THE POTENTIAL FOR HYDROGEN TO SUPPORT LOW-CARBON INDUSTRY IN MINNESOTA

USE POTENTIAL, LOGISTICAL READINESS, BARRIERS TO ADOPTION, AND RECOMMENDATIONS FOR COMMUNITY ENGAGEMENT

COMMERCE DEPARTMENT
DIVISION OF ENERGY RESOURCES

5 lakes energy

Prepared for: **Minnesota Department of Commerce, State Energy Office**
Prepared by: **5 Lakes Energy**
May 2025

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About This Project

Interest in clean hydrogen has grown in recent years, catalyzed in part by initiatives championed by the U.S. Department of Energy. Opportunities for clean hydrogen to reduce air and climate-warming pollution have attracted the attention of the states, private sector corporations, researchers, and clean energy and environmental advocates. Industrial hydrogen has the potential to reduce emissions from existing industries and support states in boosting their economies by backing emerging low-carbon industries. Cognizant of this opportunity, the state of Minnesota has charged the State Energy Office within the Department of Commerce with the task of developing deep insight into industrial hydrogen opportunities and barriers to project liftoff.

Therefore, in support of the State Energy Office's charge, this study was developed: (1) to evaluate the use potential, logistical readiness, and barriers to the adoption of clean hydrogen in potential future and current Minnesota industries, as well as (2) to provide a set of key recommendations for strategies to earn social license for new industrial hydrogen projects.

About 5 Lakes Energy

5 Lakes Energy is a Michigan-based consultancy supporting nonprofits, businesses, and government agencies in their pursuit of clean energy goals, design and implementation of climate solutions, and delivery of economic, public health, and other benefits to the people they serve.

Acknowledgements

The findings presented in this report represent the perspectives of an array of stakeholders affiliated with multiple state agencies, companies, nonprofit organizations, and graduate students and faculty. We extend our appreciation for their time and willingness to participate. This project was funded by the DOE Office of Technology Commercialization in collaboration with the Office of Clean Energy Demonstrations (OCED) as part of the DOE Technology Commercialization Fund.

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Executive Summary

With the clean economy goal outlined in Minnesota's Climate Action Framework (CAF), the state aims to "build a thriving carbon-neutral economy that produces goods and services with environmental benefits and equitably provides family-sustaining job opportunities." Minnesota's industrial sector is a significant part of the state's economy and currently accounts for 18% of the state's total greenhouse gas (GHG) emissions. Therefore, to meet the CAF's clean economy goal, Minnesota's existing and future industrial facilities will need to employ approaches that comprehensively minimize — or eliminate — their GHG emissions profiles.

Hydrogen produced with zero or minimal GHG emissions, also known as clean hydrogen, is positioned to become one tool in a comprehensive portfolio of technologies needed to reduce the carbon intensity of industrial activities. Hydrogen can be used either as a feedstock in the production of fuels, chemicals, and materials or as an energy carrier, much like fossil fuels are used today. This report focuses on five industrial applications. Three potential new low-carbon industries — the manufacturing of ammonia, iron, and sustainable aviation fuel — are already associated with explicit initiatives in Minnesota. These industries would require substantial amounts of clean hydrogen to reduce their carbon intensity to levels consistent with the CAF's clean economy goal. The manufacturing of low-carbon methanol, an important chemical and a potential marine fuel, presents the state with an additional opportunity. Low-carbon methanol could be produced by combining clean hydrogen with the highly concentrated biogenic waste carbon dioxide (CO_2) generated by Minnesota's ethanol plants — opening the door to a new industry while slashing carbon emissions from an existing one. The combustion of hydrogen to generate industrial heat is also included in this study, as a longer-term potential application, due to the limited opportunity to decarbonize a subset of Minnesota's existing facilities, those with significant high-temperature heat needs, through other means.

Four hydrogen production pathways are considered here. By convention, the pathways are assigned the colors gray, blue, yellow, and green. Gray hydrogen is produced by steam reforming of the methane in natural gas, a relatively carbon-intensive process. Blue hydrogen is produced like gray hydrogen, except that the CO_2 generated during the production process is captured for storage or use as a feedstock, resulting in a relatively low-carbon-intensity hydrogen product. Yellow and green hydrogen both refer to hydrogen obtained from water splitting via electrolysis, with the green color assigned to electricity drawn from a zero-carbon renewable source (e.g., solar or wind) and yellow, to electricity from a mixed-origin grid. The carbon intensity of yellow hydrogen varies greatly, depending on the electricity generation sources. Notably, hydrogen produced with electricity from Minnesota's existing grid would have a higher average carbon intensity than that of gray hydrogen. However, the carbon intensity of grid-powered hydrogen will decrease as the emissions associated with electricity generation approach zero by 2040 to meet Minnesota's legislative mandate for clean electricity.

The ability to produce and use clean hydrogen at scale in Minnesota will depend on a number of factors, which are summarized below.

Hydrogen infrastructure. Minnesota has two large gray hydrogen production facilities with a total annual output of 180,000 tons. Hydrogen is consumed on-site by the adjacent refineries. Expanding the production and use of hydrogen in the state will require hydrogen-specific infrastructure for production, storage, and transport. In some instances, hydrogen could be produced and consumed entirely on site. In others, hydrogen may need to be transported to facilities. When moved by pipeline, dedicated new or repurposed pipes are required due to hydrogen's propensity to embrittle (reduce the strength of) a wide range of materials. While pipelines would be the cheapest method for moving large amounts of hydrogen over long distances, the high upfront capital costs and potential resistance from the impacted communities will likely prove major barriers to building this form of delivery infrastructure. Transportation by road or rail are other options.

Clean electricity. Scaled production of green or yellow hydrogen will require significant additional carbon-free electricity that is either produced in Minnesota or imported from neighboring states and Canada. For example, to generate a sufficient amount of green hydrogen to produce enough ammonia to meet Minnesota's annual requirement for nitrogen fertilizer, about 8.9 TWh of electricity would be required. Careful planning will be needed to ensure Minnesota's ability to meet its carbon-free electricity mandate with the expansion of electrolysis-based hydrogen production.

Cost. Blue hydrogen is about twice as expensive as gray hydrogen. In addition, blue hydrogen would require a buildout of pipelines to transport the captured CO_2. Yellow and green hydrogen are about four times as expensive as gray hydrogen, with electricity procurement and water-splitting electrolyzers as the main cost drivers. Reliance on emerging technologies like electrolyzers for hydrogen production and within the relevant industries elevates project risk and thus poses financing challenges. Tax incentives could help mitigate the capital and operational cost barriers.

Permitting and regulatory frameworks. Minnesota's permitting process is a potential barrier to complex projects due to the high frequency of lengthy delays and a lack of process clarity. Clean hydrogen projects may face additional hurdles due to a lack of experience with the industry in communities and by regulators.

Industry-specific factors. The ongoing efforts and initiatives in Minnesota around low-carbon ammonia, low-carbon iron, and sustainable aviation fuel should help generate market pull for clean hydrogen, can secure early offtake agreements, and can encourage investment. Methanol production using waste CO_2 from ethanol plants would benefit from the federal 45Q carbon capture tax credit and create additional revenue for the ethanol producers. Similarly, green hydrogen-based ammonia could be combined with waste CO_2 from ethanol plants to produce urea, a farmer-preferred form of fertilizer. The use of hydrogen to generate high-temperature industrial heat would likely need additional policies and/or financial incentives to be economically viable. Replacing the current use of coal with hydrogen in industrial heat generation would have the co-benefit of reducing air pollution in addition to lowering GHG emissions.

Social license. Industrial hydrogen project liftoff will require social license, and earning social license typically involves community engagement. Issues of interest to communities impacted by large industrial projects commonly include safety, natural resource and environmental considerations, benefits to the local economy, workforce development, and transparency in project planning. These issues are especially important for projects that entail new, less familiar technologies or industries, such as hydrogen. This report provides a roadmap for addressing common community concerns relevant to industrial hydrogen projects, supported by real-world examples that demonstrate effective strategy implementation. In addition, concerns and strategies related to potential collaborations with Tribal Nations are discussed.

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Introduction

In 2022,15 state agencies in Minnesota released the first iteration of the state's Climate Action Framework, which establishes a vision for how the state will address and prepare for an increase in the frequency of extreme weather events. The framework is organized around six goals: 1) clean transportation, 2) climate-smart natural and working lands, 3) resilient communities, 4) clean energy and efficient buildings, 5) healthy lives and communities, and 6) a clean economy. In support of the framework targets, Minnesota Legislature updated the state's climate goals in 2023 to include reducing greenhouse gas (GHG) emissions by 50% from 2005 levels by 2030 and achieving net-zero emissions by 2050. The state also passed legislation establishing a carbon-free electricity standard with a utility target of 100% carbon-free electricity by 2040.

Minnesota's climate goals

- 50% GHG emissions reductions from 2005 levels by 2030
- Net-zero GHG emissions by 2050
- 80% carbon-free electricity by 2030
- 100% carbon-free electricity by 2040

The Climate Action Framework clean economy goal aims to "build a thriving carbon-neutral[1] economy that produces goods and services with environmental benefits and equitably provides family-sustaining job opportunities." Minnesota's industrial sector is a significant part of the state's economy and is the fourth largest source of GHG emissions in the state. The industrial sector emissions, which include only direct emissions from industrial facility processes and on-site fossil fuel combustion, account for 18% of Minnesota's total emissions.[2] Therefore, to meet the state's clean economy goal, Minnesota's existing and future industrial facilities will need to employ approaches that comprehensively minimize their GHG emissions profiles.

HYDROGEN PRODUCTION AND CURRENT USE

The annual global production of hydrogen is 97 million metric tons (MMT), with the United States producing 10 MMT.[3] Worldwide, hydrogen is used primarily as a feedstock[4] for crude oil refining and petrochemical production. In the United States, refining accounts for 55% of the total hydrogen

[1] In this context, 'carbon-neutral' means that the balance between carbon dioxide emitted to the atmosphere versus absorbed from the atmosphere is, on the whole, zero (neutral).

[2] "Greenhouse gas emissions in Minnesota 2005-2022," report to the legislature by Minnesota Pollution Control Agency and Department of Commerce, January 2025.

[3] "Global Hydrogen Review 2024," International Energy Agency, October 2024.

[4] A 'feedstock' is a raw material consumed in the production of a value-added intermediate or final product.

demand, while ammonia and methanol production make up 35%.[5] Minnesota has two large hydrogen production facilities with a total annual output of 0.18 MMT, which is consumed on-site by the adjacent refineries.

Table 1

HYDROGEN COLORS ASSOCIATED WITH DIFFERENT PRODUCTION PATHWAYS

	TECHNOLOGY	COLOR	ELECTRICITY SOURCE OR FEEDSTOCK	GHG FOOTPRINT
WATER-BASED	ELECTROLYSIS	GREEN	RENEWABLES	MINIMAL
		PINK	NUCLEAR	MINIMAL
		YELLOW	MIXED-ORIGIN GRID	LOW-MEDIUM
FOSSIL-BASED	PYROLYSIS	TURQUOISE	NATURAL GAS	LOW (Solid Carbon Biproduct)
	STEAM REFORMING + CARBON CAPTURE	BLUE	NATURAL GAS	LOW
	STEAM REFORMING	GRAY	NATURAL GAS	MEDIUM
	GASIFICATION	BROWN	BROWN COAL	HIGH
		BLACK	BLACK COAL	HIGH
GOELOGICAL	EXTRACTION (Passive Capture)	WHITE	IRON-RICH DEPOSITS	LOW
	WATER INJECTION AND RECOVERY (Stimulated Production)	ORANGE	IRON-RICH DEPOSITS	LOW

[5] "U.S. National Clean Hydrogen Strategy and Roadmap," U.S. Department of Energy, June 2023.

There are several hydrogen production pathways, which are commonly referred to by color, as summarized in Table 1. This report focuses primarily on four production pathways: gray, blue, yellow, and green. Gray hydrogen is the most common type produced in the United States, accounting for nearly all current hydrogen production in Minnesota. This pathway, which relies on a process known as steam reforming of methane in natural gas (SMR), is a relatively carbon-intensive process that results in emissions of ~11 kg CO_2e/kg H_2.[6] Blue hydrogen is also produced via SMR, except that the associated carbon dioxide is captured and either utilized or stored. In this report, blue hydrogen is assumed to have a 90% CO_2 capture rate. Yellow and green hydrogen both refer to hydrogen obtained from water splitting via electrolysis,[7] with the green color assigned to electricity drawn from a zero-carbon renewable electricity source (e.g., solar or wind) and yellow, to electricity from a mixed-origin power grid.

Hydrogen production via electrolysis is highly energy intensive. Therefore, for electrolysis-based hydrogen to be low-carbon, the electricity source must be heavily decarbonized. When a 60% decarbonized electric grid (electricity generated from carbon-free sources such as solar, wind, hydropower, nuclear) is used to power yellow hydrogen production, with the other 40% of electricity derived from natural gas, the hydrogen's carbon intensity is approximately the same as or higher than that of gray hydrogen (~11 kg CO_2e/kg H_2). A 90% decarbonized electric grid results in a carbon intensity of ~2.7 kg CO_2e/kg H_2, which is comparable to that of blue hydrogen (Figure 1).[7] Use of coal instead of natural gas to generate electricity would further increase the carbon intensity of hydrogen produced by a mixed-origin grid.

CARBON INTENSITY BY HYDROGEN PRODUCTION PATHWAY (kg CO_2e / kg H_2)

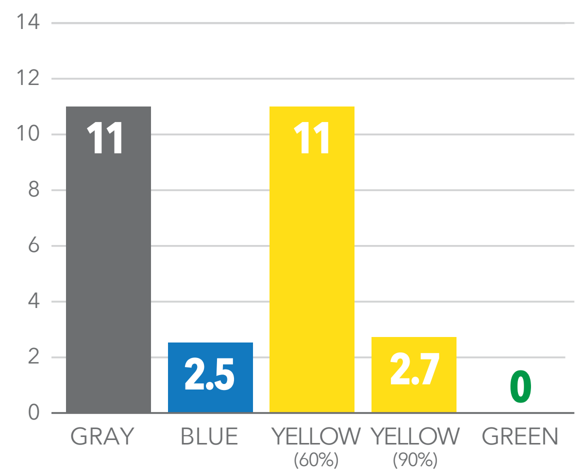

Figure 1 *Carbon intensity of hydrogen produced via gray, blue, yellow, and green pathways. Carbon intensity of yellow hydrogen was calculated for 60% and 90% decarbonized electric grids, as indicated. Carbon intensity values are for production-related emissions only and include methane leakage. Infrastructure-related emissions are not included. For calculation details, see footnote 6.*

For clarity and accuracy, this report uses the term 'low-carbon' instead of 'green' as a descriptor for selected products (ammonia, iron, and methanol). This rationale is rooted in the variability of carbon intensity, which is dependent on a multitude of factors (i.e., scope 2 and 3 emissions). The term 'low-carbon' is an acknowledgement of this reality and the carbon intensity spectrum. When referring to hydrogen, colors are used because they refer to specific production pathways.

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[6] Direct hydrogen production-related emissions only. Carbon intensity was calculated using the GTI Energy Hydrogen Production Emissions Calculator webtool (https://hypec.gti.energy/, accessed April 2025), which leverages output values from the 2021 GREET model developed by Argonne National Laboratory. The following inputs were used for calculations. Hydrogen infrastructure, transportation, and refueling compression emissions were not included. 100-year global warming potential was selected. Electricity consumption for hydrogen production was set to 1.5 J electricity/J H2. Natural gas consumption for hydrogen production was set to 1.37 J natural gas/J H2, and methane slip was set to 0.99% J CH4/J natural gas. For blue hydrogen, a 90% carbon capture rate was selected. For yellow hydrogen calculations, electricity generation mix was defined as follows: 60% decarbonized: nuclear – 20%, wind – 30%, solar PV – 10%, natural gas – 40%; 90% decarbonized: nuclear – 20%, wind – 40%, solar PV – 30%, natural gas – 10%.

[7] 'Electrolysis' is the process of using electricity to split apart the hydrogen and oxygen atoms in a water molecule, resulting in separate streams of hydrogen and oxygen gases.

POTENTIAL ROLE FOR LOW-CARBON HYDROGEN IN MINNESOTA'S INDUSTRIAL SECTOR

Low-carbon hydrogen is positioned to become one tool in a comprehensive portfolio of technologies needed to reduce industrial carbon intensity. Hydrogen can be used either as a feedstock in the production of fuels, chemicals, and materials or as an energy carrier (i.e., fuel). In Minnesota, three new manufacturing initiatives under consideration would rely heavily on clean hydrogen to ensure alignment with the Climate Action Framework's clean economy goal. These initiatives include the production of low-carbon ammonia, low-carbon iron, and sustainable aviation fuel (SAF). Another potential green hydrogen priority sector is the production of methanol, an important chemical and potential marine fuel. Methanol could be produced from the abundant and highly concentrated waste CO_2 that is generated by Minnesota's ethanol refineries. Hydrogen could also serve as a long-term decarbonization solution for high-temperature, hard-to-decarbonize process heat in certain existing facilities within Minnesota. While the heat in these facilities is currently generated via the combustion of fossil fuels, including coal, the associated combusting units and processes cannot be readily electrified.

This report is organized in three primary sections: Use Potential, Logistical Readiness and Barriers to Adoption, and Community Engagement. Use Potential provides an overview of the selected industrial sectors and hydrogen's role in reducing carbon emissions. The section covering Logistical Readiness and Barriers to Adoption discusses systemic and sector-specific factors that are likely to impact scaled hydrogen production and use. Community Engagement provides a hydrogen-focused set of guidelines for addressing potential impacts on communities and local economies where new projects would be implemented, as well as best practices for obtaining the social license needed to operate.

Use Potential

As Minnesota aims to grow its economy while meeting its decarbonization goals, careful consideration must be given to the carbon intensity of new and existing industries. This report focuses on five industries. Three potential new industries — low-carbon ammonia, low-carbon iron, and sustainable aviation fuel — are already associated with ongoing initiatives or efforts in the state. These industries would require substantial amounts of low- or zero-carbon hydrogen to be consistent with the clean economy goal described in Minnesota's Climate Action Framework. Additionally, low-carbon methanol manufacturing is included as a potential use case because it can be produced from the waste CO_2 generated by Minnesota's ethanol industry, with the opportunity to provide additional revenue to ethanol manufacturers while lowering ethanol's life cycle-based carbon intensity. Finally, the use of hydrogen to generate industrial heat is included as a longer-term potential application, due to limited decarbonization options for achieving the high temperatures required by a subset of Minnesota's existing facilities.

LOW-CARBON AMMONIA

Ammonia (NH_3) is a major ingredient in nitrogen-based fertilizer production and thus is a key input to Minnesota's agricultural sector. Ammonia is commonly synthesized using gray hydrogen produced via SMR, yielding a carbon intensity of 1.8 kg CO_2e/kg NH_3.[8] To meet Minnesota's annual nitrogen fertilizer demand, about 900,000 tons of ammonia would be needed,[9] which would result in synthesis-related emissions of 1.6 MMT CO_2e per year. One popular form of ammonia-based fertilizer is urea, which is made by combining ammonia with CO_2. However, once applied in the field, the decomposition of urea leads to the eventual release of CO_2 into the atmosphere.

> *The production of ammonia to meet Minnesota's current demand for nitrogen fertilizer emits more than 1.6 million metric tons of CO_2e per year, out of state.*

Hydrogen production accounts for most of the CO_2 emissions and energy requirements associated with ammonia synthesis. Therefore, the carbon intensity of ammonia can be significantly reduced with the use of green hydrogen. In fact, the synthesis-related carbon emissions of ammonia become negligible when renewable electricity is used to power all steps of an integrated production process (with most of the electricity dedicated to hydrogen generation).

Conventional ammonia production is highly centralized with production sites often located far from points of use but near established natural gas reserves. Due to the significant cost reductions that can be gained at higher scales in conventional ammonia production, most facilities have production capacities that range from 100,000 to more than 1 million tons per year. The price of ammonia fluctuates significantly and is highly dependent on geopolitical factors (Figure 2). In 2022, the price of ammonia reached three times the average price of 2018-2020 due to the impact of the Russia-Ukraine war on the global markets and trade. Although Minnesota is the fourth-highest consumer of ammonia-based fertilizers in the United States, virtually no ammonia is currently produced in the state. Instead, Minnesota farmers spend an estimated \$500 million to \$1 billion per year on nitrogen fertilizer, with most of that money leaving the state.[10]

An alternative approach to the current centralized system is a distributed network of smaller regional ammonia and fertilizer production facilities powered by renewable electricity, as detailed in a recent report by RMI.[11] The report suggests that technological advances may enable economic viability of ammonia production at smaller scales ranging from several thousand to 100,000 tons of ammonia

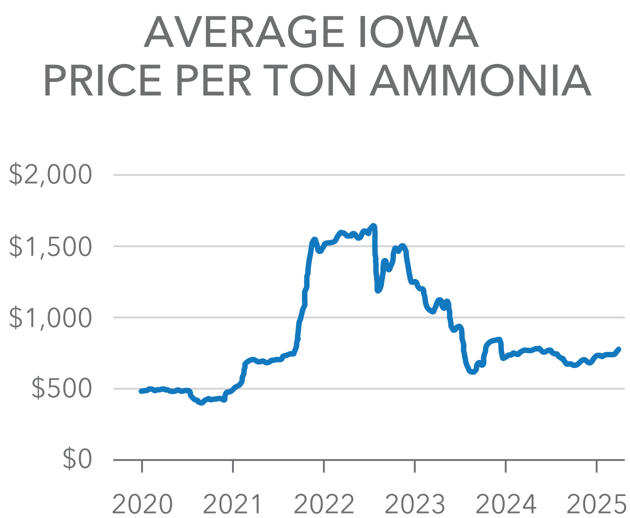

Figure 2 *Average price paid for ammonia in Iowa in the five-year period between 2020 and 2025. Source: U.S. Department of Agriculture*

[8] "Ammonia Technology Roadmap," International Energy Agency, October 2021.

[9] TJ Kirk, Anton Krimer, Sheran Munasinghe, et al., "Roadmap for Distributed Green Ammonia in Minnesota," RMI, June 2024.

[10] Farmer expenditure on nitrogen fertilizer is an estimate based on total annual nitrogen fertilizer need in Minnesota and the market price of ammonia (see Figure 2).

[11] TJ Kirk, Anton Krimer, Sheran Munasinghe, et al., "Roadmap for Distributed Green Ammonia in Minnesota," RMI, June 2024.

per year. The benefits of a smaller-scale distributed green hydrogen-based ammonia production model include price stability and a drastically reduced carbon footprint. In addition, smaller production facilities can be owned by farmers and farming co-operatives, leading to greater investment and capital retention in local economies.

LOW-CARBON IRON

Iron and steel production accounts for about 7% of the world's total annual GHG emissions. Minnesota has six operating mines[12] which produce about 85% of the iron ore consumed annually in the United States.[13] Two vertically integrated mining companies, Cleveland-Cliffs and US Steel, process iron ore into either blast furnace- or direct reduced-grade taconite pellets, which are then shipped to other states for processing to crude iron and then steel. Minnesota does not have any active iron or steel manufacturing facilities. While the state's one electric arc furnace steel scrap recycling facility, located in St. Paul, has an annual capacity of 560,000 tons, it has been idled since 2020.

> *Minnesota supplies approximately 85% of the iron ore consumed in the United States.*

Global demand for iron and steel is projected to increase by more than one-third by 2050.[14] Minnesota's abundant iron ore deposits[15] and the existing mining and taconite pellet production operations offer favorable conditions for establishing new iron production facilities. With the use of new and emerging technologies that rely on direct reduction technology for ironmaking, the state could position itself as an early adopter in the production of low-carbon iron, minimizing negative environmental impacts associated with this sector, while growing the local economy.

> *Global demand for iron and steel is projected to increase by more than one-third by 2050.*

Much of the country's crude iron production capacity relies on blast furnace technology, which uses coal coke to react with the iron-bound oxygen in iron ore to generate metallic iron. In this process, as the taconite pellets are melted at temperatures around 1600°C (2900°F), the reaction between the carbon in the coke and the oxygen in the ore results in significant emissions of CO_2 and high levels of toxic pollutants in facility exhaust, which can adversely impact nearby communities. Direct reduction is an alternative approach to ironmaking that can use either natural gas or hydrogen to strip the iron-bound oxygen from the taconite pellets in the solid state below melting temperatures. Compared to the blast furnace-based process, the direct reduction approach requires much less energy and produces significantly lower emissions of CO_2 and hazardous pollutants. The use of green hydrogen in the direct reduction process can minimize the CO_2 emissions associated with ironmaking.

[12] Two of the mines owned by Cleveland Cliffs – Minorca and Hibbing Taconite – are slated for temporary idling in May 2025 (accessed April 2025). A new Mesabi Metallics pellet plant is planned to open in 2026 (accessed April 2025).

[13] Nick Yavorsky, Chathurika Gamage, Kaitlyn Ramirez, Maeve Masterson, "Great Lakes near-zero emission steel. Memo focus: Minnesota," RMI, November 2023.

[14] "Iron and Steel Technology Roadmap," International Energy Agency, October 2020.

[15] According to the Minnesota Department of Natural Resources, non-operational deposits in the Mesabi Range contain "1.5 billion tons of potential high grade iron ore pellets. There are also over one billion tons of natural iron ore tailing basins and stockpiles that contain recoverable iron ore." "Explore Minnesota: Iron ore," March 2016.

When low-carbon iron is further processed to steel in electric arc furnaces using renewable electricity, the carbon intensity of the crude steel product can be less than 5% than that of conventionally made crude steel (Figure 3).[16]

SUSTAINABLE AVIATION FUEL

Aviation accounts for about 2.5% of the total GHG emissions in the United States and globally, and demand for travel by air continues to increase. However, long-haul air travel is difficult to electrify and thus, for the foreseeable future, will continue to rely on jet fuel, an energy-dense liquid fuel that must meet stringent requirements for composition and performance. The average carbon intensity of petroleum-based jet fuel, including its combustion, is 12.6 kg CO_2e/gal (89 g CO_2e/MJ).[17] Minnesota's annual jet fuel consumption is 350 million gallons,[18] giving rise to 4.4 MMT of CO_2e emissions.[19]

CARBON INTENSITY OF CRUDE STEEL PRODUCT (kg CO_2/kg STEEL)

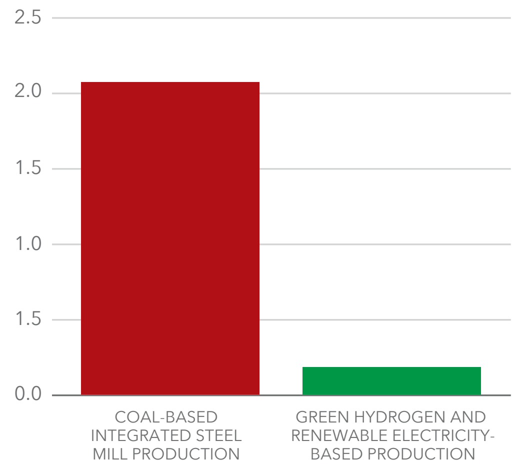

Figure 3 *Carbon intensity of crude steel based on production pathway. The left bar is for a blast-furnace to basic oxygen furnace integrated production pathway. The right bar is for a direct-reduction pathway using green hydrogen followed by renewable electricity-powered electric arc furnace. Data source: Sa Ge, Ezra Widajat, Takshi Sachdeva, et al., "A Low-Carbon Emission Flowsheet for BF-Grade Iron Ore Using Advanced Electric Smelting Furnace," Proceedings of the Iron and Steel Technology Conference, August 2024.*

The use of sustainable aviation fuel (SAF) as a drop-in replacement for petroleum-based jet fuel is the primary near- to medium-term approach to decarbonize air travel. SAF can be made via different pathways from biomass feedstocks or waste streams. In an alternative emerging pathway, termed 'power-to-liquid,' renewable electricity is used to convert captured CO_2 and water to SAF, with most of the electricity associated with hydrogen production. Due to the variety and complex nature of SAF synthesis pathways, the carbon intensity reduction of SAF compared to petroleum-derived jet fuel can be in the range of ~15-90%.[20] Cost, technological readiness, and, in some cases, feedstock availability are the main barriers to the rapid scaling of SAF. Almost all SAF production pathways require hydrogen, which can significantly impact the net carbon footprint of the fuel. Therefore, a reliable supply of low-carbon hydrogen will require scaling in parallel with SAF manufacturing capacity in the state.

> *Minnesota's jet fuel consumption accounts for 4.4 million metric tons of 'well-to-wake' GHG emissions each year.*

[16] Sa Ge, Ezra Widajat, Takshi Sachdeva, et al., "A Low-Carbon Emission Flowsheet for BF-Grade Iron Ore Using Advanced Electric Smelting Furnace," Proceedings of the Iron and Steel Technology Conference, August 2024.

[17] Matteo Prussi, Uising Lee, Michael Wang, et al., "CORSIA: The first internationally adopted approach to calculate lifecycle GHG emissions for aviation fuels," Renewable and Sustainable Energy Reviews, 150:111398, October 2021.

[18] U.S. Energy Information Association. "Table F2: Jet fuel consumption, price, and expenditure estimates, 2023," accessed April 2025.

[19] CO_2e emissions were calculated by multiplying the annual jet fuel consumption in Minnesota (350 million gallons) by the carbon intensity of jet fuel (12.6 kg CO_2e/gal).

[20] Matteo Prussi, Uising Lee, Michael Wang, et al., "CORSIA: The first internationally adopted approach to calculate lifecycle GHG emissions for aviation fuels," Renewable and Sustainable Energy Reviews, 150:111398, October 2021.

LOW-CARBON METHANOL

Methanol is an important chemical that is used as a building block to produce other chemicals, materials, and fuels. In 2020, annual methanol production capacity in the United States reached 9.4 MMT, or about 3.1 billion gallons. Global methanol demand is projected to grow at an annual rate of 2-3%.[21] Most methanol is produced from natural gas, with a resulting carbon intensity of 2.2 kg CO_2/kg.[22] To produce low-carbon methanol, green hydrogen is reacted under pressure with captured CO_2 over a catalyst.[23] In this manner, the carbon intensity of low-carbon methanol compared to methanol produced from natural gas is less than 5%.[24]

Methanol is increasingly considered as a potential sustainable marine fuel to replace existing fossil-based fuels, such as diesel fuel oil. Methanol engines and compatible infrastructure equipment are already available commercially, and methanol-fueled ships are emerging in the market. Green hydrogen-based methanol, together with green hydrogen-based ammonia, has one of the lowest calculated carbon intensities among potential alternative marine fuels. However, compared to ammonia, methanol has a higher energy density, a better environmental and safety profile, and is less polluting when burned. The use of low-carbon methanol can reduce marine fuel carbon intensity by more than 90%.[25] Minnesota's Port of Duluth is one of 10 regional ports in the Great Lakes-St. Lawrence Seaway, and of these 10, ranks as the second largest by tonnage of goods that pass through it. To meet Minnesota's and national decarbonization goals, the port's fuel must eventually be replaced with low-carbon alternatives, such as low-carbon methanol.

Use of green methanol instead of fossil-derived diesel as marine fuel could reduce 'well-to-wake' GHG emissions associated with shipping by more than 90%.

Minnesota's 18 ethanol refineries could serve as concentrated CO_2 suppliers at an appropriate scale for low-carbon methanol production. Methanol synthesis units could be located near existing ethanol plants, avoiding the need to transport the captured CO_2 over long distances (Figure 4). Because the state's annual ethanol production is 1.4 billion gallons, the industry also produces 4.2 MMT of highly concentrated biogenic CO_2.[26] Using half of this CO_2 for methanol production would yield 1.3 MMT of methanol, equivalent to over one-tenth of the current methanol supply in the United States.[27]

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[21] "Methanol price and supply/demand," Methanol Institute, accessed April 2025.

[22] "Carbon footprint of methanol," Methanol Institute, 2022.

[23] A 'catalyst' is a substance used to speed up a chemical reaction that is not otherwise consumed in the reaction.

[24] "Marine methanol: future-proof shipping fuel," Methanol Institute, May 2023.

[25] "Feasibility study of future energy options for Great Lakes shipping," United States Maritime Administration, March 2024.

[26] Biogenic CO_2 emissions from ethanol plants are estimated from the total ethanol production in the state ("Economic contribution of Minnesota's ethanol industry," University of Minnesota Extension, February 2025), using a 1:1 w/w ratio of biogenic CO_2 to ethanol (Scott Irwin, "CO_2 production by the U.S. ethanol industry and the potential value of sequestration," Farmdoc daily, 14:34, February 2024).

[27] Calculation assumes a 90% capture rate and 1.45 kg CO_2/kg methanol based on the publication: Stefano Sollai, Andrea Porcu, Vittoria Tola, et al., "Renewable methanol production from green hydrogen and captured CO_2: A techno-economic assessment," Journal of CO_2 Utilization, 68: 102345, February 2023.

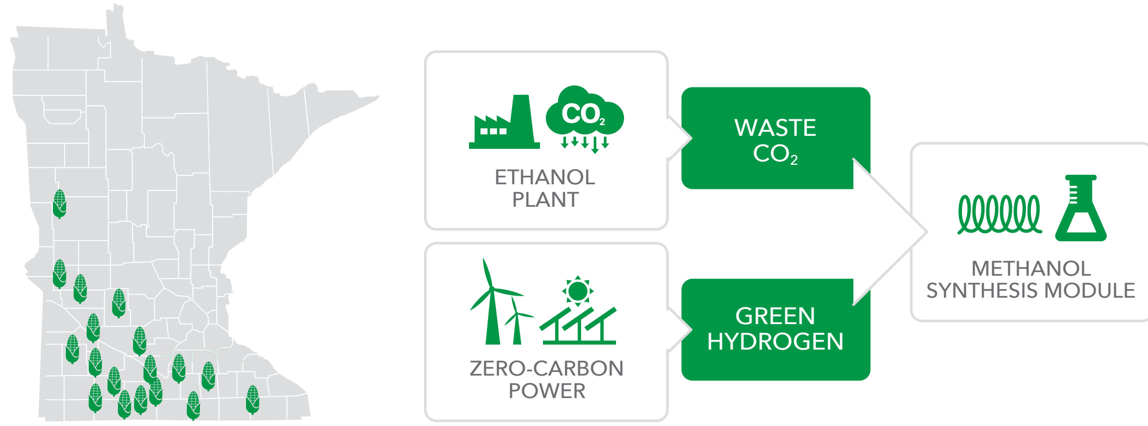

Figure 4 *Low-carbon methanol production units can be located in proximity to ethanol plants. Left: Locations of ethanol plants in Minnesota. Right: Methanol can be produced in modular units using green hydrogen and waste biogenic CO_2 from the ethanol plants.*

HIGH-TEMPERATURE INDUSTRIAL PROCESS HEAT

Based on data reported to the U.S. EPA's Greenhouse Gas Reporting Program, Minnesota's manufacturing sector emits more than 10 MMT CO_2 annually.[28] Most of these manufacturing emissions result from the combustion of fossil fuels to generate process heat, supplied to processing units at a range of temperatures from less than 100°C (212°F) to greater than 1500°C (2732°F). Electrification technologies, such as industrial heat pumps and electric boilers, are considered to be the primary options for decarbonizing low- and medium-temperature process heat needs (<500°C or 932°F). For higher temperatures, which are often less efficient to achieve through electrified technologies, the combustion of green hydrogen could offer an option to support the state toward its industrial decarbonization goals.[29] In Minnesota, the generation of high-temperature heat accounts for an estimated 2.5 MMT CO_2 emissions annually, of which 2.2 MMT (88%) is produced by the state's six active iron ore pelleting plants located in the Iron Range mining region.

> *High-temperature industrial process heat accounts for an estimated 2.5 million metric tons of direct CO_2 emissions in Minnesota each year predominantly due to natural gas and coal combustion.*

[28] Calculated from 2019, 2022, and 2023 emissions data reported to the U.S. EPA GreenHouse Gases Reporting Program, as accessible through the Facility Level Information on GreenHouse gases Tool.

[29] "U.S. National Clean Hydrogen Strategy and Roadmap," U.S. Department of Energy, June 2023.

Logistical Readiness and Barriers to Adoption

The ability to produce and use hydrogen at scale will depend on both systemic and industry-specific factors. Minnesota's current hydrogen production is primarily limited to two oil refineries, which use the hydrogen on-site for hydrocracking and hydrotreating processing steps.[30] Expanding the production and use of low-carbon hydrogen in the state may require new infrastructure, workforce development, regulatory and permitting considerations, as well as additional clean electricity generation. While the industrial sectors discussed here are complex, with each depending on extensive sets of logistical elements and potential barriers, the intent of this report is to focus specifically on factors related to hydrogen use in the relevant industries. To understand Minnesota's potential long-term hydrogen needs and related impacts, each industry-specific section lists either a current sector-based product demand in the state (low-carbon ammonia, industrial heat) or a hypothetical single facility-level demand (low-carbon iron, SAF, low-carbon methanol) together with the corresponding hydrogen, water, electricity, and electrolyzer (electric water-splitting technology) capacity requirements (Tables 2, 3, 4, 5, 6, and 7).

SYSTEMIC ELEMENTS

Hydrogen production and infrastructure

Minnesota currently has two facilities — Flint Hills Resources Pine Bend Refinery and St. Paul Park Refining Co LLC — that produce an estimated annual total of 180,000 tons gray hydrogen.[31] The state's hydrogen production has more than doubled since the early 2000s. In addition, Minnesota has three pilot-scale green hydrogen projects that can inform future efforts. The University of Minnesota West Central Research and Outreach Center (WCROC) operates an integrated ammonia project, which uses wind energy to generate hydrogen and power an ammonia synthesis process. The project has been in operation since 2013 and produces 25 tons of ammonia per year. It has recently secured $18.6 million from the U.S. Department of Energy to scale up production by a factor of 18, which will bring its capacity to 1 ton per day. CenterPoint Energy, an investor-owned natural gas utility in Minnesota, has been operating a green hydrogen project since 2022, using renewable electricity to produce up to 432 kg of hydrogen per day. The hydrogen is then blended at less than 5% by volume into the utility's natural gas distribution system. The utility's stated goal for the project is to gain operational experience for producing and distributing green hydrogen to reduce carbon emissions associated with gas-based heating. The City of St. Cloud is constructing a green hydrogen project at its wastewater treatment facility, which will use solar power and biogas to produce up to 190 tons of hydrogen per year. It is expected to be operational by the end of 2025 or early 2026 and will help the city achieve its carbon neutrality goals.

Minnesota's current hydrogen producers store and use hydrogen on-site. Consequently, the state has almost no hydrogen-compatible infrastructure, such as large storage facilities or pipelines. Hydrogen can be transported as a gas via pipelines or in high-pressure tube trailers, or as a cryogenic (cold, compressed) liquid in specialized tankers. Research into transport via liquid organic hydrogen carriers is also underway as an alternative. Although pipelines would be the cheapest method to move large amounts of hydrogen over long distances, high upfront capital

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[30] 'Hydrocracking' and 'hydrotreating' refer to hydrogen-based chemical processing steps used in crude oil refining processed. Hydrocracking is the process of splitting organic molecules to their desired sizes and lengths, while hydrotreating is the process of cleaning sulfur from the fuel (also known as hydrodesulfurization).

[31] "Minnesota refinery hydrogen production capacity," U.S. Energy Information Administration, accessed May 2025.

costs and potential resistance from the impacted communities are major barriers to expanding this form of delivery infrastructure. As the smallest molecule, hydrogen can readily interact with many materials, including steel, causing embrittlement and shortened lifespans. Therefore, dedicated new or repurposed pipelines engineered to resist such embrittlement are required for the transmission and distribution of pure hydrogen.

Minnesota is one of six states in the DOE-funded Heartland Hydrogen Hub (HH2H), which aims to establish integrated clean hydrogen projects across the region (Figure 5). The existing plans in the hub's portfolio will collectively produce up to 160 tons of hydrogen per day (58,000 tons per year). The hub will help provide networking, planning, and financial support for facilities and projects involved in hydrogen production and use. Clean hydrogen-based fertilizer production is stated as a priority of HH2H. In 2025, HH2H received an initial $20 million (of the total federal cost share of up to $925 million) to begin Phase I planning, designing, and community and labor engagement activities.

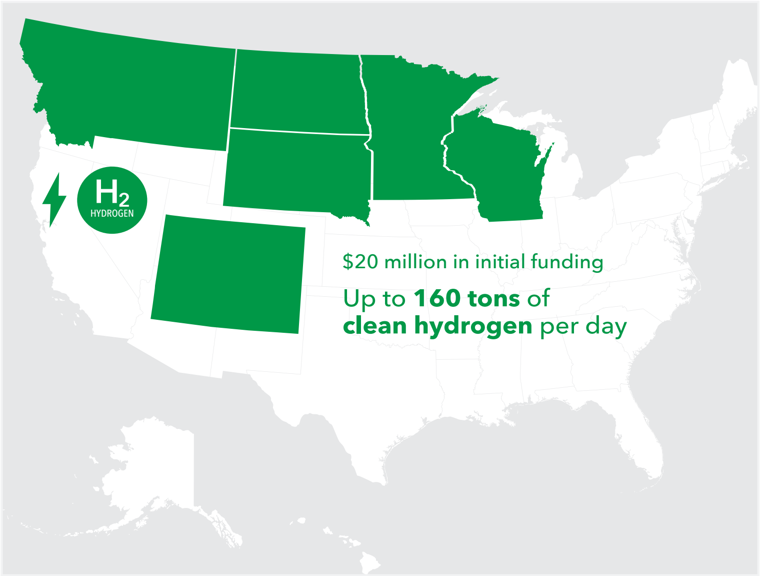
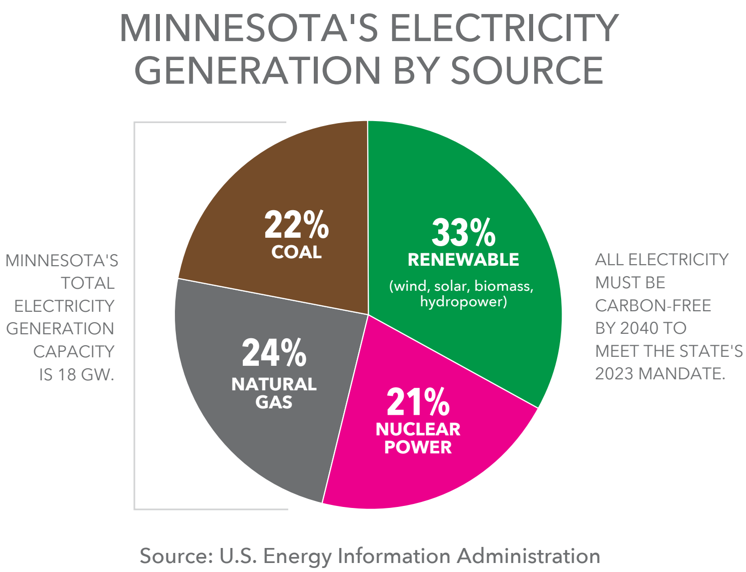


Figure 5 *Minnesota is one of six states in the Heartland Hydrogen Hub. Credit: Adapted from heartlandh2hub.com.*

Clean electricity

Scaled green hydrogen production in Minnesota would require significant additional carbon-free electricity (see Table 7) that is either produced in the state or imported from neighboring states and Canada. The state's current total summer electricity generation capacity is 18 GW. In 2023, renewables (wind, solar, biomass, and hydropower) supplied 33%; nuclear power, 21%; natural gas, 24%; and coal, 22% of total generation capacity (including on-site generation at industrial facilities) in Minnesota.[32] The state's solar and wind generation capacities are rapidly expanding, while coal is being phased out to meet the state's carbon-free electricity targets.



[32] U.S. Energy Information Administration, Electricity Data Browser, Net generation for all sectors, Minnesota, Annual, 2001-2023.

Minnesota's current nuclear moratorium[33] prohibits the state's Public Utilities Commission from issuing certificates needed to build new nuclear power plants, although a bill proposing to lift the moratorium is under consideration in the state legislature. All electricity will need to be carbon-free by 2040 to meet the mandate established by the state in 2023 (Bill HF7).

In line with the state's targets to supply entirely carbon-free electricity by 2040, the Minnesota Energy Infrastructure Permitting Act was passed in 2024. The act streamlines permitting of new energy and transmission projects, with the intent to accelerate the process of building and connecting renewable projects to the electric grid. Furthermore, both Minnesota and the Midcontinent Independent System Operator (MISO; a regional operator that coordinates and controls electric transmission in much of the Midwest) are investing in major electric grid upgrades, which will enable additional electricity generation and transmission throughout the region. In 2024, the Minnesota Public Utilities Commission approved the Minnesota Power electric utility to move forward with its High Voltage Direct Current Modernization Project, which, according to the utility, will expand transmission capacity from 500 MW to 900 MW and cost an estimated $940 million.[34] Grid North Partners, a group of 10 nonprofit and municipal co-operative utilities and investor-owned utilities in the upper Midwest, is in the process of implementing 19 transmission upgrade projects that will cost $130 million with an expected completion date by the end of 2026.[35] These upgrades are intended to improve access to wind energy and reduce grid congestion. At the time of publication of this report, the Minnesota Department of Commerce is reviewing applications to its $5.3 million Grid Resilience Grants Program intended to help fund upgrades by the state's municipal and co-operative utilities. In the last three years, MISO approved two packages of transmission upgrades (Tranche 1 and Tranche 2) in the Midwest totaling more than $30 billion in construction costs. These upgrades include plans for several new high voltage lines in Minnesota and neighboring states.

Based on Minnesota's current electricity profile, electrolysis-based hydrogen production using grid electricity would result in carbon emissions greater than that of methane-based gray hydrogen (see Figure 1). However, grid-powered hydrogen production will approach zero direct carbon emissions as the grid becomes decarbonized to meet Minnesota's mandate of having entirely carbon-free electricity by 2040. Furthermore, with generation-matching approaches, hydrogen production could ramp up during hours of excess renewable electricity generation (e.g., a windy day of moderate temperature), allowing the opportunity to capture a greater share of low-carbon electricity than the grid average. Such approaches are incentivized by the allowance for hourly GHG emissions accounting for hydrogen production in the final rules of the federal 45V tax credit (see *OVERVIEW: Federal and Minnesota tax incentives for hydrogen and relevant industries*). To accommodate larger-scale hydrogen projects requiring gigawatt electricity generation capacity, dedicated sources of carbon-free electricity may be required. Approximate electricity requirements for each potential use case described in this report are listed in the corresponding sections below (Tables 2, 3, 4, 5, and 6).

Cost

The cost of low-carbon hydrogen is a key barrier to its adoption. The price of gray and blue hydrogen depends strongly on the price of natural gas, which is the primary feedstock in both production processes. Both types of hydrogen benefit significantly from higher production capacities, which are compatible with centralized supply networks. The current price of gray

[33] A 'nuclear moratorium' is a ban or restriction on the use of nuclear energy technologies.

[34] "Minnesota Power receives key regulatory approvals for HVDC transmission project in support of a reliable, clean energy future," Minnesota Power, August 2024.

[35] "Grid North Partners utilities to implement 19 electric transmission upgrades to reduce system congestion," Grid North Partners, October 2023.

hydrogen (11 kg CO_2e/kg H_2) is $1.50-$2.50/kg. Blue hydrogen (2.5 kg CO_2e/kg H_2) costs about twice as much to produce as gray hydrogen due to the additional capital and operating expenses required for carbon capture,[36] storage, and transport. The production cost of electrolysis-based yellow and green hydrogen is about four times that of gray hydrogen and is strongly dependent on the price of electricity and electrolyzers (Figure 6). Due to the lower impact of the production capacity on the final unit price, electrolysis-based hydrogen is more amenable than gray or blue hydrogen to smaller distributed production facilities. Capital expenses associated with electrolyzer installations are expected to continue to decrease in the coming years with improved efficiencies and scaled production. The cost of zero-carbon electricity is also expected to decrease, although the increasing demand for electricity across sectors, including from data centers, could put upward pressure on electricity prices.

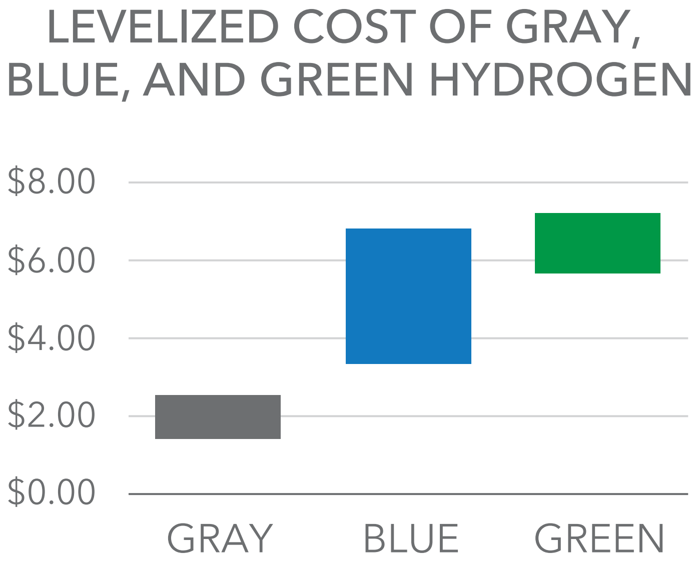


Figure 6 *Levelized cost of gray, blue, and green hydrogen. Values were calculated using the [NREL H2A-Lite tool](#) for 50-200 ton per day capacity. Default model values were used, with Minnesota selected as the production location.*

Electrolysis-based hydrogen production, as well as some of the industries that would use low-carbon hydrogen to decarbonize, rely on emerging technologies. The higher costs and risks associated with emerging industries and technologies can act as deterrents to investors, reducing the capital available for hydrogen-related projects. A number of federal and state incentives relevant to hydrogen production and related industries are intended to promote investment (see *OVERVIEW: Federal and Minnesota tax incentives for hydrogen and relevant industries*). The federal 45V hydrogen production tax credit directly impacts all hydrogen use cases discussed in this report, with the resulting credit ranging from $0.65-$3.00/kg H_2 depending on the final carbon intensity of the hydrogen product, as calculated using Argonne National Laboratory's GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model. To be eligible for the 45V credit, hydrogen project construction must begin no later than December 31, 2032. Among the commercially available production pathways, only green hydrogen produced using either dedicated or time-matched regionally generated renewable electricity is likely to be eligible for the highest ($3.00/kg H_2) credit. Hydrogen production can also benefit indirectly from the 48E or 45Y renewable energy production tax credits, which are available for clean energy generation at a separately owned facility. Lower-priced electricity enabled by the tax credits would decrease the levelized cost of green hydrogen. Several other incentives may be available for some of the industries, as discussed in the sector-specific sections below and summarized in *OVERVIEW: Federal and Minnesota tax incentives for hydrogen and relevant industries*.

[36] Often referred to as CCS or CCUS, 'carbon capture' is an electric-driven process in which carbon dioxide is captured from an exhaust stream then compressed for transport to a final destination of either geologic sequestration (pumping below ground; CCS) or utilization as a feedstock in another industrial process (CCUS).

Federal and Minnesota tax incentives for hydrogen and relevant industries

45V – Clean hydrogen production. An income tax credit of $0.60-$3.00 per kilogram of clean hydrogen produced is available during a 10-year period from the date that a qualified hydrogen production facility is placed in service. Construction of the production facility must begin on or before December 31, 2032. The credit is tiered based on the hydrogen lifecycle GHG emissions calculated with the GREET model. The renewable power used to produce hydrogen must be generated in the same geographic region as the hydrogen. Hydrogen production must be temporally matched to renewable power generation. GHG emissions of low-carbon hydrogen may be determined on an hourly basis to account for the changing carbon intensity of the supplied electricity. *Stackability restrictions*: 45V cannot be stacked *at the same facility* with 45Q (blue hydrogen production would be eligible for *either* 45V or 45Q but not both) or 45Z.

45Y – Clean electricity production. A technology-neutral tax credit of 0.3-1.5 cents per kWh of zero-emissions electricity produced at qualified facilities (including electricity production and energy storage) and sold to another entity (e.g., a hydrogen producer). To be eligible, facilities must be placed in service after December 31, 2024. Credit applies for 10 years after the facility is placed in service. The higher rate of 1.5 cents per kWh electricity applies to small facilities with an output of less than 1 MW. Credit phase-out begins at the later of: a) 2032 or b) when U.S. GHG emissions from electricity are 25% of 2022 values or lower. *Stackability restrictions*: 45Y cannot be stacked with 48E or 45Q *at the same facility.*

48E – Clean electricity investment. A technology-neutral tax credit of 6%-70% of project cost is available for investment in facilities that generate clean electricity. To be eligible, facilities must be placed in service after December 31, 2024. Manufacturing and siting criteria must be met to be eligible for the maximum credit of 70%. Credit phase-out will start at the later of: a) 2032 or b) when U.S. GHG emissions from electricity are 25% of 2022 values or lower. *Stackability restrictions*: 48E cannot be stacked with 45Y or 45Q *at the same facility*.

45Q – Carbon capture. A tax credit of $60-$85 per metric ton captured carbon oxide (e.g., CO_2) is available to qualified industrial facilities for up to 12 years of carbon capture. Construction of new facilities or carbon capture equipment must begin on or before December 31, 2032. Up to $60 per metric ton captured carbon dioxide is available when the captured carbon is used in downstream manufacturing (e.g., methanol or urea production). Up to $85 per metric ton captured carbon dioxide is available when the captured carbon is permanently sequestered. *Stackability restrictions*: 45Q cannot be stacked *at the same facility* with 45V, 45Y, 48E, or 45Z.

45Z – Clean fuel production. A tax credit of up to $1.75 per gallon is available for the domestic production of SAF at a qualified facility. For non-SAF fuels (e.g., methanol) a credit up to $1.00 per gallon is available. Fuels with a carbon intensity of less than 50 kg of CO_2e per million BTU (calculated with GREET) are eligible. Credits scale with carbon intensity reduction. *Stackability restrictions*: 45Z cannot be stacked with 45V, 45Q *at the same facility*.

Minnesota sustainable aviation fuel credit. A $1.50 per gallon tax credit is available for SAF either produced or blended in Minnesota and sold for use in aircraft departing from Minnesota airports. Credit is available for SAF sold after June 30, 2024, and before July 1, 2030. SAF must reduce life-cycle GHG emissions by at least 50%. The credit may be claimed by either the producer or the blender but only applies to the SAF portion of the blended fuel.

Permitting and regulatory frameworks

Building new facilities or modifying existing ones requires a variety of permits, which depend on the type of facility and the potential environmental impact of the project. Complex projects commonly require multiple permits to ensure compliance with all applicable regulations and an acceptable level of impact on the local communities and the environment. To help navigate the inherently complicated permitting landscape and assist project development, the Minnesota Department of Employment and Economic Development coordinates the multiagency group known as Minnesota Business First Stop. Establishing new industries in the state may face additional permitting challenges due to the lack of relevant administrative experience, the lack of a relevant regulatory framework, and the potential for resistance from impacted communities.

Minnesota's permitting process was mentioned in several stakeholder interviews as a potentially significant barrier for establishing complex projects in the state. Consistent with this sentiment, a 2024 report published by the Minnesota Chamber Foundation[37] notes that common delays for complex ('Tier 2') projects, lack of process clarity, and uncertainty that businesses face during the permitting process could hinder economic growth in Minnesota. According to the report, between 2018 and 2023, the average time to issue air permits for priority Tier 2 projects was nearly four times the 150-day goal set by the Minnesota Pollution Control Agency, which issues the permits. For the 15 water permits issued in the same period, the average time to issue was 476 days, or more than three times the 150-day goal. A permitting reform bill (HF 8/SF 577), which aims to streamline the permitting process, is currently being considered by the state's legislature.

INDUSTRY-SPECIFIC ELEMENTS

Low-carbon ammonia

Table 2

Minnesota's potential ammonia demand to meet current fertilizer needs	900,000 tons/year
Hydrogen required[a]	160,000 tons/year
Water required[b]	860 million gallons/year
Electricity required[c]	8.9 TWh
Total electrolyzer capacity needed (100%-50% capacity factor)[d]	1.0-2.0 GW
CO_2e emissions associated with conventional ammonia production	1,600,000 tons/year

[a] Assumes 180 kg H_2/ton ammonia (Patricia Mayer, Adrian Ramirez, Guiseppe Pezzella, et al., "Blue and green ammonia production: A techno-economic and life cycle assessment perspective," iScience, 26: 107389, August 2023).
[b] Assumes 20 L water/kg H_2 (Kaitlyn Ramirez, Tessa Weiss, Chathurika Gamage, Thomas Kirk, "Hydrogen reality check: Distilling green hydrogen's water consumption," RMI, August 2023).
[c] Assumes 55 kWh/kg H_2 (Pathways to commercial liftoff: Clean hydrogen, 2024 update, U.S. Department of Energy, December 2024, accessed April 2025).
[d] To calculate electrolyzer capacity, total annual electricity required was divided by 8,760 hours per year and by the electrolyzer capacity factor. Capacity factor measures how much the electrolyzer operates relative to its maximum possible output. The calculated values assume the electrolyzers would run between half and full capacity, depending on the power source—close to 100% for grid power, and potentially below 50% for intermittent renewables.

[37] "Streamlining Minnesota's environmental permitting process: Essential for economic growth," Minnesota Chamber Foundation, February 2024.

Minnesota's high fertilizer use, current lack of in-state ammonia manufacturing, and significant renewable electricity generation potential make it a prime candidate for the development of a distributed network of low-carbon ammonia and fertilizer production facilities. Recent technological and process advances enable the economic production of low-carbon ammonia at smaller scales (less than 100,000 tons per year) that are suitable for regional ammonia production.[38] Smaller, modular production facilities can be easier to finance due to lower upfront costs. They can also be manufactured and installed within shorter time frames of 1-3 years compared to large-scale plants, which can take up to 10 years to permit and build.[39] The University of Minnesota WCROC wind-to-ammonia pilot plant is the first of its kind in the world and is a valuable home resource that can provide contextualized technical and operational insights to future producers of low-carbon ammonia and fertilizer in the state (Figure 7).

Distributed low-carbon ammonia production has strong support within the state's farming community, including from the Minnesota Farmers Union, because it provides an opportunity for local ownership and control over the production of a key input for the state's agricultural sector. Farmer participation in the regional ammonia industry can be facilitated by Minnesota's many

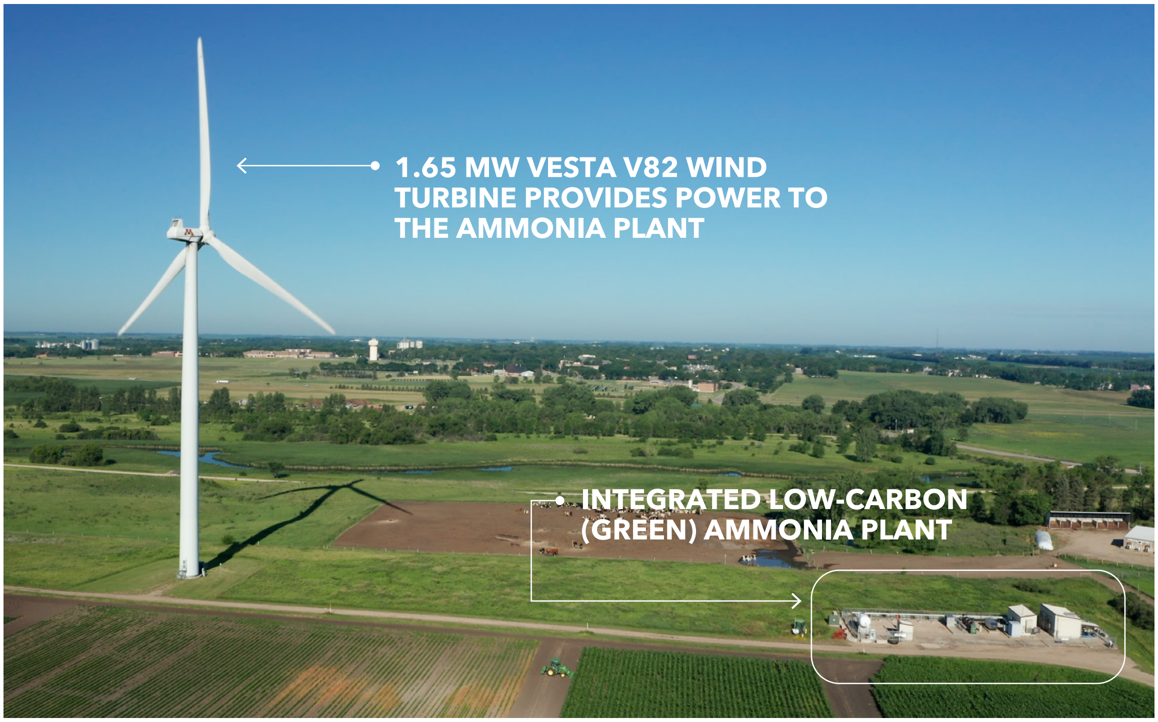


Figure 7 *An integrated green ammonia plant, operated by the University of Minnesota West Central Research and Outreach Center, has been in operation since 2013. The plant produces 25 tons of ammonia per year and has recently secured $18.6 million from the U.S. Department of Energy to scale up production by a factor of 18. Photo credit: Michael Cihak, UMN Morris.*

[38] TJ Kirk, Anton Krimer, Sheran Munasinghe, et al., "Roadmap for Distributed Green Ammonia in Minnesota," RMI, June 2024.

[39] TJ Kirk, Anton Krimer, Sheran Munasinghe, et al., "Roadmap for Distributed Green Ammonia in Minnesota," RMI, June 2024.

agricultural co-operatives, which can help plan and finance projects. Farmer-led ownership of localized low-carbon ammonia production could stabilize fertilizer prices, maintain more money in the local economies, and reduce overhead costs for Minnesota's farmers.

Although locally produced low-carbon ammonia could help stabilize market prices for farmers over time, project financing and the current cost of production are major barriers, especially for initial projects that would carry higher risk and could face challenges in securing offtake agreements. State and federal incentives, including tax credits, grants, and loans, could significantly improve the economic competitiveness of regionally produced low-carbon ammonia, as detailed in a recent report.[40] Projects with behind-the-meter renewable electricity generation can qualify for both federal 45V and 45Y/48E tax credits, as long as electricity generation occurs under separate ownership from the hydrogen and ammonia production (see *OVERVIEW: Federal and Minnesota tax incentives for hydrogen and relevant industries*). Taking advantage of both credits could reduce the levelized cost of ammonia by hundreds of dollars per ton. Grid-connected projects would be eligible for the 45V hydrogen production tax credit only but would have substantially lower capital expenses, which could give these projects an early competitive advantage. In all cases, the levelized cost of green hydrogen-based ammonia is expected to continue decreasing over time with advances in electrolyzer technologies, economies of scale, and lower renewable electricity prices.[41] In December 2024, the Minnesota Department of Agriculture launched a $6.7 million grant program to support investments in green fertilizer by the state's agricultural and electric co-operatives. The program will award successful applicants $250,000-$6.7 million, with the requirement that projects must be operational within five years of receiving the grant. Additional support may become available in the coming years through the Heartland Hydrogen Hub, although its long-term funding is uncertain at the time of publication of this report due to shifting priorities at the federal level.

Farmers generally prefer urea as a fertilizer to liquid ammonia because urea is a pelletized solid, which is easier to store and apply to fields. Urea is made by combining ammonia with CO_2, which is an abundant biproduct in other industrial processes. Especially relevant are Minnesota's 18 ethanol production facilities, which are located throughout the state's agricultural regions (Figure 4) and generate approximately 4.3 MMT of highly concentrated biogenic CO_2 each year.[42] A distributed low-carbon ammonia production network could be matched with the existing ethanol facilities for the production of low-carbon urea. Ammonia production in proximity to the state's ethanol facilities would minimize travel distances for inputs and the final product. Urea production using captured waste CO_2 would provide additional revenue for ethanol plants and make them eligible for the federal 45Q tax credit of $60/ton captured CO_2, further incentivizing a distributed low-carbon fertilizer production system.

[40] TJ Kirk, Anton Krimer, Sheran Munasinghe, et al., "Roadmap for Distributed Green Ammonia in Minnesota," RMI, June 2024.

[41] TJ Kirk, Anton Krimer, Sheran Munasinghe, et al., "Roadmap for Distributed Green Ammonia in Minnesota" RMI, June 2024.

[42] Biogenic CO_2 emissions from ethanol plants are estimated from the total ethanol production in the state ("Economic contribution of Minnesota's ethanol industry," University of Minnesota Extension, 2024), using a 1:1 w/w ratio of biogenic CO_2 to ethanol (Scott Irwin, "CO_2 production by the U.S. ethanol industry and the potential value of sequestration," Farmdoc daily, 14:34, February 2024).

Low-carbon iron

Table 3

Potential low-carbon iron production plant capacity	2 million tons/year
Hydrogen required[a]	110,000 tons/year
Water required[b]	570 million gallons/year
Electricity required[c]	5.9 TWh
Total electrolyzer capacity needed (100%-50% capacity factor)[d]	0.68-1.36 GW
CO_2 emissions associated with blue hydrogen[e]	280,000 tons/year

[a] Assumes 54 kg H_2/ton direct-reduced iron (M. Shahabudin, Alireza Rahbari, M. Akbar Rhamdhani, et al., "Process modeling for the production of hydrogen-based direct reduced iron in shaft furnace using different ore grades," Ironmaking and Steelmaking: 1, May 2024).
[b] Assumes 20 L water/kg H_2 (Kaitlyn Ramirez, Tessa Weiss, Chathurika Gamage, Thomas Kirk, "Hydrogen reality check: Distilling green hydrogen's water consumption," RMI, August 2023).
[c] Assumes 55 kWh/kg H_2 (Pathways to commercial liftoff: Clean hydrogen, 2024 update, U.S. Department of Energy, December 2024, accessed April 2025).
[d] To calculate electrolyzer capacity, total annual electricity required was divided by 8,760 hours per year and by the electrolyzer capacity factor. Capacity factor measures how much the electrolyzer operates relative to its maximum possible output. The calculated values assume the electrolyzers would run between half and full capacity, depending on the power source–close to 100% for grid power, and potentially below 50% for intermittent renewables.
[e] Emissions are associated with the production of blue hydrogen needed for 2 million tons of direct-reduced iron.

Minnesota's iron ore resources and the existing mining industry position the state well for a leading role in the production of low-carbon iron toward a robust green steel economy in the United States. Low-carbon iron production in Minnesota would increase the in-state value that can be obtained from the state's ore deposits, while minimizing the carbon intensity and pollution associated with the conventional (blast furnace) iron production process.

The University of Minnesota Natural Resources Research Institute (NRRI) is leading a feasibility study of a potential hydrogen-based direct reduction iron plant for possible development in northeastern Minnesota. The study will determine the potential size and optimal location of the facility, the energy that would be required and its source, and the economic feasibility of the project. NRRI is collaborating on the project with WCROC, the Great Plains Institute, and a consortium of industry partners (including US Steel, a major vertically integrated steel manufacturer), community-based organizations, government agencies, Tribal entities, and organized labor. The projected cost of the study is approximately $5 million. Funding contributions include $1.3 million awarded through the U.S. Department of Energy and a $2 million grant provided by the Minnesota Department of Iron Range Resources and Rehabilitation. The study is expected to take one year to complete. The proposed direct reduction iron plant could initially use natural gas, switching to hydrogen later, depending on technological, logistical, and economic constraints.

Project financing, cost competitiveness, and offtake agreements are likely to be the biggest barriers for developing a low-carbon iron industry. A recent analysis by RMI estimated that the development of a 2 million ton/year green steel facility (integrated low-carbon iron production and processing the iron to crude steel in an electric arc furnace) in Minnesota would cost $2.1 billion, not including the cost of the additional renewable energy generation capacity that would be required.[43] When hydrogen is used for iron production instead of natural gas, green hydrogen

[43] Nick Yavorsky, Chathurika Gamage, Kaitlyn Ramirez, Maeve Masterson, "Great Lakes near-zero emission steel. Memo focus: Minnesota," RMI, November 2023.

production and procurement accounts for up to 40% of the levelized cost of the final steel product, adding an estimated $150/U.S. short ton to the market price of $800-$900/U.S. short ton. However, co-location of hydrogen and iron production near iron ore sources, such as the active mining parcels in the Mesabi Range, paired with robust financial incentives, such as the 45V and 45Y/48E tax credits, may produce sufficient cost savings to make the final steel product cost competitive with, or even cheaper than, conventional steel.[44] Furthermore, the Minnesota Power High Voltage Direct Current Modernization Project, which will increase electricity transmission capacity in northern Minnesota, could expand renewable electricity options and potentially lower costs for scaled hydrogen production in the Mesabi Range. Minnesota, along with eight other states, has a state-sponsored Buy Clean program, which is intended to boost demand for low-carbon products and materials, including steel. These state programs can create the needed early market pull for low-carbon steel products, which in turn can help secure offtake agreements and incentivize investment in low-carbon iron manufacturers.

Sustainable aviation fuel

Table 4

Capacity of the announced DG Fuels SAF plant in Moorhead, MN	193 million gallons/year
Hydrogen required[a]	29,000 tons/year
Water required[b]	150 million gallons/year
Electricity required[c]	1.6 TWh
Total electrolyzer capacity needed (100%-50% capacity factor)[d]	0.18-0.36 GW
CO_2 emissions associated with blue hydrogen[e]	73,000 tons/year
CO_2 emissions associated with gray hydrogen[e]	320,000 tons/year

[a] Assumes 0.15 kg H_2/gal biobased SAF (Oscar Rosales Calderon, Ling Tao, Zia Abdullah, et al., "Sustainable aviation fuel state-of-industry report: Hydroprocessed esters and fatty acid pathways," NREL, July 2024).
[b] Assumes 20 L water/kg H_2 (Kaitlyn Ramirez, Tessa Weiss, Chathurika Gamage, Thomas Kirk,"Hydrogen reality check: Distilling green hydrogen's water consumption," RMI, August 2023).
[c] Assumes 55 kWh/kg H_2 (Pathways to commercial liftoff: Clean hydrogen, 2024 update, U.S. Department of Energy, December 2024, accessed April 2025).
[d] To calculate electrolyzer capacity, total annual electricity required was divided by 8,760 hours per year and by the electrolyzer capacity factor. Capacity factor measures how much the electrolyzer operates relative to its maximum possible output. The calculated values assume the electrolyzers would run between half and full capacity, depending on the power source–close to 100% for grid power, and potentially below 50% for intermittent renewables.
[e] Emissions are associated with the production of blue and gray hydrogen needed for 193 million gallons of bio-based SAF.

Minnesota's goal of developing a local SAF industry could help spur clean hydrogen production in the state. In 2023, the Minnesota SAF Hub was launched to bring together a wide range of partners with the goal of building a value chain for SAF supply and use. The hub's stated aim is to achieve in-state scaled SAF production of more than 100 million gallons per year by 2035. In line with this aim, DG Fuels recently announced plans to build a 193 million-gallon-per-year SAF manufacturing facility in Moorhead, Minnesota, with production expected to start in 2030. The project is currently planning to use agricultural and timber waste as its carbon feedstock.

[44] Rachel Wilmoth, Chathurika Gamage, Lachlan Wright, Sascha Flesch, "Green iron corridors: A new way to transform the steel business," RMI, April 23, 2024 (accessed May 2025), and "Cleveland-Cliffs Reaffirms Commitment to Middletown Works Decarbonization Project and Ongoing Partnership with the U.S. Department of Energy," Cleveland-Cliffs, September 16, 2024, accessed May 2025.

Because most SAF production pathways require hydrogen, large-scale SAF manufacturing projects can provide a robust and consistent market pull for regionally produced clean hydrogen. SAF production can benefit from federal 45Z tax credit and the Minnesota SAF tax credit (see *OVERVIEW: Federal and Minnesota tax incentives for hydrogen and relevant industries*). These incentives require specified reductions in carbon intensity of the final fuel product and may only be applicable when low-carbon hydrogen is used, which in turn could help offset cost premiums associated with electrolysis-based hydrogen.

A potential barrier to hydrogen adoption for SAF production is the reliance on emerging technologies for the processing and conversion of so-called second-generation feedstocks,[45] such as the agricultural residues that the DG Fuels Moorhead facility has stated it will use. To date, most SAF has been produced from vegetable oils or starch-based ethanol, which utilize mature technologies but are limited by feedstock availability and could struggle to meet the carbon intensity reductions required by financial incentives programs. The use of second-generation feedstocks can significantly lower the carbon emissions associated with SAF production. However, the facilities that rely on second-generation feedstocks have previously faced years of delays, cost overruns, and ultimate failure,[46] which in this case would create uncertainty for low-carbon hydrogen producers that rely on SAF offtake agreements.

Low-carbon methanol

Table 5

Capacity of a potential low-carbon methanol plant	50,000 tons/year
Hydrogen required[a]	10,000 tons/year
Water required[b]	53 million gallons/year
Electricity required[c]	0.55 TWh
Total electrolyzer capacity needed (100%-50% capacity factor)[d]	0.063-0.126 GW
CO_2 emissions associated with natural-gas based methanol	110,000 tons/year

[a] Assumes 0.2 kg H_2/kg methanol (Stafano Sollai, Andrea Porcu, Vittoria Tola, et al. "Renewable methanol production from green hydrogen and captured CO2: A techno-economic assessment," Journal of CO_2 Utilization, 68: 102345, February 2023).

[b] Assumes 20 L water/kg H_2 (Kaitlyn Ramirez, Tessa Weiss, Chathurika Gamage, Thomas Kirk,"Hydrogen reality check: Distilling green hydrogen's water consumption," RMI, August 2023).

[c] Assumes 55 kWh/kg H_2 (Pathways to commercial liftoff: Clean hydrogen, 2024 update, U.S. Department of Energy, December 2024, accessed April 2025).

[d] To calculate electrolyzer capacity, total annual electricity required was divided by 8,760 hours per year and by the electrolyzer capacity factor. Capacity factor measures how much the electrolyzer operates relative to its maximum possible output. The calculated values assume the electrolyzers would run between half and full capacity, depending on the power source—close to 100% for grid power, and potentially below 50% for intermittent renewables.

Minnesota currently has no methanol production facilities in the state and no stated targets for low-carbon methanol production or offtake. However, the federal 45Q tax credit could provide a strong incentive for ethanol producers to capture their waste CO_2, while modular methanol synthesis technology coming online (Topsoe, CapCO_2 Solutions) could provide a pathway to utilize that CO_2 without the need to build extensive pipeline networks (which otherwise

[45] In biofuels production, 'second-generation feedstocks' are biomass that would not otherwise be consumed for food, e.g., wood matter (second-generation) versus corn (first-generation).

[46] Craig Bettenhausen, "Will ethanol fuel a low-carbon future?," Chemical and Engineering News, February 12, 2023.

could be required for capture and storage projects). Although the 45Q tax credit provides a greater subsidy for sequestering than using the captured CO_2 ($85/ton vs $60/ton), pipeline projects needed for transporting CO_2 from points of capture to storage fields have faced strong opposition from impacted communities.[47]

As with other use cases, achieving cost-competitiveness of low-carbon methanol may be a major barrier. The modeled unsubsidized green hydrogen-based methanol price is about twice that of fossil-based methanol, with electricity and electrolyzer costs as the primary drivers.[48] The 45Q and 45V tax credits would reduce the price of low-carbon methanol, while the 45Z credit could provide additional incentives for methanol use as a marine fuel. However, due to a current lack of targets for low-carbon methanol or sustainable marine fuel use in Minnesota, offtake agreements for low-carbon methanol production facilities may be difficult to secure, which would lower investor enthusiasm. In the United States and globally, dozens of green hydrogen-based methanol projects are in different stages of planning and demonstration, with an announced total global capacity of 20.6 MMT by 2030.[49] As these facilities come online, technological improvements, lessons learned, and real price data will help make low-carbon methanol more cost competitive with its fossil-based counterpart.

High-temperature industrial process heat

Table 6

Total annual high-temperature process heat consumed by Minnesota's manufacturing facilities	13 TWh / 4.5×10^7 MMBtu / 4.8×10^7 GJ
Hydrogen required[a]	400,000 tons/year
Water required[b]	2.1 billion gallons/year
Electricity required[c]	22 TWh
Total electrolyzer capacity needed (100%-50% capacity factor)[d]	2.5-5.0 GW
CO_2 emissions associated with current high-temperature industrial heat in Minnesota	2,500,000 tons/year

[a] Assumes 33.33 kWh/kg H_2 (the lower heating value of hydrogen).
[b] Assumes 20 L water/kg H_2 (Kaitlyn Ramirez, Tessa Weiss, Chathurika Gamage, Thomas Kirk,"Hydrogen reality check: Distilling green hydrogen's water consumption," RMI, August 2023).
[c] Assumes 55 kWh/kg H_2 (Pathways to commercial liftoff: Clean hydrogen, 2024 update, U.S. Department of Energy, December 2024, accessed April 2025).
[d] To calculate electrolyzer capacity, total annual electricity required was divided by 8,760 hours per year and by the electrolyzer capacity factor. Capacity factor measures how much the electrolyzer operates relative to its maximum possible output. The calculated values assume the electrolyzers would run between half and full capacity, depending on the power source—close to 100% for grid power, and potentially below 50% for intermittent renewables.and potentially below 50% for intermittent renewables.

Minnesota has 13 large manufacturing facilities with a predominant need for high-temperature process heat (versus low or medium). In all instances, these facilities are currently burning fossil fuels to generate that high-temperature heat, emitting an estimated 2.5 MMT CO_2 annually. Six taconite pelleting plants located in the Mesabi Range are responsible for most of the high-

[47] Skylar Tallal, "Eminent domain bill passes committee, but pipeline opponents worry it's too broad to pass," Iowa's News Now, April 4, 2025, accessed April 2025.

[48] Stefano Sollai, Andrea Porcu, Vittoria Tola, et al., "Renewable methanol production from green hydrogen and captured CO_2: A techno-economic assessment," Journal of CO_2 Utilization, 68: 102345, February 2023.

[49] "Renewable Methanol," Methanol Institute, accessed May 2025.

temperature process heat emissions (2.2 MMT CO_2 from natural gas combustion). In the long term, these facilities could benefit from the push for a low-carbon iron industry in the region, which may develop green hydrogen infrastructure at scale. Other relevant facilities include four beet sugar producers, each with their own lime kiln, a pulp and paper mill with a lime kiln, a glass manufacturer, and a building interior materials manufacturer. All four of the beet sugar facilities and the interior materials manufacturer use coal as a fuel, while the other large facilities with significant high-temperature heat needs burn natural gas.

The cost of green hydrogen production may be an especially high barrier for its use to produce carbon-free industrial process heat, due to direct competition with cheap fossil fuels, requirements to replace or upgrade existing equipment to accept hydrogen, and a lack of additional incentives, which can help provide market pull. The lack of cost-effective options for using hydrogen to produce industrial heat was listed as a major barrier in a 2023 University of Michigan Clean Energy Technology Adoption Roadmap,[50] a report based on interviews with companies and industry stakeholders. Consistent with stakeholder sentiment in the University of Michigan Roadmap, the U.S. National Clean Hydrogen Strategy and Roadmap[51] suggests that hydrogen will need to be priced at $1/kg to become cost-competitive for use in industrial heat applications. Therefore, without new policies or technological breakthroughs (such as access to large geologic hydrogen reserves) green hydrogen may become a cost-effective option for industrial process heat only in the longer term or with additional incentives, which could target coal-burning facilities in particular.

Community Engagement

Industrial hydrogen project liftoff requires social license, and earning social license typically involves community engagement. Issues of interest to impacted communities include safety, environmental considerations, benefits to the local economy, workforce development, and transparency in project planning. These issues are especially important for projects that entail new, less familiar technologies or industries, such as hydrogen.

This section provides a roadmap for addressing common community concerns relevant to industrial hydrogen projects, in the format of: (a) a description of the concern, (b) the general strategy for addressing the concern, and (c) real-world examples that demonstrate effective strategy implementation. Lessons learned from prior instances of new industrial facilities seeking to build in Minnesota are also included. The intent of the section is to provide an informational resource for understanding the community-based barriers that industrial hydrogen projects may face in Minnesota.

GENERAL SKEPTICISM

Concern

The limited use of industrial hydrogen to date and the general lack of the public's familiarity with hydrogen may lead to skepticism toward hydrogen projects. A lack of clear, readily accessible information related to hydrogen and its uses can exacerbate a range of concerns in affected

[50] Sarah Crane and Steve Wilson, "Clean Energy Technology Adoption Roadmap," University of Michigan Economic Growth Institute, January 2023.

[51] "U.S. National Clean Hydrogen Strategy and Roadmap," U.S. Department of Energy, June 2023.

communities. For example, the U.S. Department of Energy conducted a series of public listening sessions related to proposed hydrogen hub projects across the United States. According to Public Health Watch, 49 of 113 public comments submitted during those sessions raised concerns about inadequate transparency or insufficient opportunities for meaningful community involvement.[52] Similarly, surveys conducted by the EFI Foundation found that community members who had opposed hydrogen hub projects felt they had received insufficient information about proposed projects.[53]

Strategy

Early and routine community engagement, transparent project planning, and the use of evidence-based education can all help build public trust and confidence in industrial hydrogen projects. The most effective approaches map to a continuum of activities, entailing successively increased community involvement in projects.[54] Multiple opportunities should be created to invite community members to voice concerns, and those concerns should be addressed. Engagement events should be held regularly throughout different stages of project development. Engagement should be co-led by trusted representatives for both communities and industrial hydrogen projects. Meetings and events should be held in different formats, including in person and online (with recorded sessions made available), accommodating people with varying needs (including spoken/written language) and/or disabilities. These activities provide direct means of collecting questions from community members, which can then be responded to in a public fashion.

Publicly available educational resources can be used by communities to learn about hydrogen as well as hydrogen-related technologies and industries. The U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office provides a comprehensive list of hydrogen-related educational resources.[55] Hydrogen Tools[56] is a Pacific Northwest National Laboratory-supported portal that offers a range of web-based technical content on the safety aspects of hydrogen and fuel cell technologies. The Texas Hydrogen Alliance provides educational resources on hydrogen infrastructure, regulation, and applications.[57] Earthjustice has developed a community guide specifically tailored to hydrogen hub projects.[58] Together, these and other resources can be utilized to help address specific community concerns around hydrogen's safety and potential impacts.

Examples

The Minnesota Ethanol Producers Association and the Minnesota Bio-fuels Association both serve as advocates for ethanol producers in the state. The Minnesota Ethanol Producers Association works to keep the legislature and the public informed of critical topics. In this regard, the association's work to help communities understand the economic and environmental benefits of a new industry has led to higher local acceptance of new projects. The Minnesota Biofuels Association is a non-profit dedicated to gaining support and representation for renewable fuels in Minnesota. A similar approach could be applied to

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[52] Kristina Marusic and Cami Ferrell, "Hydrogen Hubs Test New Federal Environmental Justice Rules," Public Health Watch, November 12, 2024, accessed May 2025.

[53] Madeline Schomburg, Nick Britton, Beth Dowdy, "Building Stronger Community Engagement in Hydrogen Hubs," EFI Foundation, February 2024.

[54] Madeline Schomburg, Nick Britton, Beth Dowdy, "Building Stronger Community Engagement in Hydrogen Hubs," EFI Foundation, February 2024.

[55] "Hydrogen and Fuel Cell Technologies Office Educational Publications," U.S. Department of Energy, accessed May 2025.

[56] Hydrogen Tools Portal, accessed April 2025.

[57] "Education" topics, Texas Hydrogen Alliance, accessed May 2025.

[58] "Federal Hydrogen Hub Community Guide," Earthjustice, January 29, 2025, accessed May 2025.

hydrogen projects by, specifically, aligning messaging content with familiar energy concepts and reporting tangible benefits.

The Midwest Industrial Transformation Initiative (MITI) of Minnesota has cultivated a practice of collecting questions received from community members and then capturing those questions with paired responses and sharing them with community audiences. Ultimately, MITI aims to build a Q&A repository that will be publicly available. In this practice, MITI sometimes receives questions that cannot be readily answered, and is direct with community members about these knowledge gaps. MITI reports that the practice has already aided in building community trust.

SAFETY

Concern

Hydrogen is a highly flammable, clear, odorless gas that requires careful management to ensure safety. Historical accidents involving hydrogen may negatively influence the public's perception of hydrogen projects coming to their communities. For example, at a 2024 anti-Mid-Atlantic Clean Hydrogen Hub protest in Philadelphia, the famous image of the burning Hindenburg airship was used to draw attention to hydrogen's potential explosiveness.[59] In 1937, the German passenger airship LZ 129 Hindenburg caught fire while attempting to land in Lakehurst, New Jersey. Filled with hydrogen gas, the sudden and rapid ignition of the airship's contents ultimately killed all crew and passengers and one groundcrew, totaling 36 deaths. This widely publicized tragedy is a powerful illustration of the risks associated with hydrogen if it is not properly managed.[60]

Strategy

A robust safety plan and associated educational resources should be included in all hydrogen project proposals, ensuring that all relevant safety measures are clearly communicated to the public. Pipeline infrastructure documents should be available online and engagement opportunities should be provided to give community members access to experts who can field questions and address public concerns regarding safety. For example, the Dutch natural gas pipeline company Gasunie dedicates a portion of its website to explaining the challenges and successes of safely transporting hydrogen through gas pipelines.[61] Additionally, third-party consulting companies could be hired to validate risk assessments associated with hydrogen pipelines.

All workers who will interact with the hydrogen infrastructure should be extensively trained and a clear description of safety approaches and protocols should be made public. First responders, especially firefighters, should be included in project planning. Discussions with local fire departments, hazmat teams, and other first responders can ensure access to appropriate emergency equipment and training. First responders who may need to deal with hydrogen-related emergencies should receive hydrogen safety training and be provided with easy access to training materials and safety information.[62] Having first responders who are prepared to deal

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[59] Rebecca McCarthy, "The Battle Over Philly's Clean Hydrogen Revolution," Philadelphia Magazine, February 8, 2025, accessed May 2025.

[60] "The Hindenburg Disaster," History.com, February 9, 2010, updated April 30, 2025, accessed May 2025.

[61] "Hydrogen through natural gas pipelines: safe and sustainable," Gasunie, accessed May 2025.

[62] "Safety Planning for Hydrogen and Fuel Cell Projects," Hydrogen Tools Portal, 2017, accessed May 2025.

with potential hydrogen-related emergencies could increase support for industrial hydrogen projects in communities by addressing a key concern regarding safety.

Examples

The United States currently has more than 1,600 miles of pipelines dedicated to hydrogen transport, predominantly located in Texas (Figure 8). Because Texas's hydrogen industry has existed for 50 years with no major incident, the state's regulatory framework for hydrogen can serve as an example for other states (see *CASE STUDY: Lessons learned from Texas's 50-year-old hydrogen industry*). In 2023, the Texas Legislature created the Texas Production Policy Council to study the state's hydrogen industry and make policy recommendations that would ensure

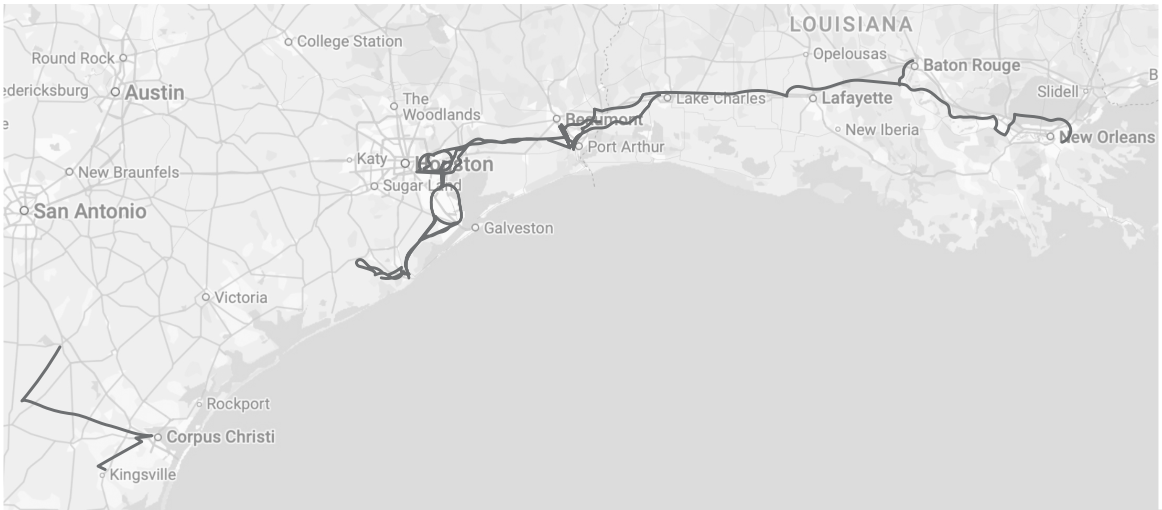

Figure 8 *Map of hydrogen pipelines in Texas and Louisiana. Adapted from respectmyplanet.org*

effective regulatory oversight while maximizing economic opportunities around hydrogen. This form of proactive analysis and policy development should help prevent major accidents and build public confidence in the hydrogen industry over time.

As a counterexample, the oil boom of the early 2000s in western North Dakota highlights the consequences of insufficient early-stage planning and community engagement in industrial projects. The rapid expansion of oil extraction in the Bakken fields between 2006 and 2015 outpaced the implementation of adequate safety protocols, leading to serious safety incidents, including at least 74 worker fatalities.[63] Community engagement also lagged behind, which resulted in strained local infrastructure and other challenges.[64] Public backlash and mounting safety concerns eventually pushed the oil industry to adopt improved practices, such as pre-shift safety briefings, first responder safety training, and more consistent communication with local governments.[65] This example underscores the need for comprehensive safety protocols and regulations as well as proactive community engagement to prevent devastating consequences in a growing clean hydrogen industry.

[63] "Why North Dakota's oil fields are so deadly for workers," PBS News Hour, June 24, 2015, accessed May 2025.

[64] Karin Becker, "Help wanted: Health care workers and mental health services. An analysis of six years of community concerns from North Dakota's oil boom residents," Journal of Rural Studies, 63: 15-23, October 2018.

[65] Dave Johnson, "Blood sweat and fears on the Bakken oil field," Industrial Safety and Hygiene News, June 1, 2015, accessed May 2025.

CASE STUDY

Lessons learned from Texas's 50-year-old hydrogen industry

Texas's role as a national leader in hydrogen development emerged from its legacy rooted deep in fossil fuel production. Most of the hydrogen in Texas today is produced via steam reforming of natural gas (i.e., 'gray' hydrogen).[66] Nevertheless, Texas's approach offers valuable insights for the national expansion of a clean hydrogen industry. Texas has been a hydrogen producer for more than 50 years. The state has 48 hydrogen production plants, largely located near existing oil refineries, and more than 1,000 miles of dedicated hydrogen pipelines (see Figure 8).[67] Texas aims to expand its low-carbon hydrogen industry through the U.S. Department of Energy-funded HyVelocity Hydrogen Hub, with a vision to create up to 45,000 jobs.

In 2023, the Texas Legislature created the Texas Production Policy Council to study the state's hydrogen industry and make policy recommendations that would ensure effective regulatory oversight while maximizing the economic opportunities of hydrogen production. According to the council's initial 2024 report to the legislature,[68] Texas has a well-regulated conventional hydrogen industry. No major incident has been reported in the industry's 50-year history. Hydrogen regulation is primarily overseen by the federal Occupational Safety and Health Administration, the Railroad Commission of Texas, and the Texas Commission on Environmental Quality, which ensure compliance with federal, state, and local codes and regulations at all points of the hydrogen infrastructure. Hydrogen is regulated similarly to Texas's refinery and petrochemical industries. Notably, transportation of hydrogen via pipelines is governed by the same state and federal regulations that apply to natural gas pipelines. In its 2024 recommendations to the legislature, the council points out that maintaining regulatory consistency between hydrogen and other similar industries is a valuable approach supported by the industry's safety record in Texas and that having a distinct regulatory approach for hydrogen production "would create an exceedingly complex administrative challenge." However, the council's 2024 report also provides several recommendations to ensure the continued long-term safety of hydrogen infrastructure in the state. The recommendations include: 1) the development of pipeline-related standards and regulations that account for hydrogen's propensity to cause material embrittlement, 2) updates to leak detection and repair rules that recognize the technological differences between hydrogen and natural gas, 3) the creation of centralized points of contact (individuals) at state agencies who are specifically focused on hydrogen and its regulation, 4) the development of hydrogen training and education programs available to the public, and 5) streamlining and standardizing the permitting process for hydrogen projects. Texas's experience can provide valuable guidance to other states in establishing effective regulatory oversight to promote a safe hydrogen industry and infrastructure.

Texas's hydrogen industry does not appear to have a strong history of community engagement. However, in line with other U.S. Department of Energy-funded hydrogen hubs, community engagement has been an integral component of planning activities for the HyVelocity Hub, which received $22 million of Phase I funding in 2024. The community engagement effort is led by the Houston Advanced Research Center (HARC), a nonprofit research, policy, and program implementation organization, which since 2001 has been focused on sustainable development solutions. According to HARC, the center will apply a "metric-based approach" and "engage local

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[66] Nat Levy, "The Rise of Hydrogen," Texas Engineer Digital Issue, accessed May 2025.

[67] "Regional hydrogen hub will advance the clean hydrogen ecosystem in Texas, southwest Louisiana, and the Gulf Coast," Texas A&M Energy Institute, October 17, 2023, accessed May 2025.

[68] "Hydrogen Energy Development in Texas: A Report for the 89th Texas Legislature, " Texas Hydrogen Production Council, December 2024.

communities in the project area to understand local concerns, develop mitigation plans, and address how project leaders and the community can maximize the local economic, health, and environmental benefits."[69] HARC's leadership role is supported by diverse stakeholders including community advocates, labor, and economic organizations as well as other nonprofits, academia, local governments, and industry. Such wide-ranging support should help HARC facilitate productive dialogues and collaborations in project planning.

As in other parts of the country, industrial clean hydrogen projects in Texas may face community opposition. One cautionary example is a $2.2 billion proposal by Avina Inc. to build a green hydrogen-based ammonia plant near Corpus Cristi with an annual output of 800,000 tons. Opposing groups are concerned about the facility's potential impact on the region's water supply. The groups disagree with Avina's projected water requirements, reflecting a lack of trust between the project owner and the impacted community.[70] Concerns around water requirements for large hydrogen projects are likely to become increasingly relevant across the United States, as drought frequency and severity increase with rising temperatures.

ENVIRONMENT AND PUBLIC HEALTH

Concern

Common community concerns around large industrial projects include potential impacts on the environment and public health, such as increased air and water pollution and GHG emissions. Some such concerns have been raised by community groups and environmental organizations that worry about the potential impacts of industrial hydrogen production relying on fossil resources either as feedstocks or for electricity generation.[71] Additionally, some communities have raised concerns about the potential impacts of electrolysis-based hydrogen production on local freshwater resources, especially in locations where water is scarce or water rights have historically been controversial.[72]

Communities have also raised concerns regarding the large land areas needed for the renewable energy required to power industrial-scale green hydrogen production and the conversion of existing agricultural lands to clean energy projects. Developers are often willing to pay a premium to use prime farmland for solar panel installations, which drives concerns related to both land affordability for Minnesota's farmers and an increase in what some label as unappealing landscapes.[73]

Strategy

In many cases, the environmental concerns around hydrogen adoption can be addressed through educational resources that clearly describe approaches and measures integrated in projects to minimize negative impacts. Evidence and data can help counteract misinformation.

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69 "HARC to Lead Community Engagement for $1.2B HyVelocity Hydrogen Hub," HARC, November 21, 2024, accessed May 2025.

70 Christian Robles, "Texas Water Fight Shows Pushback on 'Clean' Hydrogen," E&E News, June 17, 2024, accessed May 2025.

71 Molly Peterson, "As US bets big on hydrogen for clean energy, local communities worry about secrecy and public health, Grist, July 29, 2024, accessed May 2025.

72 Dylan Baddour, "Water Scarcity and Clean Energy Collide in South Texas," Texas Tribune, April 12, 2024, accessed May 2025.

73 Wanda Patsche, "The Problem with Clean Energy and Solar Panels," April 29, 2023, and Hannah Yang, "The Battle Over Land Use: Crops Versus Solar Farms," November 7, 2023.

To address GHG emissions concerns, proposed low-carbon hydrogen projects should conduct comprehensive life cycle assessments to demonstrate the net emissions reductions when compared to existing competing technologies or products. For example, although building a new green hydrogen-based direct reduced iron facility in Minnesota would result in a small increase in GHG emissions in the state's industrial sector, the emissions would be significantly lower than those associated with conventional iron and steelmaking (see Figure 3), which is still common in the United States and globally. Publicly available emissions tracking can bring transparency to hydrogen projects and allow communities to observe the environmental impacts of those projects over time. Maximized use of local renewable energy and transparent accounting of GHG emissions can allow hydrogen projects to deliver environmental benefits to local communities while building trust. In instances when hydrogen would enable the transition of hard-to-decarbonize existing industries away from coal, which is used for process heat in some of Minnesota's facilities, another major benefit to nearby communities would be reduced air pollution, which can easily be publicly tracked and reported.

Concerns related to water availability and usage practices, whether generally or in relation to green hydrogen production, are especially likely in regions already facing water stress due to drought, like portions of southern Minnesota, or regions with controversial histories related to water rights and usage, such as the Iron Range, where freshwater bodies are central to Tribal ancestral practices related to wild rice. While environmental impact assessments can help guide appropriate siting and permitting to ensure the sustainable use of local resources, different cultures approach freshwater resource practices through different cultural lenses. Impact assessments that may satisfy one local group may not universally satisfy all other local groups. Project developers should first consider using non-freshwater sources such as treated municipal wastewater or industrial effluent, including the incorporation of more intensive management practices such as ultrapurification. Ultimately, it is crucial to practice intentional siting with community-appropriate, long-term water safeguards, and to ensure appropriate and accessible means of public dissemination of impact assessments for meaningful public comment.

Concerns related to the use of farmland for solar energy projects can be partly addressed via co-location of photovoltaic systems and agricultural production, known as agrivoltaics or dual-use solar. Combining solar energy projects with crop or livestock production can optimize land use and potentially increase the overall value to farmers and landowners.[74]

Examples

Minnesota's iron ore mines have a complicated history with local Tribes and environmental advocates. The state's first new iron ore mine and pelleting plant in 50 years is owned by Mesabi Metallics. Scheduled to begin production in 2026, the facility will be the state's first zero-discharge mining operation, using only recycled water and stormwater. In addition to 99% or greater baghouse particulate filtration systems, the facility will be one of just two mines to entirely enclose its crushed ore stockpiles, further reducing airborne particulate matter. The facility will also employ some electrified alternatives of mining and material management equipment, which will reduce the need for on-site combustion of fossil fuels.[75]

One successful example of the use of agrivoltaics is the Big Lake solar farm in Sherburne county, Minnesota. The site is a former potato farm that was converted into a solar array by owner-developer US Solar. While US Solar has generally practiced intentional land management strategies, Big Lake represents the company's early foray into the combination of

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74 "Agrivoltaics: Solar and Agriculture Co-Location," U.S. Department of Energy, accessed May 2025.

75 "Environmental Sustainability," Mesabi Metallics, accessed May 2025.

active farming with a functioning solar installation, known as agrivoltaics. The developer started with a demonstration site, planting crops like peppers and broccoli between its rows of solar panels, before opening the site to community members to plant and manage their own plots on the 1-MW solar installation.[76]

LOCAL ECONOMY

Concern

Economic concerns related to new industrial hydrogen projects include the potential displacement of existing jobs, the creation of only a limited number of new jobs, long-term economic project viability, and the extent of financial benefits for host communities from developed projects.

Strategy

New industrial projects should provide meaningful employment opportunities for local communities. For example, in discussions related to hydrogen hubs, U.S. DOE officials have emphasized "the important role labor unions will play in ensuring that the hydrogen industry is made up of quality jobs with smooth workforce transition pathways."[77] As the hydrogen industry grows, equitable access to local high-quality jobs will be key to ensuring that meaningful economic benefits are available to host communities.

When companies seek to build new industrial facilities in Minnesota, the Department of Employment and Economic Development (DEED) can help align regionally available workforce skills and labor pools with job demands for proposed projects, informing optimal project siting. DEED's research and analytical capabilities can also be used to evaluate direct and indirect economic impacts on host communities, enabling informed decision-making on projects. DEED's involvement in project planning and the evaluation of economic impact can help establish trust within host communities, which could otherwise be skeptical of claims made by outside companies. In addition, DEED manages a Job Training Incentives Program, which provides grants up to $200,000 to new or expanding businesses for worker training. Grant requirements include the establishment of new permanent, well-paying jobs, and preference is given to projects that provide training for certain groups of potential workers such as those classified as "long-term unemployed."[78] Developers could also work with the Department of Labor and Industry to create local union apprenticeship programs for hydrogen professions and universities to support the state's growing hydrogen economy.

Additionally, an array of existing state programs and initiatives to support effective workforce development for new industries could readily be leveraged to ensure that appropriate workforce pipelines are put in place for hydrogen jobs. The Minnesota State Centers of Excellence, particularly the centers for Advanced Manufacturing, Engineering, and Energy, present an opportunity for intentional engagement between industry and state educational institutions. The Minnesota Jobs Skills partnership (MJSP) provides pre-development grants to Minnesota State

[76] "Mixing solar and farming could be key to clean energy future," UMN West Central Research and Outreach Center, November 7, 2023, accessed May 2025, and Dreek Morgan and Monika Vadali, "Big Lake Agrivoltaics Project: Integrating Solar Power with Local Farming," Great Plains Institute, December 19, 2024, accessed May 2025.

[77] Shalin Jyotishi, "Labor Unions at the Center of DOE's $7 Billion Clean Hydrogen Hubs Project," New American, October 31, 2023.

[78] "Job Training Incentive Program Guide," Minnesota Department of Employment and Economic Development, accessed May 2025.

Centers of Excellence and other Minnesota state institutions to explore emerging market and workforce needs. The program also allows for collaboration with Tribal communities to assess opportunities for tailored workforce training developed in partnership with Native organizations.

One effective approach to addressing a variety of economic concerns is the use of binding agreements, which are legally enforceable contracts between developers and communities that guarantee specific benefits in exchange for local support. According to the EFI Foundation, such agreements are favored by community members and can include commitments to job creation, local hiring, training programs, and environmental protections.[79] Inclusion of community members in decision-making processes increases overall support for proposed projects. Community or co-operative ownership models could also be considered for smaller hydrogen-related projects, such as the distributed green hydrogen-based ammonia production approach described above.

Example

In southern Minnesota, ethanol projects gained strong community support by leveraging co-operative ownership models that involved local farmers. Co-operatives boosted Minnesota's ethanol production from less than 1 million gallons in 1989 to 1.3 billion gallons in 2022. In 2022, ethanol producers purchased an estimated $3.1 billion of Minnesota corn, helping support 22,350 workers, who earned $1.6 billion in wages. This example demonstrates a positive impact that a new industry can have on local economies by increasing product demand, supporting the local workforce and creating well-paying jobs.[80]

COLLABORATING WITH TRIBAL NATIONS

Concern

The federal government recognizes eleven Tribal Nations within the state of Minnesota. There is an overarching concern that the voices of Tribal Nations may not always be authentically heard or engaged in new industrial projects that directly impact the Nations. One such example is the Line 3 project to replace and expand an aging crude oil pipeline running from Alberta, Canada, through northern Minnesota. The project was opposed and challenged by the Anishinaabe People of Northern Minnesota and environmental groups, who argued that the project was approved without full assessment of oil spill risks and long-term harm to wetlands and Tribal resources in northern Minnesota. Despite strong objections from the impacted Tribes, Line 3 was completed and became operational in 2021.[81]

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[79] Madeline Schomburg, Nick Britton, Beth Dowdy, "Building Stronger Community Engagement in Hydrogen Hubs," EFI Foundation, February 2024.

[80] Brigid Tuck, "Economic Contribution of Minnesota's Ethanol Industry, 2022," University of Minnesota Extension, March 2023.

[81] Emilie Karrick Surrusco, "Tribes Defend Minnesota Waterways from Dangerous Line 3 Pipeline," Earthjustice, October 1, 2021, accessed May 2025.

Strategy

To ensure respectful and productive collaboration with Tribal Nations, proposed hydrogen projects should establish dedicated Tribal engagement forums rather than appointing a single Tribal representative to broader stakeholder groups. Opportunities should be provided for Indigenous communities to define their preferred methods of participation. Appointment of individuals who have a strong history of collaboration with Tribal Nations could facilitate dialogue between Tribes and project developers, helping to address concerns and ensure access to economic benefits, including workforce training and business partnerships.

Examples

The MITI green iron project offers a strong example of early and meaningful Tribal engagement in an industrial decarbonization effort. Led by NRRI, the project has partnered with Tribes in Minnesota to explore the use of green hydrogen for ironmaking. This collaboration began at the pre-design stage, encouraging early engagement and Tribal-defined participation. By working through trusted intermediaries like NRRI, the project builds on existing relationships and supports respectful, two-way communication. The partnership also opens opportunities for Tribal economic inclusion, including future roles in workforce development and site services. As one of the only hydrogen-adjacent projects in Minnesota with a Tribal partner, it offers a valuable model for integrating Indigenous perspectives into hydrogen planning.

An example of a Tribal-led clean energy development is the Red Lake Solar Project, which aims to achieve energy sovereignty for the Red Lake Nation while creating jobs. This project has been made possible through coalitions, federal grants, nonprofit support, and technical assistance from renewable energy groups, demonstrating that investment in Tribally led, community-centered projects can result in long-term benefits. The initiative also reflects how clean energy infrastructure can align with Indigenous values and self-determination when Native communities are empowered to lead the planning and development process.[82]

Conclusions and Key Takeaways

As Minnesota aims to grow its economy while meeting long-term net-zero GHG emissions goals, decarbonizing the state's industrial sector will be a critical objective. Clean hydrogen can play a key role in this effort, by helping the state to introduce new low-carbon industries and possibly eliminate the need for fossil fuels in certain hard-to-decarbonize industrial heat applications. The new low-carbon industries of interest to Minnesota include ammonia, iron, sustainable aviation fuel (SAF), and potentially methanol. While developing these industries in Minnesota could contribute small increases in GHG emissions to the state's industrial sector, they could also help to offset emissions associated with carbon-intensive versions of these industries in other states. Furthermore, because the products from these sectors are major inputs to other sectors in the state, such as agriculture, construction, and transportation, supporting these new low-carbon industries has the potential to reduce the net carbon intensity of Minnesota's economy more broadly. Key takeaways from the report are summarized below.

[82] "Red Lake Solar Project," Clean Energy Economy MN, accessed May, 2025.

OPPORTUNITIES

- Establishing new clean industries in the state could increase revenue and add high-quality jobs in line with the clean economy goal in Minnesota's Climate Action Framework.
- Regional small-scale production of green hydrogen-based ammonia under the ownership of Minnesota farmers could provide price stability for a major agricultural input, reduce overhead costs for farmers, and reduce the carbon intensity of Minnesota's agricultural products.
- Green hydrogen production can synergize with Minnesota's existing ethanol industry. Hydrogen can be either directly combined with the highly concentrated biogenic CO_2 generated by the ethanol plants to make low-carbon methanol, or green hydrogen-based ammonia can be combined with CO_2 to produce urea, a preferred form of fertilizer. Capture and utilization of waste biogenic CO_2 can reduce the carbon intensity of ethanol, make the production plants eligible for the federal 45Q tax credit, and provide additional revenue through the sale of CO_2-derived products.
- Low-carbon methanol is a potential marine fuel that could help decarbonize shipping in the Great Lakes.
- Low-carbon iron production can synergize with existing mining operations in the state, drawing on the existing infrastructure, knowledge, and workforce, while increasing the value that can be obtained from the state's iron ore resources.
- Low-carbon hydrogen can help SAF produced in Minnesota to meet the carbon intensity requirements for accessing the federal and state financial incentives. In turn, SAF production can help develop early offtake agreements for regional clean hydrogen projects, lowering barriers to financing of a nascent clean hydrogen industry in the state.
- Use of green hydrogen for industrial high-temperature process heat can significantly lower GHG emissions of several industries in the state and, if replacing coal, drastically reduce air pollution associated with those facilities.

OVERCOMING BARRIERS

- High capital and production costs are major barriers for large-scale low-carbon hydrogen projects, which negatively impact the cost-competitiveness of the hydrogen-based products. Federal financial incentives can help mitigate the cost barriers, but the future of existing programs and funds is uncertain due to shifting priorities at the federal level.
- Reliance on emerging technologies for the production of low-carbon hydrogen and hydrogen-based products elevates project risk and thus poses challenges to project financing.
- State-based financial incentives and support programs, such as tax credits, grants, and loans, are needed to help finance and promote low-carbon, hydrogen-related projects and industries.
- Electrolysis-based low-carbon hydrogen production at industrial scale would require significant additional renewable electricity generation or procurement. Therefore, careful planning will be needed to ensure Minnesota's ability to meet its carbon-free electricity mandates.
- The permitting process in Minnesota is widely acknowledged to be a major challenge for the development of complex industrial projects in the state.
- A robust regulatory framework for hydrogen in the state may be needed to ensure safety and gain community trust for large hydrogen projects. Minnesota can learn from Texas's history and experience in developing a safe hydrogen industry.

GAINING SOCIAL LICENSE

- Community concerns related to hydrogen projects focus on safety as well as impacts on local economies, clean water resources, and the environment more generally.
- Successful hydrogen adoption in Minnesota will depend on public trust developed through early and regular engagement, transparent communication, and tailored educational efforts. Addressing skepticism with evidence-based resources can significantly increase public confidence and project acceptance.
- Well-designed, robust, publicly available regulations and safety plans can help prevent accidents and build public confidence in the hydrogen industry over time.
- Workforce development programs and binding agreements can help ensure that host communities meaningfully benefit from hydrogen and hydrogen-related industrial projects.
- For projects that impact Minnesota's Tribal Nations, engagement will need to be tailored to the specific preferences and needs of the Nations involved. The Midwest Industrial Transformation Initiative approach to developing Minnesota's green iron hub can serve as a model for incorporating Tribal Nations in decision-making from initial stages of project development.

Table 7

		Target amount per year[a]	Hydrogen required (tons/year)	Water required (million gallons/ year)[b]	Electricity required (TWh)[c]	Total electrolyzer capacity required at 100%-50% capacity factor[d] (GW)	CO_2e emissions associated with blue hydrogen (tons/year)[e]	CO_2e emissions associated with gray hydrogen (tons/year)[e]	CO_2e emissions associated with conventional production (tons/year)[f]
INDUSTRIAL SECTOR	Low-carbon ammonia	900,000 tons/year	160,000[g]	860	8.9	1.0-2.0	N/A	N/A	1,600,000
	Low-carbon iron	2,000,000 tons/year	110,000[h]	570	5.9	0.68-1.36	270,000	N/A	-
	Sustainable aviation fuel	193,000,000 gallons/year	29,000[i]	150	1.6	0.18-0.36	73,000	320,000	-
	Low-carbon methanol	50,000 tons/ year	10,000[j]	53	0.55	0.063-0.126	N/A	N/A	110,000
	High-temperature process heat	13 TWh / 4.5×10^7 MMBtu/ 4.8×10^7 GJ	400,000[k]	2,100	22	2.5-5.0	N/A	N/A	2,500,000
	TOTAL	-	710,000	3,700	39	4.4-8.8	-	-	-

[a] For ammonia and industrial heat, the target amounts are total annual needs in Minnesota. For iron, SAF, and methanol, the target amounts are for single potential facilities.
[b] Assumes 20 L water/kg H_2 (Hydrogen reality check: Distilling green hydrogen's water consumption. RMI, August 2023).
[c] Assumes 55 kWh/kg H_2 (Update 2024. Pathways to commercial liftoff: Clean hydrogen. U.S. Department of Energy. 2024).
[d] To calculate electrolyzer capacity, total annual electricity required was divided by 8,760 hours per year and by the electrolyzer capacity factor. Capacity factor measures how much the electrolyzer operates relative to its maximum possible output. The calculated values assume the electrolyzers would run between half and full capacity, depending on the power source—close to 100% for grid power, and potentially below 50% for intermittent renewables.
[e] CO_2e emissions associated with blue and gray hydrogen are provided only for non-integrated industries, where hydrogen is used as a feedstock.
[f] CO_2e emissions associated with conventional production are provided for industries, where the use of green hydrogen and renewable electricity at an integrated facility can reduce emissions associated with production of the target product to near zero.
[g] Assumes 180 kg H_2/ton ammonia (Patricia Mayer, Adrian Ramirez, Guiseppe Pezzella, et al., Blue and green ammonia production: A techno-economic and life cycle assessment perspective. iScience 26: 107389, August 2023).
[h] Assumes 54 kg H_2/ton direct-reduced iron (M Shahabuddin, Alireza Rahbari, M Akbar Rhamdhani, et al., Process modeling for the production of hydrogen-based direct reduced iron in shaft furnace using different ore grades. *Ironmaking and Steelmaking*: 1, May 2024).
[i] Assumes 0.15 kg H_2/gal biobased SAF (Sustainable aviation fuel state-of-industry report: Hydroprocessed esters and fatty acid pathways. NREL, July 2024).
[j] Assumes 0.2 kg H_2/kg methanol (Stefano Sollai, Andrea Porcu, Vittoria Tola, et al., Renewable methanol production from green hydrogen and captured CO_2: A techno-economic assessment. *Journal of CO_2 Utilization*. 68: 102345, February, 2023).
[k] Assumes 33.33 kWh/kg H_2 the lower heating value of hydrogen.