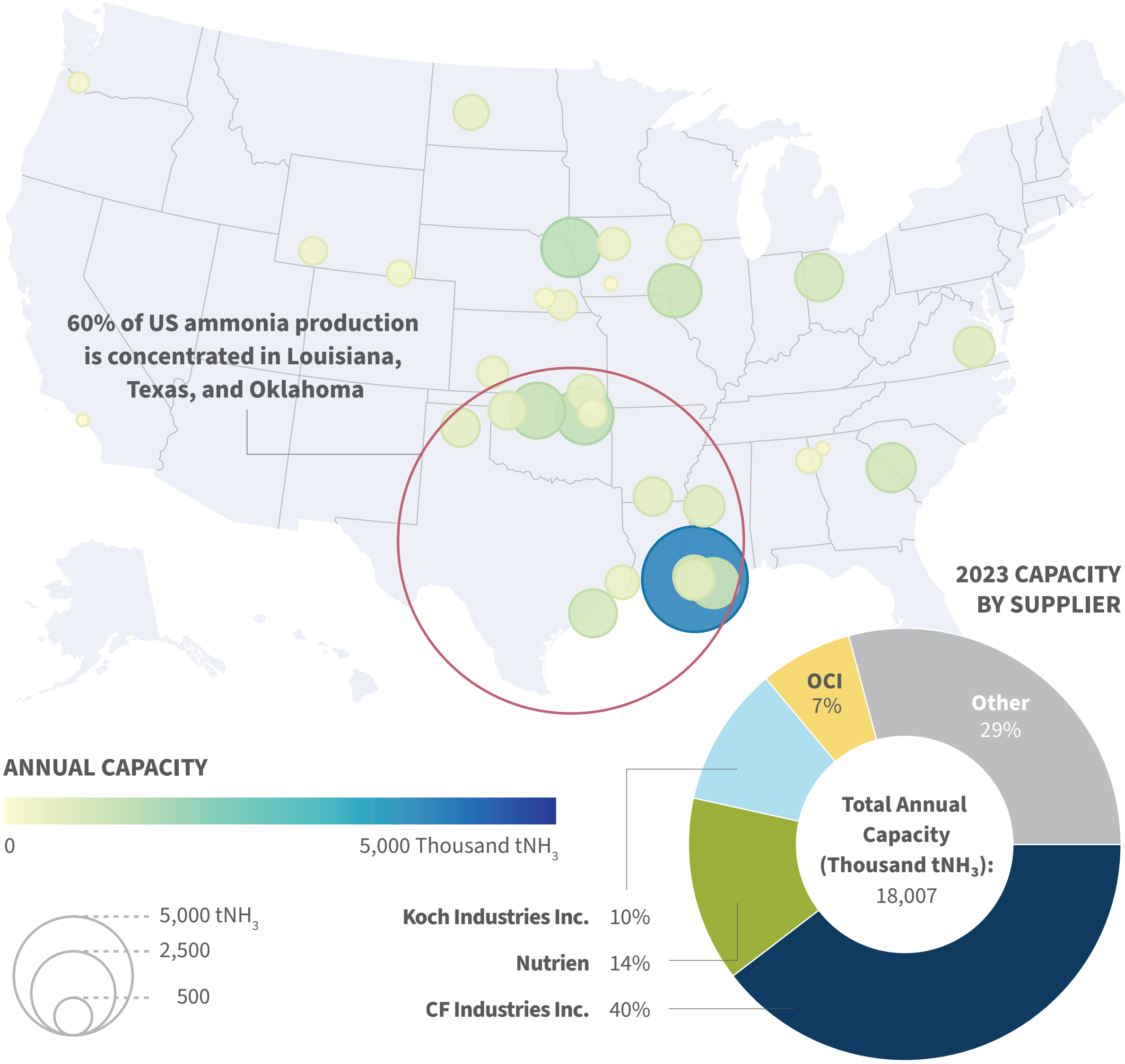
- Engagement with key stakeholders in Minnesota's low-carbon fertilizer space, including state agencies, financial institutions, nonprofit organizations, project developers, and original equipment manufacturers (OEMs), through bilateral conversations and focus-group discussions

- Formulation of targets and a suggested implementation strategy for DGA through emissions reduction goals, business model proposals, and policy recommendations

The US Fertilizer Market

In the United States, domestic production of ammonia is dominated by 17 manufacturers and is geographically centralized within the Gulf Coast region due to the strategic access to natural gas reserves and well-established pipeline infrastructure. Three major ammonia producers, CF Industries, Nutrien, and Koch Industries, provide 64% of the entire domestic ammonia supply, with the majority of their ammonia manufacturing plants concentrated in Louisiana, Oklahoma, and Texas (see Exhibit 1).[3]

Exhibit 1 **Ammonia Production Capacity Profile by Location and Company**



60% of US ammonia production is concentrated in Louisiana, Texas, and Oklahoma

RMI Graphic. Source: RMI analysis; Nutrien, **https://nutrien-prod-asset.s3.us-east-2.amazonaws.com/s3fs-public/uploads/2024-01/Nutrien_2023Fact%20Book_Update_12624.pdf**

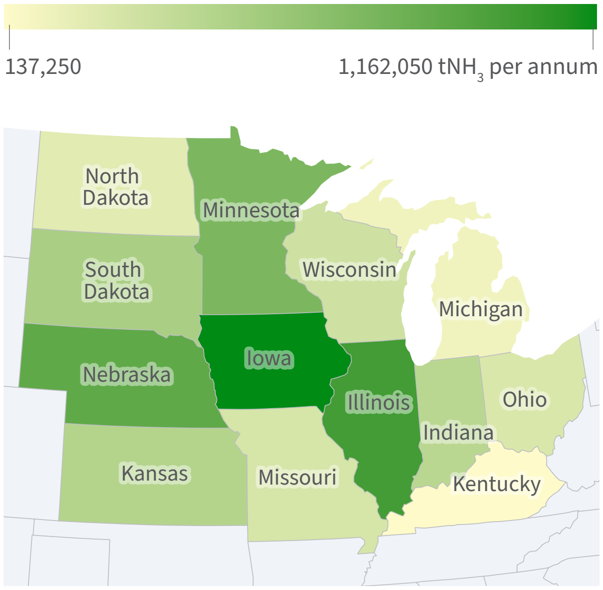
With approximately 80% of US ammonia consumption going to agricultural fertilizers, farms in the Midwest represent the primary consumption hub, with corn driving roughly 50% of all US agricultural ammonia demand. Minnesota is the fourth highest-consuming state of ammonia fertilizer, driving over 10% of market demand, yet no ammonia production facilities are located in the state (see Exhibit 2).

Minnesota, along with many other Midwestern states, relies on ammonia transported from the Gulf through a complex network encompassing pipelines, barges, railways, and trucks, facilitated by market intermediaries ranging from logistics and distribution entities to wholesalers, agricultural retailers, integrated distributors, and cooperatives (see Exhibit 3).

The existing market structure, while serving as the backbone of fertilizer distribution in Minnesota and the broader Midwest region, falls short in ensuring consistent stability regarding both fertilizer prices and volumes of fertilizer.

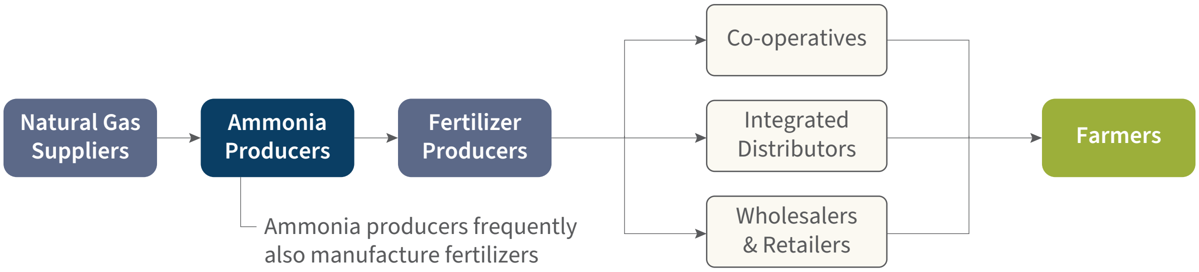
Exhibit 2

Ammonia Demand in the US Midwest for Corn Crops



RMI Graphic. Source: RMI analysis; USDA, **https://downloads.usda.library.cornell.edu/usda-esmis/files/j098zb09z/0z70b374s/w9506686w/acrg0622.pdf**

Exhibit 3 Illustrative Fertilizer Market Structure



RMI Graphic. Source: RMI adaption from DOE, **https://liftoff.energy.gov/wp-content/uploads/2023/12/20230921-Pathways-to-Commercial-Liftoff-Chemicals-Refining.pdf**

Distributed Green Ammonia Opportunity

DGA can address the challenges of the current fertilizer market. DGA shortens supply chains so that production is located more closely to ammonia consumption and shifts feedstocks away from natural gas–based feedstocks toward renewable electricity, increasing certainty of supply and price stability for consumers.

Technology Profile of Distributed Green Ammonia

A new wave of technology that efficiently and economically produces ammonia at scales far smaller than traditional ammonia plants creates an opportunity to shift fertilizer production toward a distributed business model. Conventional ammonia synthesis processes have seen significant cost reductions in scaling up production volumes. Consequently, most units are sized to produce 100,000 to more than 1 million tpa.

New production processes, deriving from the Haber-Bosch (HB) process,[i] employ technology with different operational and design advantages that forgo the need to upsize plants to reduce production costs. Regional-scale systems slightly modify the traditional integrated ammonia synthesis plant to optimize for production up to 100,000 tpa, whereas single-farm systems rely on novel, modular containerized style units for easily replicable construction and standardizable mass production, best for production scales up to 3,500 tpa (see Exhibit 4, next page). These new ammonia production technologies can be specifically tailored to meet the needs of off-takers. They are well suited for the demand of a single, large US farm, which needs at most 3,500 tpa,[ii] and up to the scale of an agricultural cooperative, which needs between 3,500 and 100,000 tpa.

Commercial maturity for these newer ammonia production systems is low, but technological maturity is generally high, depending on the specific process considered. Although there are alternative ammonia production methods that have yet to achieve full technology readiness levels (TRLs), this report focuses primarily on TRL 9 technologies that are derived from the Haber-Bosch process.

Deployment of DGA projects is necessary to take full advantage of learning curves, especially for modular systems, as cost-effectiveness is achieved with increased technology installation. Developing DGA projects will only reinforce cost reduction and technological de-risking, creating a positive feedback loop of falling costs. Projects must overcome the challenges associated with first-of-a-kind project development, but once projects get off the ground, DGA can offer broad benefits to consumers, local communities, developers, and financiers over incumbent ammonia production technology and business models.

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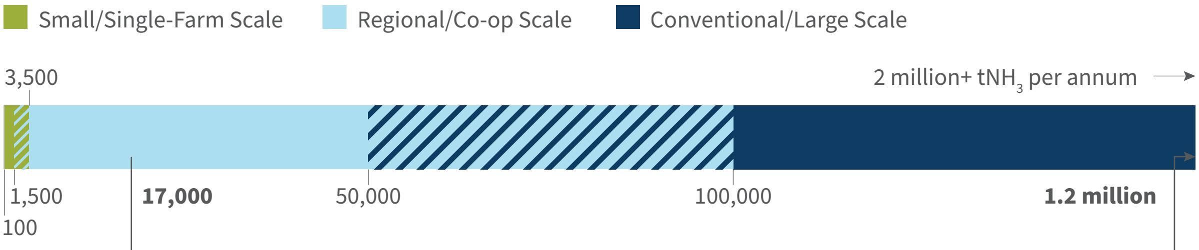
[i] Haber-Bosch refers to the conventional, industrial ammonia synthesis process where hydrogen and nitrogen are combined at a high pressure and high temperature.

[ii] The 3,500 tpa amount is based on stakeholder engagement and average use volume.

Exhibit 4 **Different Scales of Ammonia Production, with Examples of Current Green Ammonia Projects**



H2F

Iberdrola and Fertiberia in Puertollano, Spain

- 100 MW solar PV, 5 MW battery storage, 20 MW PEM electrolysis, and 11 high-pressure hydrogen storage tanks
- In operation since 2022, H2F produces **17,000 mtpa of green ammonia** at its neighboring plant

NEOM Green Hydrogen Complex

NEOM, ACWA Power and Air Products in Saudi Arabia

- 4 GW of solar power, 650 mtpd of hydrogen, saving over 3 million tpa of CO_2
- In construction and scheduled to come online in 2025, producing **1.2 million tpa of green ammonia**

RMI Graphic. Source: RMI analysis; Fertiberia, **https://www.fertiberia.com/en/greenammonia/h2f-project/;** Air Products, **https://www.airproducts.com/energy-transition/neom-green-hydrogen-complex**

Active players in the green ammonia landscape

For small-scale systems, the Haber-Bosch technology is modified and improved so that it can be better integrated with renewable energy systems and operate at a single-farm level through containerized and low-maintenance devices. TRL levels vary across OEMs (between 3 and 9), but these systems can be differentiated into three categories:

1. Miniaturized Haber-Bosch, a process that optimizes the synthesis loop for small-scale production

2. Enhanced Haber-Bosch synthesis, a process that involves improved and more efficient synthesis at lower pressure and lower capital expenditures (capex) than traditional Haber-Bosch through reactor and catalyst modifications

3. Novel and alternative ammonia synthesis methods, which include less proven methods such as electrochemical and nonthermal plasma ammonia production

In the miniaturized Haber-Bosch space, Talus Renewables is demonstrating proof of concept with its recent commercial 15-year offtake agreement with the Kenya Nut Company, an agribusiness based in Nairobi, Kenya.[4]

Regional-scale systems feature minimal modifications to the Haber-Bosch process to allow for low capital expenditures and/or low-pressure synthesis at a smaller scale than conventional industrial-scale plants. These modifications are often in the form of design improvements, increased flexibility, catalyst innovation, or solid oxide electrolyzer integration into the Haber-Bosch synthesis. The TRL levels are usually higher, ranging from 6 to 9, with some projects expected to reach final investment decision this year. An initial effort in that direction is represented by ReMo Energy, a DGA OEM, which signed a memorandum of understanding for offtake with the logistics company Trammo for a 20,000 tpa facility to be built in Illinois.[5] In the ammonia technology space, incumbent Topsoe is designing regional-scale solid oxide–based modular plants of 100 megawatts (MW), the equivalent of 100,000 tpa, in collaboration with First Ammonia.[6]

Although not exactly DGA, larger-scale green ammonia projects, with production profiles similar to those of conventional centralized plants, are also underway. In Africa, Stamicarbon is developing a 300,000 tpa green ammonium nitrate plant in Angola and a 200,000 tpa renewable power-to-fertilizer plant in Kenya.[7] In the United States, Atlas Agro, a leading green ammonia project developer, has announced the Pacific Fertilizer Plant in Richland, Washington, with a production capacity of 700,000 tpa of nitrogen fertilizers.[8] This project relies on green ammonia synthesis technology from KBR, another incumbent OEM.

Fertilizer Market Dynamics and Distributed Green Ammonia Advantages

Cyclical downturns in commodity markets for ammonia-based fertilizers are exacerbated by the significant influence of supply and demand shocks on market participants. This phenomenon is particularly pronounced due to the high level of global integration in these markets. These challenges primarily manifest in price volatility and disruptions in supply chains, leading to adverse effects on farmers. DGA can act as a direct hedge to these challenges while providing a series of additional co-benefits in local investment and renewable energy integration.

From supply chain disruption to simplification

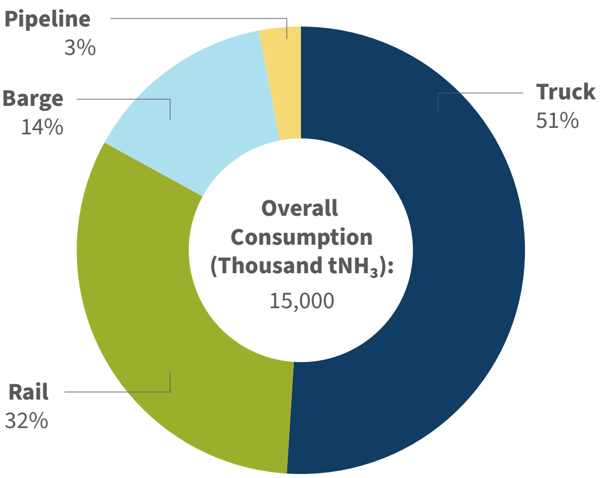
Multistep transport processes to deliver traditionally produced ammonia to users expose supply chains to weather or labor disruptions and increase pass-through costs. In the United States, ammonia is primarily transported by pipelines, trucks, railways, and barges (see Exhibit 5 for volume shares, next page), yet these modes of transportation are not always reliable. Railway strikes in 2022 threatened to halt the transport of ammonia via rail, which is the mode of transport for over 32% of ammonia.[9] Droughts in the Mississippi River, a core connector between fertilizer producers in the Gulf and consumers in the Midwest, hindered the transport of ammonia to farms in fall 2023 via barge, which accounts for 14% of overall ammonia transportation.[10] During the past decade, unintended stoppages and malfunctions among barges have increased by 700%.[11] Historically, weather patterns such as prolonged cold spells have resulted in production shutdowns due to high natural gas costs from increased home heating demands.

Logistics costs vary depending on factors such as such as the point of origin, the chosen mode of transportation, and the frequency of loading and unloading. Collectively, extended transportation routes, pass-through costs associated with multistep supply chains, and the utilization of high-cost transportation methods such as trucking can contribute to substantial expenses in the distribution of ammonia from the Gulf to the Midwest, often escalating logistics costs to well over \$300/tNH_3.[12]

With distributed ammonia production, fertilizer supply chains shift from spanning thousands of miles with multimodal transport to being "within the backyard" of farming communities, leading to more reliable supply and significant cost reductions. Simplifying supply chain logistics can shield consumers from the geopolitical instability and unpredictable transportation that can impact fertilizer supply.

Exhibit 5

Ammonia Transportation Modes and Volumes



RMI Graphic. Source: RMI analysis; Fertilizer Institute, **https://www.tfi.org/wp-content/uploads/2024/03/TFI-fertilizer-logistics-and-transportation.pdf**; US Geological Survey, **https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-nitrogen.pdf**

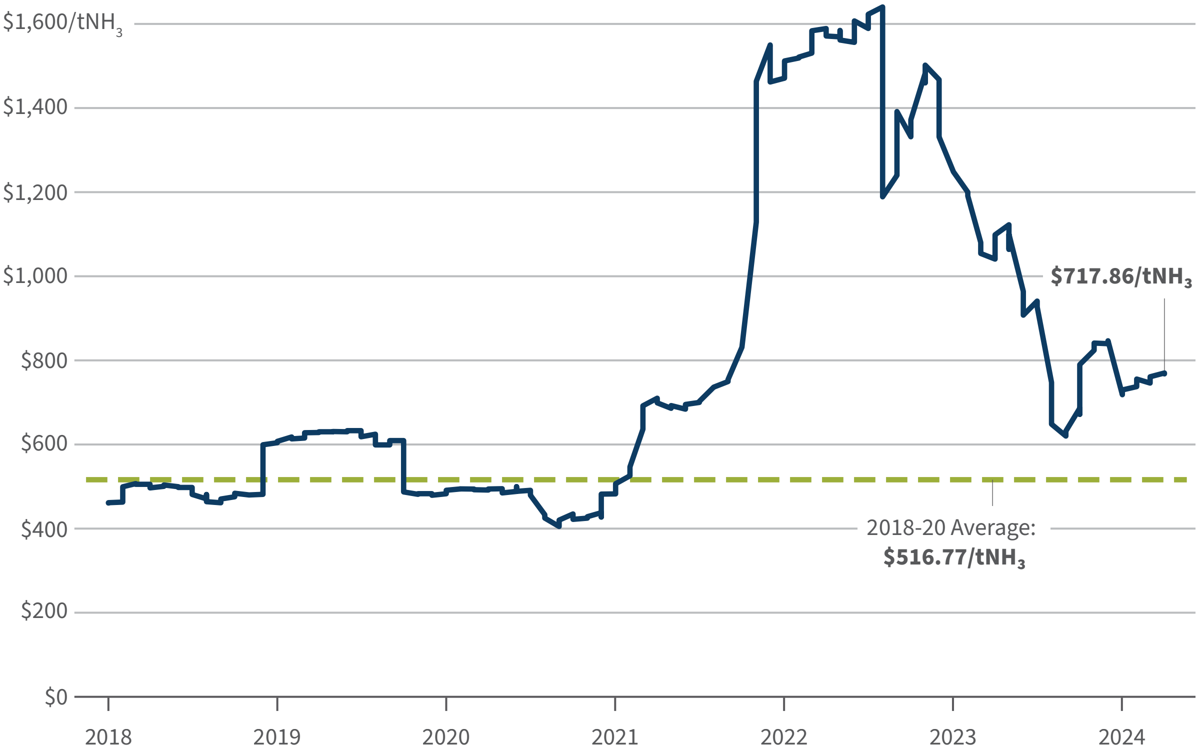
With the logistical challenges of fertilizer procurement lessened, the uncertainty of predicting how much ammonia will be available and of long lead times is also reduced. Localizing production also helps limit supply chain pass-through costs by streamlining distribution. This not only maximizes cost reduction but also minimizes the opportunity for supply chain disruptions to add unexpected costs and for intermediaries to inflate costs along the way.

From price volatility to stability

Imports and international pricing dynamics of ammonia significantly influence the pricing of ammonia in the US market. The United States produces most of the ammonia it consumes but still imports about 10% of its ammonia, mainly from Trinidad and Tobago or Canada. Domestic ammonia production prices rose only slightly with recent natural gas price volatility related to the Russian invasion of Ukraine, but in 2022 market prices rose three times over the market average from 2018 to 2020, reaching upward of \$1,600/tNH_3 from \$516/tNH_3. As of April 2024, despite the low natural gas prices, ammonia market prices were still 1.49 times higher (equivalent to \$767/tNH_3) than the market average from 2018 to 2020 (see Exhibit 6, next page).

Because ammonia imports, especially lately, have been significantly higher priced than domestic ammonia, imports have had a price-setting effect on the US market. Typically, wholesale ammonia prices are not capped or predictable because contracts hinge on the fluctuating price of natural gas, with benchmarks such as the Cost and Freight (CFR) Tampa reflecting the average cost of ammonia production in the Gulf region (inclusive of transportation to its destination).

Exhibit 6 **Delivered Ammonia Market Prices in Iowa, US Midwest**



RMI Graphic. Source: RMI analysis; USDA, **https://mymarketnews.ams.usda.gov/viewReport/2863**

Minnesota farmers, like those in the rest of the Midwest, face considerable cost burdens due to ammonia's intricate supply chain dynamics and reliance on fossil fuels. Farmers' ability to procure fertilizer at the required volumes and prices is limited because they rely heavily on intermediaries to ensure timely availability during critical application seasons. However, the centralized nature of the supply chain necessitates farmers placing orders months in advance, demanding meticulous understanding of both local farming patterns and global production trends to ensure adequate supply.

This financial burden is reflected in the substantial decrease in net income for US farms when the price of ammonia increased after Russia's invasion of Ukraine, leading to widespread losses averaging $191 per acre through 2022.[13] Facing escalating expenses, some farmers may turn to synthetic fertilizer alternatives like manure, despite its labor-intensive application process and diminished nitrogen availability. This shift could impact crop yields, potentially driving up demand and market prices for agricultural products, thereby amplifying the broader economic repercussions stemming from fertilizer price volatility.

Producing ammonia with renewable energy will help stabilize fertilizer prices by decoupling ammonia production from natural gas price fluctuations and linking it with the set yearly cost of renewable electricity. This will reduce the current strain on farmers from constantly fluctuating and rising ammonia prices by ensuring that they can purchase fertilizer at more stable and affordable costs. Even with the shift to renewable-based ammonia, a future fertilizer market would not be isolated from price volatility given the seasonality of fertilizer demand, but green production can limit the severity of price volatility compared with production that relies on natural gas.

Distributed green ammonia co-benefits

Local investment

Moving fertilizer production to the Midwest could further benefit local economies by accelerating growth of renewable energy generation and creating green jobs in farming communities. Investments would spur a series of benefits, including the creation of a new specialized workforce of agronomists and technicians to operate distributed ammonia plants. This would provide the additional benefit of increasing investment in cooperative systems and ultimately increase the retention of dollars spent in local areas. Farmers and farming cooperatives (co-ops) will be the main beneficiaries of this transition, unlike in the current system where centralized producers define market dynamics.

Operational advantages for renewable electricity integration

New distributed ammonia production technologies will better enable integration with renewable electricity feedstocks. Conventional ammonia production technology must consistently maintain and operate high temperatures and pressures for the reaction of converting hydrogen and nitrogen into ammonia to occur. When these processes move away from the consistently supplied fossil feedstocks toward intermittently available renewable electricity, they require additional buffer in electricity supply through batteries or oversized renewables that increase costs and complexity. Newer, smaller-scale ammonia production processes are typically far more flexible in operation and can more readily adjust production to changes in renewable energy availability, providing opportunities for cost reduction and system simplification.

Project simplification and standardization

Once technological maturity is reached for distributed ammonia production, projects will have a lower financing risk and be more attractive to investors. Several distributed projects have been announced in recent years in the United States, involving companies such as ReMo Energy, Talus Renewables, First Ammonia, and Atlas Agro. Talus, in partnership with Landus Cooperative, opened the first plant in June 2024.

Deployment of DGA projects is necessary to prove the concept and the viability of the DGA pathway. Project developers and investors alike will appreciate the shorter construction periods; lower engineering, procurement, and construction (EPC) costs; and smaller amounts of capital required, making access to debt and equity financing a potentially easier ask. Once plants are operational, these systems may see less costly operation and maintenance costs alongside improved production resiliency given their more simplistic system design and technical improvements, which allow for lower pressure and lower temperature synthesis compared with conventional technology.

In addition, small-scale, containerized ammonia production facilities can be manufactured and installed much faster than large-scale ammonia plants (i.e., 1–3 years versus 3–10 years). The ability to go online sooner enables a faster return on investment, and the stackability of modular systems provides further benefits. Modular ammonia production systems can be installed in phases, allowing the farm or co-op to generate revenue as they gradually scale with a better understanding of offtake demand.

Many of these advantages give DGA business models a long-term economic edge compared with large-scale ammonia production processes. Nonetheless, key risks need to be addressed to effectively scale DGA.

Risks Related to Distributed Green Ammonia

Reshaping the fertilizer industry with a transition to DGA production requires the first wave of projects to access financing and establish early offtake contracts. This is particularly challenging for new players given the hesitancy of consumers to disrupt the status quo. Lack of product differentiation for green fertilizers and general perceptions of risk, cost premiums, and low commercial maturity create a challenge in getting these initial projects off the ground.

Heightened investment risk perception

First-of-a-kind distributed fertilizer projects involve a heightened perception of risk, a potential cost premium, and at times a lower TRL. This creates reluctance among capital providers and hesitation across off-takers to pivot to DGA production pathways. Both agricultural co-ops and lending institutions view the distributed pathway as high-risk because one has not yet been operated on a commercial scale. New ammonia reactors are only recently starting to being fully optimized and integrated into a unit with electrolyzers and powered by renewable electricity. Whole-system testing is important to validate OEMs' claims on a unit's ability to efficiently follow and operate at varying electricity loads in projects not connected to the grid.

Cost competitiveness

DGA's cost competitiveness is relative to changing fertilizer market prices, creating uncertainty about their economic advantage for off-takers. Fertilizer purchasers — notably agricultural co-ops and other market intermediaries — will benchmark DGA prices against ammonia market prices, and costs are a significant driver of buyer interest. Although DGA production costs in context of current fertilizer price spikes may appear competitive, buyers' expectations of price cyclicality may create hesitancy to commit to new fertilizer purchasing agreements. In other words, buyers may fear being locked into a price that appears competitive when market prices are high but that may not be the lowest price when market prices fall. Their concern stems from the ammonia market's typical cycle of price volatility and stability. Essentially, buyers are hedging against the risk of overpaying in the future as they anticipate prices of ammonia may become more stable as volatility factors are mitigated. By contrast, DGA producers expect their production cost to decrease in the long term. As production costs fall, DGA producers can increase their returns and see greater margins — even if market costs are higher or lower than the price contracted with off-takers.

Lack of targeted policy support

There is a critical need for policy that supports DGA deployment. The Inflation Reduction Act (IRA) has been instrumental in improving DGA economics, but other support programs that incentivize innovation, de-risk financing and investing, and provide supplementary financing to reduce burden on developers are still required. Leveraging existing tax credit structures where possible and engaging with existing support for co-ops, farmers, and stakeholders will be critical to enable early projects to secure offtake and illustrate the viability of the technology pathway. To help get early DGA projects with fertilizer applications off the ground, project developers should prioritize business models centered on economically strong agricultural co-ops in Midwestern states with robust policy support, such as Minnesota. Additionally, expanding buyer and investor education will provide greater clarity about the advantages of DGA, its costs, and its technological readiness. State and federal policy support should also be strengthened and expanded.

Developing Distributed Green Ammonia in Minnesota

Minnesota provides an ideal enabling environment for the first wave of DGA projects, owing to its supportive policy environment, strong renewable energy profile, and sizable demand for fertilizer demand. Minnesota is the fourth largest consumer of ammonia for agricultural use in the United States, with a current demand reaching 747,000 tpa for nitrogen fertilizers.[14,iii] Similar to other states in the Corn Belt such as North Dakota, Minnesota grapples with the intertwined challenges of price fluctuations and increased transportation expenses stemming from limited connectivity to the central ammonia pipeline distribution network. Moreover, Minnesota boasts abundant wind energy potential. These factors are further strengthened by the existence of grants incentivizing local production of green fertilizers by co-ops.

Current Landscape in Minnesota

Efforts to produce locally

Green ammonia projects are ramping up in the Midwest, and Minnesota is already positioning itself to tap into the opportunity to produce fertilizers closer to consumption. The state's dependence on external fertilizer sources has prompted a push for local production and decoupling ammonia synthesis from natural gas price fluctuations. In 2013, the University of Minnesota launched a first-of-its-kind green ammonia pilot program in Morris, in western Minnesota, to show the opportunity for distributed production.[15] This effort has gained momentum since the Russian invasion of Ukraine, which prompted other market actors to find opportunities in local low-carbon fertilizer production.

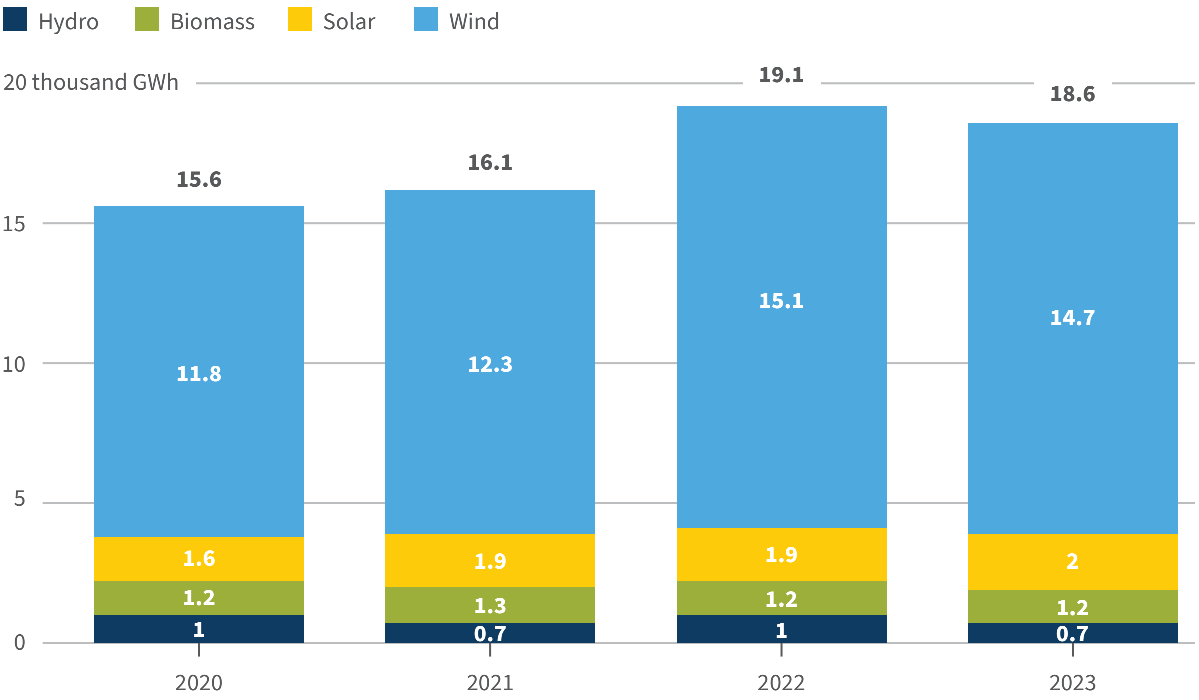
The Heartland Hydrogen Hub, a project funded by the US Department of Energy (DOE) that spans Minnesota, North Dakota, and South Dakota, is a more recent example of local production. As part of the hub, Xcel Energy is planning a large-scale urea plant that uses CO_2 offtake from ethanol refineries combined with green ammonia.[16] This project leverages Minnesota's ample sources of biogenic CO_2 from its ethanol refineries, as well as from several pulp and paper mills.

Similar projects have also been announced in North Dakota, which may look to Minnesota for customers given its large demand for nitrogen fertilizer. For example, NextEra plans to build a wind-powered $1.3 billion ammonia facility in Spiritwood.[17]

> **Minnesota provides an ideal enabling environment for the first wave of DGA projects, owing to its supportive policy environment, strong renewable energy profile, and sizable demand for fertilizer demand.**

[iii] Requiring 911,000 tons of ammonia for production.

Exhibit 7 **Cumulative Renewable Energy Generation in Minnesota, 2020–23**



RMI Graphic. Source: US Energy Information Administration, **https://www.eia.gov/electricity/data/browser/#/topic/0?agg=2,1,0&fuel=9cdd&geo=g00004&sec=g&linechart=ELEC.GEN.WND-US-99.A~~~~~~~~~~~~~~~~&columnchart=ELEC.GEN.COW-US-99.A&map=ELEC.GEN.COW-US-99.A&freq=A&start=2018&end=2023&ctype=linechart&ltype=pin&rtype=s&pin=&rse=0&maptype=0**

Abundant renewable energy resources

Minnesota's efforts to produce green ammonia locally would not be possible without its excellent renewable energy profile (see Exhibit 7). In 2023, renewable energy accounted for 33% of Minnesota's electricity generation, with 54% of the state's total energy capacity coming from carbon-free sources including renewables, nuclear, and hydropower.[18]

Wind energy alone accounts for more than three-fourths of Minnesota's renewable generation. Most of Minnesota's utility-scale (1 MW or larger) wind farms are located in the southwestern part of the state where flat land is abundant.[19] This locality coincides with the majority of the state's farmland where direct-application ammonia fertilizer is typically utilized over urea.

In 2023, solar energy also provided almost 4% of Minnesota's total electricity generation, and hydropower accounted for more than 1% of the state's total electricity generation.[20] About 90% of the state's solar power came from utility-scale installations. Although there are nearly 30 utility-scale hydroelectric power plants in the state, most of the plants are small: The largest has a capacity of 76 MW.[21]

The state's utilization of multiple forms of alternative energy resources is ahead of many other states, and, largely thanks to the availability of high winds throughout Minnesota, there are still opportunities for further development to support additional endeavors such as clean fertilizer production.

Existing Policy Landscape

To understand how Minnesota can best support the deployment of DGA systems, it is essential first to understand the existing policy landscape at the federal and state levels.

Federal policy

In recent years, the federal government, through the US Department of Agriculture (USDA), has prioritized and financially supported domestic fertilizer production and deployment of renewable energy projects for farmers.[22] The DOE has made the development of clean hydrogen a priority in its strategy, and the IRA represented a key milestone in supporting electrolytic hydrogen and incentivizing green ammonia.[23]

The Biden administration set a target of reaching 100% carbon–free electricity by 2035 and net-zero GHG emissions by 2050.[24] The DOE's Industrial Decarbonization Roadmap establishes that decarbonizing fertilizer is connected to the generation of hydrogen from low-carbon energy, highlighting ammonia as a key use of clean hydrogen.[25] Besides the federal government's recognition of green ammonia as key to decarbonize fertilizer emissions to reach its national decarbonization goals, there is federal support for innovative fertilizer production pathways. The IRA includes clean electricity tax credits and a clean hydrogen production tax credit, described below.

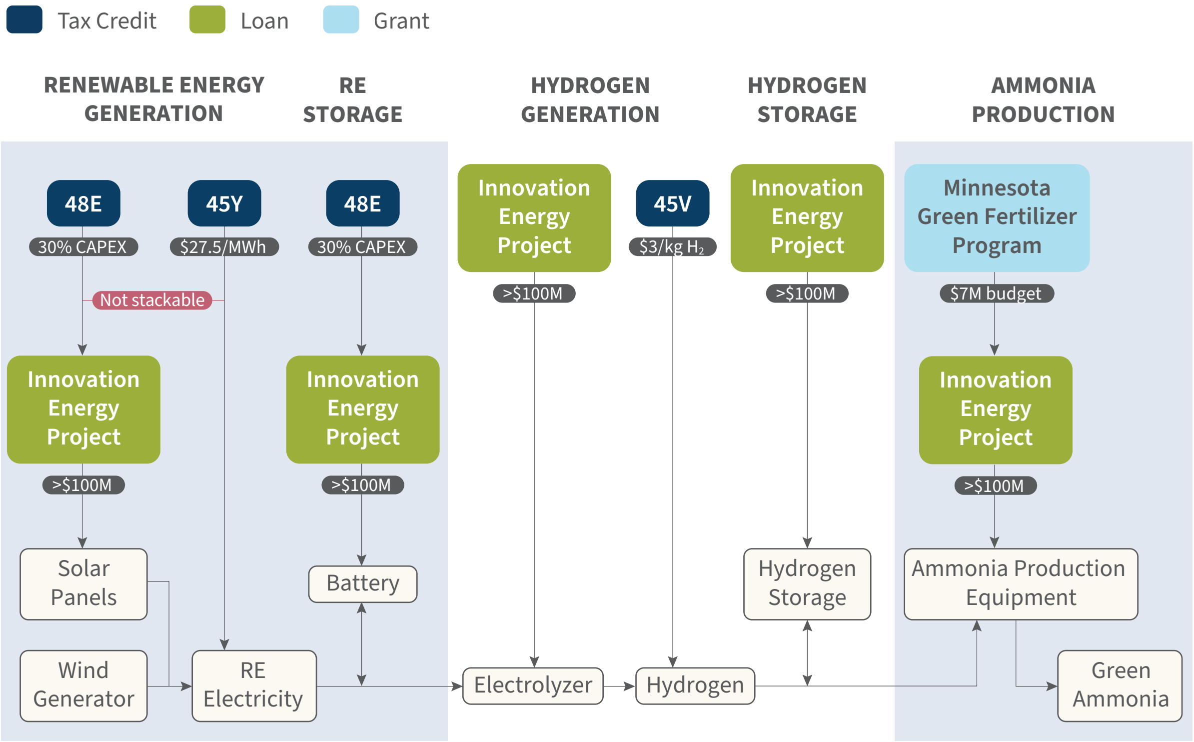
The Bipartisan Infrastructure Law created the DOE Regional Clean Hydrogen Hub program and allocated $7 billion to support the creation of hydrogen hubs.[26] The Heartland Hydrogen Hub, which includes Minnesota, was one of the seven hydrogen hubs selected,[27] with green fertilizer production mentioned as one of the main uses of hydrogen. In addition, DOE announced a $1 billion hydrogen demand program to design and implement demand-side incentives.[28]

The DOE's Loan Program Office (LPO) is another federal funding mechanism, with guaranteed loans through its Title 17 for innovative energy projects.[29] IRA provided an important boost to the LPO by appropriating $11.7 billion to issue new loans and increasing its existing loan program authority by $100 billion.[30] Although there is no minimum loan size, guarantees are usually $100 million and cannot exceed 80% of the anticipated project costs. Projects eligible under Title 17 must include a new or significantly improved technology not widely adopted in the United States.[31] They must demonstrate that the technology is used in three or fewer facilities and can catalyze the market by being employed in other commercial projects.

Exhibit 8 (next page) presents the main federal tax credits and LPO loan program across the value chain for green ammonia production, including renewable energy and electrolytic hydrogen generation and storage.

> **In recent years, the federal government has prioritized and financially supported domestic fertilizer production and deployment of renewable energy projects for farmers. The DOE has made the development of clean hydrogen a priority in its strategy, and the IRA represented a key milestone in supporting electrolytic hydrogen and incentivizing green ammonia.**

Exhibit 8 Federal Tax Credits and LPO Loans for Which Green Ammonia Production Is Eligible



RMI Graphic. Source: RMI analysis; IRA Guidebook, **https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**

Primary federal tax credits and financial support mechanisms that apply to green ammonia projects include:[32]

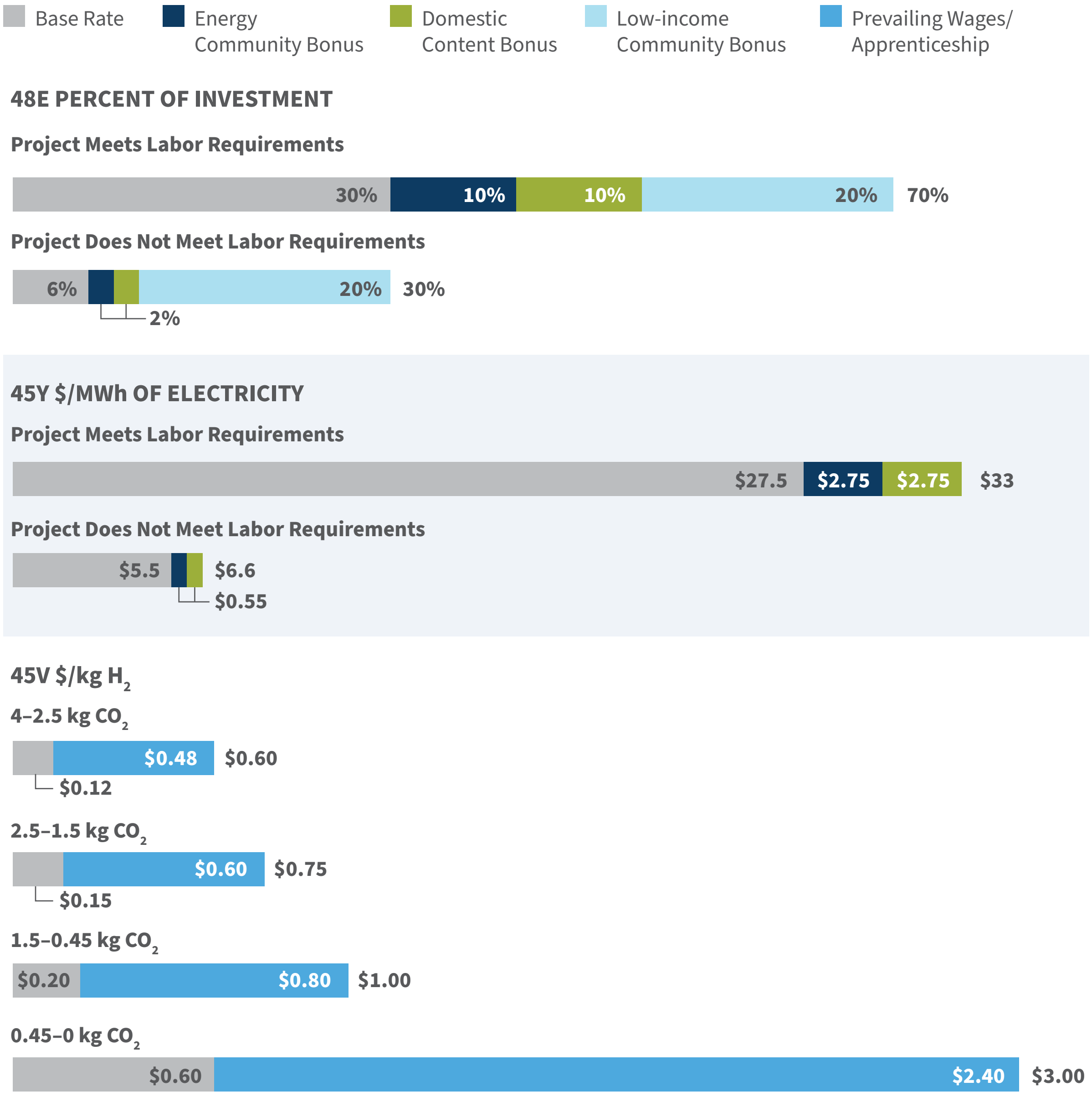
- **48E:** The 48E tax credit for clean electricity subsidizes 30% of the project's capital expenditure when prevailing and apprenticeship requirements are met. It can reach up to 70% with the domestic content, energy community, and low-community bonuses, as shown in Exhibit 9 (next page). The IRA also added stand-alone battery technologies under the scope of the tax credit.

- **45Y:** The production tax credit 45Y provides a base rate of $27.5/MW hour (MWh) when prevailing and apprenticeship requirements are met. Bonuses similar to those in the 48E tax credit are applicable to 45Y.

- **45V:** The 45V clean hydrogen production tax credit offers up to $3/kg of hydrogen produced with less than 0.45kg of carbon dioxide equivalent (CO_2e) per kilogram of hydrogen produced. Dedicated renewable projects producing hydrogen will be able to take advantage of this tax credit and stack it with either 45Y or 48E. The US Internal Revenue Service (IRS) published the 45V tax credit guidance in December 2023, opening a comment period that closed in March 2024. However, there is no official timeline for when the IRS will publish the final guidance, and it could be released as late as the end of 2024.

- **LPO innovative energy projects:** Technologies across the entire value chain for green ammonia production are eligible for the DOE LPO program, including renewable energy and green hydrogen generation and storage. The Haber-Bosch process is eligible as a technology to reduce GHG emissions from industrial applications such as ammonia production.

Exhibit 9 **Federal Tax Credits**



RMI Graphic. Source: RMI analysis; IRA Guidebook, **https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**

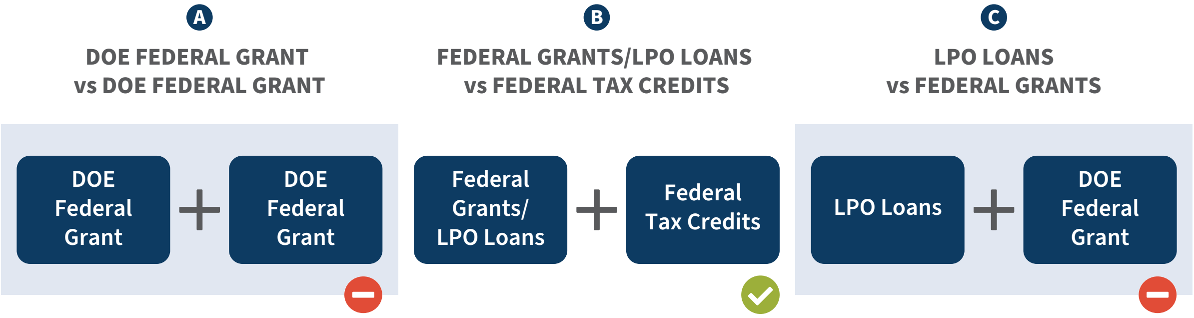
Several federal funding mechanisms are stackable, but there are some limitations based on the project's scope (see Exhibit 10, next page):

(a) Two federal grants cannot support the same project, scope of project, or budget.

(b) Federal tax credits are stackable with DOE federal grants and LPO loans.

(c) LPO loans are not stackable for projects that are expected to benefit directly or indirectly from another federal support program, such as grants.

Exhibit 10 **Stackability Rules for Federal Fundings Mechanisms**



RMI Graphic. Source: RMI analyses based on LPO's Title 17 Program, **https://www.energy.gov/lpo/title-17-clean-energy-financing; IRA Guidebook, https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**

State policy

Minnesota has developed robust climate goals and targets. It set a goal of 100% carbon-free electricity by 2040. Its Climate Action Framework, published in 2022, aims to reduce the state's GHG emissions by 50% from 2005 levels in 2030 and achieve net-zero emissions by 2050.[33] Thanks to these efforts, GHG emissions from Minnesota's power sector have dropped by 40% over from 2012 to 2022.[34]

To reach the goal of achieving 100% clean electricity by 2040, Minnesota's Public Utilities Commission undertook a permitting reform for renewable energy projects. In December 2023, a working group proposed 12 reforms that could reduce permitting to nine months. The report was used to design a package that the Minnesota Legislature passed under the Energy Infrastructure Permitting Act in May 2024, which was waiting to be signed by the governor as of the publication of this report.[35]

Minnesota is also the only Corn Belt state with specific incentives for in-state green fertilizer production. Minnesota's Department of Agriculture is designing a $7 million green fertilizer grant program to reduce fertilizer emissions.[36] The grant's objective is to provide financial support to co-ops that invest in a green fertilizer production facility in Minnesota. Co-ops must have long-term offtake agreements to purchase the green fertilizer and obtain training in nutrient management best practices, in alignment with the state nitrogen fertilizer management plan.[37]

Momentum in Minnesota with a First Wave of Commercial Projects

DGA production is already competitive with large-scale green ammonia production and can be competitive with grey and blue ammonia production pathways under specific assumptions, especially concerning natural gas pricing. Minnesota has good renewable energy generation, which makes DGA projects there economically feasible. The development of technologies and standardization of production solutions will strengthen DGA's market position. Modeled scenarios relating to cost factors, learning rates, and system configurations provide insights into when and how much cost reductions should be expected. In the coming years, a reduction in the levelized cost of ammonia (LCOA) of 30% will be achieved, as the cost of electrolyzers and modular ammonia synthesis systems continue to decline.

Distributed Green Ammonia Cost Analysis

Cost factors

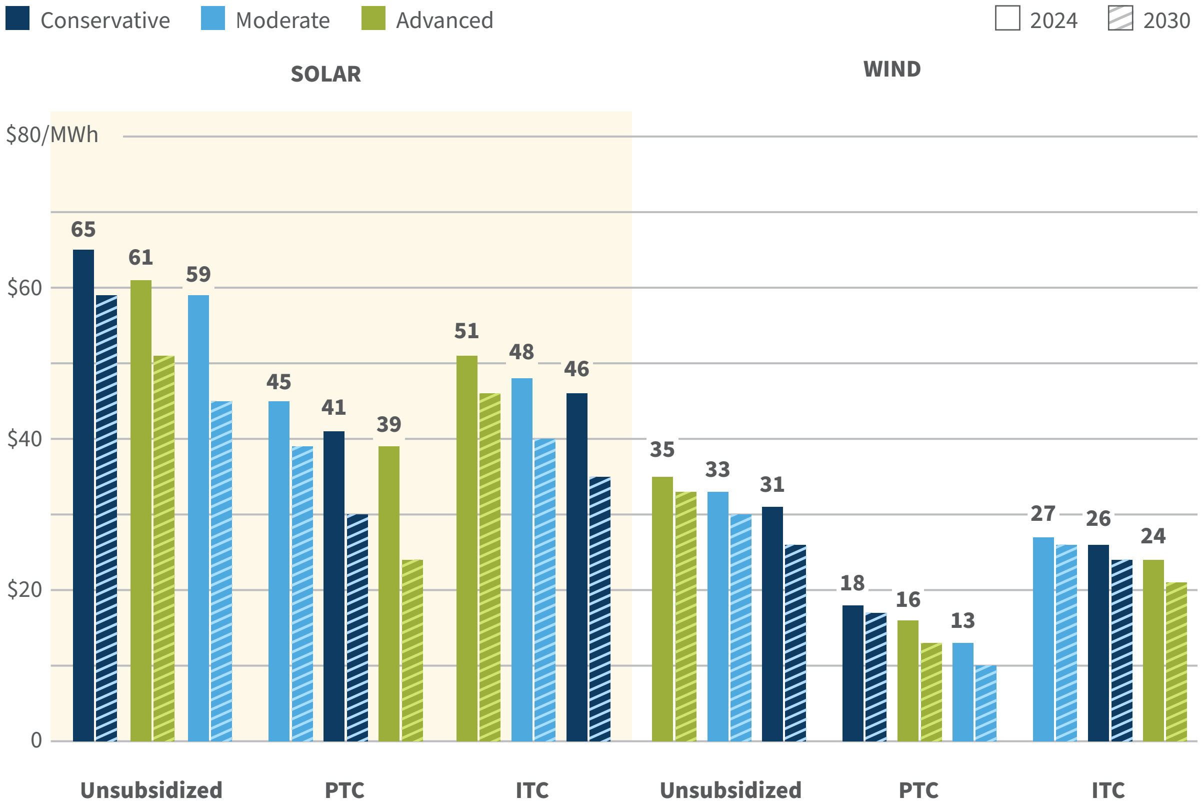
To calculate LCOA, the authors used a system optimization model they developed. This model designs an ammonia production system using various technical assumptions and market development scenarios. Such an approach makes it possible to determine the sensitivity of LCOA to changes in the main cost components — the cost of energy, the cost of hydrogen production, and the cost of nitrogen and ammonia production.

For a DGA project, energy is one of the primary cost factors, and it can vary within a wide range of 30%–80% of total LCOA, depending on the scenario. Whereas the cost of grey ammonia constantly fluctuates in response to natural gas price changes, the price of green ammonia is proportional to the cost of renewable energy (RE) available on-site.

Two power supply configurations were used in the analysis: behind the meter (BTM) and in front of the meter (FTM). In a BTM configuration, local RE generating and storing capacities are constructed to supply the ammonia plant. Energy supply and thus production rates depend on the wind and solar energy availability profiles in the plant location. By contrast, with an FTM configuration, energy is always available from the local energy grid. This decreases upfront project capital expenditures compared with a BTM alternative, because required feedstock production and storage capacities are lower.

A comparison between FTM and BTM energy supply configurations shows that FTM can provide a lower LCOA if energy cost is below \$40/MWh, though this cost is below average market prices. It is important to highlight that Minnesota has favorable conditions for RE generation, especially for wind; see for levelized cost of energy (LCOE) modeling results. By 2030, the cost of solar energy will drop significantly, and therefore the consumption profile will shift toward higher solar energy utilization (see Exhibit 11, next page). Total cost reduction in this share of LCOA is expected to be 15% by 2030. Moreover, modeling results for a 10 ktpa and 50 ktpa (see Exhibit 12, page 24) production scales, demonstrate that flexible DGA systems allow for lower cost of energy compared with large-scale ammonia production (see Exhibit 13, page 25).

Exhibit 11 LCOE for Solar and Wind Energy Generation in Minnesota Considering Scenarios with an Investment Tax Credit (ITC), Production Tax Credit (PTC), and Unsubsidized Energy Generation

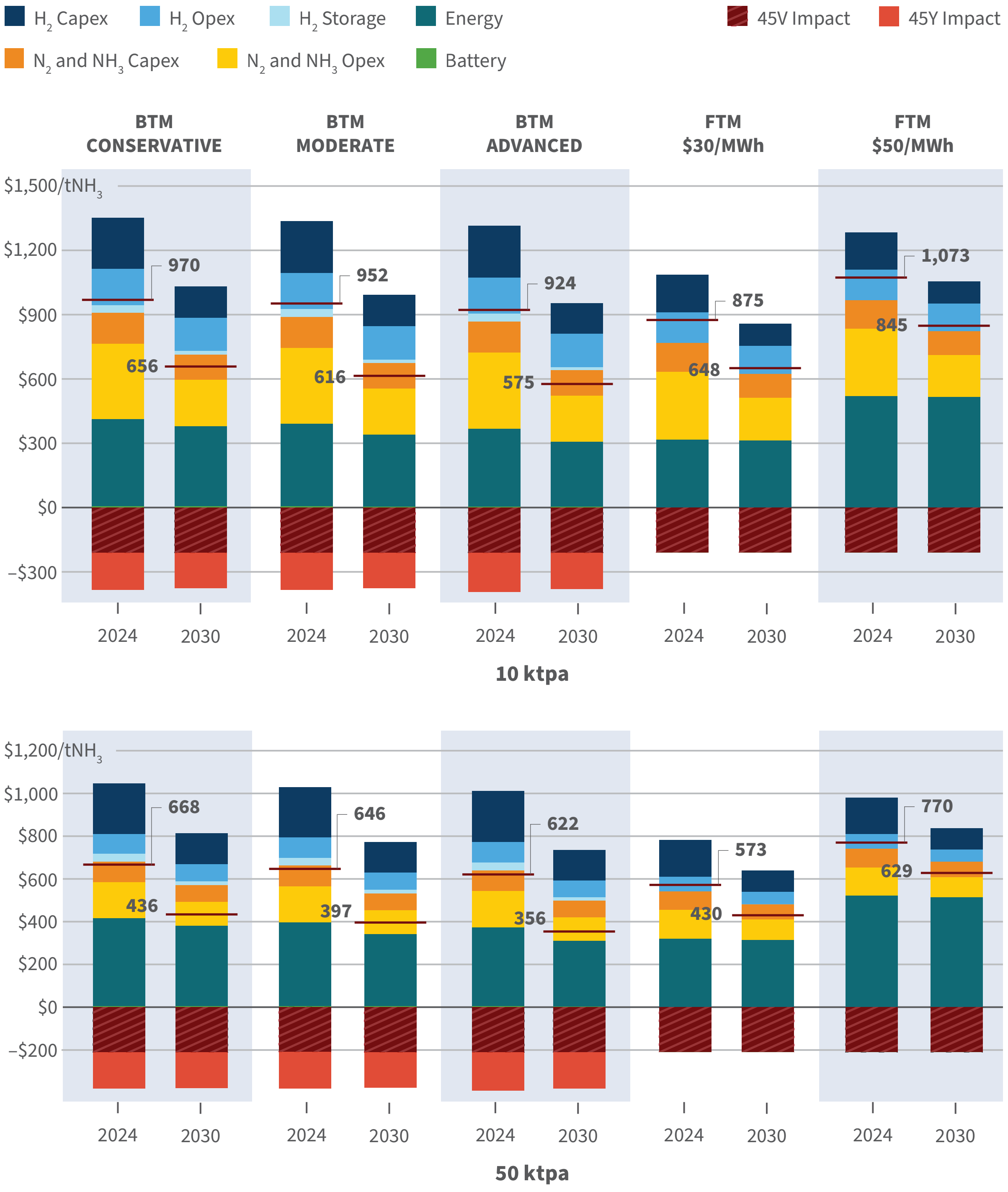


Note: LCOE calculation results. Three options of tax credit application were considered — unsubsidized energy generation, production tax credit (PTC), and investment tax credit (ITC). For each case three RE scenarios — conservative, moderate, and advanced (from left to right in each section of the exhibit) — from the Annual Technology Baseline (ATB) analysis by National Renewable Energy Laboratory (NREL) were used. Calculation was made for the most favorable locations in Minnesota. Bars are presented in pairs: The first bar represents 2024 results, and the second bar represents 2030 results. The DOE's Land-Based Wind Market Report: 2023 Edition states that an average unsubsidized LCOE of wind energy in the Midwest has reached the level of $32/MWh, based on data from already operational wind farms. As can be seen in the exhibit, this cost level nearly matches RMI's modeling result for 2024 using a moderate RE scenario from NREL ATB 2023.

RMI Graphic. Source: RMI analysis

Hydrogen costs can make up to 20% of a subsidized LCOA for a BTM configuration and are estimated to be around 3% for FTM projects, where energy is the major cost factor. Considering learning curves of electrolyzers and market dynamics, a 40% cost reduction in hydrogen is expected by 2030. Hydrogen expenses include capital expenditures and operating expenditures (opex) related to hydrogen production, operation, and maintenance, excluding energy costs. The dynamics of capital and operating expenditures associated with hydrogen show that the role of operating expenditures is most significant with small-scale production facilities, and that they decrease as ammonia production scales up. Hydrogen storage expenditures are relatively small across all analyzed scenarios. Analysis included deployment of pressurized canisters for DGA production and pipeline storage for large-scale systems, which is a cheaper option.

Exhibit 12 **LCOA Modeling Results for Two DGA Production Scales**

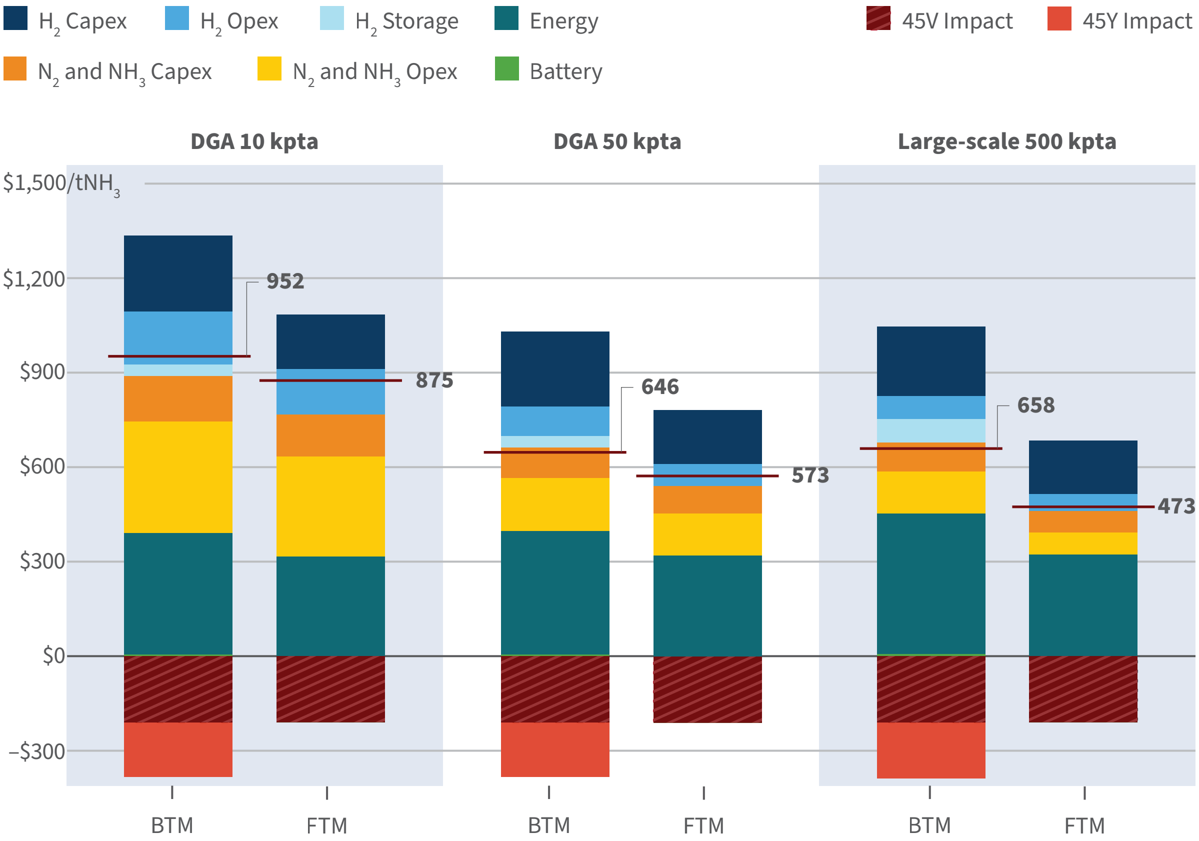


Note: The 10 kpta DGA comparison considers a BTM configuration with three RE scenarios from NREL ATB 2023, and a FTM configuration with two energy cost levels. Cost levels for 2024 and 2030 can be compared for each provided scenario. LCOA values are provided on top of the plot bars.

For the 50 ktpa DGA production scale, three RE scenarios for a BTM configuration and two energy cost levels for a FTM configuration are considered. Compared with a 10 kpta DGA, an increased ammonia production volume lowers the total LCOA by minimizing (1) opex related to hydrogen production, (2) capex related to nitrogen and ammonia production, and (3) opex related to nitrogen and ammonia production. Change of hydrogen-related capex and energy-related capex and opex is insignificant relative to the 10 ktpa production case.

RMI Graphic. Source: RMI analysis

Exhibit 13 Comparative Analysis of DGA and Large-scale Ammonia Production Pathways



Note: Green ammonia production is modeled using a moderate RE scenarios by NREL ATB 2023 and a $3/MWh FTM energy price for comparison. As can be seen, flexible DGA ammonia synthesis systems can allow a competitive LCOA level, compared with a large-scale electrified conventional Haber-Bosch system. With low energy costs, DGA systems become competitive with grey and blue production pathways. The analysis considered air separation units (ASU) to be deployed for DGA and pressure swing absorption units (PSA) to be used for industrial-scale production. DGA can benefit from flexibility and scalability of PSA systems because they are well matched with RE sources. Both ASU and Haber-Bosch reactors, by contrast, benefit from economy of scale.

RMI Graphic. Source: RMI analysis

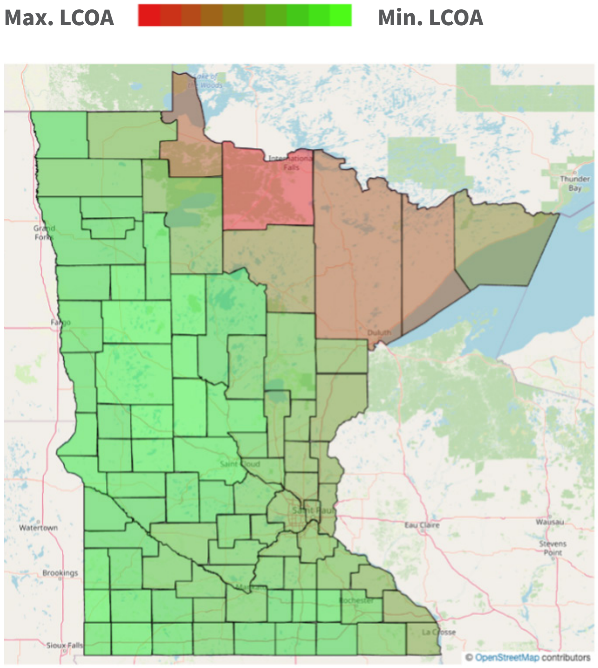
Costs associated with nitrogen and ammonia production account for 50% of a subsidized LCOA. Share of these costs is lower for an FTM configuration than for a BTM configuration, and it further declines for large-scale systems. As the DGA market matures, a 30% cost reduction can be achieved in this cost factor by 2030. EPC costs can comprise a significant share of the project budget, especially in developing sectors like hydrogen production and novel ammonia synthesis systems. Considering EPC costs, modular and stackable DGA systems can benefit from standardized feedstock production solutions as technologies evolve.

The last cost factor of LCOA is tax credits. Analysis considered 45V and 45Y tax credits, which were applied to hydrogen production and energy generation (for a BTM configuration) subparts of the ammonia production system. The 45Y incentives for RE generation include two available subsidy mechanisms: an investment tax credit (ITC) and a production tax credit (PTC). The financial calculation used the 45Y mechanism, which provides the lowest LCOE. As LCOA is calculated considering the whole service life of the ammonia plant, the total impact of the 45V hydrogen credit is lower relative to a credit value calculated over a single year.

Exhibit 14 shows LCOA distribution across Minnesota counties, reflecting the areas most favorable for DGA production. Locations with the cheapest energy allow for the lowest LCOA. The data used for the map doesn't include transportation costs, assuming that a DGA production facility is placed near end users.

Exhibit 14

A Map of LCOA for a BTM DGA Production Across Minnesota Counties



Note: Because a BTM DGA system in Minnesota would primarily use wind energy, DGA projects in central and western parts of the state, which have the most favorable wind conditions, would have the lowest production costs. A more accurate estimation of a particular production location would require consideration of other factors, such as permitting to construct required RE capacity and the suitability of ammonia for local soil.

RMI Graphic. Source: RMI analysis

Cost Dynamics and Competitive Position

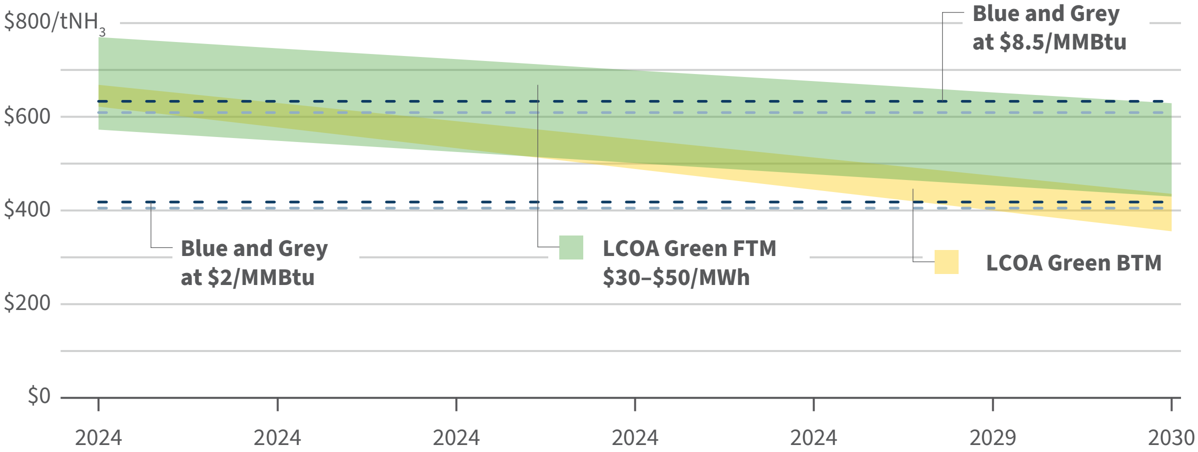
Regular fluctuations in natural gas prices and geopolitical factors abruptly inflating ammonia market prices (to \$1,600/tNH_3) indicate that DGA ammonia production is already a viable solution. Assuming highly favorable wind conditions, the western and central parts of Minnesota are the most feasible locations for BTM DGA projects. Today, with high natural gas prices, DGA production of 50 kilotons per annum (ktpa) can already be competitive with blue and grey pathways. By 2030, DGA production of 50 ktpa can reach cost parity with grey and blue ammonia pathways even considering moderate RE market forecasts and low natural gas prices (see Exhibit 15, next page).

A 10 ktpa–scale system will be cost-competitive in a scenario with moderate and high natural gas prices. LCOA levels for centralized grey and blue production pathways are presented in Exhibit 16 (next page). Recognizing that levelized production costs and market costs are different, this comparison allows for the estimation of feasible ammonia price ranges and the value of a green premium. Importantly, the share of transportation expenses in these LCOA calculations was estimated to be around \$180/tNH_3 (assuming ammonia delivery to Traverse County), while in unfavorable market conditions it can increase up to \$300/tNH_3. A DGA production pathway implies ammonia production close to end-users, therefore transportation expenses were excluded.

Compared with DGA systems, large-scale blue and grey ammonia facilities can be profitable in high-cost environments. Even if the feedstock price increases from \$2/million British thermal units (MMBtu) to \$5/MMBtu (an increase of 2.5 times, see Exhibit 16), the feedstock cost for the hydrogen production increases by less than two times. This shows that grey and blue ammonia plants have a reduced sensitivity to feedstock pricing. As DGA will have to compete with these production pathways, lowering production cost, especially by targeting improved system efficiencies and securing low electricity prices, will be essential to remain competitive.

From 2024 to 2030, there will be a steady decline in the LCOA for both FTM and BTM DGA systems, as shown in Exhibit 15. Both become increasingly competitive with blue and gray ammonia over time. In fact, market development and commissioning of new projects will lead to a significant decrease of equipment costs in DGA.

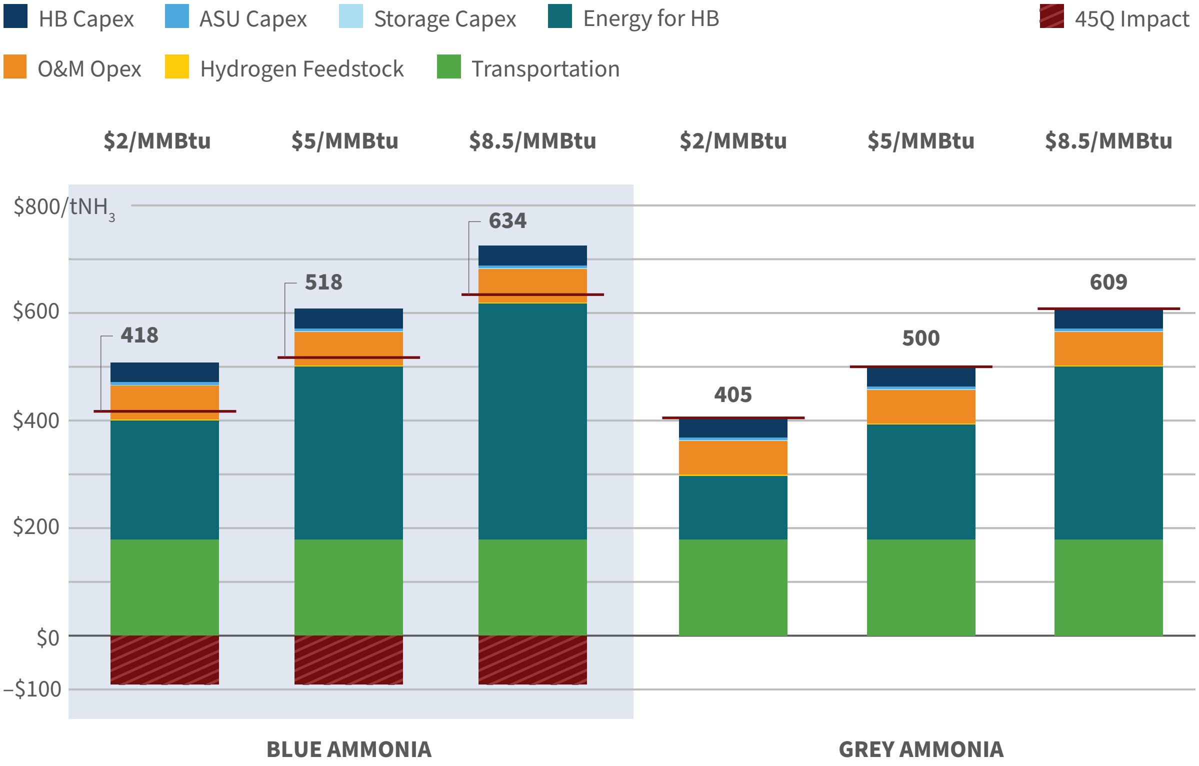
Exhibit 15 LCOA for FTM and BTM Green Ammonia Projects



Note: Projections of LCOA from 2024 to 2030 for BTM and FTM DGA systems at 50 ktpa in Minnesota compared with blue and grey ammonia production costs in the US Gulf. LCOA ranges for centralized blue and grey ammonia production are calculated with a natural gas price range of $2–$8.5/MMBtu.

RMI Graphic. Source: RMI analysis

Exhibit 16 LCOA for Blue and Grey Ammonia Production Considering Different Natural Gas Prices



Note: Delivered LCOA calculation results considering blue and grey centralized ammonia production in the Gulf using different market prices for natural gas prices from recent years: minimum ($2/MMBtu), average ($5/MMBtu), and maximum ($8.5/MMBtu). The capture rate for blue SMR is assumed at 85%. The application of 45Q incentive minimizes the cost difference between blue and grey ammonia. 45Q refers to the production tax credit based on the quantity of CO_2 captured and stored during the hydrogen synthesis process. The transportation cost assumes pipeline distribution from Louisiana to Iowa and distribution to demand centers in Minnesota by trucks.

RMI Graphic. Source: RMI analysis

This will result in an estimated 30% LCOA reduction for DGA ammonia pathways by 2030. With an estimated 20% learning curve effect for water electrolyzers and 10% for balance of plant equipment, there will be a 50% reduction in capital expenditures for both categories by 2030 due to a rapid growth of cumulative installed capacity in the coming years. For nitrogen synthesis equipment, a 10% total capital expenditure reduction by 2030 is expected. Novel small-scale ammonia synthesis systems cost will reduce 20% by 2030.

The importance of FTM systems accessing lower-cost electricity is evident in the projected decline in the LCOA for green ammonia. Access to cheaper electricity from diverse and large-scale power sources allows FTM systems to lower their operational costs over time, making DGA production increasingly competitive compared with blue and grey ammonia. As a result, the ability to tap into lower-cost grid electricity is crucial for driving down production costs and enhancing the economic viability of DGA.

Target Setting

The design of a coordinated plan for Minnesota to produce low-carbon fertilizers requires alignment between policymakers, investors, lenders, and developers to successfully deploy the first wave of DGA projects. Setting an ambitious target will help to anchor and measure the state's success in adopting green fertilizer, and new business models will help to scale successful frameworks.

Minnesota targets

To align DGA roadmap targets with existing statewide efforts, the overall 50% emissions reduction target from the **Minnesota Climate Action Framework** was used as an anchoring objective.[38] Drawing from 2020 production emissions, RMI established that total production emissions associated with annual Minnesota purchases of fertilizer is 2,267,991 tons CO_2e. Of those production emissions, 87% are attributable to nitrogen fertilizers. To meet annual Minnesota's nitrogen demand, approximately 900,000 tons of ammonia is needed. To reach a 50% reduction of emissions from ammonia production by 2030, the state would need to produce or import 450,000 tons of green ammonia per year. Achieving this target with production alone would necessitate a capacity of approximately 1 GW of electrolyzers and 2.5 GW of renewable energy. For context, no electrolyzer has been deployed in Minnesota, and the state will need to install new wind and solar that amounts to 40% of its current capacity of 6.3 GW to meet production requirements. To reach net-zero emissions by 2050, 2 GW of electrolyzer and 5 GW of renewable energy capacity dedicated to green ammonia production would be required, according to projections (see Exhibit 17).

Exhibit 17 **Minnesota Ammonia Targets**

🟦 Targets

Year	CO_2 Reduction	Ammonia Production Capacity	Required Electrolyzer Capacity	Required Renewable Energy Capacity
2030	50%	450 kt per year	1 GW	2.5 GW
2050	Net-Zero	900 kt per year	2 GW	5 GW

RMI Graphic. Source: RMI analysis

Business Models and Project Finance Risk Mitigation

Getting the first wave of projects off the ground will help de-risk DGA, spurring deployment of new systems in the future, which will ultimately help Minnesota reach its 2050 emissions reduction target. Effective business models play a crucial role in risk mitigation when structured appropriately. In the context of DGA projects, the initial focus is on minimizing risks associated with technology and offtake. Technology risks stem from DGA's novelty and its relatively low commercial maturation. Offtake risks center on securing a long-term offtake agreement from a creditworthy off-taker. It is paramount to address both.

Mitigating these risks commences with meticulously structuring project finance and contracts. This entails crafting offtake agreements tailored to the specifics of the project, considering factors such as the type and duration of the agreement. Establishing a suitable legal and business entity, often through a special purpose vehicle (SPV), offers insulation from liability. For smaller-scale ventures, joint ventures can be considered. Key tools for minimizing risk in project financing include assessing offtake contracts, prioritizing the creditworthiness of off-takers, and opting for SPV structures to shield parent companies from direct exposure. Evaluating the efficacy of these business models necessitates a comprehensive examination of their ability to address the unique risks inherent in DGA projects while also fostering profitability.

Beyond these tools, factors that determine the efficacy of a green ammonia business model include the type of offtake contract (i.e., length and price arrangements) and the ownership structure. The risk tolerance of investors, off-takers, and project developers informs both of these arrangements.

In considering pricing structures for ammonia offtake agreements, options include: (1) fully flexible price model; (2) floor-to-ceiling price model; and (3) fixed-price model. The fully flexible price model mirrors the current system in fertilizers, offering familiarity for off-takers but potentially making it more challenging for project developers to secure financing from lenders because the product price is unpredictable. The floor-to-ceiling price model offers the advantage of prearranged floor and ceiling prices, providing a semi-floating price for off-takers, yet it carries inherent risk because it relies on price estimations. Lastly, the fixed-price model offers a steady income stream and increases the likelihood of securing financing from lenders, although it may pose difficulties for agricultural co-ops seeking to enter into such offtake agreements.

In terms of length, short-term agreements are commonplace in the fertilizer market, whereas long-term agreements, though less common in this sector, can be instrumental in securing financing for ammonia projects. In general, conventional ammonia contracts are short term, with prices anchored to CFR Tampa spot prices — the benchmark for ammonia prices that fluctuate according to natural gas price variability. However, longer-term contracts, similar to power purchase agreements for clean electricity, might be generally preferred given the nascency of green ammonia projects.

As for ownership structures for these projects, a variety of actors within the ammonia ecosystem can be involved. During initial deployment of DGA projects, OEMs will likely play a role in demonstrating commercial proof of concept. However, traditionally, we would see initial ownership from project developers, often following a build-operate-transfer model. Co-ops, whether electric or agricultural, could also take ownership of DGA projects. Although co-ops might lack expertise in operating DGA systems, co-op ownership would directly reduce reliance on external suppliers for ammonia required for electricity or agricultural applications. Another ownership model could involve ethanol producers, where ethanol facilities would own a DGA facility to combine ammonia with captured biogenic CO_2 to produce low-carbon urea.

Standard Business Model

As an example, consider a standard business model where an agricultural co-op represents the primary revenue source (see Exhibit 18, next page). In such a scenario, risks related to technology and off-taker creditworthiness must be mitigated. The agricultural co-op's involvement introduces revenue stability but also necessitates careful management of technological risks associated with this novel ammonia production process. Technology risk can be mitigated through the involvement of credible project developers and technology providers. Additionally, ensuring the creditworthiness of the off-takers becomes crucial to guarantee consistent revenue streams and overall project viability. Both of these factors determine the willingness of investors and lenders to provide capital and the overall economic sustainability of the project, which can be addressed through long-term offtake agreements and credible players involved in the project development.

Co-op Owned Business Model

An alternative business model involves direct ownership from agricultural co-ops. Although this model presents similar challenges as the standard business model, it relies on farmers for the only revenue stream, so the project's feasibility hinges primarily on revenue stability. Without a direct offtake agreement in place, ensuring the economic viability of the project becomes uncertain. However, agricultural co-ops would gain full control over their supply chain, thereby avoiding additional costs incurred through intermediaries.

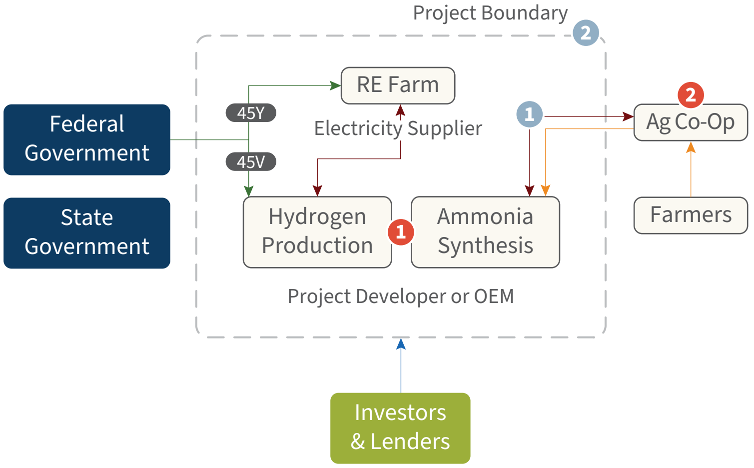
Moving Forward

These are just a few of the high-level risk considerations and mitigation tools project developers will encounter when assessing business models. Additional mitigation tools will vary depending on each project's specifics. Apart from economic tools, those developing a DGA project should also explore how policy can reduce overall investment risks.

Exhibit 18 Standard and Co-Op-Owned Business Models

→ Capital/Investments → Incentives → Revenue ↔ Bilateral Offtake Agreement

STANDARD



KEY RISKS

① **New Technology** — DGA projects are still in their first commercial wave.

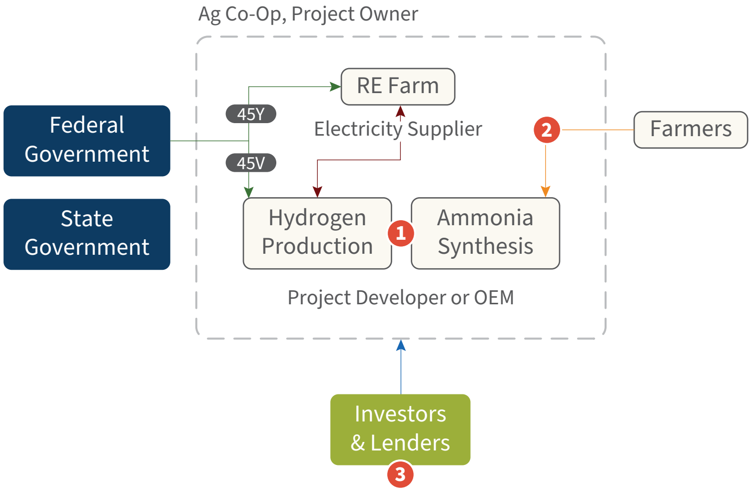
② **Creditworthiness** — Suppliers should ensure ag co-ops are at least medium-sized and financially sound.

DYNAMICS

① **Contract** — Length and type of contract will mainly determine the economic viability.

② **Ownership**— Different types and players could be involved in the ownership, from ag co-ops to OEMS.

CO-OP-OWNED



KEY RISKS

① **New Technology** — DGA projects are still in their first commercial wave.

② **Revenue Stability** — Farmers, unless locked into an offtake agreement, do not represent a stable income source.

③ **Securing Financing** —Without having secured a large, credit-worthy offtaker, it might be more difficult to convince lenders.

RMI Graphics. Source: RMI analysis

Key Recommendations

Future Policy Considerations

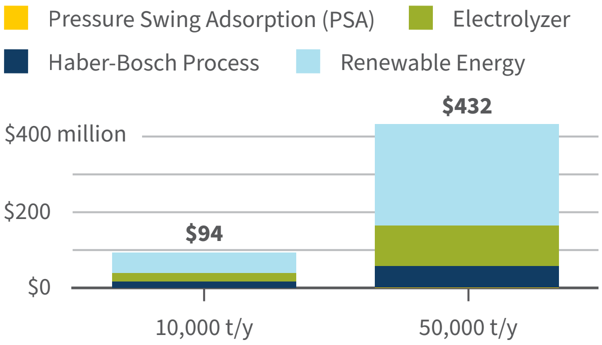
Policy Recommendation 1: Allocate Minnesota's green fertilizer grant for maximum impact

The Minnesota Department of Agriculture (MDA) is currently reviewing feedback received from stakeholders in its request for information on how to design the fertilizer grant program.[39] MDA can consider different alternatives to leverage the $7 million in current funding, along with potential additional funding, for maximum impact to help accelerate the first wave of DGA projects in the state.

Green ammonia plants, even relatively small-scale distributed ones, are capital intensive. Estimated capital expenditures for 10 ktpa and 50 ktpa systems range from $94 million to $432 million, including capital expenditures for RE generating capacity (see Exhibit 19). The broad goals of the grant are to support deployment of the first wave of projects and move the state toward reaching the proposed production targets. In addition, these initial projects can serve as case studies to help future projects raise capital and reach final investment decision.

Exhibit 19

Total Capital Expenditure of Main Equipment for Distributed Green Ammonia Production Systems



RMI Graphic. Source: RMI analysis

This list is not meant to be exhaustive, and some options might not be permitted under the current grant guidance, but it is presented here to encourage more radical thinking:

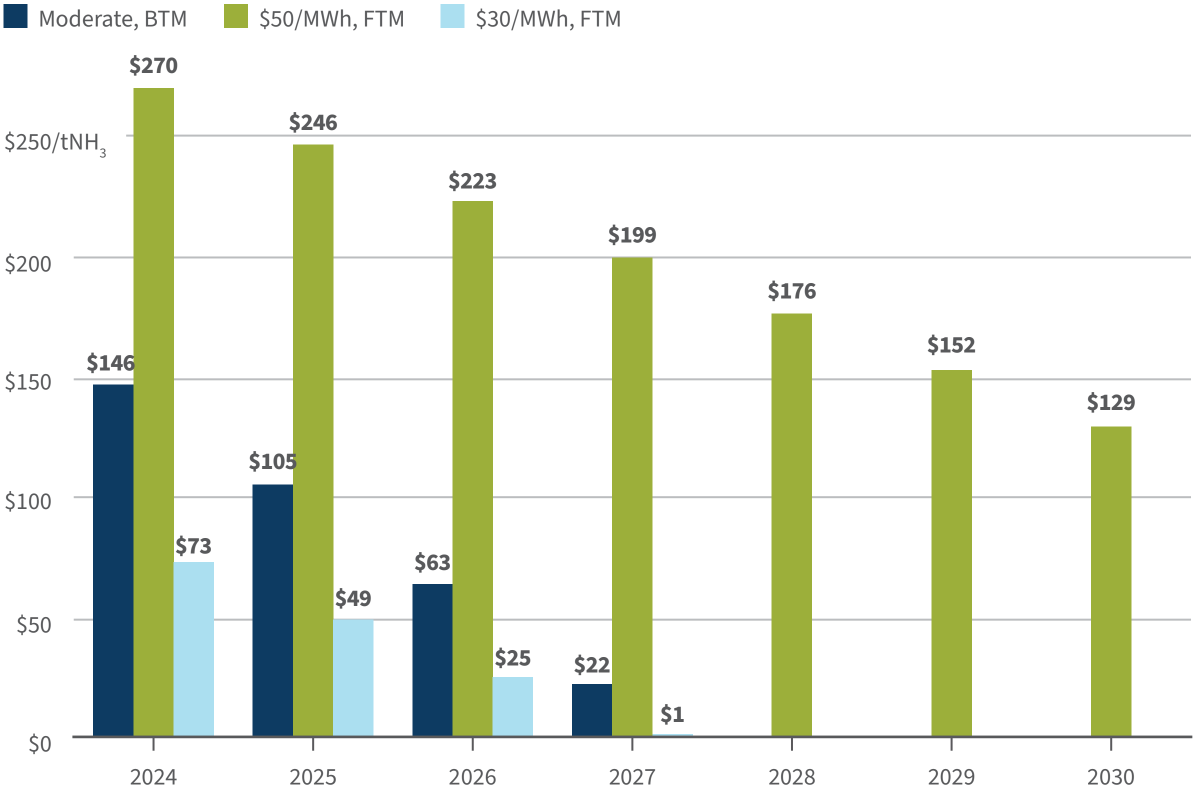
- Provide direct capital expenditure support for one project. For a single, 10 ktpa system this could offset more than 7%, whereas supporting a 50 ktpa system would offset only 2% of project costs.
- Fund pre-feasibility and feasibility studies for DGA systems to support developers and ensure that the grant facilitates practical, data-driven decisions for implementing decentralized ammonia production facilities in Minnesota.
- Provide funding as cost share if projects unlock federal funds such as LPO loans, up to a specified amount per project (or limited based on estimated production).
- Fund a supply-side competitive auction for green ammonia production. This would help close the gap with conventional ammonia by awarding contracts to producers that can offer the most competitive production volume with offtake agreements at the lowest subsidy required (see Policy Recommendation 2).

Policy Recommendation 2: Design a competitive mechanism to provide subsidies to make DGA projects bankable

DGA projects need offtake agreements to be bankable and reach final investment decision. Also, as shown in Exhibit 20, green ammonia projects are more expensive than conventional ammonia in the short term, making it difficult to close these offtake agreements. Based on the available budget and the deployment targets, Minnesota could fund a competitive auction to incentivize green ammonia for fertilizer production, in a structure similar to the one used by the European Hydrogen Bank.[iv]

Exhibit 20 provides a sense of the range of the premium needed to design an auction system. The cost gap between DCA and grey ammonia will vary based on the financial situation of each project and developer, and it does not have to be fully covered by state funding. However, Minnesota can play a crucial role in closing the gap by providing the needed funding to developers to close offtake agreements, ensure demand, and make these projects financially viable.

Exhibit 20 **Cost Gap Between DGA and Grey Ammonia**



Note: This exhibit illustrates three cost scenarios for a DGA facility of 50 ktpa: (1) Moderate, BTM; (2) $50/MWh, FTM; and (3) $30/MWh, FTM. The 2024 and 2030 LCOA values for each of these scenarios is drawn from Exhibit 13, and those values are then compared with the cost of grey ammonia production at $5/MMBtu ($499.69/tNH$_3$) to establish the cost gap.

RMI Graphic. Source: RMI analysis

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iv The European Hydrogen Bank uses an auction system where companies bid to win a set amount of money (the premium) per kilogram of clean hydrogen they produce over a specific period.

The auction process could have the following criteria:

- **Eligibility:** Establish eligibility criteria for producers, including offtake agreements, carbon intensity thresholds, and a minimum production capacity.

- **Bidding:** Producers submit bids specifying:
  - The amount of green ammonia they can produce over a defined period (e.g., per year).
  - The minimum subsidy required per ton to sign the offtake agreement.

- **Evaluation and awarding contracts:** The auctioneer (a Minnesota government agency) would evaluate bids based on factors such as:
  - Cost competitiveness: producers that require the lowest amount of support to fulfill the supply contract.
  - Project viability: the technical and financial feasibility of the proposed production process.

- **Subsidy to close the gap:** Winners would be awarded contracts guaranteeing the requested subsidy per ton of ammonia produced for a set period. The government would essentially pay part of the difference between the production cost of incumbent grey ammonia and the producer's production cost for green ammonia. The subsidy can be a fixed premium on top of hydrogen offtake prices.

Additional considerations:

- **Reference production cost:** Minnesota can establish a reference cost for grey ammonia. This could be based on the average market cost of conventional grey ammonia. For example, Exhibit 20 presents the cost gap of $500 per ton of ammonia with a natural gas price of $5/MMBtu for different configurations of green ammonia versus grey ammonia.

- **Budget constraints:** The total program budget available would likely influence the final subsidy provided, where only viable projects that require a lower subsidy would be competitive in the auction.

Policy Recommendation 3: Provide access to lower capital cost with guaranteed loans

Co-ops can leverage LPO loans to access capital for the equipment needed for green ammonia production at a lower interest rate than conventional loans. LPO loans require projects to be innovative, implementing a technology that is not widely currently available on the market, such as DGA.

The recently created Minnesota Climate Innovation Finance Authority is seeking public comments through a request for information to act as a State Energy Financing Institution (SEFI) and leverage federal LPO funding.[40] Since SEFI-supported projects are exempt from the innovation requirement, Minnesota's green bank could co-lend loans with the LPO to produce green ammonia using commercial technologies, improving access to low-cost capital from federal funding.

Loans guaranteed with LPO funding can provide better interest rates than commercial banks, lowering the cost of capital and boosting the projects' financials. As of June 2024, the interest rate for the LPO's Title 17 projects was around 5%, notably lower than the 7% used in this report's analysis of BTM DGA systems (see Exhibit 21).[41]

The state can also develop its own loan program. North Dakota has adopted this model, where the legislature provides the Bank of North Dakota with $150 million for its Clean Sustainable Energy Loan Fund for green fertilizer projects in the state.[42]

Exhibit 21

Comparison of the Impact of a Lower Interest Rate on LCOA in 2024

Interest Rate	LCOA \$/tNH$_3$
7%	$646
5%	$630

RMI Graphic. Source: RMI analysis; LPO's Title 17 financial program, **https://www.energy.gov/lpo/articles/pricing-lpo-financing-program**.

Policy Recommendation 4: Advocate to unlock existing USDA funding streams that aim to increase national production of fertilizer

The United States Department of Agriculture (USDA) has immediate opportunities to support green ammonia production for fertilizers. The USDA's Rural Energy for America Program received $145 million in funding from the IRA for 700 loans and grants to expand access to renewable energy.[43] In addition, the Fertilizer Production Expansion Program awarded $500 million in grants to increase US-made fertilizer production to spur competition and combat price hikes on US farmers.[44] Considering the importance of fertilizer in the state, Minnesota could advocate for the USDA to launch another round of the Fertilizer Production Expansion Program, focusing on DGA systems.

Policy Recommendation 5: Ensure an enabling environment for DGA deployment in the state

- **Workforce training:** Incentives to support workforce development through training and skills programs will be necessary for the establishment and longevity of this new industry. Minnesota can adapt existing grant programs, such as the training grant programs form the Minnesota Department of Employment and Economic Development (DEED), to develop the new workforce for green ammonia and hydrogen projects.[45]

- **One-stop shop permitting:** A one-stop shop permitting initiative would expedite the deployment of green hydrogen and ammonia production infrastructure, enhancing efficiency and reducing costs while minimizing uncertainty and simplifying project management. It should involve implementing streamlined approaches to permitting and regulatory approval, along with developing clear guidance on hydrogen and ammonia permitting, with stakeholder engagement focusing on environmental, energy, and equity priorities. The initiative should also aim to facilitate project rollout by enabling quick commissioning through centralized permitting processes and environmental impact assessments. As an example, the EU, through the Net-Zero Industry Act, sets a 12-month permitting time limit for hydrogen projects with an annual capacity equal or less than 1 GW.[46]

- **Develop clear guidance for green ammonia certification:** Leveraging Minnesota's founding role in the Midwest Renewable Energy Tracking System (M-RETS), policymakers can establish clear criteria and definitions for what constitutes green ammonia within the M-RETS system. M-RETS will play a key role in providing the tracking infrastructure that developers can use to comply with 45V federal tax credits for hydrogen production because it anticipates issuing hourly renewable energy certificates during the next 12 to 18 months.[47] This can provide a foundation for a green ammonia certification scheme.

Moving Forward

The deployment of DGA systems to help decarbonize fertilizer emissions in Minnesota faces unique challenges. The evolution of ammonia to serve new markets will have a price-setting impact that could make it difficult for new players and projects to succeed in the fertilizer industry. In addition, the lack of product differentiation for fertilizers makes it challenging to increase buyers' willingness to pay for and thereby incentivize green fertilizer offtake without a green certification or other label that adds value in the market. Given the importance of fertilizers to the state's agriculture sector and the complex market dynamics, Minnesota should take a comprehensive and coordinated approach to design and implement policies to understand the impact of the different levers available

Future Work

There are multiple avenues to explore beyond the roadmap for DGA production presented here. Additional areas for research and analysis include:

- Evaluating applications of ammonia beyond fertilizers and how demand can smooth out the seasonal demand of ammonia for fertilizers
- Exploring additional policy and market mechanisms to accelerate green ammonia production and use across the Midwest
- Identifying the most effective low-carbon nitrogen fertilizer options and alternatives to decrease overall consumption emissions and assessing the most suitable solution to fully decarbonize the fertilizer sector
- Understanding the techno-economic feasibility and CO_2 sourcing for low-carbon urea as well as the infrastructure buildout needed to guarantee effective carbon management and utilization
- Engaging an array of stakeholders, including DGA ammonia suppliers, fertilizer distributors, farm groups, and state policymakers, to raise awareness of the DGA opportunity and accelerate project deployment

Conclusion

Minnesota is uniquely positioned to take advantage of DGA. The current centralized ammonia production system can provide farmers with low-cost fertilizer, but also exposes farmers to price volatility and supply chain disruptions. Localized, distributed ammonia production can complement the existing system to hedge against negative outcomes as well as reduce emissions from fertilizer production.

To enable the deployment of DGA projects in the state, credible consortia with effective business models and targeted policy support should be prioritized. Critically, easier access to capital tools, supplementary subsidies to offset the initially higher production cost of green ammonia, certification schemes to differentiate green ammonia from conventional production, faster permitting tracks, and in-state workforce training need to be introduced to fully realize the benefits and opportunities presented by DGA in the state. The cost of DGA is likely to fall rapidly as modular, containerized systems are able to take advantage of lessons learned by the first systems to be deployed and of rapid, iterative improvements in manufacturing.

The successful implementation of DGA projects in Minnesota and beyond hinges on collaborative efforts, innovative solutions, sound business models, and robust policy frameworks. By addressing these areas of further work and seizing opportunities, Minnesota can unlock the full potential of DGA and pave the way for a sustainable future in agriculture and beyond.

Appendices

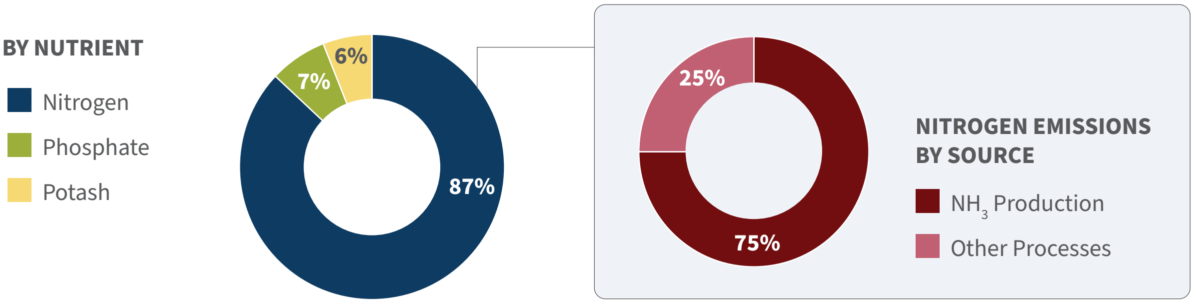
Appendix 1: Emissions from Fertilizer Production

Emissions stemming from fertilizer production are highly dependent on the nutrient produced. Three nutrients are needed for healthy plant growth: nitrogen, phosphorus, and potassium (potash). Phosphorus and potash are extracted from deposits and have comparatively low production emissions; in contrast, conventional nitrogen fertilizers are directly reliant on fossil fuels, incurring substantial emissions. This issue is exacerbated because nitrogen is the most critical — and subsequently the most used — fertilizer nutrient for plant growth.

All synthetic nitrogen fertilizers use ammonia as a precursor. Ammonia itself can be used as a fertilizer in the form of anhydrous ammonia. Conventional ammonia synthesis begins with hydrogen production via steam methane reformation (SMR), a carbon-intense process in which hydrogen is extracted from natural gas. Next, the hydrogen is combined with atmospheric nitrogen using the Haber-Bosch process, yielding ammonia. Accounting for the natural gas and energy consumption, producing 1 ton of ammonia emits around 2.34 tons of CO_2, equaling 2.85 tons CO_2 per ton of nitrogen. For comparison, the most common potash fertilizer, muriate of potash, has a per nutrient carbon intensity of 0.42 tons CO_2 per ton potash.[v] The stark difference in per nutrient carbon emissions illustrates why nitrogen is the primary nutrient contributing to fertilizer emissions. Further processing of ammonia into other nitrogen-based fertilizers will incur additional emissions based on fuel and electricity consumption needs and will further increase the per nutrient carbon intensity.

A look at fertilizers purchased in Minnesota confirms the dominance of nitrogen as the driver of production emissions. In 2020, nitrogen sales made up half of Minnesota's nutrient tonnage purchased but accounted for 87% of total associated production emissions. Exhibit A1 illustrates that nitrogen emissions significantly outpace emissions from other nutrients, with the main driver being the production of ammonia.

Exhibit A1 **Production Emissions Breakdown of Fertilizer Nutrients Purchased in Minnesota**



RMI Graphic. Source: RMI Analysis; MDA, **https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data**; International Fertiliser Society, **https://www.fertilizerseurope.com/publications/the-carbon-footprint-of-fertilizer-production-regional-reference-values/**; Brentrup et al., **https://www.researchgate.net/publication/329774170_Updated_carbon_footprint_values_for_mineral_fertilizer_from_different_world_regions**

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[v] Based on RMI analysis.

The SMR process to separate hydrogen from natural gas produces over half of the production emissions associated with ammonia. Since hydrogen is used a chemical feedstock, the only way to decarbonize this component of the value chain is to produce hydrogen cleanly, with electrolysis powered by renewable energy. If renewable energy is also used to power the auxiliary stages of ammonia and fertilizer production, emissions are eliminated and what remains is a zero-carbon, green ammonia product.

A special case arises with the popular and versatile fertilizer urea. In 2020, urea and other urea-based fertilizers made up over 62% of Minnesota's total nitrogen sold, reflecting a broad preference for urea. Urea is currently produced in integrated facilities where conventional ammonia production routes the CO_2 stream from the SMR flue to the ammonia outlet where they are combined to form urea. Using this method, some of the CO_2 emissions from SMR hydrogen production are temporarily captured within the urea, though they will be released downstream during usage.

Due to urea's reliance on CO_2, decarbonizing urea production must involve a net-zero source of carbon. Biogenic CO_2 emerges as the most attractive candidate for early production, as alternatives such as direct air capture are far out from commercial viability. Minnesota has ample sources of biogenic CO_2 from its ethanol refineries, as well as a number of pulp and paper mills. This route is already being considered through the Heartland Hydrogen Hub, a DOE-funded project that spans Minnesota, North Dakota, and South Dakota. As part of the hub, Xcel Energy is planning a large-scale urea plant that use CO_2 offtake from ethanol refineries combined with green ammonia.[48]

It is important to note that Minnesota does not produce its own fertilizers but instead imports fertilizer from other states. In addition to production emissions, transportation of fertilizer incurs emissions at different rates depending on method. This dimension was analyzed to gauge its impact as part of the whole fertilizer value chain.

Emissions from Fertilizer Transportation

Since conventional ammonia production relies on natural gas as a feedstock, ammonia production is found primarily in regions with large oil and gas operations, such as the US Gulf Coast. Fertilizer produced in the Gulf Coast is distributed across the country by truck, rail, water, and pipeline, with trucking and rail carrying the vast majority of fertilizer tonnage. Rail is typically used for longer distances, carrying larger volumes, whereas trucks are used for distribution along shorter routes. Trucking is much more carbon intensive than rail: in 2017, national transportation of fertilizer using only trucking contributed over 10 times the emissions as fertilizer transported by only rail.[vi]

Emissions from fertilizer transportation to Minnesota were estimated to be around 130,000 tons CO_2. Compared with the total life cycle of said fertilizers, transportation amounts to only 1.7% of total emissions. While comparatively small, emissions savings can still be achieved through distributed ammonia production by producing fertilizers onsite, negating the need for transportation.

Urea, again, presents a unique scenario, this time within the discussion of transportation. A complicating factor in the integration of biogenic CO_2 for green urea production is the transportation of CO_2. Although CO_2 pipelines are an established technology, pipelines would be difficult to integrate into the decentralized model because an extensive network would be needed. An alternative would be trucked CO_2, with the trade-off being increased cost and potential associated transportation emissions. These constraints may signal green urea production is more suited for a centralized, dedicated plant position close to its CO_2 source.

Emissions from Fertilizer Usage

The usage of fertilizers releases emissions upon application to the soil. Nitrogen fertilizers are especially polluting and are responsible for nearly all use emissions. When applied, a proportion of nitrogen is lost through denitrification, in which organisms convert fertilizer to nitrous oxide (N_2O). N_2O is a greenhouse gas 298 times more potent than CO_2 that diffuses through the soil and is lost to the air. Though released in small quantities, the intensity of N_2O has significant ramifications for the climate. Assuming all fertilizer purchased in Minnesota in 2020 was used, Minnesota experienced approximately 5.6 million tons of CO_2e emitted due to fertilizer use alone, around 2.5 times the emissions associated with the production of said fertilizers.[vii]

Herein lies Minnesota's main fertilizer emissions problem. As discussed above, fertilizer production does not occur in Minnesota; it is instead imported from out-of-state. With transportation emissions low, emissions actually occurring in Minnesota are almost entirely due to fertilizer use. Unfortunately, this issue cannot be solved by green ammonia, since the end product is identical to its conventionally produce counterpart and will behave identically.

In addition to denitrification, the loss of nitrogen to the atmosphere as gaseous ammonia, or volatilization, can occur when nitrogen is reconverted to ammonia in the soil. This results in an indirect loss of nitrogen as N_2O. Gaseous losses are greatest with surface application due to proximity to the atmosphere. Another way nitrogen can be lost is with leaching, where nutrients move past the roots of plants where they cannot be absorbed. This is more likely to happen with fertilizers that are converted into nitrate in the soil, which is not held on to by soil particles. The likelihood of nitrogen loss is not only dependent on the fertilizer used. Soil conditions, such as acidity, temperature, and moisture, can affect how much nitrogen is lost.

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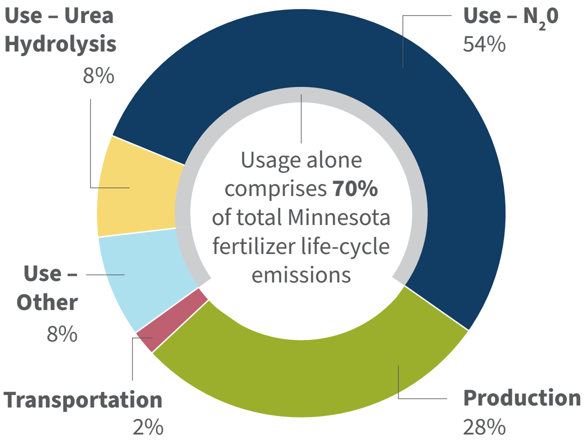
vi RMI analysis
vii RMI analysis

Urea is unique in the emissions attributed to it. As explained above, urea requires a source of CO_2 in its production — CO_2 that is initially captured within the fertilizer but released upon usage in a process called urea hydrolysis. To have a truly green product, the CO_2 for production must come from net-zero sources such as biomass. But urea does not only emit CO_2; it is one of the highest emitters of N_2O. Urea is not readily absorbed by crops, so it must be converted to ammonium and nitrate. This process begins with the hydrolysis process mentioned above: The naturally occurring soil enzyme urease converts urea into ammonia and carbamic acid (part of carbamic acid ultimately becomes CO_2 and is released to the atmosphere). A portion of the ammonia will be lost to the atmosphere as gas before it can be converted to ammonium and nitrate. These issues are exacerbated by urea's common surface application use as a top dressing.

Fertilizer usage emissions are also exacerbated by inefficient use (see Exhibit A2). Excess nitrogen applied is lost to the environment with no benefit. An important step to addressing fertilizer emissions is increasing nitrogen use efficiency, which has been found to be the single most effective method to reduce fertilizer emissions.[49]

Exhibit A2

Total Emissions Attributable to Minnesota Fertilizer Purchases by Value Chain Component



RMI Graphic. Source: RMI Analysis; MDA, **https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data**; International Fertiliser Society, **https://www.fertilizerseurope.com/publications/the-carbon-footprint-of-fertilizer-production-regional-reference-values/**; Brentrup et al., **https://www.researchgate.net/publication/329774170_Updated_carbon_footprint_values_for_mineral_fertilizer_from_different_world_regions**; US CBO, **https://www.cbo.gov/publication/58861**; US Census Bureau, **https://data.census.gov/table/CFSAREA2017.CF1700A13?q=cf1700a13&comm=22**; USGS, **https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information**

Inhibitors can be deployed with fertilizers to decrease nitrogen loss. Urease inhibitors, specific to urea use, apply a coating to urea that restricts the process of urea hydrolysis and subsequently the formation of ammonia, which prevents loss of that ammonia as gas. Regulation of urea has precedent; Germany requires the addition of a urease inhibitor when urea is used. Another form of inhibitor is a nitrification inhibitor, which delays the conversion of ammonium to nitrite. This gives crops more time to absorb ammonium while reducing nitrification, the process that releases N_2O to the atmosphere. Nitrification inhibitors can also prevent leaching since ammonium is held by soil, in contrast to nitrate (which nitrite converts to), which travels past the roots. Application can affect the output of emissions, too. Quickly incorporating urea into the soil or injecting urea, rather than simply applying it the topsoil, can limit the loss of nitrogen. However, this is not always possible due to various constraints such as no-till zones.

Ultimately, the most effective mitigation method for urea involves a transition away from urea and urea-based fertilizers to alternative nitrogen fertilizers. Urea and urea ammonium nitrate could be replaced by fertilizers that perform better on a use emissions base, such as ammonium nitrate.[50] Ammonium nitrate's nitrogen is readily available for crop uptake and does not suffer from use emissions to the same degree as urea.

The issue of fertilizer use requires more investigation because it represents more than twice the emissions of fertilizer production. Emissions mitigation is best used in tandem; Gao and Serrenho have found that combining a variety of use-based emissions mitigation approaches with green ammonia production can reduce 84% of worldwide synthetic nitrogen fertilizer emissions by 2050.49 For Minnesota, a holistic reduction of agriculture emissions requires a collection of mitigation efforts that include a deep look into use emissions. However, deployment of green ammonia is an important step to decarbonization of the industry.

Appendix 2: Model Methodology and Additional Information

We utilized an optimization model to assess the competitive position of DGA in Minnesota and evaluate its main cost factors and their dynamics. This model allows the analysis of levelized cost of green ammonia production for a given geographical location under various market scenarios.

Renewable Energy Generation Assumptions

Scenario	Unit	Value
CONSERVATIVE 2024		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1333.32
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind Operations & Maintenance (O&M)	$/kW-year	29.75
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1331.39
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005
MODERATE 2024		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1292
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	29.20
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1289.51
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005

Scenario	Unit	Value
ADVANCED 2024		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1273.96
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	28.10
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1259.24
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005
CONSERVATIVE 2030		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1273.96
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	28.65
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1205.96
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005
MODERATE 2030		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1150.00
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	27.00
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1038.44
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005

Scenario	Unit	Value
MODERATE 2030		
Wind Lifetime	years	30
Onshore Wind Capex	\$/kW	1095.87
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	\$/kW-year	23.70
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	\$/kW	917.37
Solar Degradation	%/year	0.005
Solar O&M	\$/kW-year	0.005

Ammonia and Nitrogen Production Assumptions

Production Scale	10 ktpa	50 ktpa	500 ktpa
Cost of a HB Reactor	\$1,726/tNH_3	\$1143/tNH_3	\$630/tNH_3
Cost of Pressure Swing Adsorption (PSA)	\$48/tN_2	\$26/tN_2	–
Cost of Air Separation Unit (ASU)	–	–	\$140/tN_2

Assumptions for Blue and Grey Ammonia Production Pathways

Parameter	Value
Capex Grey Steam Methane Reformer (SMR)	\$713/kgH_2 per day
Opex Grey SMR	\$22.11/kgH_2 per day
Capex Blue SMR	\$1735/kgH_2 per day
Opex Blue SMR	\$48.66/kgH_2 per day
Capture Rate Blue SMR	85%
Value of 45Q*	\$0.51/kgH_2
HB Capex	\$500/tNH_3
ASU Capex	\$75/tNH_2
NH_3 Storage	\$160/tNH_3
ASU & HB O&M	4% of Capex
Storage O&M	3% of Capex

* Section 45Q refers to the production tax credit based on the quantity of CO_2 captured and stored during the hydrogen synthesis process.

Appendix 3: Target Development

Targets for 2030 were developed using the Minnesota fertilizer sales data for 2020 as a baseline, with the assumption that sales remain flat over the decade. This approach was chosen since sales growth was slow decade over the previous decade, with only a 4% increase from 2010 to 2020. In addition, Minnesota has signaled its desire to reduce nitrogen fertilizer usage, which was assumed to offset any potential market growth.

Assuming all nitrogen fertilizer sold is synthetic with ammonia as a precursor, ammonia demand was determined by taking the total nitrogen sold (747,576 tons) and proportionally calculated based on the nitrogen content of ammonia by weight (82%), for a total of 911,678 tons of ammonia. The emissions-reduction targets of 50% for 2030 and net-zero for 2050 were chosen, in line with Minnesota's stated goals. Green ammonia was assumed to have zero production emissions associated with it, meaning half of ammonia demand by 2030 (approximately 450,000 tons) and all ammonia demand by 2050 (approximately 900,000 tons) would need to come from green ammonia.

Endnotes

1. *Making Net-Zero Ammonia Possible: An Industry-Backed, 1.5C-aligned Transition Strategy*, Mission Possible Partnership, 2022, **https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Making-1.5-Aligned-Ammonia-possible.pdf**.

2. Eric Thorp, "EU Industrial Demand Uptick Could Be Short-Lived," *Energy Intelligence*, February 14, 2023, **https://www.energyintel.com/00000186-4f13-d910-af96-5f9b6d9f0000**, and "Iowa Production Cost," United States Department of Agriculture (USDA), accessed May 26, 2024, **https://mymarketnews.ams.usda.gov/viewReport/2863**.

3. *2023 Fact Book*, Nutrien, 2023, **https://nutrien-prod-asset.s3.us-east-2.amazonaws.com/s3fs-public/uploads/2024-01/Nutrien_2023Fact%20Book_Update_12624.pdf**.

4. "Kenya Nut and Talus Renewables to Manufacture Sustainable Fertilizer with Hydrogen," *Talus Ag*, November 2, 2023, **https://www.talusag.com/blog/kenya-nut-and-talus-renewables-to-manufacture-sustainable-fertilizer-with-hydrogen**.

5. "Trammo, ReMo Sign Green Ammonia MOU; Illinois Plant Expected Up in 2024," *Green Markets*, October 21, 2022, **https://fertilizerpricing.com/trammo-remo-sign-green-ammonia-mou-illinois-plant-expected-up-in-2024**.

6. "First Ammonia and Uniper announced cooperation on green ammonia project in Texas," *Uniper*, October 31, 2023, **https://www.uniper.energy/news/first-ammonia-and-uniper-announced-cooperation-on-green-ammonia-project-in-texas**.

7. Isabel Keltie, "Minbos and Stamicarbon sign MoU on green ammonia," *World Fertilizer Magazine*, June 30, 2022, **https://www.worldfertilizer.com/environment/30062022/minbos-and-stamicarbon-sign-mou-on-green-ammonia/**, and "Maire Tecnimont Group Starts Preliminary Work on Renewable Power-to-Fertilizer Plant in Kenya," Stamicarbon, May 17, 2021, **https://www.stamicarbon.com/press-release/maire-tecnimont-group-starts-preliminary-work-renewable-power-fertilizer-plant-kenya**.

8. "Pacific Green Fertilizer," Atlas Agro, accessed May 30, 2024, **https://www.atlasagro.ag/projects/pacific-green-fertilizer/**.

9. *Fertilizer Logistics and Transportation*, The Fertilizer Institute, March 2024, **https://www.tfi.org/wp-content/uploads/2024/03/TFI-fertilizer-logistics-and-transportation.pdf**.

10. *Fertilizer Logistics and Transportation*, 2024.

11. *Fertilizer Logistics and Transportation*, 2024.

12. Alexandra Diemer and Luca Zullo, *Securing a Better Future Through the Development of Green Ammonia Fertilizer Pathways*, 2023.

13. Michael Langemeier, Michael Gunderson, and Nathanael Thompson, “2023 Purdue Crop Cost and Return Guide,” *Purdue Agricultural Economics Report*, Purdue University, 2023, **https://ag.purdue.edu/commercialag/home/paer-article/2023-purdue-crop-cost-and-return-guide/#:~=Variable%20cost%20per%20bushel%20in%202023%20is%20estimated,to%20%244.98%20per%20bushel%20from%202013%20to%202015**.

14. “Fertilizer Use and Sales Data,” Minnesota Department of Agriculture, accessed May 30, 2024, **https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data**.

15. “Lead Green Ammonia,” West Central Research and Outreach Center, University of Minnesota, accessed May 30, 2024, **https://wcroc.cfans.umn.edu/news/lead-green-ammonia**.

16. “Heartland Hydrogen Hub,” University of North Dakota Energy & Environmental Research Center, accessed May 30, 2024, **https://undeerc.org/research/projects/heartland-h2-hub.html**.

17. “Scores are in on 2nd fertilizer plant proposals competing for $125M,” Agweek, 2024, **https://www.agweek.com/agribusiness/scores-are-in-on-2-nd-fertilizer-plant-proposals-competing-for-125m**.

18. *2024 MN Energy Factsheet*, Clean Energy Economy Minnesota, 2024, **https://www.cleanenergyeconomymn.org/wp-content/uploads/2024/04/2024-Minnesota-Energy-Factsheet.pdf**.

19. “Profile Analysis: Minnesota,” EIA, accessed May 20, 2024, **https://www.eia.gov/state/analysis.php?sid=MN**.

20. *2024 MN Energy Factsheet*, 2024.

21. “Profile Analysis: Minnesota,” 2024.

22. “Biden-Harris Administration Invests in Clean Energy and Fertilizer Production to Strengthen American Farms and Businesses as Part of Investing in America Agenda,” USDA, March 28, 2024, **https://www.usda.gov/media/press-releases/2024/03/28/biden-harris-administration-invests-clean-energy-and-fertilizer#:~:text=Through%20FPEP%2C%20USDA%20provides%20grants,fertilizer%20production%20plants%20and%20more**.

23. “US National Clean Hydrogen Strategy And Roadmap | Hydrogen Program,” Energy.gov, n.d. **https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap**.

24. “Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing US Leadership on Clean Energy Technologies,” The White House, April 22, 2021, **https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/**.

25. *Industrial Decarbonization Roadmap*, US DOE, September 2022, **https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf**.

26. “Regional Clean Hydrogen Hubs,” Energy.gov, n.d., **https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0**.

27. “Regional Clean Hydrogen Hubs Selections for Award Negotiations,” Energy.gov, n.d., **https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations**.

28. “Biden-Harris Administration to Jumpstart Clean Hydrogen Economy with New Initiative to Provide Market Certainty and Unlock Private Investment,” Energy.gov, n.d., **https://www.energy.gov/articles/biden-harris-administration-jumpstart-clean-hydrogen-economy-new-initiative-provide-market**.

29. “Title 17 Clean Energy Financing,” Energy.gov, n.d., **https://www.energy.gov/lpo/title-17-clean-energy-financing**.

30. “Inflation Reduction Act of 2022,” Energy.gov, n.d., **https://www.energy.gov/lpo/inflation-reduction-act-2022**.

31. “Title 17 Clean Energy Financing.”

32. *Building a Clean Energy Economy Guidebook*, CleanEnergy.gov, January 2003, Version 2, **https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**.

33. *Greenhouse gas emissions in Minnesota 2005-2020: Biennial report to the Legislature tracking the state’s contribution to emissions contributing to climate change*, Minnesota Pollution Control Agency and Department of Commerce, January 2023, **https://www.pca.state.mn.us/sites/default/files/lraq-2sy23.pdf**.

34. “The Next Step in Our Clean Energy Transition,” Our Minnesota Climate, n.d., **https://climate.state.mn.us/next-step-our-clean-energy-transition**.

35. Kelsey Misbrener, “Minnesota advances legislation to improve large-scale solar + storage permitting,” Solar Power World, May 21, 2024, **https://www.solarpowerworldonline.com/2024/05/minnesota-advances-legislation-large-scale-solar-permitting**.

36. “Green Fertilizer Program, Minnesota Department of Agriculture, n.d., **https://www.mda.state.mn.us/green-fertilizer-program**.

37. “Minnesota Nitrogen Fertilizer Management Plan,” Minnesota Department of Agriculture, n.d., **https://www.mda.state.mn.us/pesticide-fertilizer/minnesota-nitrogen-fertilizer-management-plan**.

38. *Greenhouse gas emissions in Minnesota 2005-2020: Biennial report to the Legislature tracking the state’s contribution to emissions contributing to climate change*, Minnesota Pollution Control Agency and Department of Commerce, January 2023, **https://www.pca.state.mn.us/sites/default/files/lraq-2sy23.pdf**.

39. “Green Fertilizer Program,” n.d.

40. “Minnesota Joins US Climate Alliance, Commits to Upholding Paris Climate Agreement,” Minnesota Department of Commerce, February 13, 2024, **https://mn.gov/commerce/news/?id=17-606815**, and “State Energy Financing Institution (SEFI) Toolkit,” Energy.gov, n.d., **https://www.energy.gov/LPO/SEFIToolkit**.

41. “Pricing for LPO Financing by Program,” Energy.gov, n.d., **https://www.energy.gov/lpo/articles/pricing-lpo-financing-program**.

42. “CSEA Approves $7 Million Loan for Fertilizer Development,” North Dakota Industrial Commission, March 4, 2024, **https://www.ndic.nd.gov/sites/www/files/documents/Press-Releases/2024/240304-CSEA-Fertilizer-Development-Loan.pdf**.

43. “Rural Energy for America Program (REAP),” USDA Rural Development, April 8, 2024, **https://www.rd.usda.gov/inflation-reduction-act/rural-energy-america-program-reap**.

44. “Fertilizer Production Expansion Program,” USDA Rural Development, May 30, 2024, **https://www.rd.usda.gov/programs-services/business-programs/fertilizer-production-expansion-program**.

45. “Minnesota Job Skills Partnership,” Minnesota Department of Employment and Economic Development, accessed May 30, 2024, **https://mn.gov/deed/business/financing-business/training-grant/**.

46. “Questions and Answers: The Net-Zero Industry Act and the European Hydrogen Bank*,” European Commission, March 16, 2023, **https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_1666**.

47. Rachel Terada, *Readiness for Hourly: US Renewable Energy Tracking Systems, Center for Resource Solutions*, June 15, 2023, **https://resource-solutions.org/wp-content/uploads/2023/06/Readiness-for-Hourly-US-Renewable-Energy-Tracking-Systems.pdf**.

48. “The Heartland Hydrogen Hub,” Agricultural Utilization Research Institute, March 11, 2024, **https://www.youtube.com/watch?v=_wzOCTwZ8kc**.

49. Yunhu Gao and André Cabrera Serrenho, “Greenhouse Gas Emissions from Nitrogen Fertilizers Could Be Reduced by up to One-fifth of Current Levels by 2050 with Combined Interventions,” *Nature Food*, February 9, 2023, **https://doi.org/10.1038/s43016-023-00698-w**.

50. *Decision 2013/20: Compliance by the European Union with its Obligations to Report on Strategies and Policies for Air Pollution Abatement (ECE/EB.AIR/129)*, United Nations Economic Commission for Europe, 2015, **https://unece.org/DAM/env/documents/2015/AIR/EB/ECE_EB.AIR_129_ENG.pdf**.

TJ Kirk, Anton Krimer, Sheran Munasinghe, Elina Rodriguez, Joaquin Rosas, and Quailan Homann, *Roadmap for Distributed Green Ammonia in Minnesota*, RMI, 2024, **https://rmi.org/roadmap-for-distributed-green-ammonia-in-minnesota/**.

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