

Low Carbon Emission “Green” Iron Production in Minnesota

Humphrey School Capstone Report

**The Hubert H. Humphrey School of Public Affairs,
The University of Minnesota**

**Nuzhat Fatima
Jason Janisch
Md Mursalin Rahman Khandaker**

PA 8081: Capstone Workshop
Science, Technology, and Environmental Policy
Instructor: Steve Kelley, Director of Graduate Studies

Spring 2025

Minnesota Department of Commerce



HUMPHREY SCHOOL
OF PUBLIC AFFAIRS
UNIVERSITY OF MINNESOTA

Subject Keywords:

Industrial decarbonization, green iron, Direct Reduced Iron (DRI), hydrogen steelmaking, Electric Arc Furnace (EAF), taconite, Minnesota Iron Range, iron mining, DR-grade pellets, Cleveland-Cliffs, U.S. Steel, Mesabi Metallics, renewable energy, emissions reduction, carbon dioxide (CO₂), decarbonization, hydrogen, natural gas DRI (NG-DRI), environmental permitting, Tribal sovereignty, water quality, workforce transition, social license, stakeholder engagement, Minnesota Department of Commerce, mining economics, blast furnace (BF), basic oxygen furnace (BOF), Scope 1 emissions, Scope 2 emissions, Scope 3 emissions, Natural Resource Research Institute (NRRI), Midwest Industrial Transformation Initiative (MITI).

Abstract

Steel is essential to modern life, used in everything from infrastructure to transportation. Yet the industry that produces it is one of the most polluting in the world, responsible for approximately 7 to 9 percent of global carbon dioxide emissions. As the push to decarbonize grows stronger, new technologies are emerging to replace the traditional blast furnace (BF) method with lower-emission alternatives such as electric arc furnaces (EAFs), which use direct-reduced iron (DRI) as feedstock. This shift presents a major opportunity for Minnesota. Northeastern Minnesota is rich in iron ore and has long supplied taconite pellets to steelmakers in other states. But as the industry transitions from BFs to EAFs, which cannot use taconite in its current form, Minnesota must adapt.

Developing the capacity to convert taconite into DRI would significantly reduce emissions while adding more value to local resources. With demand for BF-grade pellets declining, in-state DRI production could help economically revitalize Iron Range communities and position Minnesota as a leader in clean ironmaking. This paper explores whether Minnesota has the resources, infrastructure, and industry interest to support a DRI facility. While the state has key inputs such as iron ore, water, and natural gas, limited renewable electricity and environmental permitting challenges remain.

Realizing green iron in Minnesota is not just technological issue; it requires navigating complex political, social, and environmental dynamics. Addressing legacy harms from mining and ensuring inclusive stakeholder engagement will be essential, and supportive policy and sustained collaboration are necessary for Minnesota to lead in this next phase of steelmaking.

List of Units used in this document

Unit	Explanation
MTPA	Million Tons Per Annum, used to quantify annual production capacity of iron or steel facilities.
MtCO₂e/t	Metric tons of carbon dioxide per ton of steel, used to express emission intensity.
TWh	Terawatt-hours, used to measure annual electricity consumption of large-scale facilities.
GWh	Gigawatt-hours, also used for energy, often for slightly smaller-scale electricity consumption.
GW	Gigawatt, used for peak electrical power demand.
MMBTU	Million British Thermal Units, a unit of energy typically used for natural gas consumption.
kWh/kg	Kilowatt-hours per kilogram used to quantify electricity needed to produce 1 kg of hydrogen.
M³	Cubic meters, unit of volume, often used for water consumption.
Million gallons	Unit for water volume, used in the U.S. to express industrial water requirements.
% Fe	Percent Iron, the concentration of iron content in ore or pellets.

List of Acronyms used in this document

Acronym	Full form
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BF- BOF	Blast Furnace-Basic Oxygen Furnace
CO₂	Carbon dioxide
DOE	Department of Energy
DRI	Direct Reduced Iron
EAf	Electric Arc Furnace
ENRTF	Environment and Natural Resources Trust Fund
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
GLIFWC	Great Lakes Indian Fish and Wildlife Commission
H₂	Hydrogen gas
IDI	In-depth Interview
IRA	Inflation Reduction Act
IRP	Integrated Resource Plan
IRRR	Minnesota Iron Range Resources and Rehabilitation
IRRRB	Iron Range Resources and Rehabilitation Board
LCA	Life Cycle Assessment
MPCA	Minnesota Pollution Control Agency
MISO	Midcontinent Independent System Operator
NG	Natural Gas
NG-DRI	Natural Gas-Direct Reduced Iron
NRRI	Natural Resources Research Institute
PUC	Minnesota Public Utilities Commission
PJM	Pennsylvania-New Jersey-Maryland Interconnection
TEDF	Taconite Economic Development Fund
R&D	Research and Development
U.S.	United States

Table of Contents

1. Project Introduction	7
1.1 Background	7
1.2 Research Methodology	8
1.3 Timeline	8
2. Iron Mining in Minnesota	8
2.1: Iron Range and mining	8
2.2 Ironmakers in Minnesota	10
2.2.1:Vertically Integrated Minnesota Miners	11
2.2.2 Merchant Iron Mining Operators.....	11
2.2.3 Domestic Producers and Consumers of DRI / EAF Operators	12
3. Low Carbon Iron in Minnesota: Technical Feasibility	14
3.1 Current Ironmaking	14
3.1.1: Blast furnace / basic-oxygen furnace (BF-BOF).....	14
3.1.2 Electric Arc Furnace (EAF).....	15
3.1.3 Natural Gas Based Direct Reduced Iron (NG–DRI)	15
3.1.4 Hydrogen-Based Direct Reduced Iron (H ₂ –DRI).....	15
3.2 Emissions in Ironmaking Pathways	16
3.2.1: Blast Furnace/Basic Oxygen Furnace (BF/BOF):.....	16
3.2.2: Electric Arc Furnace (EAF).....	16
3.2.3: Natural Gas Based Direct Reduced Iron (NG–DRI).....	16
3.2.4: Hydrogen-Based Direct Reduced Iron (H ₂ –DRI).....	16
3.3: Raw Material Availability	17
3.3.1 Water.....	18
3.3.2 Electricity	18
3.3.3 Natural Gas.....	18
3.3.4 Iron Ore	18
4. Social and Political Considerations in Minnesota’s Green Iron Transition	19
4.1 Definitions, Methodology and an Overview	19
4.2 Overview of Identified Issues Shaping the Green Iron Transition in Minnesota	20
4.3 Workforce Transition and Local Economic Development	20
4.4 Water Quality	24
4.5 Tribal Engagement	26
4.6 Permitting, Social License, and the Business Perspective	26
5. Relevant Policies	29
5.1 Overall Policy Landscape	29
5.2 Demand-side Policies	29
5.2.1 Clean Procurement: Buy Clean	29
5.3 Supply-side Policies	31
5.3.1 Clean Electricity	31
5.3.2 Clean Hydrogen.....	31
5.3.3 Workforce Development.....	32
5.4 Research and Development (R&D)	33
5.4.1 R&D Efforts in Technological De-Risking	33
5.4.2 Social De-Risking.....	34

6. Constraints, Limitations and Disclosures..... 35
7. Findings 36
8. Recommendations..... 40
9. References 42
10. Appendix..... 46

1. Project Introduction

1.1 Background

Steel is one of the most widely used materials in the world and is found in buildings and bridges to cars and aeroplanes. Its production process, however, is responsible for roughly 7% of global CO₂ emissions, making the decarbonization of the steel sector a critical piece in efforts to meet international climate targets. In recent years, a major trend in the steel industry, both globally and in the United States has been the shift toward green steel. This is steel produced with significantly reduced carbon emissions across the entire production process.

Traditionally, steel is made by feeding raw iron ore into a blast furnace (BF), where coal acts as a reducing agent to produce molten iron. This molten iron is then further refined in a basic oxygen furnace (BOF). This traditional process is broadly referred to as the BF-BOF method and it is historically how steel has been made. In contrast, green steel production primarily uses the Direct Reduced Iron (DRI) method as the first major step. In this process, a reducing agent removes oxygen from the iron ore, preferably green hydrogen, though natural gas is often used as an interim solution. The resulting DRI is then melted in an Electric Arc Furnace (EAF) to produce steel. When both the reducing agent and the electricity used in the EAF come from renewable sources, the DRI–EAF route can produce near-zero emissions steel and is a much more environmentally-friendly option than the traditional BF-BOF route.

The shift toward green steel is both timely and highly relevant for Minnesota. Historically, the state has had a natural abundance of taconite, a low-grade iron ore, present in rock formations in the Mesabi Iron Range. This ore is processed into taconite pellets within the state and then shipped to steel mills in other parts of the country, where it is converted into steel. This supply chain structure illustrates that Minnesota’s taconite pellets occupy the upstream, low value-added stage of the steel production process. However, as green steel gains momentum, Minnesota risks losing its position in the steel supply chain because its primary product, taconite pellets, does not have a high enough iron content to be used in electric arc furnaces. At the same time this presents a rich opportunity for the state to move up the value chain by transitioning from taconite pellet production to in-state production of higher-grade DRI. **Thus, the green steel shift, for Minnesota, is broadly a green iron issue.**

Determining whether Minnesota is ready to take advantage of this industry shift requires careful consideration across multiple dimensions, from technological feasibility and resource availability to economic, social, and political factors. Against this backdrop, this research paper aims to highlight key considerations for assessing Minnesota’s position in the green steel transition. This will be examined through the lens of four key research questions:

1. How much hydrogen, electricity, and water will be consumed if a decarbonized iron industry is established in Minnesota?
2. What are the emissions savings of a transition to green iron process in Minnesota?
3. What are the impacts on stakeholders involved, economically, politically, and socially? What risks are there from an equity standpoint?
4. What policies are there to enable the transition to green iron in Minnesota?

This research was conducted as a student capstone project at the Humphrey School of Public Affairs at the University of Minnesota. Capstone projects are student-led initiatives carried out in partnership with a client, where the research direction is shaped collaboratively based on the client’s goals and evolving priorities. In this case, the client is the Minnesota Department of Commerce (Commerce), specifically its Energy Resources Division. Commerce is the de-facto state energy office, and is currently exploring the feasibility and potential pathways for Minnesota to participate in the decarbonization of industry. The agency serves primarily in an advisory capacity, and the role of the Capstone team has been to conduct research that establishes the key facts and considerations associated with the green steel

transition. On that front, the research questions in this project emerged from conversations with the client and reflect shared interests in understanding what it would take for Minnesota to play a more active role in the transition toward green steel. Thus, the goal of this research is not to advocate for a particular position, but rather to present an assessment of the issues at hand. This has been the guiding principle driving this project.

1.2 Research Methodology

This research was conducted using a combination of literature review and primary data collection, guided by the project’s research questions.

The literature review was informed primarily by online searches and focused on identifying sources relevant to the topic and applicable to the Minnesota context. As such, the review is limited by the availability of publicly accessible materials at the time of research. The secondary sources consulted include a range of grey literature including white papers, policy briefs, local and regional newspaper articles, and opinion pieces.

In addition, the capstone team conducted in-depth interviews (IDIs) with individuals identified as key stakeholders in Minnesota’s potential transition to green iron production, using an internal stakeholder mapping process. These stakeholder groups included representatives from steel operators with mining operations in Minnesota, environmental advocacy groups, electric utilities, trade associations, trade schools, local economic development agencies, and nonprofits with various levels of engagement with this issue. In total, the team identified and contacted approximately 60 stakeholders across these groups via email. Responses were received and interviews were conducted with 13 individuals. The purpose of these interviews was to better understand both the concerns and the hopes that different stakeholders hold regarding this transition in Minnesota from a qualitative perspective. Most interviews were conducted virtually via video conferencing, with a few held in person during the team’s site visit to the Iron Range in April 2025. Before each interview, participants received a set of guiding questions tailored to their organization to help shape the discussion. The interviews followed a semi-structured format, allowing for flexibility and open-ended dialogue. All interviews were recorded and transcribed, and the content was analyzed using qualitative research methods. Insights from these interviews are reflected throughout the report, both through direct quotes and, more commonly, through broader themes that reinforce and expand upon findings from the literature review.

1.3 Timeline

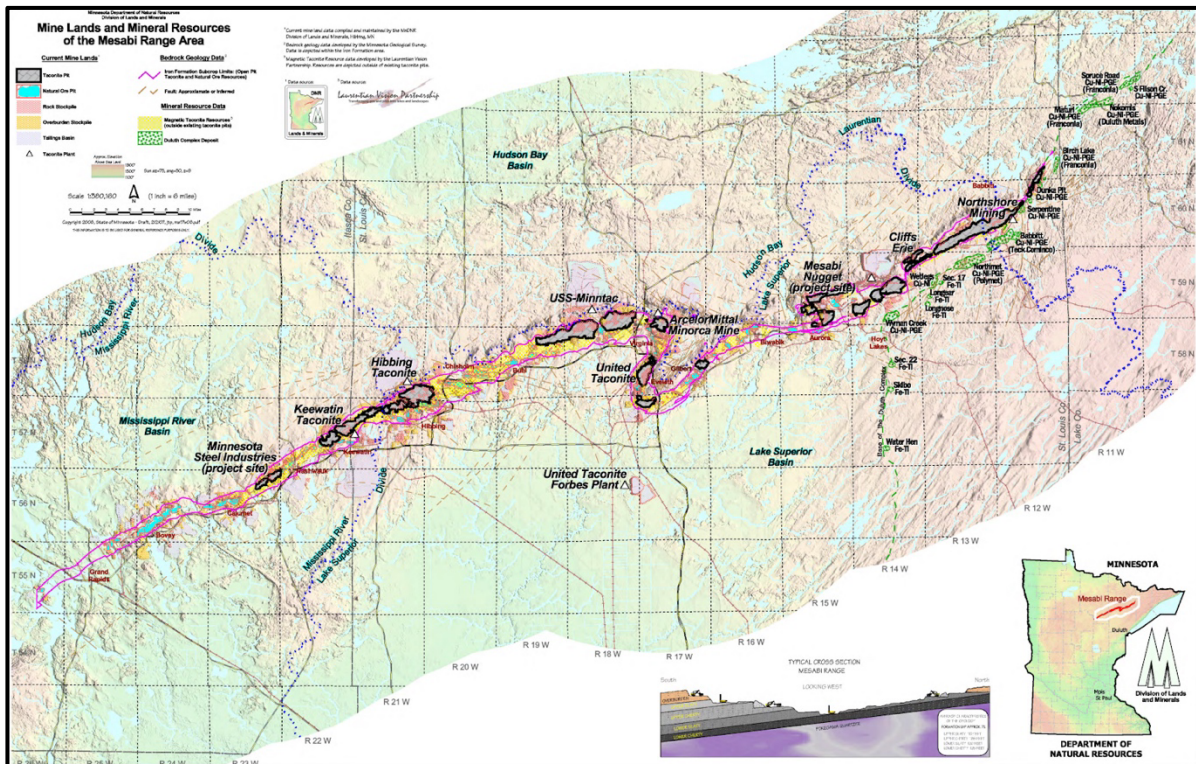
This research was conducted between January and May 2025. Initial meetings between the Commerce and the capstone team took place in December 2024 to finalize the research questions and establish expectations for the final deliverable. The research questions were divided among the three members of the capstone team. While each researcher worked independently on their assigned question, the overall goal was to produce a cohesive and collaborative final paper.

2. Iron Mining in Minnesota

2.1: Iron Range and mining

Minnesota fits into today’s steel value chain predominantly as a supplier of iron-ore blast furnace grade and direct reduced (DR) grade pellets, the raw material input to primary iron-making. These pellets are produced at six operating plants in northeast Minnesota along a geologic iron formation known as the Mesabi Range.

Figure 1: Mine lands and mineral resources of the Mesabi Range



(Source: Minnesota Department of Natural Resources)

The production of taconite pellets from iron ore is a complex and integrated process involving mining, mineral extraction, and pellet induration.

Once a suitable iron-ore resource is identified through geologic exploratory methods and confirmed with drilling and lab work, the surface material covering the ore, the overburden, is removed, often stockpiled or repurposed, exposing the surface of the ore deposit. A section of the ore deposit is then drilled with an engineered pattern of holes to allow for the safe and efficient blasting and fracture of the mineral body. Once blasted, the ore is loaded onto haul trucks with large excavators and transported to the mineral processing plant. This run-of-mine material can range in size up to 5 feet in diameter and has a typical iron oxide content of 20-30% by weight.

The mineral extraction process involves crushing and grinding the iron-oxide ore to a small enough size to allow the non-iron-bearing minerals, called gangue or tails, to be separated and discarded. Several successive stages of dry crushing and then wet grinding are used to reduce the size of the rocks to grains of powder less than 0.1 mm in diameter. Magnetic separators then extract the iron-bearing particles from the wet slurry mixture. The particles not collected by the magnetic separator are pumped to tailings storage ponds where the particles settle, and the water is reclaimed. The separated iron particles, called concentrate, are pumped to the pelletizing facility when producing blast furnace grade pellets, or to a fine grinding step when producing DR grade pellets.

In the fine grinding step, the wet concentrate is ground smaller to further liberate any non-iron particles and a flotation separation process is used to capture and reject them. This results in a higher purity iron concentrate which is required for direct-reduced iron making. Once upgraded, this higher purity concentrate is pumped to the pelletizing facility.

In the pelletizing facility, the iron concentrate slurry is dewatered with disc filters, leaving a mainly dry iron powder. This dried iron concentrate is mixed with steel-making additives and a binding compound

before being rolled into a small spherical shape in a balling drum. These green balls then enter the indurating furnace and are fired to temperatures above 1200F, creating the hardened taconite pellets.

These finished iron-oxide pellets, containing approximately 65% iron by weight, once cooled, are shipped via train and boat to steel mills predominantly on the Great Lakes where the iron and steel-making processes occur.

Annual statewide production of taconite pellets has varied from 28 million to 39 million tons over the last 10 years.

Figure 2: Integrated Blast Furnaces near the Great Lakes



(Source: Global Steel Tracker)

2.2 Ironmakers in Minnesota

Examining who is most likely to develop an iron-making plant in Minnesota can help us estimate how much green iron could be made and what demands it will put on the area's resources. Likely developers of a green iron plant in Minnesota include the current vertically integrated Minnesota iron ore miners and steel makers, ClevelandCliffs and U.S.Steel; international green steel-makers with eye toward entering or expanding in the U.S. market, such as SSAB, or Stegra (H2GreenSteel, 2023); current domestic producers and consumers of Direct Reduced Iron and EAF operators, such as NuCor, Steel Dynamics, and ArcelorMittal; and proposed merchant mining operators, such as Mesabi Metallics, Calumet Reclamation, and MagIron.

2.2.1: Vertically Integrated Minnesota Miners

Vertically integrated mining companies are companies that own and operate facilities along the complete steel value chain including iron-ore mines, raw and finished steel making facilities, and steel finishing facilities. These companies have established iron mining and processing facilities in Minnesota along with substantial ore reserves. A hydrogen based iron facility would essentially be a bolt-on to their existing mineral processing and pellet making operations offering significant advantages over other green-field operations. Additional advantages these operators could realize include potential energy-savings from directly charging hot DR-grades pellets into the direct-reduced iron plant, reduced shipping expenses and emissions, and the ability to consume the direct-reduced iron at their own steel making facilities.

◆ Cleveland Cliffs

Cleveland Cliffs operates four taconite plants in Minnesota and invested more than 100 million dollars in 2019 to upgrade their Northshore Mine facility in Silver Bay to make DR-grade pellets. In 2018, Cliffs explored building a direct-reduced iron plant on the Iron Range. Cliffs ultimately rejected the Minnesota location and chose Toledo, Ohio, citing, among other reasons, a more expedited permitting process and proximity to their end-customer. Currently, Cliffs is exploring several other decarbonizing technologies that would allow the continued use of their blast-furnace pellets. These technologies include the direct injection of hydrogen into their blast furnaces, carbon capture, and electric ore smelting. In 2024, Cliffs received a 500-million-dollar grant from the Department of Energy to offset costs related to the electric smelting project at their Middletown, Ohio facility (Cleveland Cliffs Inc., 2022).

◆ United States Steel

U.S. Steel operates two taconite plants in Minnesota, recently investing \$150M into their Keetac facility to produce DR-grade pellets. U.S. Steel has been investing heavily in acquiring and building EAFs that need iron metallics as raw material and has a stated corporate goal of net-zero by 2050. U.S. Steel is listed as a partner with the University of Minnesota’s Natural Resource Research Institute on a 2024 Department of Energy grant exploring the feasibility of green iron production in Minnesota (U.S. Steel Corporation, 2022).

2.2.2 Merchant Iron Mining Operators

Merchant iron mining operators are companies that in the past made, currently make, or intend to make, iron-based feedstocks to sell to steel makers. These feedstocks can be in the form of minimally processed lump ore, iron-oxide concentrate, iron-oxide pellets, or metallized iron. These companies have secured access to in-ground iron-ore, or natural ore stockpiles, and facilities or plans for facilities in Minnesota. The iron products made by the merchant iron mining operators could be used to make hydrogen based iron metallics. Co-locating the DRI facility using these feedstocks in Minnesota would have some of the advantages listed for the integrated operations including energy, shipping, and emissions savings.

◆ MagIron

MagIron is a hematite iron ore scam mining operation that purchased some of the assets of the bankrupt Magnetation scam mining operation. Their Plant 4 facility has the capability to produce 2.0 MTPA iron-ore concentrate annually. This concentrate could then be used to create DR grade pellets or iron using other experimental and emerging technologies. The project has secured necessary operating permits but has yet to announce a restart of operations (MagIron LLC, 2024).

◆ **Mesabi Metallics**

Mesabi Metallics is constructing a 7 MTPA DR-grade pellet plant in Nashwauk, Minnesota. Their original project plans included a DRI and EAF facility on the same campus however the current scope of work no longer includes these processes. The company plans to start operations in 2026 and sell their pellets on the global market. Eventually, Mesabi Metallics plans on building two DRI plants in the United States (Mesabi Metallics, 2023).

◆ **Scranton Holdings / Calumet Reclamation**

Scranton Holdings is designing a decarbonized pig iron plant near Minot North Dakota, with plans to source iron-ore from Minnesota. There has been a grant of \$10M From the state of North Dakota to develop the project. They plan to build a 2 MTPA iron plant using natural gas as a fuel and carbon capture and sequestration to reduce greenhouse gas emissions.. Given the North Dakota investment and announced project plans this DRI project will not be in Minnesota. The project team has been vocal that permitting timelines are a big part of their location selection (Industrial Commission of North Dakota, 2024).

2.2.3 Domestic Producers and Consumers of DRI / EAF Operators

Companies that currently produce direct-reduced iron in the United States may be likely candidates to expand operations to Minnesota. Further, companies that operate electric arc furnaces consume the bulk of the direct reduced iron domestically and may be equally interested. As these operators push to make higher and thinner grades of steel, their need for high-purity iron feedstocks will grow. Competition for high-quality scrap steel is expected to increase as electric arc furnaces continue to displace blast furnaces in raw steel production. Controlling access to iron-ore feedstocks and iron making facilities may be advantageous to EAF operators’ overall business.

◆ **Nucor**

Nucor is the largest EAF steel maker in the United States and consumes a significant amount of iron-metallics in its operations. They currently operate a 2.5 MTPA natural gas field direct reduced iron facility in St. James Parish, Louisiana. Their total steel making capacity is approximately 30 million tons per year. Nucor’s current emissions intensity for their scope 1, 2, and 3, emissions is 0.77 metric tons of CO₂ equivalent per ton of steel produced, among the lowest in the world. Nucor has a stated goal of reducing this to net-zero by 2050. As global trade patterns shift due to geo-politics, Nucor may find it advantageous to increase their domestic production or secure additional domestic units of DRI. This could drive the development of a DRI plant in Minnesota or at least the consumption of additional DR-grade pellets if the DRI facility is built elsewhere in the United States (Nucor Corporation, 2022).

◆ **Steel Dynamics**

Steel Dynamics is another large EAF steel maker in the United States. Historically, Steel Dynamics sourced pig iron from Russia and Ukraine however this changed with Russia’s invasion in 2021. Steel Dynamics found alternate supplies of pig iron from India and Brazil and increased their utilization of scrap in steel production. Prior to this, in 2007, Steel Dynamics, in partnership with Kobe Steel, began construction of an iron nugget plant on the Iron Range. The project, called Mesabi Nugget, operated until its indefinite idling in 2015. Technological problems plagued the project. When the pig iron market dropped substantially in 2014 and 2015 operations were terminated (Steel Dynamics Inc., 2022). Speculatively, like Nucor, Steel Dynamics may find it advantageous to secure and develop new primary iron resources.

◆ **ArcelorMittal**

ArcelorMittal operates a 2 MTPA direct-reduced iron plant near Corpus Christi, Texas. The plant was built by Voestalpine, a European steel maker, and opened in 2016. ArcelorMittal purchased the facility in 2022 for \$1 billion. ArcelorMittal has had a long time presence in the U.S. steel industry before

selling the majority of their holdings, including the Minorca Mine in Minnesota, to Cleveland Cliffs in 2020. According to the World Steel Association, ArcelorMittal is the second largest steel producer in the world.

2.2.4: European Green Steel Makers

The policy landscape in Europe has accelerated investment in green steel making and the development of green steel technical expertise. The European Union implemented a cap and trade carbon tax system in 2005 and has been phasing it in over the last twenty years. This has spurred research and development of hydrogen-based steel making to reduce CO₂ emissions. Some of these companies have announced their interest in expanding green steel making to the United States.

◆ SSAB

SSAB is a Swedish-based global steel maker with operations worldwide and in the United States. At their Lulea, Sweden facility, SSAB has conducted exhaustive bench and pilot studies of hydrogen-based iron making. Currently, they are building a 2.5 million ton green iron plant with production expected by the end of 2028. In April 2024, SSAB was awarded a 500-million-dollar grant from the Department of Energy to build a green iron plant on the Gulf Coast of the United States. Since then, SSAB has quietly ended that project.

◆ Stegra (H2GreenSteel)

Stegra, formerly known as H2 Green Steel, is a start-up Swedish-based green steel maker building a 2.5 million ton plant in Boden, Sweden. Production is expected to begin in late 2026. In late 2023, Vale, a global iron-ore supplier, and Stegra, signed an agreement to jointly develop hydrogen-based industrial hubs in Brazil and North America. The joint effort is still in the feasibility phase and no specific projects have been announced (H2GreenSteel, 2024).

◆ Thyssenkrupp

Thyssenkrupp is a German industrial conglomerate with steel making and decarbonization businesses. They are currently building a hydrogen-based green iron plant in Duisburg, Germany with a goal of being operational in 2027. Thyssenkrupp used to own a steel processing facility in Calvert, Alabama however sold the facility to Arcelor Mittal and Nippon Steel in 2014.

3. Low Carbon Iron in Minnesota: Technical Feasibility

This section outlines the major iron production pathways relevant to Minnesota’s future: the traditional blast furnace–basic oxygen furnace (BF–BOF) route, electric arc furnace (EAF) steelmaking, and emerging technologies based on natural gas (NG–DRI) and green hydrogen (H₂–DRI).

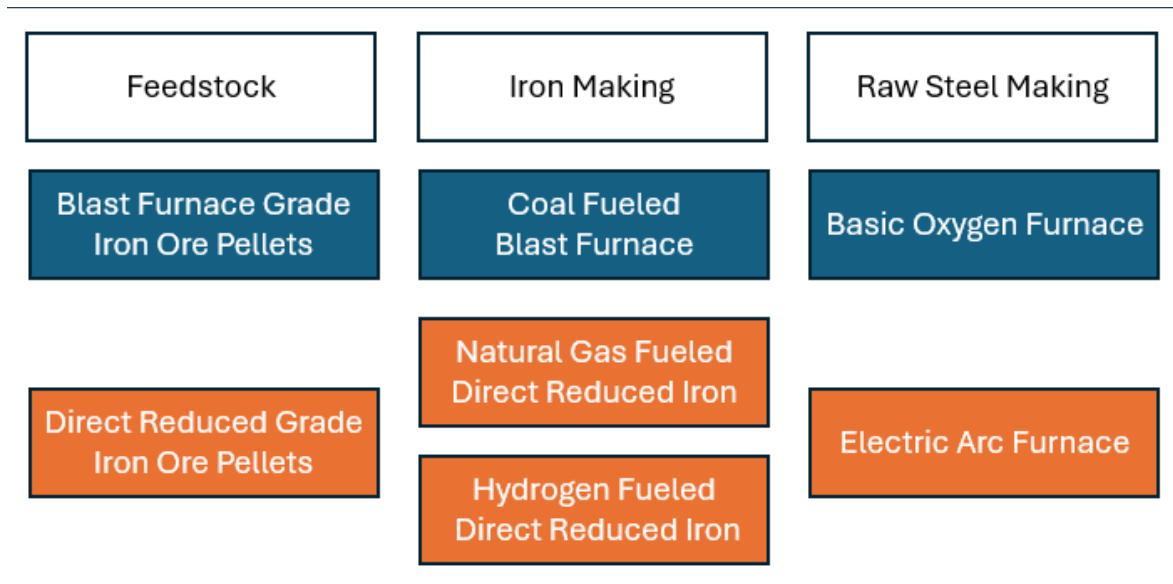
3.1 Current Ironmaking

3.1.1: Blast furnace / Basic Oxygen furnace (BF-BOF)

There are currently two predominant raw steel-making methods in the United States: from iron-ore in a blast furnace / basic-oxygen furnace (BF-BOF) or from recycled scrap and iron-metallics via an electric arc furnace (EAF). The blast furnace process involves combining and melting iron-ore, which is nominally 65% iron, coking coal, and other additives in a large vessel to create a very pure molten metallic iron. During the smelting process, iron-oxide ore reacts with carbon from the coking coal and forms carbon dioxide. The product is a molten metallic raw iron, which is then transferred to a basic oxygen furnace, where additional ingredients are added to further refine the steel. This two-step iron-to-steel process is commonly called integrated steelmaking.

In the blast furnace, undesirable metallic contaminants such as copper, silica, and phosphorus, are drawn out of the molten iron by limestone flux creating a slag by-product and leaving a very pure metallic iron. This high purity, low residual iron is required to make the thinnest, strongest, and highest surface finish steels used in exposed automotive applications.

Figure 3: Iron and Steel making



Minnesota currently produces iron in the form of taconite pellets, which are shipped to blast furnaces in other states. As a rule of thumb, the scope 1 and 2 greenhouse gas emissions intensity of the BF/BOF steelmaking is 2 tons CO₂ per ton of finished steel.

3.1.2 Electric Arc Furnace (EAF)

The Electric Arc Furnace (EAF) process is a flexible and efficient method of steelmaking that primarily relies on electricity to melt recycled scrap steel, with the option of adding virgin iron inputs such as direct reduced iron (DRI), pig iron, or hot metal. It is widely used for the production of long steel products and, with increasing technological improvements, is now capable of producing flat products of high quality (World Steel Association [WSA], 2022). In a typical EAF operation, large buckets filled with steel scrap and other metals are charged into the furnace. Once charged, graphite electrodes are lowered into the furnace and used to strike an arc of high-voltage electricity, which melts the metal through resistive and radiative heating. Oxygen lances and natural gas burners may be used to assist in preheating the charge and accelerating the melting process. Once molten, refining takes place through slag-forming reactions that help remove unwanted elements like sulfur (S) and phosphorus (P). Fluxing agents such as lime (CaO) are used to adjust slag chemistry and trap impurities. Alloying elements are also added to tailor the final steel composition. After melting and refining, the molten steel is tapped into a ladle for secondary metallurgy and is eventually cast into semi-finished shapes like billets, blooms, or slabs using continuous casting machines (U.S. Department of Energy [DOE], 2008).

3.1.3 Natural Gas Based Direct Reduced Iron (NG–DRI)

This transitional route reforms natural gas to produce syngas (CO + H₂), which reduces iron ore into DRI (Midrex, 2023). Typical reactions include:

- ◆ $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$ (Steam reforming)
- ◆ $\text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2$
- ◆ $\text{Fe}_2\text{O}_3 + 3\text{H}_2 \rightarrow 2\text{Fe} + 3\text{H}_2\text{O}$

3.1.4 Hydrogen-Based Direct Reduced Iron (H₂–DRI)

Hydrogen-based direct reduced iron (H₂–DRI) is an emerging low-carbon steelmaking technology that uses green hydrogen instead of fossil fuels, eliminating CO₂ emissions during iron ore reduction (SSAB, 2022; HYBRIT, 2021). The process begins with beneficiation and pelletizing of ore into DR-grade pellets, followed by hydrogen production via electrolysis:

- ◆ Electrolysis:
 $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$

In the shaft furnace, hydrogen reduces iron ore without producing CO₂:

- ◆ Reduction:
 $\text{Fe}_2\text{O}_3 + 3\text{H}_2 \rightarrow 2\text{Fe} + 3\text{H}_2\text{O}$

The only by-product is steam, which can be recycled. The resulting sponge iron is either hot charged into an electric arc furnace (EAF) or briquetted as HBI for later melting. Pilot projects like HYBRIT and H₂ Green Steel demonstrate that, when powered by renewable electricity, H₂–DRI can cut emissions by over 95% compared to conventional blast furnace steelmaking (Rocky Mountain Institute, 2023; IEA, 2020).

3.2 Emissions in Ironmaking Pathways

The choice of ironmaking pathway greatly influences the overall greenhouse gas emissions associated with steel production. Each route—whether traditional blast furnace–basic oxygen furnace (BF–BOF), electric arc furnace (EAF), natural gas–based direct reduced iron (NG–DRI), or hydrogen-based direct reduced iron (H₂–DRI)—carries distinct Scope 1, 2, and 3 emission profiles. This section summarizes the emissions intensity for each pathway, focusing on how much carbon dioxide (CO₂) is emitted within Minnesota (Scopes 1 and 2) and beyond its borders (Scope 3). Understanding these emissions is critical for evaluating the environmental impact of shifting Minnesota’s iron ore industry toward low-carbon and green steel production. Detailed descriptions of the emission categories, stepwise emissions and overall emissions can be found in Appendix 10B.

3.2.1: Blast Furnace/Basic Oxygen Furnace (BF/BOF):

While the state’s **Scope 1** emissions stem from diesel use in mining and natural gas for pellet induration (~1–2 MtCO₂ annually), **Scope 2** emissions result from electricity consumption in processing plants (~1.6 MtCO₂ in 2006) (Minnesota Pollution Control Agency [MPCA], 2009). However, over **90% of lifecycle emissions** (~50 MtCO₂/year) occur downstream at integrated steel mills in states like Indiana and Ohio (Minnesota Department of Natural Resources [DNR], 2023; CarbonChain, 2023; Rocky Mountain Institute [RMI], 2023). This results in total emissions of 2.2 tCO₂/ton of steel (IEA, 2020).

3.2.2: Electric Arc Furnace (EAF)

EAFs melt steel scrap and DRI using electricity and are increasingly used for flat products. Graphite electrodes generate intense heat; fluxes help remove impurities like sulfur and phosphorus. EAFs emit low **Scope 1 emissions** (~0.05–0.10 tCO₂/t steel) from graphite oxidation and gas burners (World Steel Association [WSA], 2022; CarbonChain, 2023). **Scope 2 emissions** vary with electricity source, typically ~0.16–0.24 tCO₂/t (IEA, 2020; RMI, 2023). With renewable energy, emissions can be near zero. **Scope 3** emissions are relatively minor (~0.1–0.3 tCO₂/t) (CarbonChain, 2023).

3.2.3: Natural Gas Based Direct Reduced Iron (NG–DRI)

A 2 MTPA NG-DRI facility emits 1.0–1.3 tCO₂/t steel (Midrex, 2023; CarbonChain, 2023; Suer et al., 2022), shifting a large share of emissions from Scope 3 (BF mills) to Minnesota’s **Scope 1** (0.6–0.7 tCO₂/t). While electricity use increases slightly (**Scope 2** ~0.05–0.1 tCO₂/t), this remains minor unless the EAF is in Minnesota. The approach yields a ~45–60% emissions reduction compared to BF–BOF (IEA, 2020; RMI, 2023).

3.2.4: Hydrogen-Based Direct Reduced Iron (H₂–DRI)

This method emits **near-zero Scope 1 emissions**, except for residual diesel use in mining (~0.01 tCO₂/t steel). **Scope 2 emissions** depend on electrolyzer electricity (3–4 MWh/t steel) but are minimized if powered by renewable sources (Midrex, 2023; HYBRIT, 2022). **Scope 3 emissions** are limited to supply chain and minor inputs (e.g., graphite electrodes), ~0.05–0.1 tCO₂/t (Roosevelt Institute, 2022). Total emissions: 0.1–0.3 tCO₂/t—representing a ~90–95% reduction (IEA, 2020; HYBRIT, 2022). Table 3 compares the emissions related to ironmaking pathways.

Table 3: Emissions Comparison: Ironmaking Pathways Using Minnesota Ore (Per Ton of Steel)

<i>Category</i>	<i>Current Taconite + BF-BOF</i>	<i>Natural Gas DRI + EAF</i>	<i>Hydrogen DRI + EAF</i>
<i>Total CO₂ Emissions (tCO₂/t steel)</i>	2.0 – 2.5	1.0 – 1.3	0.1 – 0.3
	(mostly from BF steel mill)	(Mostly from MN DRI + EAF)	(Mostly indirect / residual)
<i>Scope 1 Emissions (in MN)</i>	~0.05 – 0.1	~0.6 – 0.7	~0 – 0.05
	(Mining, pelletizing)	(+ DRI furnace on-site)	(If mining is electrified, near-zero)
<i>Scope 2 Emissions (in MN)</i>	~0.04 – 0.06	~0.05 – 0.1	0 – 0.05
	(Electricity for mills)	(Compressors, plant loads)	(H ₂ production powered by renewables)
<i>Scope 3 Emissions (downstream)</i>	~1.9 – 2.4	~0.3 – 0.5	~0.05 – 0.1
	(CO ₂ from BF/BOF steel mills)	(EAF melting, transport)	(Residuals like electrodes, limestone)
<i>MN Emissions Share</i>	~5%	~50%+	<5%
	(Most emissions occur elsewhere)	(DRI plant shifts CO ₂ to MN)	(Most emissions avoided or recycled)
<i>Emissions Reduction compared to BF (%)</i>	–	~45 – 60%	~90 – 95%
<i>Status</i>	Current baseline	Transitional option	Long-term end state

3.3: Raw Material Availability

Establishing a 2 million tons per year (2 MTPA) hydrogen-based direct reduced iron (H₂-DRI) plant requires planning of raw material supply chains to meet the substantial inputs needed for production. To estimate how much hydrogen-based iron making may occur in Minnesota we looked to determine if any major input to green iron production would be a constraining element. The major raw materials include high-grade iron ore pellets, green hydrogen, electricity, and process water—with requirements on purity and sustainability, especially in the context of closed-loop industrial systems. Detailed descriptions of the availability and need based analysis can be found in Appendix 10C.

Table 4: Raw Material Availability

<i>Raw Material</i>	<i>Approximate Amount Required Annually (to produce 2MPTA DRI)</i>	<i>Availability</i>
<i>DR-Grade Taconite Pellets</i>	3 million tons	Good
<i>Water</i>	900-1,500 million gallons	Good
<i>Natural-Gas</i>	23 million british thermal units	Good
<i>Electricity (demand)</i>	4.7 - 7.4 terrawatt hours	Poor
<i>Electricity (peak)</i>	1 gigawatt	Poor

3.3.1 Water

A 2 MTPA H₂-DRI plant requires ~3.4–5.6 million m³/year of water. Electrolysis (45–70 kWh/kg H₂) consumes 2.1–3.2 million m³ for producing ~106,000 tons of H₂/year (Midrex, 2023; Maupin, 2018; Dieter, 2020). Pelletizing requires another ~0.2–0.4 million m³. Cooling and dust suppression add ~1.0–2.0 million m³/year.

Water availability in the Iron Range is sufficient. Legacy mine pits and generous water appropriations suggest no major constraints (Maupin, 2018; Dieter, 2020).

Discharge volumes vary. Without recycling, discharge may be 340,000–560,000 m³/year. However, ZLD systems at H₂ Green Steel and HYBRIT recycle 99.9% of water, reducing discharge to as low as 2,000–20,000 m³/year (H₂ Green Steel, 2024; Energy Research Centre of the Netherlands, 2022).

3.3.2 Electricity

A 2 MTPA H₂-DRI plant requires 106,000 tons of H₂ requiring ~4.77–7.42 TWh annually (Rocky Mountain Institute, 2023). This represents 50–75% of Minnesota Power’s current energy sales (Minnesota Power, 2025). Future scenarios in their IRP consider this growth feasible with renewable energy investments however energy supply is likely the constraining element in the pace of green iron development.

3.3.3 Natural Gas

For a 2 MPTA NG-DRI iron plant, estimated gas use is ~23 MMBtu/year. Industry stakeholders report that regional pipelines can likely meet this demand with system upgrades (Center for Energy and Environmental Policy Research [CEEPR], 2024).

3.3.4 Iron Ore

A 2 MPTA DRI plant requires ~ 3 MTPA of 67% Fe, DR-grade taconite pellets. Three Minnesota facilities—Keetac, Minorca, and Northshore—currently produce DR-grade pellets. A fourth, Mesabi Metallics, is under construction (Minnesota DNR, 2024). While ore access is abundant, it is largely controlled by U.S. Steel and Cleveland-Cliffs.

4. Social and Political Considerations in Minnesota’s Green Iron Transition

Steel production is one of the most carbon-intensive industrial activities worldwide. In Minnesota, the Iron Range has historically anchored the state’s mining economy, but technical innovation alone cannot drive a successful green iron transition, as there are social and political issues associated with the mining sector that can affect how Minnesota traverses a possible transition to green iron. Realizing a green iron economy will require careful navigation of permitting processes, respect for the interests of Tribal communities, and proactive workforce transition strategies. These broader social and political considerations are as important as technological advancement to ensure that Minnesota is able to actualize its green iron potential.

4.1 Definitions, Methodology and an Overview

The shift to DRI is more than just a technological change; it is a transformation with wide-reaching economic and social consequences. And so, projects of this scale can reshape local economies and impact jobs and livelihoods, thereby altering community dynamics. Different groups will experience the risks and benefits differently, with varying concerns about what the transition might bring. Beyond questions of technological and resource feasibility, it is essential to identify the full range of stakeholders and understand which issues matter most to each group in order to ensure that a green iron future in Minnesota supports equitable and inclusive development.

It would be important to firstly define stakeholder. For the purposes of this paper, “stakeholder” refers to individuals and organizations that would be directly or indirectly affected by the green iron transition and would thus have a vested interest in the topic. Stakeholders vary in their level of engagement with the transition and represent a wide spectrum of interests. To capture this range of perspectives, the Capstone team identified and contacted over 60 stakeholders, drawing from internal team discussions, professional connections, background research, and consultations with Commerce, the client. Broadly, those contacted included representatives from steel companies with mining or other operations in Minnesota, Tribal Nations, environmental advocacy groups, educational institutions engaging research related to green iron, electric utilities, trade association and schools, local economic development agencies, and nonprofits engaged in related issues. Thirteen individuals spread across these groups responded and agreed to be interviewed. To protect anonymity, participants are referenced in broad terms throughout this report. Most interviews were conducted virtually, with a few held in person during a site visit to the Iron Range. Participants were provided with a list of guiding questions in advance, and the interviews followed a semi-structured format to allow for open-ended, conversational dialogue. All interviews were recorded and transcribed, and qualitative research methods were applied to analyze the content.

Insights from these interviews are integrated with a literature review of relevant sources found through online searches, including newspaper articles, organizational websites, and other published materials. Where appropriate, commentary from the interviews is woven into the discussion alongside literature-based insights. In some cases, the perspectives shared do not come directly from members of a particular stakeholder group, but from individuals who work closely with or have knowledge of those communities. For example, many interviewees discussed the importance of Tribal inclusion and perspectives and discussed past Tribal concerns. These secondhand insights are included when relevant, especially in cases where direct interviews with certain groups were not possible. We acknowledge the complexity of representing stakeholder perspectives and do not claim to speak on behalf of any group. No stakeholder group is monolithic, and a wide range of views may exist within each community. Capturing the full scope of those perspectives was not possible within the time and resource constraints of this project. Given this, the aim of this report is not to offer a definitive account, but rather to provide

a survey of key social and political dimensions and identify groups who may be affected by, or engaged in, the green iron transition.

4.2 Overview of Identified Issues Shaping the Green Iron Transition in Minnesota

Based on the literature review as well as the IDIs, several cross-cutting social and political issues emerge as critical to consider in ensuring that a green iron future in Minnesota promotes equitable and inclusive development. One of the most prominent concerns centers on workforce transitions and how the green iron shift could help revitalize the economy of northeastern Minnesota, a region long shaped by the boom-and-bust cycles of the global and domestic steel industry. Ensuring job stability and high-quality employment remains an important priority, particularly for Iron Range workers and local economic development agencies, as well as local governments that rely on mining activity to sustain communities and tax revenue. At the same time, understanding the historical context of Minnesota’s mining industry in relation to a green iron transition is essential to recognizing longstanding concerns about the limited inclusion of Tribal Nations in decision-making related to iron mining. These concerns often relate to the environmental impacts of mining, particularly on water quality and the protection of culturally significant resources such as wild rice. These concerns overlap with those voiced by environmental organizations, particularly around the management of tailings basins from Minnesota’s ferrous mining sector and the environmental impacts on water bodies. In particular, environmental permitting has become a highly contested space where these multiple priorities interact. On a related note, some steel companies have voiced concerns that Minnesota’s extensive and often time-consuming permitting processes could discourage future investment which could affect the Iron Range economy. Thus, there are points of tension as well as potential areas of alignment amongst these diverse needs: the need to honor Tribal sovereignty and environmental stewardship, the desire of Iron Range workers to preserve mining-related livelihoods, and the dependence of local governments and economic development agencies on tax revenues from mining activity.

4.3 Workforce Transition and Local Economic Development

A recurring theme that emerged from both stakeholder interviews and the literature is the boom-and-bust nature of the iron economy in Northeast Minnesota. The region’s primary output, taconite pellets, has been highly sensitive to global market dynamics and the strategic decisions of dominant producers such as the US Steel and Cleveland-Cliffs. For example, employment in mining decreased during national or global recessions, as seen during the early 2000s and 2008 downturns ([Kaul 2018](#)). And then, as the global economy recovered from the 2008 recession, the contribution of the mining industry to Minnesota’s GDP saw a marked increase ([Kaul 2018](#)). At the same time, this cyclicity is exacerbated by the industry’s exposure to global commodity prices, such as steel, and the declining production of raw steel made in the United States by blast furnaces. In 2015, U.S. steelmakers were hit hard by a sharp rise in steel imports, especially from China, which made up 29% of the market. This caused demand for domestic steel to fall, leading many steel mills in the Great Lakes region to shut down. Since those mills no longer needed iron ore, mining operations in Minnesota also scaled back, resulting in facility closures and layoffs across the Iron Range ([Kraker 2016](#)). More recently, layoffs by Cleveland-Cliffs have brought renewed attention to the risks posed by this ongoing economic cycle. In March 2025, the company issued layoff notices to more than 600 employees as part of its plan to close the Minorca mine in Virginia and the Hibbing Taconite facility in Minnesota. Challenges in the automotive industry drove this decision: Cliffs reported \$400 million in losses in the fourth quarter of 2024, pointing to slowdowns in auto manufacturing. This is significant because most of the taconite pellets produced on the Iron Range are used to make steel for the auto sector ([Burnes 2025](#)). Together, these examples illustrate how the Iron Range economy is tied to global markets. For communities on the Iron Range, this has translated into a long-standing experience of economic uncertainty.

In this context, the literature suggests that many Iron Range miners are strong supporters of the green iron transition. Mining has long been central to the identity of Northeast Minnesota, with a legacy shaped by over a century of labor struggles and the establishment of robust labor unions. Rather than seeing the industry decline, miners are eager to see it evolve and grow stronger to remain relevant in a changing world. They see it as a way to modernize the iron industry and maintain its relevance in a changing economic and environmental landscape, especially in the context of breaking the risks associated with the boom-and-bust nature of work in the Iron Range ([Lovrien 2024](#); [Kraker 2022](#)). However, past and ongoing layoffs have caused significant hardship for workers, reinforcing their desire for a transition that genuinely considers and addresses their needs. One of these needs is greater support during transitional periods when workers are displaced due to shifts in industry. Further details on the specific strategies this support might involve were not clearly identified in either the literature or the stakeholder interviews conducted. At this point, it is important to note that the transition to green iron may not fundamentally break Minnesota out of its historic boom-and-bust cycle. Producing DRI and DRI-grade pellets would represent a form of product diversification and help keep Minnesota relevant within the national and global steel supply chain. However, because steel production remains highly sensitive to broader economic conditions, this shift alone is unlikely to shield the state from the volatility that has characterized its mining economy.

Another key theme relevant to the economic and workforce development arena is that of retraining workers to be able to readily transition to green iron jobs. Across the interviews, several consistent themes emerged regarding workforce training, reflecting a general sense of optimism among stakeholders such as local economic development agencies. Respondents noted that, due to the cyclical nature of work on the Iron Range, the region’s workforce has developed a high degree of adaptability over time. They also emphasized that regional educational institutions, particularly Minnesota North Colleges, have become increasingly attuned to these workforce needs and offer strong training programs aimed in part at attracting younger individuals to the field. This view has also been shared by a representative from a mining company during an IDI: the representative noted that the transition to DRI is unlikely to demand a dramatically different skill set from traditional iron mining; core skills such as electrical and mechanical maintenance, which exist in today’s iron ore mining and pelletizing plants, are largely transferable to DRI production as well. So, the current workforce would still remain very relevant. The one area where new skills might be needed is handling combustible gases: working with hydrogen and natural gas brings a set of safety issues that need to be addressed. In Minnesota mines, employees may require additional safety training if hydrogen becomes a large part of operations. Additionally, if combustion-based equipment is replaced by electrical systems, for example, if an electric furnace is used, retraining might be needed around maintenance and safety protocols for electrical equipment versus natural gas-fueled systems.

What the mining company representative stressed on however, is the challenge of attracting younger generations to careers in mining. They referenced the company’s partnership with the Rock Ridge School District in Virginia, Minnesota, especially a grant supporting the development of an academy model designed to introduce students to mining careers at an early stage. This finding is consistent with concerns expressed by other interviewees, particularly representatives from local economic development agencies, who noted that the mining workforce on the Iron Range is aging. They emphasized the need to engage younger generations to maintain a strong workforce ready to support the green iron transition when it occurs. More on this topic is discussed later in this section.

An interesting range of perspectives emerged across interviews regarding the role of mining companies in the green iron transition and how actively they are engaging with employees in that process within the state. In one interview, a representative from a mining company with operations in the state discussed relationships with labor union partners, but their comments focused on the company’s steel plants across the Great Lakes region rather than Minnesota. They described largely positive relationships with unions, noting support on the part of the unions for the company’s strategy to maintain iron ore operations and efforts to decarbonize steel facilities through federal partnerships. However, the representative did not indicate that discussions about DRI were taking place with employees in Minnesota. This observation aligned with comments from two other interviewees (one

from a local economic development agency and one from a Minnesota nonprofit focused on green iron) who similarly noted limited engagement by mining companies in general around DRI development in the state. Their focus, they said, remains on the immediate operational needs of current mining activities, rather than on long-term workforce development related to green iron. Taken together, these interviews suggest that while local stakeholders are enthusiastic about green iron opportunities, mining companies have so far shown limited involvement at the local level in Minnesota. While these observations are based on a small number of interviews and cannot be generalized to all actors within each stakeholder group, this contrast in viewpoints may indicate a gap in perceptions between mining companies, who are among the largest employers in the Iron Range, and local economic development agencies regarding the level and nature of support workers need to be meaningfully empowered in the green iron transition.

From an economic footprint perspective, the literature suggests there is broad agreement that the role of mining in the regional economy of Northeast Minnesota has shifted significantly over time. During the 20th century, mining had a substantial employment footprint and became central to the region’s economic identity. However, in more recent decades, automation and outsourcing have contributed to a steady decline in mining-related jobs. Today, other sectors have emerged as dominant employers: healthcare and social assistance make up 21.1% of local employment, followed by retail (11.7%) and accommodation and food services (8.7%). In contrast, mining now accounts for just 5.3% of the workforce ([Kaul 2018](#)). Given these figures, it may be tempting to question the continued economic relevance of mining, especially considering its relatively small share of the workforce.

However, the limited size of mining employment belies the sector’s broader economic importance. Mining continues to exert an outsized influence on the regional economy through three key channels: firstly, mining offers significantly higher wages than many of the region’s dominant employment sectors. Although mining no longer represents the largest share of employment in Northeast Minnesota, it continues to offer significantly higher wages averaging around \$90,000 annually, compared to the regional average of \$43,000 ([Kaul 2018](#)). In contrast, the region’s dominant employment sectors, such as healthcare, retail, and hospitality, often provide lower wages, limited benefits, and greater job instability due to part-time or seasonal work. Because mining offers well-paying union jobs, it remains an important source of employment in the region. In relation to this, one perspective shared by a representative from a local economic development agency during an IDI is that the shift to green iron could enhance economic security for workers and help narrow the wage and benefits gap between mining and the lower-paying, non-union, service-sector jobs that are now prevalent in much of Northeast Minnesota.

Secondly, mining has brought a lot of economic value to the region of Northeast Minnesota. This perspective emerged both in local newspaper coverage and through several stakeholder interviews. For example, a study conducted by the Labovitz School of Business and Economics at the University of Minnesota-Duluth estimated that although approximately 4,000 individuals were directly employed in iron mining in 2010, an additional 2,300 jobs were found in supporting industries, and another 5,000 were sustained through induced economic activity in sectors such as retail, food service, and transportation ([Kaul 2018](#)). Moreover, while direct contributions to Minnesota’s economy from iron mining totaled \$1.7 billion, the total economic impact, accounting for indirect and induced effects, approached \$3 billion, representing 5.3% of the state’s gross product and an estimated 30% of the economic output in Northeast Minnesota and adjacent areas ([Kaul 2018](#)). Additionally, according to estimates from the Iron Range Resources and Rehabilitation Board (IRRRB), every job in the mining sector helps generate roughly one and a half to two additional jobs in surrounding industries ([Kraker 2016](#)). While these figures may be somewhat dated, a stakeholder interview with a representative from a local economic development agency reinforced this perspective, suggesting that it remains relevant today. The representative emphasized that the economic impact of mining extends far beyond direct employment, creating ripple effects throughout the community. Supporting industries such as testing labs, transportation services, and local retail also benefit, reinforcing the idea that mining continues to play a significant role in driving economic activity in Northeast Minnesota.

Thirdly, mining boosts the local economy by operating as a de facto export sector ([Kaul 2018](#)). Export is loosely used here, as it refers to the selling of iron to out-of-state markets. But the effect is the same: it brings new capital into northeastern Minnesota. This gives mining a distinct advantage over most local businesses, where money is either recirculated within the region or into box stores, a view shared by a representative from a local economic development agency during an interview. So, beyond providing high wages that support local spending, mining injects entirely new dollars into the local economy.

These trends show the continued importance of mining to the regional economy in northeastern Minnesota. They help explain why local development agencies and local governments are eager to see mining remain a key economic driver, particularly if green iron proves to be a viable path forward. One of the key reasons why there is a lot of enthusiasm here extends beyond just the creation of jobs but also because there is a real opportunity for green iron to retain more economic value within Minnesota, as a representative from a local economic development agency noted during an IDI. Similarly, in another IDI, a representative from an educational institution involved in green iron research emphasized that expanding the state’s iron portfolio to include higher-value products, such as DR-grade pellets, direct reduced iron (DRI), and hot briquetted iron (HBI), could significantly boost economic returns. These products can sell for \$200- \$300 per ton, compared to roughly \$65 per ton for taconite, meaning more value stays in-state and can be reinvested into local communities.

Alongside this optimism, during interviews, several representatives from local economic development agencies and local governments have also voiced important cautions, highlighting some key challenges that must be addressed to ensure scaled green iron production delivers meaningful benefits to their communities. The first recurrent concern has been the demographics of the current mining workforce in the Range. Like other rural areas in the state, the Iron Range is experiencing an aging population: around 26.7% of the residents are aged 65 years or older ([Minnesota Compass](#)). This presents a real challenge for both the traditional mining industry and efforts to build a robust workforce for future green iron jobs. Several interviewees suggested potential strategies to address this issue, and one key strategy identified is through generating greater interest among younger people in pursuing careers in mining. In addition, an interviewee from a local development agency emphasized that attracting a larger, younger workforce to the region will require more than just competitive wages; it also depends on broader support systems for workers and their families. For instance, a documented shortage of childcare availability in the Iron Range ([Conley 2024](#); [Gruba 2024](#)), along with concerns about adequate housing, were both identified by interviewees as potential barriers to workforce attraction and retention.

On a concluding note to the economic development module: A representative from a Northeast Minnesota local government shared an important insight around how tax revenue from mining is distributed. While tax revenue is critical for municipal operations, the representative noted that only a small portion of it returns directly to their respective city, despite hosting two major mining facilities that have generated approximately \$38 million in production tax revenue over the past seven years. Approximately half of this revenue is distributed regionally through the Iron Range Resources & Rehabilitation Board (IRRRB). Because the tax is tied to production levels, the city’s financial returns depend on decisions made by the mining companies, decisions the municipality has little power to influence. The representative emphasized that while the city would welcome efforts to modernize through green iron, it lacks the authority to require or guide such investments from these companies. It is important to note that this perspective reflects the views of a single local government official and was not echoed in the broader literature reviewed. Still, it offers an important on-the-ground perspective on the limited decision-making power at the municipal level, adding nuance to the larger conversation around the distribution of economic benefits of ferrous mining in local communities, and highlighting an area that may warrant deeper exploration in future research and stakeholder engagement.

4.4 Water Quality

The environmental impacts of iron mining and processing in Minnesota, as reflected in the literature, have often created tension between mining companies, environmental organizations, and Tribal Nations. Minnesota’s state identity is closely tied to water, but the historical record reveals a pattern of pollution from mining operations that has affected some of the state’s regional waterways. This section explores how water quality issues related to iron mining have been perceived and addressed by various groups. On one end of the spectrum are environmental organizations, many of which take a strong stance against mining (both ferrous and non-ferrous) in part due to its potential to pollute water. Closely aligned with these concerns are some Tribal Nations, for whom clean water is essential to the harvesting of culturally significant resources such as wild rice and fish, both of which are tied to subsistence and treaty rights. On the other side of the spectrum are mining companies, which while making strides to reduce their environmental impacts, have been criticized for inconsistent adherence to environmental standards and for lobbying efforts aimed at loosening regulatory oversight at the state level. Meanwhile, the perspectives of local residents, many of whom rely on the Iron Range mining industry for jobs and economic stability, exhibit more gradation. While there is concern among community members about protecting clean waterways, particularly with regard to health and recreational access, there is also frustration around protracted permitting processes and legal challenges that delay mining projects. Thus, broadly, the challenge lies in balancing environmental protection with the need to preserve livelihoods and respect the needs of Tribal Nations.

To begin with, several local and regional newspaper articles, opinion pieces, and a few stakeholder interviews highlight past instances in which mining activity in Northeast Minnesota has had negative impacts on Tribal Nations through its impact on water. These sources also emphasize the importance of greater Tribal involvement in shaping the future of green iron development. As part of this project, the Capstone team submitted interview requests to representatives from Tribal natural resource departments and Tribal government administrations, including Bois Forte, Grand Portage, Fond du Lac, Leech Lake, Mille Lacs Band of Ojibwe, and the 1854 Treaty Authority, but did not receive responses. As a result, the insights presented in this section are necessarily limited and should not be interpreted as speaking on behalf of any Tribal Nation or community. Where available, secondary perspectives were included from individuals affiliated with local economic development agencies and a regional educational research institute. These sources offered views on how Tribal concerns may intersect with the green iron transition. The intent here is to report on themes reflected in publicly available discourse, not to substitute for or represent the full range of perspectives held by Tribal Nations. This remains an important area for deeper engagement in future research and stakeholder collaboration.

The relationship between Tribal Nations and the iron mining industry in Northeast Minnesota has been long-standing, complex, and often marked by tension. Much of the existing literature traces this dynamic back more than a century, beginning with the arrival of European settlers to lands traditionally inhabited by the Anishinaabe people. Although treaties were signed that ceded territory to the US government, the outcomes have often disadvantaged Tribal communities in practice. For example, while Ojibwe treaty rights such as those to hunt, fish, gather, and sustain livelihoods on the land remain legally recognized, large-scale mining operations have over time compromised the ability to exercise those rights ([Rukavina 2022](#)). In recent decades, this has materialized in the form of environmental damage to water bodies caused by iron mining and processing, which has harmed wild rice, a vital food source and culturally significant plant for Tribal communities.

Concerns have been raised about mercury pollution from the taconite industry and its effects on Tribal communities. Public comments from Tribal representatives in the context of past lawsuits against mining companies, as well as communication with federal bodies such as the Environmental Protection Agency (EPA) suggest dissatisfaction with the stringency and enforcement of federal and state regulations on mercury emissions ([Younes 2024](#)). One example is a public comment submitted in July 2023 by the Air Program Coordinator of the Fond du Lac Band of Lake Superior Chippewa, on behalf of the Band, in response to the EPA’s proposed amendments to the National Emission Standards for Hazardous Air Pollutants for Taconite Iron Ore Processing. Broadly, the letter conveyed the Band’s

view that the proposed 30% reduction in mercury emissions from new and existing iron ore processing plants was insufficient to protect the health of their community or uphold their federally recognized Treaty rights, which guarantee the ability to hunt and grow and harvest wild rice and fish across more than eight million acres in Northeastern Minnesota and parts of Michigan ([Fond du Lac Reservation, 2023](#)).

Further within the realm of iron mining and water quality, the management of tailings basins has been a point of concern for several community groups including Tribal Nations. A useful source for understanding concerns around tailings basins from the perspective of the Grand Portage Band in particular is a 2023 letter the Band submitted to the Minnesota Department of Natural Resources (DNR), expressing concerns about Cleveland-Cliffs’ proposed expansion of the Northshore Mine tailings basin near Mile Post 7 in Silver Bay, Minnesota, without pursuing a full environmental review ([Drouillard 2024](#); [Johnson 2024](#)). At a high level, the letter conveyed the Band’s urgency in urging the Minnesota Department of Natural Resources (DNR) to conduct a full Environmental Impact Statement (EIS) in order to evaluate the cumulative impacts of the proposed project and obtain a new dam permit, grounding their argument in being able to exercise treaty rights, and connecting the project’s impacts to larger environmental justice concerns. Importantly, the Band also raised concerns about access to dam safety information. In 2021, Tribal agencies including Fond du Lac, the Great Lakes Indian Fish and Wildlife Commission (GLIFWC), and the 1854 Treaty Authority requested dam inspection documents from the Minnesota DNR. When the documents were released more than a year later, they were heavily redacted. The Grand Portage Band expressed the view that, as governmental co-regulators, Tribal agencies should have received unredacted versions of the reports and questioned the appropriateness of the redaction ([Grand Portage Reservation, 2023](#)).

While these articles and letters offer valuable insight into how certain Tribal Nations have responded to specific mining development projects, it is important to acknowledge that each Tribal Nation has its own priority and community needs. This analysis does not assume that the perspectives presented are representative of all Tribal Nations in Northeast Minnesota. However, these sources do highlight recurring concerns rooted in past harms and perceived regulatory shortcomings. Taken together, they suggest that some Tribal Nations may approach the green iron transition with caution.

Lastly, concerns about water quality have also been raised by environmental organizations and advocacy-focused nonprofits. These groups tend to adopt a cautious stance toward mining although an IDI with a representative from a local nonprofit focused on environmental advocacy and regulation related to water shared that their bigger concern was with sulfide mining and non-ferrous mining, not necessarily ferrous mining. Even so, some of the staunchest critics of ferrous mining have been conservationists focused on protecting Minnesota’s waterways. The aforementioned cases about the Northshore tailings basin as well as mercury emissions affecting water are examples of cases where organizations such as WaterLegacy have legally fought for stronger regulation against mining companies with respect to their management of runoff that pollutes water bodies and affects the lifeways of indigenous communities ([Younes 2024](#); [Drouillard 2024](#); [Johnson 2024](#)). The literature suggests that environmental-focused groups approach the green iron transition with cautious scrutiny. While they are likely to remain critical of potential greenwashing and continue raising questions about land use, water quality, and community impacts, there is also a measure of optimism. Many recognize that decarbonizing steel production holds significant potential for both climate and public health benefits such as cleaner air. They often cite the fact that steelmaking accounts for nearly 10% of global CO₂ emissions ([Brown 2024](#)) and thus see cleaner production on the Iron Range as part of the solution to climate change.

Lastly, while this specific perspective was not widely reflected in the literature, it did emerge during an IDI with a representative from an environmental advocacy group: the representative emphasized that an environmental advocacy organization such as theirs is not seeking to obstruct the development of green iron. Instead, they are open to working collaboratively with a range of stakeholders, including those who strongly support mining, because they recognize the importance of jobs and local economic development for regional communities. Their goal is to support the growth of green iron in a way that

equitably distributes benefits, particularly to historically marginalized groups such as Tribal Nations, while maintaining strong environmental protections.

4.5 Tribal Engagement

While the literature and interview content in the previous section highlight concerns raised by Tribal Nations regarding the historical impacts of iron mining in Minnesota, a more optimistic outlook for a green iron future also emerged in some stakeholder interviews. It is important to note that these more positive perspectives were not gathered directly from Tribal members, as the Capstone team did not receive responses to interview requests from Tribal representatives. However, the following insights were shared by other stakeholders who have engaged with Tribal communities to varying degrees. Broadly, the interviews framed the green iron transition as an opportunity for Tribal Nations to expand their role in renewable energy development, create pathways for Indigenous individuals to access employment in the emerging green iron sector, and advocate for stronger Tribal consultation and engagement throughout the process.

Several interviewees noted that the shift to green iron, particularly the development of a single iron plant, would require a substantial amount of electricity. This point was also discussed in earlier sections of this paper. Meeting the increased energy demand will require expanding energy resources, especially clean energy infrastructure that can support green iron production. Over time, this need is expected to grow as green hydrogen potentially replaces natural gas as the main input in the reduction process. To that end, more distributed energy resources will be needed.

This shift creates an important opportunity for Tribal communities to take on a more active role in renewable energy development. For example, if a Tribe invests early in renewable projects like a solar array, it can sell the generated power directly to hydrogen producers, creating a reliable source of income. In the past, Department of Energy loan programs required that Tribal-funded infrastructure projects be located on reservation land, which limited access for many Tribes whose reservations are in remote areas with little industrial relevance. That requirement has since been removed. Now, Tribes can invest in and own renewable energy assets located off-reservation, with access to very low-interest or even zero-interest federal loans. This allows Tribes to participate more fully in the clean energy economy by developing wind or solar projects and supplying energy to hydrogen facilities or other industrial users. These insights were provided during an IDI by a representative from an educational institute conducting green iron research as well as two representatives from two separate local economic development agencies. Broadly, Tribal energy sovereignty is closely tied to Tribal sovereignty and the broader principle of Indigenous self-determination. In the most hopeful scenarios, Tribal leaders may view green steel projects as opportunities to bring skilled jobs and new sources of revenue to their communities, while also ensuring that treaty rights and culturally significant resources, such as wild rice, are protected through cleaner and more responsible industrial practices ([Smith 2024](#)).

4.6 Permitting, Social License, and the Business Perspective

The social and political dimensions of the green iron transition, as outlined above, appear to interact (and in some cases, clash) most clearly in the arena of environmental permitting. This process reveals the specific stakes and priorities held by different groups involved in or affected by green iron development, and it has been a recurring topic in both the literature and the interviews conducted by the Capstone team.

In broad terms, Minnesota’s environmental permitting process is more comprehensive and stringent compared to that of many other states in the U.S. This thoroughness has elicited mixed impacts for various stakeholder groups. While environmental advocates and Tribal communities may view

Minnesota’s more comprehensive permitting process as a way to ensure greater environmental oversight and community protection, it has also contributed to longer permitting timelines and increased business uncertainty. These delays are often cited as concerns by mining operators, local economic development authorities, municipal governments, and workers who are eager to see timely project implementation and economic investment. While the team attempted to gather specific feedback on permitting challenges during interviews, most responses remained general. Interviewees often acknowledged permitting as a barrier but did not offer detailed suggestions as to what changes they would like to see. Some general perspectives on improving the permitting process highlight the importance of maintaining a social license to operate, which could be viewed not only as a genuine community engagement piece, but also as a risk mitigation strategy for businesses. Securing community support early on can help avoid costly legal challenges later. One way to achieve this is by adopting a more integrated, systems-level approach to permitting, rather than the piecemeal structure currently observed in Minnesota. An in-person interview with an iron operator in Minnesota suggested that permitting processes might benefit from a streamlined approach, where public comment periods begin earlier in the process but do not continue at every stage.

From a business standpoint, developing an iron plant, whether for producing green iron or traditional taconite, represents a substantial financial commitment. Stakeholder interviews estimated that a single plant could require investments exceeding \$1 billion. In one interview, a representative from a Minnesota-based iron operator noted that Minnesota’s requirement for an Environmental Impact Statement (EIS) sets it apart from other states such as Alabama, Arkansas, Mississippi, Tennessee, and Kentucky. These other states follow federal air and water quality regulations but do not require a state-specific EIS. The interviewee estimated that permitting in those states can be completed in approximately six months, while in Minnesota the timeline is often viewed as undefined. This uncertainty, combined with the scale of the investment required, was identified as a major barrier to attracting and sustaining industrial development. As a case in point, the interviewee referenced Hyundai’s decision to invest in a steel plant in Louisiana ([Mody 2024](#)), suggesting that the state’s relatively streamlined permitting process played a key role in securing the project. The view that the EIS process is a significant barrier to business was also echoed in another interview with a representative from a mining operator in the country.

In the literature, there are several additional examples that further reinforce the idea that permitting, and in particular, the environmental review process, can act as a barrier to business investment in Minnesota. Cliffs’ plant in Toledo, Ohio, which was completed in 2020, is the first facility in the Great Lakes region to produce hot-briquetted iron (HBI). While the company initially considered building the facility in Minnesota, permitting challenges were cited as a key factor in the decision to locate the plant in Ohio instead. Another example is Calumet Reclamation, a company planning to recover iron ore from old mining waste on the western Mesabi Iron Range by 2025. The project is expected to create around 150 high-paying union jobs ([Brown 2024](#)). Unlike conventional mining operations, Calumet’s work falls under the category of “scram mining,” which involves collecting iron from surface waste piles rather than blasting or deep excavation ([Brown 2024](#)). This approach should, in theory, allow for a quicker and more flexible permitting process. However, despite these advantages, Calumet ultimately decided to process its material in North Dakota, citing Minnesota’s permitting challenges as a primary reason for moving the project out of state ([Brown 2024](#)).

Other perspectives that support faster permitting are commonly held among local residents, who express strong enthusiasm for seeing mining projects become operational. Many residents view these developments as vital to revitalizing the Iron Range economy and supporting long-term regional growth. Public support for these projects see these as key sources of skilled, union-supported employment in a region with deep labor roots. Additionally, there is a shared understanding that economic success in one town can bring benefits to neighboring communities across the Range. Given this context, a unifying theme across these perspectives is the call for a more streamlined permitting process and stronger support from state leaders to help move such projects forward ([Mesabi Metallics 2025](#)). Local governments and economic development agencies broadly share these perspectives and

are among the strongest supporters of the iron industry; they tend to view the green iron transition with optimism.

Broadly speaking, at the same time, support for faster permitting often stands in tension with the perspectives of Tribal Nations and environmental groups, who have voiced concerns and called for more rigorous review processes, such as the Environmental Impact Statement (EIS) requested in relation to the Northshore tailings basin discussed in earlier sections. These more cautious perspectives create a complex dynamic. As noted by a representative from a local economic development nonprofit, companies may hesitate to propose projects due to concerns about future opposition or backlash from certain communities. This hesitancy discourages early investment, leading to fewer proposed projects, which frustrates workers and communities eager for new economic opportunities. The result is a self-reinforcing cycle where limited trust leads to inaction, which in turn sustains uncertainty.

In a separate interview, another interviewee offered an interesting insight that may present a potential way to break this cycle. They pointed to Minnesota’s current permitting system, which is often seen as piecemeal and drawn out, sometimes delaying projects for years or even decades. In their view, Minnesota could benefit from adopting a systems-level approach to permitting. This would involve evaluating the full scope of a project early in the process rather than addressing one permit at a time. It would also require assessing cumulative impacts on water, land, air, ecosystems, and surrounding communities, and involving all key stakeholders, including Tribal Nations, local residents, environmental organizations, and industry, from the outset. This contrasts with a more minimal permitting process that meets only baseline legal requirements. While that model might result in quicker initial approvals, it increases the risk of legal challenges, public opposition, and project delays. By comparison, early and meaningful engagement could potentially lead to stronger, more resilient projects that advance more smoothly with greater public support. Given Minnesota’s robust environmental standards and the need to uphold Tribal treaty rights, permitting is inherently complex. However, creating space for open dialogue earlier on and proactive risk assessment can build trust and reduce conflict over the long term as Minnesota considers a green iron future. The interviewee described the systems-level approach as a way to help projects earn a social license to operate by demonstrating a strong commitment to protecting natural resources, honoring Indigenous rights, and leaving a positive long-term legacy. This, in turn, can serve as a social de-risking strategy for businesses and potentially encourage greater investment.

5. Relevant Policies

5.1 Overall Policy Landscape

This section focuses on exploring whether policies exist that can create an enabling environment for green iron development in Minnesota. Although the green iron and steel industry is primarily driven by private investment, public policy instruments can play an important role in incentivizing their growth. Given the extremely capital-intensive nature of steel and iron production, private companies are highly sensitive to economic conditions and are generally unwilling to invest in new facilities without strong assurances or clear signals that their investments will yield returns.

A recurring concern across both the existing literature and several of the interviews conducted by the team is the challenge that companies often need additional policy support to feel confident that the surrounding environment is enabling investment in clean steel and iron. There are also cross-sectoral issues: for example, the long-term development of green iron will depend in part on the parallel development of green hydrogen infrastructure as well as availability of clean electricity. Therefore, it is important to gauge if policy tools can play a role in encouraging more green iron development through the expanded availability of clean electricity and hydrogen.

In this section, we outline key themes that emerged regarding policies that could serve as levers for advancing green iron initiatives. Broadly, we have categorized the policies into demand-side and supply-side approaches, with additional distinctions based on whether they operate at the federal, state, or local level. It’s also important to note that federal and state policies generally focus on decarbonizing steel, which makes it difficult to determine their specific implications for green iron production in Minnesota. Where possible, we have attempted to connect steel-related policies to iron production in the state, but these links are based on informed assumptions, as there is limited literature available on this topic at present.

5.2 Demand-side Policies

On the demand side, policies are designed to nudge buyers toward considering clean steel as a viable alternative to conventional steel. The literature notes that steel typically accounts for only a small proportion of the total cost of finished products like buildings and vehicles. As a result, even if green steel is significantly more expensive than conventional steel, it would have a minimal impact on the overall cost of the final product ([Gamage et al 2024](#)). This makes demand-side policies particularly viable ([Gamage et al 2024](#)).

The issue of demand was also explored in an interview with a mining company representative. They explained that a major economic challenge for green hydrogen-based DRI facilities is the extremely high capital costs. For green iron investments to be viable, there must be sustained demand, with customers willing to pay a premium for green steel. However, there is currently very little willingness to pay higher prices within the U.S. market. Within the demand-side policy space, a prominent example is clean steel procurement mandates, where governments or large buyers, such as automakers and construction companies, are required to use low-carbon steel in their projects ([Gamage et al 2024](#)).

5.2.1 Clean Procurement: Buy Clean

One specific example of a clean procurement policy is the federal Buy Clean initiative introduced through the Inflation Reduction Act (IRA), which directs \$650 billion in federal funding toward the purchase of low-carbon materials including iron and steel ([Energy Transitions Commission](#)). Under this policy, government agencies are required to prioritize clean materials, such as low-carbon steel, for federally funded projects like roads, bridges, and buildings. This guaranteed demand gives steelmakers greater confidence that investments in cleaner production technologies will be profitable over time.

However, the literature also identifies a key caveat with the way Buy Clean currently works: it typically focuses on purchasing the cleanest materials currently available, rather than pushing the industry to develop new green steel. The way Buy Clean works is that it firstly ranks existing steel products based on how much carbon they produce and directs government purchases to the top 25% of the cleanest products. Thus, the problem is that companies wanting to invest in new, zero-emission plants need a guaranteed long-term market, but because Buy Clean only rewards what is available now, companies may be reluctant to build new facilities. Since steel plants last for decades, producers need confidence that demand for low-carbon steel will stay strong over the long term before making big investments in cleaner technologies ([Gamage et al 2024](#)).

The literature also outlines a possible reform to this: instead of just buying from the cleanest steel plants that already exist, the federal government could help by giving steel producers more long-term certainty ([Gamage et al 2024](#)). In other words, improving Buy Clean would mean looking further into the future. If buyers like the government, automakers, or construction companies sign contracts today to buy clean steel in the future, it would give steelmakers the confidence to invest in new, cleaner production methods. Another strategy is to group buyers together: if multiple government agencies, private companies, and industries all commit to buying clean steel, it would create a large, stable market that encourages investment ([Gamage et al 2024](#)). To make this work, broader changes would also be needed, including updates to procurement rules, new financial incentives, and infrastructure improvements to help clean steel become widely available ([Gamage et al 2024](#)). The Federal Acquisition Regulation (FAR), which controls how the government buys goods and services, is being updated to focus more on clean materials ([Gamage et al 2024](#)). Improving the FAR and government buying practices is important to help plan ahead and support investment in clean steel ([Gamage et al 2024](#)).

At the state level, Minnesota has passed Buy Clean legislation as well. In May 2023, Buy Clean/ Buy Fair was passed into law. This requires the state’s Department of Administration and Department of Transportation to create a policy that limits embodied carbon from materials used in state projects ([Graves et al 2024](#)). The policy also establishes a six-year Environmental Standards Procurement Task Force, which will develop recommendations for incorporating low-carbon materials into public projects and propose timelines for setting standards across various materials ([Kvam 2023](#)). For instance, materials like structural steel and reinforcing steel used in state projects are supposed to be within embodied carbon limits anticipated between 2026 and 2028, using Environmental Product Declarations (EPDs) to assess the environmental impact of materials ([Graves et al 2024](#)).

Minnesota’s Buy Clean/Buy Fair policy mainly focuses on steel rebar and structural steel. Structural steel is used to build the frames of buildings and bridges, and rebar is used to make concrete stronger. These products are usually made in EAFs that use scrap steel, not iron ore. Because of this, the currency scope of the policy would likely not benefit Minnesota’s iron ore industry in a direct way. But there could be an opportunity in the future. If a steel company makes low-carbon steel using DRI from Minnesota and provides an Environmental Product Declaration (EPD) to show it meets Buy Clean standards, that steel could be used in state projects. In that case, Minnesota’s iron ore could become more valuable. However, if clean steel is made from scrap or iron from other places, Minnesota’s ore might not be part of the supply chain. To suit Minnesotan iron ore better, over time these Buy Clean standards can be expanded to include all steel products and not just rebar and structural steel ([Carey et al 2023](#)).

5.3 Supply-side Policies

The policies discussed in this section are categorized as supply-side because they focus on enabling the production and delivery of key inputs, such as electricity and hydrogen, that are essential for green iron and steel development.

5.3.1 Clean Electricity

In this section, the discussion around clean electricity highlights not a specific policy, but rather a policy gap that still needs to be addressed.

One key input for DRI production is electricity, which has already been identified in earlier sections of this paper as a key barrier. The literature similarly highlights it as an area requiring close attention from a policy perspective. Minnesota has a state goal to use 100 percent carbon-free electricity by 2040, but the regional grid operator, but a major challenge for clean energy projects is the long wait to connect to the grid. In this context, transmission has been identified as a frequent barrier to major steel production, serving as the "common-carrier infrastructure" that connects different energy sources to industrial users ([Carey et al 2023](#)). The Midcontinent Independent System Operator (MISO), along with PJM Interconnection (PJM) are the two main electricity operators in the Great Lakes region. They have 3,042 and 1,734 active projects waiting to connect which are mostly solar, wind, or battery storage projects ([Carey et al 2023](#)). PJM has said it has a two-year backlog and has stopped reviewing new requests until at least 2025. Since these electricity grids cross state lines, no single state can solve the problem on its own; regional cooperation is needed. Only Minnesota and Illinois are fully following federal best practices for interconnection ([Carey et al 2023](#)). Although this paper didn't go deep into transmission, it's an essential issue to address, especially as electricity for green steel might come from utilities, rooftop solar, or other smaller energy sources.

Another concern is that several energy-intensive industries, such as data centers, are emerging alongside green steel production, contributing to increased electricity demand. This raises the risk that electricity costs could become too high for these industries to remain competitive ([Gamage et al 2024](#)). Government-backed loans could help with this issue. If clean electricity projects are financed with regular market-rate loans, the high interest costs could be passed on to industrial customers. In this case, government-backed or concessional loans could lower interest rates and extend repayment periods, making electricity more affordable. Backstops for cost overruns, which act as financial safety nets to cover unexpected expenses, could also help keep projects on track. Overall, making clean electricity more affordable is seen as an important way to lower production costs for low-carbon industries like green steel ([Gamage et al 2024](#)).

5.3.2 Clean Hydrogen

Hydrogen is a key input in DRI production but it is an extremely costly resource. Policies aimed at reducing the cost of producing hydrogen could help enhance DRI production.

Within the realm of green hydrogen policy, the IRA introduced the 45V hydrogen production tax credit, which offers up to \$3 per kilogram for producing low-carbon hydrogen. This is a tiered system: Tier 1, the cleanest hydrogen, should emit less than 0.45 kg of CO_{2e} per kg of hydrogen to be able to avail the \$3 per kg credit. The credit is meant to lower hydrogen costs and make it cheaper to produce cleaner iron and steel ([Energy Transitions Commission](#)). However, the U.S. does not yet have clear federal rules for hydrogen. It is still unclear if FERC will oversee hydrogen pipelines, storage, imports, and exports. There are also no common national standards yet for blending hydrogen into natural gas pipelines that are interstate. This matters because some states, like Minnesota, already allow gas companies to include hydrogen-based fuels in their innovation plans ([Carey et al 2023](#)). Furthermore, local regulations also affect the production, transportation, and use of hydrogen ([Carey et al, RMI, 2023](#)). In Minnesota, Executive Order 22-22 directed state agencies to review how prepared the state's regulations are for supporting hydrogen development ([Carey et al 2023](#)). Minnesota has taken positive

initial steps by asking state agencies to review how prepared their regulations are for supporting hydrogen, but more action and support will be needed ([Yavorsky et al 2023](#)).

There is also the development of the Heartland Hydrogen Hub (HH2H), which is a federally-backed initiative to advance clean hydrogen production across the Upper Midwest. The U.S. DOE allocated \$925 million to HH2H as part of its Regional Clean Hydrogen Hubs program, established under the 2021 IIJA. The hub covers three states: Minnesota, North Dakota, and South Dakota. The hydrogen production methods proposed include natural gas with carbon capture and electrolysis leveraging nuclear energy. However, the primary intended users of the hydrogen produced from HH2H are the agriculture and ammonia sectors, along with power. For example, Xcel Energy is a key partner in the HH2H effort. It plans to leverage its renewable energy assets to produce clean hydrogen. This hydrogen will be integrated into power generation, natural gas distribution systems, and agricultural and industrial applications ([Xcel Energy 2023](#)). While steelmakers are not the primary focus at this stage, they may be able to tap into the hub’s hydrogen supply, storage, and transmission infrastructure in later phases ([Yavorsky et al 2023](#)).

5.3.3 Workforce Development

Workforce development is also another area where policy could play a role. The literature suggests that states like Michigan, Minnesota, Pennsylvania, and Wisconsin have several broad workforce development programs, but not ones that are steel-specific retraining programs ([Carey et al 2023](#)). At the more local level in Northeast Minnesota, where the focus is on preparing workers for DRI production, several interviewees did not express major concerns about retraining. They felt that strong local partnerships and existing programs are already in place, and that DRI-specific training would not differ significantly from current mining and ore processing work. The main difference would be the need for additional training on handling combustible gases such as natural gas and hydrogen.

However, a broader concern emerged: based on the interviews, local economic development agencies believe that mining companies with operations in Minnesota are not showing clear signs of wanting to invest in more DRI production in the state. As a result, there has been limited engagement or communication with workers about future opportunities in DRI. At the same time, companies like Cleveland-Cliffs have emphasized a commitment to building on their existing business models, which means continuing to use iron ore while working to lower environmental impacts.

The Middletown steel plant serves as an example of combining low-emissions strategies with the continued use of iron ore pellets. Based on their experience with the Toledo DRI plant, they found that core skills such as electrical maintenance, mechanical maintenance, and operations are highly transferable and match the skills currently used in iron ore mining and pelletizing plants. This observation contrasts with some of the existing literature on workforce development and Minnesota’s position in the green steel transition. While the literature suggests that Minnesota’s workforce development programs, particularly those related to steel, are not especially strong ([Carey et al 2023](#)), there are also contrasting viewpoints. Some interviewees indicated that, from a workforce perspective, the transition to green steel (which is a transition to green iron in the case of Minnesota) may be less of a concern compared to other challenges.

At the local level, the Department of Iron Range Resources and Rehabilitation (IRRR). IRRR is a state agency funded by a portion of the local taconite production tax paid by mining companies in place of property taxes, based on tons of iron pellets produced. Most of this revenue is legislatively distributed to local governments, schools, and counties. The remainder supports IRRR programming, including economic development and job training initiatives ([IRRB Biennial Report](#)). Within the IRRR’s programming, the Taconite Economic Development Fund (TEDF) is a state fund established in 1992 to support and enhance iron mining operations in northeastern Minnesota. When annual production exceeds 30 million tons, mining companies become eligible for a rebate of up to 25.1 cents per ton from their taconite tax payments. However, these rebated funds can only be used for specific purposes under Minnesota law. They must go toward things like training workers or improving local infrastructure that

supports the mining workforce (such as roads or water systems near mining sites), upgrading or buying equipment and buildings used in mining, or doing research and development on new mining technologies, as long as that research happens in Minnesota ([IRRB Biennial Report](#)).

In an interview, a representative from the IRRR shared that initially, the TEDF was designed to support mining companies by providing matching funds for capital improvements, encouraging reinvestment in their facilities. However, a successful legislative change has now expanded the fund’s allowable uses to include workforce development. While this new option has not yet been utilized, it presents an important opportunity to equip workers with the skills needed for emerging technologies in the steel industry. The representative explained that any use of TEDF dollars must be jointly approved by both company management and labor unions, which has shaped how the funds are prioritized. At present, their shared priority is maintaining plant operations and protecting jobs, with a focus on immediate survival rather than long-term workforce transition. However, if market conditions begin to indicate a more extended downturn, there may be an opportunity to redirect some of this funding toward retraining efforts. This aligns with an earlier interview insight noting that, for now, most mining companies operating in Minnesota are focused on continuing their current mining practices and are not actively planning a shift toward DRI.

5.4 Research and Development (R&D)

5.4.1 R&D Efforts in Technological De-Risking

While the demand and supply-side policies above focus on steel, some research and development efforts at the federal and local levels are more directly targeted at green iron production. One key policy under the R&D umbrella is the Industrial Demonstrations Program (IDP), funded by the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA), and managed by the Department of Energy (DOE). The program provides around \$6 billion to help decarbonize heavy industries like iron and steel. Decarbonizing primary steel production in the US could benefit from this in particular ([Energy Transitions Commission](#)). The IDP has been used to support projects related to green steel, but none specifically tied to Minnesota. For example, Cleveland-Cliffs’ strategy has focused on strengthening and repurposing existing assets for long-term use, as seen in the Middletown and Butler Works projects. While these examples are not Minnesota-specific, they show how programs like the IDP can help companies pursue newer technologies that involve higher technological risks or cost premiums compared to traditional options. Federal support through initiatives like the IRA plays an important role in making investments in newer, less proven technologies more financially viable.

At the more local level, there is research being done specifically focused on green iron. Most of the work in this area is being led by the Natural Resources Research Institute (NRRI), a research center at the University of Minnesota Duluth. NRRI collaborates closely with private industry, the State of Minnesota, the U.S. Department of Energy, and the U.S. Department of Defense. Interestingly, some of NRRI’s testing equipment has been partially funded through state legislation. During a site visit to NRRI’s campus in Coleraine, the capstone team learned that much of NRRI’s work involves being contracted by private companies, such as steel producers like U.S. Steel, to conduct pilot projects. For example, a grant from the U.S. Department of Energy supported NRRI’s DRI Simulator project, which began in 2017 and became operational in 2024. The simulator is described as an important tool for helping the iron and steel industries reduce the risks associated with transitioning to higher-grade DR pellets ([Breneman 2023](#)). Thus, one of NRRI’s main contributions has been helping private industry de-risk green iron technologies from a technological perspective.

An interview with a representative from NRRI provided additional insights into the institute’s role in technological de-risking. The representative explained that NRRI has played a significant role in helping the iron mining industry adopt new technologies, such as innovations that can reduce grinding energy use by up to 40 percent. NRRI’s approach involves testing and scaling new technologies at a smaller scale before they are implemented at full industrial scale. The representative referred to US

Steel’s investment in its Keetac facility. NRRI led pilot-scale demonstrations to refine U.S. Steel’s processing technologies for producing DR-grade pellets. NRRI’s role was to ensure that Keetac’s new process would be efficient, cost-effective, and scalable before moving to full industrial production ([Breneman 2023](#)). The effort allowed U.S. Steel to troubleshoot and refine the design before construction began, ultimately saving time, reducing costs, and speeding up the project timeline. The representative also noted that organizations such as the Iron Range Resources and Rehabilitation Board (IRRRB) frequently rely on NRRI to evaluate the viability of new technologies proposed by companies. Another notable trend in Minnesota’s policy and research landscape is the growing focus on using scrap or waste materials to produce steel. For example, NRRI has been involved in studies focused on reprocessing waste materials from past mining operations to produce high-quality iron ore concentrate. One such study was conducted for MagIron, a company aiming to supply low-carbon iron units by restarting Plant 4 in Bovey, Minnesota. NRRI’s test results showed that historic mining waste can be successfully processed into high-quality concentrate, which is crucial for producing DR-grade pellet feeds essential for lower-emission steelmaking ([Breneman 2023](#)).

Additional work in recycling steel comes from projects funded by the Minnesota Legislature through the Environment and Natural Resources Trust Fund (ENRTF). In May 2023, the Legislature approved 86 projects ([Minnesota Legislature](#)), including a research initiative titled “Environment-Friendly Decarbonizing of Steel Production with Hydrogen Plasma” (2023-171). Led by the University of Minnesota, this project explores a new method of steel production using microwave hydrogen plasma instead of fossil fuels. The goal is to reduce carbon emissions and find ways to make use of lower-quality iron ore, mining tailings, and other iron waste that would otherwise be discarded. Results are expected by 2026 and could influence future steel industry practices.

5.4.2 Social De-Risking

R&D efforts mainly focus on reducing technological risks, but addressing social risks is also a key component. The Natural Resources Research Institute (NRRI) plays a significant role in this area, as noted by a representative during an interview who referred to the Midwest Industrial Transformation Initiative (MITI). Within that space, one of NRRI’s three main strategic areas is ecosystem resilience. The institute’s team of scientists studies Minnesota’s ecosystems, including forest health and the environmental impacts of mining, providing a foundation for assessing how new industrial projects could affect water use, dust, heat needs, and ecosystem stress. They focus on key questions such as how clean water needs to be and how much water would be used.

This environmental assessment connects directly to permitting. In Minnesota, permitting is often handled step-by-step, with each permit reviewed separately rather than as part of a broader system. Through MITI, NRRI is advocating for a more holistic approach that considers cumulative impacts from the start. For example, before building a tailings pond, they assess potential downstream risks, including impacts on rivers.

Community engagement is also a central part of NRRI’s social de-risking work. They emphasize that serious permitting must involve all affected groups, including Tribal Nations, local communities, labor, industry, and local governments, from the beginning. NRRI aims to create a “safe space” where stakeholders can raise concerns and receive clear answers early in the process. The goal is to support a single, integrated conversation about risks and impacts rather than a series of disconnected discussions later on where the public may feel their inputs haven’t been taken into account and take legal action, which slows down business investment further into the process and increases uncertainty. Thus a more systems-level stakeholder engagement process can make permitting more holistic and act as a business de-risking strategy.

6. Constraints, Limitations and Disclosures

Our research was constrained by the practical time demands of the academic calendar and the allotted duration for this project - one semester. This time constraint limited our ability to deeply dig into many issues surrounding the development of decarbonized iron in Minnesota. We were able to surface a number of contentious and disputed elements at the heart of green iron development; however, we did not have the time to fully research the multifaceted nature of these issues. Often we have only been able to speak with a single stakeholder and gain their perspective which likely does not provide a balanced and complete view. Similarly, given the contemporary nature of this subject area, we relied heavily on readily accessible publications and media accounts. We did not have the time to delve into publications of deep research, peer reviewed journals, or seek alternate viewpoints.

We only examined, in a limited fashion, the feasibility of hydrogen-based iron making. We did not examine the feasibility of alternative decarbonized iron making methods. There are a number of iron-making methods currently in various stages of conceptual development that may offer pathways for Minnesota to consider.

We did not make an economic analysis of the cost of producing decarbonized iron in Minnesota or the demand for decarbonized steel. Ultimately for a product to be successful in the long term it must be accepted by the market and be preferred over competitive offerings. If the cost of decarbonized iron and steel is too high compared to alternative options the likelihood of a successful green iron industry in Minnesota is severely diminished.

We could not provide an analysis of the technological readiness of various equipment needed to implement hydrogen-based iron making in Minnesota. Hydrogen generation, storage, and transportation, and hydrogen field direct reduced iron furnaces are critical production elements that still embody significant technological risk.

We could not investigate the waste streams of hydrogen generation via the electrolysis of water. Some form of water treatment is often required ahead of an electrolyzer. The byproducts of water treatment will need to be disposed of. Water use and discharge are important and critical issues in many places but particularly in northern Minnesota.

Another key limitation of our research is that, particularly when exploring the social and political aspects of a potential shift to DRI, we relied heavily on online resources which were mainly media articles. We were not able to find peer-reviewed articles pertinent to DRI and social issues in the Minnesotan context. This made our work subject to the biases of internet search algorithms and media framing. It is possible that the issues and opinions highlighted in many of the news sources we consulted do not fully capture the complexities of the situation, instead flattening it into a simple pro-mining or anti-mining narrative. We attempted to gain a more holistic and nuanced understanding by interviewing a range of individuals engaged in different aspects of life on the Iron Range. However, as researchers working under time and resource constraints, there were limits to how much ground we could cover. While we made an effort to highlight diverse perspectives with as much nuance as possible, we acknowledge that some media biases may still be reflected in our findings.

The views expressed in this paper are not necessarily the views of each individual author. While we undertook significant effort to find language that all authors could agree to, we were not always successful. In the case of disagreement, we erred on the side of including disputed language and points of view.

7. Findings

As Minnesota explores pathways to decarbonize its iron industry, a range of strategic considerations has emerged based on technical, economic, social and political research done in this article. This section synthesizes key findings into six strategic focus areas that could shape Minnesota’s leadership opportunities in low-carbon ironmaking. From a technical point of view, the analysis identifies how hydrogen-based DRI technologies, resource availability, transitional approaches like natural gas-based DRI, and emissions management strategies can be aligned to support a phased, practical, and competitive transition. Rather than prescribing a specific path, this framework highlights opportunities and challenges that decision-makers may weigh as they consider Minnesota’s role in the future green steel economy.

7.1 The steel industry’s emissions challenge and Minnesota’s emerging opportunity

Steelmaking is responsible for approximately 7–9% of global CO₂ emissions annually. In order to meet urgent climate targets, significant time, investment, and technological innovation have been directed toward low-carbon ironmaking solutions. Several promising decarbonization pathways are under development. Among these, hydrogen-based DRI is one of the most commercially advanced methods. According to the International Energy Agency (IEA), hydrogen DRI is already at Technical Readiness Levels 7–8 (IEA 2020), meaning the technology has been demonstrated at pilot scale, integrated with auxiliary systems, and is now ready for full-scale commercialization.

Minnesota has the potential to stand out as a national leader for green iron development. The National Renewable Energy Laboratory (NREL) has identified Minnesota as one of the lowest-cost regions in the United States to produce decarbonized iron, citing the state’s unique combination of high-quality iron ore resources, industrial experience, bulk logistics infrastructure, renewable energy access, hydrogen storage potential, and a strong academic and research network. Furthermore, colocating DRI production facilities alongside existing taconite pellet operations could unlock significant energy and emissions savings: hot taconite pellets exiting induration furnaces can directly feed into DRI furnaces, eliminating the need for reheating and reducing energy and carbon costs. Converting taconite into metallic iron before shipping could also cut freight costs and emissions substantially by removing up to 35% of the pellet’s non-metallic weight (mostly oxygen). Thus, Minnesota holds an opportunity to transition from simply exporting low-value raw materials to becoming a national leader in producing clean, high-value green iron.

Further on this front, we also gathered perspectives on how Minnesota’s production of DRI and higher-grade iron feedstock could strengthen U.S. national security. Currently, a good amount of EAF iron metallic feedstock is imported from countries like Brazil and Canada. If Minnesota were able to produce it at scale, it could help the United States become more self-sufficient in EAF iron metallic supply. There could also be transportation cost benefits, though this would depend on geographic context. For example, shipping iron pellets from Minnesota to the Gulf States might not offer significant savings compared to importing from overseas. However, transporting iron within the Great Lakes region could be more cost-effective rather than importing from other countries.

7.2 Green Iron pathways: A phased approach through Natural Gas and Hydrogen

Although hydrogen DRI is the ultimate goal for a fully decarbonized iron industry, the transition will likely proceed in phases — with natural gas-based DRI (NG-DRI) serving as an important intermediate step. Natural gas DRI is a commercially mature, low-risk technology already in wide industrial use. Leading equipment suppliers are designing DRI furnaces capable of operating flexibly with blends of natural gas and hydrogen, allowing gradual fuel switching as clean hydrogen supply scales up and becomes more affordable.

From an emissions perspective, moving from the blast furnace–basic oxygen furnace (BF–BOF) route to NG-DRI would offer global benefits. While Minnesota’s local Scope 1 emissions would initially rise (potentially doubling or tripling from about 3 MtCO₂/year to 6–8 MtCO₂/year as DRI plants are built), this localized increase would replace far greater emissions downstream. Steel produced via NG-DRI and electric arc furnaces (EAF) emits about 45–50% less CO₂ per ton compared to BF–BOF steel (roughly 1.2 tCO₂ vs. 2.2 tCO₂ per ton). Companies like Cleveland-Cliffs have demonstrated that DRI-EAF operations can drive major corporate-wide emission reductions.

Nonetheless, this interim phase will involve a temporary trade-off: Minnesota’s industrial emissions will grow until hydrogen becomes widely available. However, once hydrogen displaces natural gas not only in DRI operations but also in taconite pellet induration (where natural gas combustion is a major emissions source), Minnesota’s industrial emissions could fall below current levels. Therefore, NG-DRI provides a challenging yet realistic bridge, offering near-term decarbonization while building toward the eventual hydrogen-driven transformation.

7.3 Resource requirements, market shifts, and the central role of carbon-free electricity

Building a hydrogen-based green iron industry in Minnesota will require not only abundant raw materials but also major infrastructure investments, especially in carbon-free electricity. A single 2 million ton per year (2 MTPA) hydrogen direct reduced iron (H₂-DRI) plant would demand roughly:

- **3 million tons of DR-grade pellets annually,**
- **3.4–5.6 million cubic meters of water** per year (for hydrogen electrolysis, pelletizing, cooling, and dust control), and
- **4.77–7.42 terawatt-hours (TWh)** of carbon-free electricity annually to produce approximately 106,000 tons of hydrogen.

While Minnesota has ample access to high-grade iron ore and water, the availability of carbon-free electricity will be the primary constraint. Supplying the required electricity would equate to about 50–75% of Minnesota Power’s current total annual sales. Even under optimistic scenarios outlined in Minnesota Power’s 2025 Integrated Resource Plan, achieving this scale of clean power will likely take more than five years. Behind the meter distributed generation and Tribal energy generation initiatives may help accelerate development. Until then, limited renewable energy generation and grid capacity may delay green iron expansion.

This technical constraint coincides with significant structural shifts in the steel market. Over the past two decades, raw steel production from traditional blast furnaces (BFs) in the United States has declined sharply — falling from approximately **50 MTPA to just 23 MTPA**. Simultaneously, production from electric arc furnaces (EAFs) has risen dramatically. The trend is accelerating: in March 2025, Cleveland-Cliffs announced the idling of its Dearborn Works blast furnace, the Minorca taconite mine in Minnesota, and further reductions at its Hibbing Taconite facility. As new EAF projects across the country come online, older blast furnaces are increasingly likely to be permanently shuttered, and with them, their demand for traditional taconite pellets.

This structural decline presents both a risk and an opportunity for Minnesota. If the state remains focused solely on producing standard taconite pellets, it risks economic contraction as blast furnace demand erodes. However, by investing in green iron production — converting its abundant iron ore into high-value, decarbonized metallic iron — Minnesota can position itself at the forefront of the emerging EAF-based steel economy.

7.4 Stakeholder Dynamics: Permitting, Trust, and Tribal Engagement

Social and political considerations are as critical as technical feasibility. Stakeholder sentiment around Minnesota’s green iron transition is mixed but can be summarized as cautiously hopeful. Workers, educational institutions, local governments, and economic development agencies broadly support green iron development, seeing it as a way to sustain jobs, revitalize the Iron Range economy, and adapt to declining blast furnace demand. Tribal Nations and environmental groups acknowledge the potential for emissions reductions and Tribal energy sovereignty but remain wary due to the historical impacts of mining, concerns over regulatory laxity, and threats to water resources and treaty rights.

Permitting stands out as a major friction point. Industry stakeholders criticize Minnesota’s lengthy and uncertain permitting processes as barriers to investment, comparing them unfavorably to states like Ohio, Texas, and Louisiana, where iron and steel projects advance more quickly. Meanwhile, Tribal and environmental groups advocate for rigorous environmental reviews to protect communities and natural resources. These competing views reflect deeper tensions between the need for business certainty and the imperative for environmental and social safeguards.

Addressing these challenges will require deliberate, coordinated action. A systems-level approach to permitting emphasizing early stakeholder engagement, cumulative impact assessments, and respect for Tribal sovereignty – could streamline project approvals while maintaining strong protections. Collaborative models like MITI offer useful templates. Without reforms, Minnesota risks losing green iron investments to other regions; with them, it could become a national leader in clean industrial innovation that benefits both the economy and local communities.

7.5 Economic Imperatives and Market Shifts

Minnesota’s traditional taconite pellet economy is facing a long-term decline. According to a 2020 UMD Bureau of Business and Economic Research report, iron mining has a direct economic impact of more than \$2.0 billion dollars annually in the Arrowhead Region of Minnesota. In 2019 the industry supported 4,000 direct, 4,960 indirect and inferred jobs across multiple economic sectors including hospitals, education, suppliers, and restaurants. Additionally, \$159 million in mining taxes and royalties was collected from the iron mining industry with \$53 million of that going to directly fund the state’s university and public school systems. A decline in taconite pellet production would negatively impact the region and the state. As electric arc furnaces (EAFs) replace blast furnaces nationwide, demand for blast furnace-grade pellets will continue to erode. Already, closures like Cleveland-Cliffs’ Minorca mine and reductions at Hibbing Taconite reflect this trend. Green iron production offers a chance to reposition Minnesota’s economy by moving up the steel value chain: from raw material supplier to producer of high-value, low-carbon metallic iron. Failure to adapt could deepen economic distress on the Iron Range, risking thousands of direct and indirect jobs, reductions in mining tax revenues, and broader regional impacts.

7.6 Policy Support and Collaborative Development

The path to green iron will not be market-driven alone. State and federal incentives, particularly those linked to clean procurement standards that give steelmakers a sustained market and demand, will be important to help steelmakers feel more confident about making the capital-intensive investments. Other cross-sectoral issues such as the development of green hydrogen and of clean electricity infrastructure including transmission bottlenecks will be equally important.

The path to green iron will not be market-driven alone. State and federal incentives - particularly those linked to clean procurement standards that give steelmakers a sustained market and demand will be

important to help steelmakers feel more confident about making the capital-intensive investments. Other cross-sectoral issues such as the development of green hydrogen and of clean electricity infrastructure including transmission bottlenecks will be equally important.

On the social de-risking front, cross-sector collaboration among Tribal governments, private companies, environmental organizations, and public agencies will be instrumental in ensuring that all stakeholder perspectives are heard and considered. A permitting process that a more systems-level, early and meaningful engagement among stakeholders can help build trust and reduce conflict, rather than deter private investment. In the past, prolonged public comment periods have delayed projects and discouraged investments that could have brought economic benefits to the state.

8. Recommendations

Based on the above research and findings, the following actions are recommended:

8.1 Conduct Comprehensive Future Studies Including Carbon Cost Analysis

Future studies are required to fully inform Minnesota’s green iron development strategy. Key research priorities should include:

- (1) detailed techno-economic modeling comparing natural gas-based and hydrogen-based DRI under different carbon pricing scenarios, including analysis of the imputed cost of carbon (both formal and shadow carbon costs) on project economics;
- (2) life-cycle assessments (LCA) of water use, emissions, and land impacts associated with large-scale hydrogen production and ironmaking;
- (3) market projections for DR-grade pellets, DRI, and hot briquetted iron (HBI) in a rapidly evolving global steel landscape;
- (4) infrastructure readiness studies focused on hydrogen electrolyzers, storage, and DRI furnace adaptation;
- (5) social impact assessments on workforce transitions, Tribal rights, and environmental justice. Incorporating carbon cost modeling is particularly important because the financial competitiveness of green iron heavily depends on whether and how carbon emissions are priced in future steel markets.

8.2: Conduct a detailed study of factors leading to past and recently announced Direct Reduced Iron producers

The decisions to locate Direct Reduced Iron producers outside of Minnesota and consider policy solutions to correct any deficiencies need to be identified. Key research priorities should include:

1. A review of the site-selection factors influencing where direct-reduced iron and value added iron projects have located, or plan on locating, in the United States over the past twenty years;
2. An examination of which entities control Minnesota’s public and private iron ore minerals and an analysis of if they are available for green iron production;
3. A detailed study of ore and iron-product transportation, freight, and logistics costs of getting iron-units in various forms to likely customers and end markets;
4. A study of the cost and availability of natural gas and renewable electricity;
5. A review of tax and incentive policies;
6. A review of state permitting and regulations via the establishment of dedicated commission.

8.3 Develop a renewable energy allocation framework that allows equitable access to industries competing for large amounts of limited renewable energy.

As Minnesota accelerates its transition to a clean energy economy, the demand for renewable electricity will increasingly exceed near-term supply. Sectors such as green hydrogen, electric transportation, data centers, and sustainable aviation fuel are all competing for clean power which is limited. Without proper planning, DRI may lose out to faster-moving or more politically connected industries. To avoid this, Minnesota could adopt a renewable energy allocation framework that ensures transparent, equitable access to carbon-free electricity across sectors. This framework would prioritize not just speed or profitability, but broader public values like emissions reductions, workforce development, and workforce capacity building.

Key components of such a framework could include a priority scoring system that ranks projects based on greenhouse gas reductions per megawatt-hour, job creation, partnerships with Tribal or local communities, and alignment with net zero goals. Dedicated carve-outs could reserve a portion of renewable supply for hard-to-abate sectors like green industrial hydrogen, while geographic equity mechanisms would help ensure fair distribution to rural and economically disadvantaged regions. Cross-sector coordination between state energy, climate, and economic development agencies would be essential to align clean energy deployment with Minnesota’s 2040 net-zero targets and long-term industrial strategy.

8.4 Develop a green iron tax credit for producers in Minnesota.

This could be a green iron tax credit for DRI production in Minnesota, for example, a tax credit amount for every ton of DRI or HBI produced in Minnesota for producers. To our knowledge, no such program currently targets green iron specifically. This credit could include a provision that distinguishes ore-based DRI from recycled steel, with a tiered structure offering higher incentives for producers using Minnesota-sourced iron ore over recycled scrap steel.

8.5 Develop “Buy Clean” policy aimed at residents in the state.

One gap in the current policy landscape is the absence of demand-side incentives aimed at everyday consumers. To address this, policymakers could create a tax credit for residents who purchase vehicles or other products made with certified low-carbon steel. This could be an income tax credit to residents who buy vehicles or appliances made with certified low-carbon steel. This could be similar to a clean steel vehicle tax credit, and could also build upon Buy Clean/ Buy Fair: for example, verification through Environmental Product Declarations (EPDs) as outlined in Minnesota’s Buy Clean/ Buy Fair law.

8.6 Monitor the current green iron policy space and carve out specific provisions for it in existing policies.

The broad policy outlook suggests new green iron-specific legislation may not be necessary; there is potential to adapt existing policies to better support green iron development by making specific pathways for it in current policies. For example, many policies do not directly target iron or steel but instead affect components of their production. Minnesota’s 2024 permitting reform bill includes provisions that eliminate the need for a Certificate of Need (CN) in certain cases. Although this reform does not explicitly address industrial decarbonization or iron and steel production, it could indirectly support green iron by making it easier for clean energy projects to connect to the grid. This could expand access to clean electricity needed for DRI production. Ongoing monitoring will be important to better understand how these policy changes might support green iron development in Minnesota.

9. References

1. 2023 projects. (n.d.). Legislative-Citizen Commission on Minnesota Resources. Retrieved May 6, 2025, from <https://www.lccmr.mn.gov/projects/2023-index.html#202307e>
2. Agora Industry. (2023). Steel transformation: How green hydrogen will change the industry. Available from https://www.agora-industry.org/fileadmin/Projekte/2021/2021-06_IND_INT_GlobalSteel/A-EW_298_GlobalSteel_Insights_WEB.pdf. Accessed on 2/8/2025.
3. ArcelorMittal Texas HBI (2016). ArcelorMittal Sustainability. Available from <https://northamerica.arcelormittal.com/sustainability>. Accessed on 3/10/2025.
4. Blucher, F. S., et al. (2019). Water use in pelletizing. Available from <https://storage.blucher.com.br>. Accessed on 2/11/2025
5. Breneman, J. (2023, August 1). Iron and steel industries are all in for 'decarbonization'. NRRI | Natural Resources Research Institute. Retrieved May 6, 2025, from <https://nrri.umn.edu/news/decarbonize-iron-steel>
6. Brown, A. (2024, October 14). *Good news on the Iron Range: \$2 billion Mesabi Metallics is finally happening, for real this time*. Minnesota Reformer. <https://minnesotareformer.com/2024/10/14/good-news-on-the-iron-range-2-billion-mesabi-metallics-is-finally-happening-for-real-this-time/#:~:text=In%20addition%2C%20the%20global%20steel,DRI%20plants%20in%20other%20states>
7. *Build Mesabi. Build Itasca! Advocates Gather at State Capitol in Support of Mesabi Metallics Project*. (2025, April 11). Mesabi Metallics. <https://www.google.com/url?q=https://www.mesabimetallics.com/build-mesabi-build-itasca-advocates-gather-at-state-capitol-in-support-of-mesabi-metallics-project%23~:text=3Dimportance%2520of%2520Mesabi%2520Metallics%25E2%2580%2599%2520project.a%2520caption%2520sheet%2520are%2520attached&sa=D&source=docs&ust=1745260451272567&usg=AOvVaw3QTqTkebYSQ-93K0BxGyWk>
8. Burnes, J. (2025, March 20). *Cleveland-Cliffs set to layoff 630 steelworkers at Minorca, Hibbing Taconite*. Minnesota Reformer. <https://minnesotareformer.com/2025/03/20/cleveland-cliffs-set-to-layoff-630-steelworkers-at-minorca-hibbing-taconite>
9. CarbonChain. (2022). Steelmaking CO2 benchmarking. Available from <https://www.carbonchain.com/blog/understand-your-steel-emissions>. Accessed on 2/4/2025.
10. Carey, L., Brickman, A., Yavorsky, N., Gamage, C., & Rosas, J. (2023, September 26). Opportunities for near-zero-Emissions steel production in the Great Lakes. RMI. Retrieved May 6, 2025, from <https://rmi.org/gap-analysis-for-near-zero-emissions-steel-production-in-the-great-lakes/>
11. Center for Energy and Environmental Policy Research/MIT. (2024). Decarbonizing U.S. iron and steel: Policy and industrial pathways. Available from <https://ceep.mit.edu/wp-content/uploads/2024/07/The-Roosevelt-Project-Iron-and-Steel-Decarbonization-by-2050.pdf>. Accessed on 3/1/2025
12. Cleveland-Cliffs Inc. (2022). Sustainability report. Available from <https://www.clevelandcliffs.com/sustainability>. Accessed on 12/4/2024.
13. [Congress.gov](https://www.congress.gov). (2023). Domestic Steel Manufacturing: Overview and Prospects. Available from <https://www.congress.gov/crs-product/R47107>. Accessed on 3/1/2025.
14. Conley, J. (2024, May 13). *'Families' needs over corporate greed': US childcare providers, parents hold day of action*. Common Dreams. <https://www.commondreams.org/news/childcare-crisis>
15. Dieter, C. A. (2018). Water availability and use science program: Estimated use of water in the United States in 2015. US Geological Survey.
16. Drouillard, S. L. (2025, November 26). *Breaking point: Minnesota's mining legacy includes massive lake of wastewater*. Great Lakes Now. <https://www.greatlakesnow.org/2024/11/breaking-point-minnesotas-mining-legacy-includes-massive-lake-of-wastewater/>
17. Energy Research Centre of the Netherlands. (2022). Hydrogen DRI and water recovery. Available from <https://www.rvo.nl/files/file/2022-05/NL-Dutch-solutions-for-a-hydrogen-economy-V-April-2022-DIGI.pdf>. Accessed on 2/22/2025.
18. Energy Transitions Commissions. (2023, April). UNLOCKING THE FIRST WAVE OF BREAKTHROUGH STEEL INVESTMENTS. International Opportunities: THE UNITED KINGDOM, SPAIN, FRANCE, AND THE UNITED STATES. Retrieved May 6, 2025, from <https://www.energy-transitions.org/wp-content/uploads/2023/04/Unlocking-the-First-Wave-of-Breakthrough-Steel-Investments-International-Opportunities-April-2023.pdf>
19. Gamage, C., Ramirez, K., Iyer, N., & Krause, T. (2024, April). Steel decarbonization policy levers. RMI. <https://rmi.org/insight/steel-decarbonization-policy-levers/>
20. Grand Portage Reservation Water Quality. (2023). *Re: Mile Post 7 West Ridge Railroad Relocation, Dam Extensions, and Stream Mitigation Project – Environmental Assessment Worksheet*. Minnesota Department of Natural Resources.

- <https://files.dnr.state.mn.us/input/environmentalreview/mp7wrr/attachment-a/finding-of-fact-13-d-grand-portage-chippewa-comment-letter.pdf>
21. Graves, R., Georgieff, N., Jacobson, R., & Alexander, B. (2024). Embodied Carbon Policy Development in the Upper Midwest. American Council for Energy Efficient Economy. Retrieved May 6, 2025, from https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160831719_7f65b1ac-a5c1-41df-b86b-b0a5d40a2e87.pdf
 22. Gruba, S. (2024, June 6). *Local view: Minnesota must fund child care like it does education*. Duluth News Tribune. <https://www.duluthnewstribune.com/opinion/columns/local-view-minnesota-must-fund-child-care-like-it-does-education#:~:text=On%20Monday%2C%20May%2013%2C%20I,care%20centers%20that%20day>
 23. H2 Green Steel. (2023). Project Boden: Sustainability and water management. Available from <https://www.technologyreview.com/2023/10/04/1080140/2023-climate-tech-companies-h2-green-steel-renewable-energy-industrial-clean-iron-hydrogen/>. Accessed on 3/1/2025
 24. H2 Green Steel. (2024). Water use and recycling plan. Available from <https://h2-tech.com/news/2024/10-2024/aquatech-and-john-laing-to-deliver-water-technology-as-a-service-for-steegra-at-large-scale-green-steel-facility/>. Accessed on 3/15/2025
 25. Huhta, P. (2023). *Fond du Lac Band of Lake Superior Chippewa’s Comments on the Environmental Protection Agency (EPA) Office of Air and Radiation’s Proposed National Emission Standards for Hazardous Air Pollutants: Taconite Iron Ore Processing Amendments, Docket ID No. EPA-HQ-OAR-2017-0664*. The Grist. <https://www.documentcloud.org/documents/24810971-0281-2023-fond-du-lac-comments/?responsive=1&title=1>
 26. HYBRIT (SSAB, LKAB, Vattenfall). (2021). HYBRIT pilot report. Available from <https://www.hybritdevelopment.se/en/april-7-2021-hybrit-ssab-lkab-and-vattenfall-building-unique-pilot-project-in-lulea-for-large-scale-hydrogen-storage-investing-a-quarter-of-a-billion-swedish-kronor/>. Accessed on 2/22/2025.
 27. Industrial Commission of North Dakota (2024). *CLEAN SUSTAINABLE ENERGY AUTHORITY*. Available from <https://www.ndic.nd.gov/sites/www/files/documents/Clean-Sustainable-Energy-Authority/Meetings/2024/CSEA-TR-Meeting-1-16-2024.pdf>. Accessed on 4/20/2025.
 28. International Energy Agency. (2020). Iron and steel technology roadmap. Available from <https://www.iea.org/reports/iron-and-steel-technology-roadmap>.
 29. Johnson, C. (2024, September 21). *Company seeks to expand massive lake of mine waste near North Shore*. Star Tribune. <https://www.startribune.com/company-seeks-to-expand-massive-lake-of-mine-waste-near-north-shore/601149015>
 30. Kaul, G. (2018, October 17). *Mining Is a Small Part of Minnesota’s Economy. So Why Is It Such a Big Political Issue?* MinnPost. Retrieved April 27, 2025, from <https://www.minnpost.com/economy/2018/10/mining-is-a-small-part-of-minnesotas-economy-so-why-is-it-such-a-big-political-issue/>
 31. Kraker, D. (2016, April 11). *Explaining the iron range downturn: Layoffs amid the challenges of a global economy*. MPR News. <https://www.mprnews.org/story/2016/04/11/explaining-the-iron-range-economic-downturn>
 32. Kvam, I. (2023, August 16). New jobs, cleaner building materials: Minnesota’s Buy Clean Buy Fair law. Fresh Energy. Retrieved May 6, 2025, from <https://fresh-energy.org/buy-clean-buy-fair-law>
 33. Lovrien, J. (2024, May 23). *Keetac’s new DR-grade pellet plant up and running*. Duluth News Tribune. <https://www.duluthnewstribune.com/news/local/keetacs-new-dr-grade-pellet-plant-up-and-running#:~:text=%E2%80%9CIt%20should%20give%20us%20extra,of%20United%20Steelworker%20Local%202660>
 34. MagIron LLC (2024). Available from <https://magironusa.com/>. Accessed on 2/28/2025.
 35. Maupin, M. A. (2018). Summary of estimated water use in the United States in 2015 (No. 2018-3035). US Geological Survey.
 36. Mesabi Metallics (2023). Available from <https://www.mesabimetallics.com/environmental-sustainability/>. Accessed on 3/10/2025.
 37. Midrex Technologies, Inc. (2023). World direct reduction statistics 2022. Available from https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2023.Final_.pdf. Accessed on 3/15/2025.
 38. Minnesota Department of Commerce. (2023). Governor Walz Signs Bill Moving Minnesota to 100 Percent Clean Energy by 2040. Available from <https://mn.gov/commerce/news/?id=17-563384>. Accessed on 2/23/2025.
 39. Minnesota Department of Natural Resources. (2024). State Mineral Leases. Available from (https://www.dnr.state.mn.us/lands_minerals/min_leases.html)

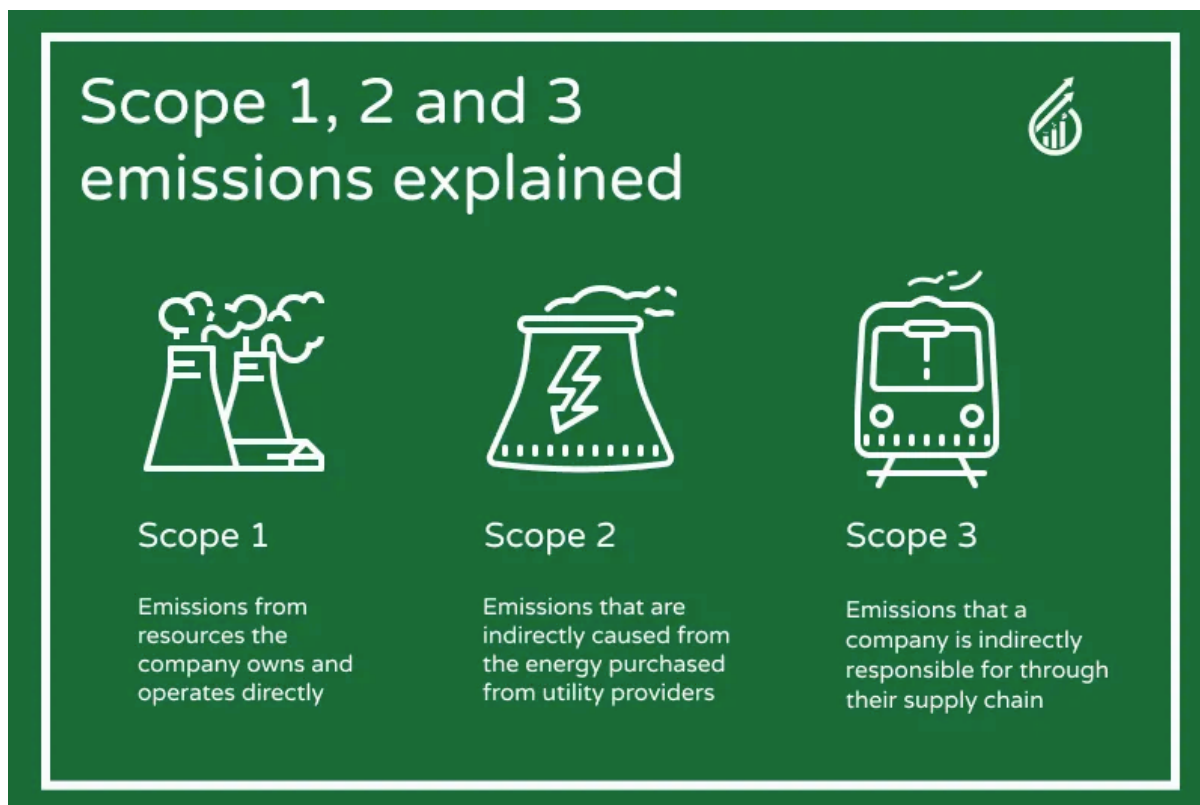
40. Minnesota Department of Natural Resources. (2023). Taconite production summary and facility data. Available from <https://www.dnr.state.mn.us>
41. Minnesota Iron Range Resources and Rehabilitation. (2022). BIENNIAL REPORT, Fiscal Years 2021-2022. https://mn.gov/irrrb/assets/Biennial%20Report2122_tcm1047-554343.pdf
42. Minnesota Pollution Control Agency. (2020). Greenhouse gas emissions in Minnesota 2005-2020. Available from <https://www.pca.state.mn.us/sites/default/files/Iraq-2sy23.pdf>. Accessed on 3/7/2025
43. Minnesota Power (2025). *MINNESOTA POWER SERVES LARGE INDUSTRY*. Available from https://www.lrl.mn.gov/archive/minutes/senate/2023/energy/20230118/energy_20230118_December-2022-One-Page-Large-Industrial-Customer-Fact-Sheet.pdf. Accessed on 4/15/2025.
44. MinnPost. (2023). How low-emissions steelmaking could be big business for Minnesota’s Iron Range. Available from <https://www.minnpost.com/business/2023/12/how-low-emissions-steelmaking-could-be-big-business-for-minnesotas-iron-range/>. Accessed on 2/20/2025.
45. MPCA. (2023). Water permits and regulations. Available from <https://www.pca.state.mn.us/business-with-us/water-permits-and-regulations>. Accessed on 2/20/2025
46. Minnesota Steel Industries. (2007). Final Environmental Impact Statement: Minnesota Steel Project, Itasca County, Minnesota. Prepared for the Minnesota Department of Natural Resources. Available from https://files.dnr.state.mn.us/input/environmentalreview/minnsteel/feis/feis_1.pdf. Accessed on 2/20/2025.
47. Mody, S. (2025, March 24). *South Korea's Hyundai announces \$21 billion U.S. investment*. CNBC. <https://www.cnbc.com/2025/03/24/south-korea-hyundai-us-investment.html>
48. Nucor Corporation. (2022). Sustainability report and scope 1, 2, 3 emissions. Available from <https://www.nucor.com/sustainability/>. Accessed on 3/15/2025.
49. *Older adults* | *MN compass*. (n.d.). Minnesota Compass. <https://www.mncompass.org/older-adults>
50. Olmez, G. M., Dilek, F. B., Karanfil, T., & Yetis, U. (2016). The environmental impacts of iron and steel industry: a life cycle assessment study. *Journal of Cleaner Production*, 130, 195-201.
51. Rechberger et al. (2021). Green Hydrogen for Low-Carbon Steelmaking. Available from https://www.primetals.com/fileadmin/user_upload/landing_pages/2021/Green_Steel/Publications/downloads/Green_Hydrogen_for_Low-Carbon_Steelmaking_.pdf. Accessed on 2/20/2025
52. Rocky Mountain Institute. (2023). Opportunities for Near-Zero-Emissions Steel Production in the Great Lakes. Available from <https://rmi.org/insight/green-steel-great-lakes/>. Accessed on 3/8/2025.
53. Rocky Mountain Institute. (2023). Hydrogen Reality Check: Distilling Green Hydrogen’s Water Consumption. Available from <https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/>. Accessed on 3/15/2025.
54. Rocky Mountain Institute. (2023). Reality Check. Available from <https://rmi.org/reality-check/>. Accessed on 3/15/2025.
55. Roosevelt Institute. (2022). Leading with Industrial Policy: Lessons for Decarbonization from Swedish Green Steel. Available from <https://rooseveltinstitute.org/publications/leading-with-industrial-policy/>. Accessed on 3/10/2025.
56. Rukavina, S. (2022). Complicating the Constructed Narrative of Minnesota’s Iron Range. *Tapestries: Interwoven voices of local and global identities*, 11(1).
57. Smith, L. (2024, October). Building Tribal Energy Sovereignty. *The Circle: News from the American Perspective*, 45(10). <https://thecirclenews.org/wp-content/uploads/2024/10/Oct-2024-The-Circle.pdf#:~:text=clean%20energy%20future,to%20fossil%20fuel%20infra%02structure%20development>
58. Société Générale. (2022). Green steel: H2GS investor report. Available from <https://wholesale.banking.societegenerale.com>. Accessed on 3/15/2025.
59. Suer, J., Traverso, M., & Jäger, N. (2022). Review of life cycle assessments for steel and environmental analysis of future steel production scenarios. *Sustainability*, 14(21), 14131.
60. Superchi, F., Mati, A., Carcasci, C., & Bianchini, A. (2023). Techno-economic analysis of wind-powered green hydrogen production to facilitate the decarbonization of hard-to-abate sectors: A case study on steelmaking. *Applied Energy*, 342, 121198.
61. SSAB. (2022). HYBRIT technology overview. Available from <https://www.ssab.com/en/about-us/hybrit>. Accessed on 3/15/2025.
62. SSAB. (2025). Annual report. Available from https://www.ssab.com/api/download?file=-/media/files/company/investors/annual-reports/2024/ssab_annual_report_2024.pdf?m=20250320120634. Accessed on 3/9/2025.
63. Steel Dynamics Inc. (2022). ESG and corporate responsibility report. Available from <https://www.steeldynamics.com/sustainability-reporting/>. Accessed on 3/9/2025.

64. U.S. Department of Energy. (2008). Steel industry profile. Office of Industrial Technologies. Available from <https://www.energy.gov/eere/iedo/steel>. Accessed on 3/9/2025.
65. U.S. Environmental Protection Agency. (2023). Emission factors for stationary combustion. Available from <https://www.epa.gov/climateleadership/ghg-emission-factors-hub>. Accessed on 2/17/2025.
66. U.S. Steel Corporation. (2022). Best for All® sustainability report. Available from <https://www.ussteel.com/sustainability/esg-data-hub>. Accessed on 2/17/2025.
67. World Steel Association. (2011). Water management in the steel industry. Available from <https://worldsteel.org/publications/fact-sheets/>. Accessed on 2/17/2025.
68. World Steel Association. (2022). Steel statistical yearbook 2022. Available from <https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2022.pdf>. Accessed on 3/20/2025.
69. Xcel Energy, Heartland Hydrogen Hub selected for up to \$925 million federal award. (2023, October 13). Xcel Energy. Retrieved May 6, 2025, from <https://investors.xcelenergy.com/news-events/news-releases/news-details/2023/Xcel-Energy-Heartland-Hydrogen-Hub-selected-for-up-to-925-million-federal-award/default.aspx>
70. Yavorsky, N., Gamage, C., Ramirez, K., & Masterson, M. (2023, November). Great Lakes Near-Zero-Emissions Steel, Memo Focus: Minnesota. RMI. Retrieved May 6, 2025, from https://rmi.org/wp-content/uploads/dlm_uploads/2024/02/MN_steel_memo.pdf
71. Younes, L. (2024, July 23). *Minnesota tribes paying the price for steel industry's pollution*. MinnPost. <https://www.minnpost.com/other-nonprofit-media/2024/07/tribes-in-minnesota-are-paying-the-steepest-price-for-the-steel-industrys-mercury-pollution/>

10. Appendix

10A: Scope 1,2 and 3 Emissions

Figure 4: Scope 1, 2 and 3 emissions.



(Source: Emission Index)

10B: Emissions Profiles

Current Taconite-Based Ironmaking Process in Minnesota

Minnesota’s taconite production process generates greenhouse gas (GHG) emissions across all three scopes, with the most significant emissions occurring downstream in out-of-state steelmaking facilities that rely on blast furnace–basic oxygen furnace (BF–BOF) systems.

Scope 1 Emissions – Direct Emissions in Minnesota

The primary source of Scope 1 emissions in Minnesota’s iron mining sector comes from the combustion of natural gas in the pellet induration stage. During this process, iron ore concentrate is rolled into green pellets and fired at temperatures exceeding 1,250°C using natural gas or coal. This step emits approximately 40–60 kg CO₂ per ton of pellets (Minnesota Steel Industries, 2007). Across Minnesota’s six pellet plants, this amounts to over 1 million metric tons of CO₂ annually.

In addition, significant Scope 1 emissions are produced by diesel-powered mining equipment, including haul trucks and loaders. Estimates suggest this mining fleet contributes around 10–20 kg CO₂ per ton of pellets, depending on production intensity (Minnesota Steel Industries, 2007). For example, a 4-million-ton pellet operation might emit 40,000–80,000 tCO₂/year from diesel alone.

Combined, the furnace fuel combustion and diesel mining operations constitute the bulk of Minnesota’s current Scope 1 emissions from taconite production.

Scope 2 Emissions – Indirect Emissions from Electricity Use

Minnesota’s iron ore processing is also energy-intensive from an electrical perspective, particularly during ore crushing, grinding, and magnetic separation. These processes rely on a significant amount of purchased electricity, contributing to Scope 2 emissions. In 2006, taconite-related electricity consumption produced approximately 1.6 million metric tons of CO₂ (Minnesota Pollution Control Agency [MPCA], 2009).

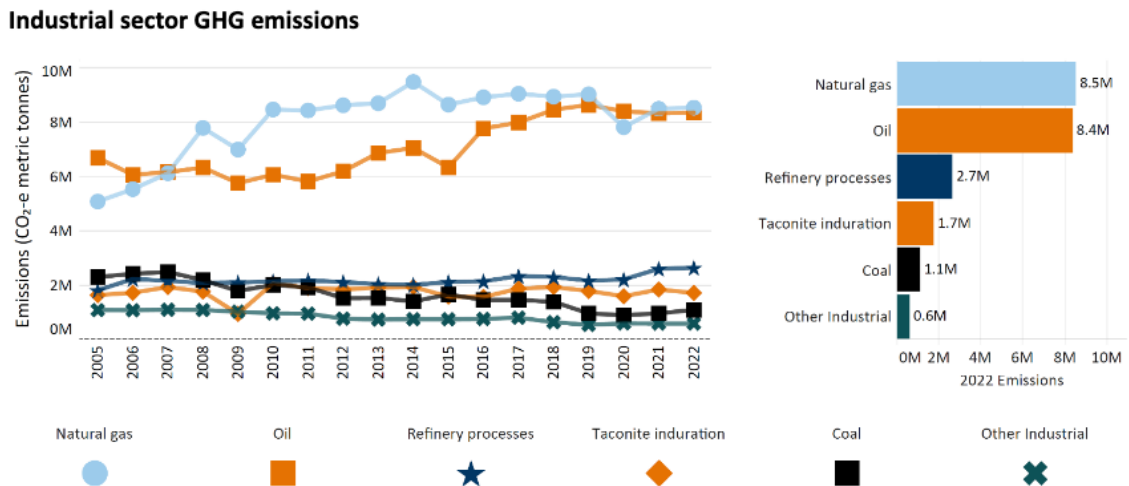
However, Minnesota’s electric grid has significantly decarbonized over the past two decades, transitioning from coal to wind, solar, hydro, and natural gas (Minnesota Department of Commerce, 2023). This transformation has led to substantial reductions in Scope 2 emissions, and the state's target of achieving 100% carbon-free electricity by 2040 could eventually bring Scope 2 emissions near zero for electrified processes (Minnesota Department of Commerce, 2023).

Scope 3 Emissions – Downstream Emissions from BF–BOF Steelmaking

While in-state Scope 1 and 2 emissions are notable, the largest share of emissions associated with Minnesota’s iron industry falls under Scope 3, particularly from the use phase of taconite pellets. After production, pellets are transported to integrated steel mills in states such as Indiana and Ohio, where they are used in coal-fueled blast furnaces (Congress, 2023).

Blast furnace–based steelmaking is among the most carbon-intensive industrial activities, emitting approximately 2.2 tons of CO₂ per ton of steel produced (CarbonChain, 2023). Given that around 1.5 tons of taconite pellets are required to make one ton of steel, downstream emissions from pellet use are significant. Minnesota exports about 35 million tons of pellets per year, enabling the production of more than 23 million tons of steel. This results in an estimated 50 million metric tons of downstream CO₂ emissions annually, which are not counted in Minnesota’s emissions inventory but are directly linked to its iron exports (Rocky Mountain Institute, 2023).

Figure 5: Industrial sector GHG emissions in Minnesota



(Source: MPCA, 2020)

Total Emissions (Minnesota Iron Industry)

The territorial (Scope 1+2) emissions of Minnesota’s iron mining and pelletizing industry are approximately 2–3 million metric tons of CO₂ per year in recent years. This is about 1–2% of Minnesota’s economy-wide GHG emissions. By including the use-phase (Scope 3), the full carbon footprint associated with Minnesota’s iron ore reaches tens of millions of tons, but those emissions are

counted in the inventories of other states (e.g. Indiana, Ohio) where integrated steel mills operate. In summary, the current taconite-based pathway has a high-emissions profile (≈ 2.2 tCO₂/ton steel) when considering the steel product, with only a small fraction of those emissions occurring within Minnesota’s borders (Minnesota Department of Natural Resources, 2023; Olmez, G.M. et al. 2016).

Emissions by step:

⇒ BF-BOF

Each step of taconite production contributes to the carbon footprint:

Mining

Diesel combustion in haul trucks and loaders emits roughly 10–20 kg CO₂ per ton of pellets produced (files.dnr.state.mn.us). For example, one study estimated $\sim 42,500$ tCO₂/year from mining equipment to support ~ 4 Mt of pellets (files.dnr.state.mn.us), emitting approximately 11 kg CO₂/ton.

Concentrating: This stage’s direct CO₂ is minimal (e.g. $\sim 1,900$ tCO₂/yr of on-site fuel in one case (files.dnr.state.mn.us)). However, it draws significant electricity for crushing, grinding, and pumping. If drawing from a fossil-heavy grid, this indirect energy use can add on the order of 30–50 kg CO₂/ton of pellets (Scope 2). In Minnesota, taconite processing electricity contributed ~ 1.6 million tCO₂ in 2006 (files.dnr.state.mn.us) (not including on-site fuel combustion).

Indurating

The pellet furnace is the largest emitter on-site. Natural gas combustion for heating pellets and drying furnace air generates about 40–60 kg CO₂ per ton of pellets (files.dnr.state.mn.us). For instance, pellet indurating was estimated at $\sim 152,000$ tCO₂/year for ~ 3.8 Mt pellets (≈ 40 kg CO₂/ton) in a Minnesota plant design (files.dnr.state.mn.us^[SEP]). Some CO₂ is also released from limestone (CaCO₃) added as flux, as it calcines to CaO during firing (typically a smaller component, but contributes a few kg CO₂/ton).

Downstream BF-BOF Steelmaking

Scope 3 (Use-phase) – When these taconite pellets are used in blast furnaces, large CO₂ emissions occur at the steel mill (outside Minnesota). Each ton of pellets used in a coal-fired blast furnace results in roughly 0.9–1.0 tons of CO₂ at the furnace (since ~ 1.5 t pellets make 1 t steel (epa.gov)), and BF-BOF emits ~ 2.2 tCO₂ per t steel (carbonchain.com). This is by far the biggest emissions stage, though it’s not within Minnesota’s borders. It is included here as Scope 3 (downstream) for the pellet producer.

⇒ Electric Arc Furnace (EAF):

The electric arc furnace process involves combining scrap steel, pig iron, direct-reduced iron, and other iron metallics in a vessel and melting them with a strong electric current. The EAF is a single-stage process, and additives are added to it to achieve the desired final properties of the finished steel. These steel-making vessels can range in size and are often much smaller than blast furnaces. As such, EAFs are usually referred to as mini-mills. The quality of the finished steel is primarily controlled through the careful selection of the input metallics as well as through slag formation (Olmez, G.A. et al., 2018).

Scope 1 Emissions – Direct Emissions in EAF Iron Making

Scope 1 emissions from EAF operations are limited and primarily arise from two sources: the combustion of natural gas used for ladle preheating or supplemental heating, and the oxidation of graphite electrodes used to melt iron in the furnace. Additional emissions may occur from carbon injections required for slag foaming. Altogether, these sources typically contribute around 0.05 to 0.10 metric tons of CO₂ per ton of steel produced (CarbonChain, 2023; World Steel Association, 2022; Rocky Mountain Institute, 2023). In some optimized hydrogen DRI operations—such as HYBRIT in Sweden—Scope 1 emissions have been measured even lower, owing to advanced energy management systems and reduced reliance on fossil fuels (HYBRIT, 2021).

Scope 2 Emissions – Indirect Emissions from Electricity Use

Indirect emissions stem from electricity used to operate the EAF, are more significant and depend largely on the carbon intensity of the local power grid. EAFs typically consume between 400 to 600 kilowatt-hours (kWh) per ton of steel. If the electricity comes from a carbon-intensive grid, this could result in 0.16 to 0.24 metric tons of CO₂ per ton of steel. However, with a zero-carbon grid—such as Sweden’s or Minnesota’s target under its 2040 Clean Energy Standard—Scope 2 emissions could drop to near zero (Minnesota Department of Commerce, 2023; Rocky Mountain Institute, 2023; HYBRIT, 2022).

Scope 3 Emissions – Downstream Emissions from EAF Steelmaking

Scope 3 for EAF operations include upstream and downstream activities such as the manufacturing and transport of graphite electrodes, alloying elements, refractory materials, and other process inputs. While highly variable, these typically range from 0.1 to 0.3 metric tons of CO₂ per ton of steel, depending on sourcing and logistics (IEA, 2020; CarbonChain, 2023). The use of green hydrogen, reduced reliance on coal, and localized supply chains can dramatically lower these indirect emissions. Downstream Scope 3 emissions (e.g., transportation of finished steel products) are generally modest and depend on the distribution network and end-use application.

Total Emissions

When hydrogen DRI is paired with an EAF powered by renewable electricity, the emissions footprint can be as low as 0.2 to 0.6 tCO₂ per ton of steel, or even lower under optimal configurations (Rocky Mountain Institute, 2023; HYBRIT, 2022). This stands in stark contrast to the traditional blast furnace–basic oxygen furnace (BF-BOF) route, which emits around 2.2 tCO₂ per ton of steel on average (IEA, 2020). As Minnesota and other regions explore decarbonized ironmaking, these figures demonstrate that the EAF pathway offers a promising and scalable solution for low-emission steel.

⇒ Natural gas- based Ironmaking (mid-term transition)

The Natural Gas–DRI process offers a cleaner alternative to traditional blast furnace steelmaking. In this method, natural gas is used to reduce iron ore into a solid-state metallic form known as sponge iron or DRI, which is then melted in an EAF. This route emits significantly less CO₂ than the conventional blast furnace route and has become the dominant method in regions with abundant natural gas supplies, such as the Middle East and the southern United States (IEA, 2020).

The process begins with beneficiation and pelletizing of low-grade iron ore into high-purity DR-grade pellets containing over 67% Fe. The reduction gas, or syngas, is produced by reforming natural gas (primarily methane, CH₄) with steam. This generates a mixture of hydrogen (H₂) and carbon monoxide (CO), both of which serve as reductants.

As an intermediate step, many steelmakers are adopting natural gas-based DRI paired with EAFs. This is a proven technology (e.g. MIDREX®) that significantly cuts emissions versus coal, though not as much as using hydrogen (Midrex, 2023). The steps in Minnesota would be:

Mining

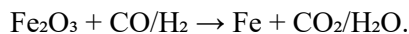
Same taconite mining operations in Minnesota. No change in this step – diesel equipment and associated CO₂ continue as in the current process.

DR-Grade Pelletizing

Minnesota mines would produce DR-grade pellets (indistinguishable from those in the hydrogen scenario). U.S. Steel is upgrading Keetac to produce 68% Fe DR-grade pellets (Center for Energy and Environmental Policy Research, 2024). The process is still concentrating and indurating, likely still using natural gas in pellet furnaces initially. Emissions here are similar to current pellet production, perhaps with slightly higher energy use to achieve greater purity.

Natural Gas DRI

Instead of sending pellets to a blast furnace, they are fed to a direct reduction reactor in Minnesota that uses reformed natural gas. In a MIDREX or ENERGIRON DRI shaft, methane (CH₄) is converted to a hot syngas (H₂ + CO) which reduces the iron ore:



A portion of the carbon in natural gas ends up as CO₂ emissions in the exhaust. The DRI output is solid sponge iron (~90–94% metallization). This DRI can be discharged hot into briquettes (HBI) or fed to an EAF. The key difference from hydrogen DRI is that fossil carbon is still the reductant, so significant CO₂ is generated. However, it is much less carbon-intensive than a blast furnace, because natural gas has a lower C/H ratio and no coal combustion is needed (Suer, J. et al. 2022, Superchi, F et. al. 2023)

Shipping DRI/HBI

Similar to the hydrogen case, the product (hot briquetted iron) would be shipped to an EAF steel plant. If Minnesota doesn't host the EAF, this means rail or barge transport to a mill (e.g. to Electric Arc furnaces in the Great Lakes region). Cleveland-Cliffs is already doing this: it produces ~1.6 Mt of HBI annually at its Toledo, Ohio plant using Minnesota pellets (Cleveland Cliffs Inc., 2022; Center for Energy and Environmental Policy Research, 2024), and ships that HBI to its EAFs and BOFs to lower their coke use.

EAF Steelmaking

The HBI is melted in an EAF (could be at a mill outside Minnesota, such as in Ohio or Pennsylvania). The EAF uses electricity (which may have some CO₂ footprint unless renewable) and some carbon injection (often a small amount of natural gas or coke is injected to foamy slag). The EAF step's emissions are relatively small compared to the iron reduction. As noted before, EAFs emit ~0.3 tCO₂/ton on average if grid-powered, and much less if using a cleaner power mix. The NG-based pathway shifts a large CO₂ burden onto Minnesota's balance sheet (Scope 1), even as it lowers overall emissions per ton of steel.

Scope 1 Emissions – Direct Emissions in Minnesota

This now includes the direct emissions from the DRI plant in addition to pelletizing. If Minnesota builds a gas DRI facility, it becomes a major point source of CO₂. For example, a 2 MTPA DRI plant could emit on the order of 1–1.5 MtCO₂ annually on-site. In per-ton terms, Minnesota's Scope 1 would jump to about 0.6–0.7 tCO₂ per ton of steel (mining + pelletizing ~0.1, DRI ~0.5–0.6). This is a several-fold increase in Minnesota's iron industry emissions compared to the current taconite-only operations. Currently ~0.1 t of a BF-bound ton of steel is emitted in MN; with NG-DRI, ~0.6–0.7 t would be emitted in MN for that same ton of steel (Midrex 2023; MinnPost, 2023; CarbonChain 2022).

Scope 2 Emissions – Indirect Emissions from Electricity Use

There would be some increase in electricity use – the DRI plant requires oxygen separation, compressors, etc., and the pellet plant might need upgrades – but this is relatively small compared to the hydrogen case. Perhaps on the order of an extra 50–100 kWh per ton steel for the DRI process (e.g. for CO₂ removal compressors). If Minnesota's grid is still decarbonizing, this could add maybe ~0.02 tCO₂, which is minor. Overall Scope 2 might be a bit higher than current, but not dominant. (If the EAF is in Minnesota, then Scope 2 would include the EAF power; that scenario would significantly boost Minnesota's power demand and associated emissions unless the EAF is renewably powered (International Energy Agency, 2020).

Scope 3 Emissions – Downstream Emissions from EAF Steelmaking

Upstream of the DRI plant, natural gas supply has some scope 3 emissions (methane leakage, processing CO₂). Those add a few percent (~5–10%) to the gas CO₂ footprint, which could be on the order of 0.05 tCO₂e per ton steel. Downstream, the EAF emissions (if out-of-state) are Scope 3 for Minnesota's

ironmaker. As discussed, that might be ~ 0.3 tCO₂/ton. So from a full-chain perspective, NG-DRI-EAF might emit ~ 1.0 – 1.3 tCO₂/ton, split roughly half in Minnesota (DRI) and half out-of-state (power generation and EAF). This is 40–60% lower total CO₂ than the ~ 2.5 t/ton of the BF-BOF route (Suer, J. et al. 2022, CarbonChain, 2022). But it is higher than the pure hydrogen route.

Overall Impact and Comparison

The natural gas DRI pathway is often seen as a stepping stone. It achieves substantial CO₂ reductions in the near term using commercially available tech (natural gas-based DRI plants and EAFs), but it does not reach the deep decarbonization possible with hydrogen. In Minnesota, adopting NG-DRI would mean the Iron Range transitions from just mining to also producing metallic iron – increasing in-state emissions. Minnesota’s iron industry emissions might roughly double or triple (going from ~ 3 MtCO₂/yr for pelletizing to perhaps ~ 6 – 8 MtCO₂/yr once a DRI plant is added at full scale). This is because what was previously emitted at distant blast furnaces (Scope 3) is now partly emitted at the Minnesota DRI plant (Scope 1). However, globally this shift is beneficial: Each ton of steel made via NG-DRI instead of BF avoids roughly 1 to 1.5 tons of CO₂. For example, BF-BOF: ~ 2.2 tCO₂/ton vs. NG-DRI-EAF: ~ 1.2 tCO₂/ton on average (CarbonChain, 2022), which is around 45% less carbon per ton. Cleveland-Cliffs has reported significantly lower CO₂ intensity for its DRI-EAF production, contributing to a one-third reduction in company-wide emissions since 2017 (MinnPost, 2023; Cleveland-Cliffs Inc., 2022). This intermediate state is a major improvement over the status quo in steelmaking emissions.

Stepwise Emissions

The natural gas DRI-EAF route cuts total emissions by roughly 50% compared to the BF route, but it relocates a lot of emissions to Minnesota (where the DRI plant operates).

Quantitatively:

Mining + Pelletizing: These remain identical to current emissions. Let’s say ~ 0.08 – 0.1 tCO₂ per ton of steel in Minnesota for mining and pellet production (Scopes 1+2), as before. No change here, aside from possible efficiency improvements.

DRI Production (NG)

This is the new major source in Minnesota. In a gas-based DRI furnace, roughly 1.1–1.4 tCO₂ is emitted per ton of steel produced (Olmez et al. 2016) (including the downstream EAF). For example, an MIT analysis noted 0.77–1.1 tCO₂/ton steel for NG-DRI-EAF vs ~ 1.9 for BF-BOF (Olmez et al. 2016), Industry data put it at ~ 1.2 tCO₂/ton on average (if using typical grid power) (carbonchain.com). To break that down: the DRI shaft itself likely contributes ~ 0.6 – 0.8 tCO₂/ton steel, coming from the oxidation of natural gas (CH₄ → CO₂). The remaining ~ 0.2 – 0.4 tCO₂ comes from the EAF electricity and carbon usage.

In the Minnesota Steel project example, DRI production was estimated to emit ~ 1.445 MtCO₂ for 2.5 Mt steel (≈ 0.58 tCO₂/ton) (files.dnr.state.mn.us), and the EAF “Steel Mill” another 0.22 t/ton (files.dnr.state.mn.us) – totaling ~ 0.80 t/ton direct. (They achieved a low number by using efficient natural gas reforming and some scrap in the EAF.) More typically, if the grid is fossil-heavy, you get around 1.0–1.2 tCO₂/ton.

EAF Steelmaking: Emissions here depend on where the EAF is and its power source. If the HBI is melted at a mill in a state with average grid mix, the EAF might emit ~ 0.2 – 0.3 tCO₂/ton (Scope 3 from Minnesota’s perspective). If that EAF is in Minnesota and the grid is partly fossil, it would show up as Scope 2 in Minnesota. For instance, using today’s grid, an EAF might use ~ 500 kWh/ton with ~ 0.4 kg/kWh CO₂, adding ~ 0.20 tCO₂. Many DRI-EAF operations also use some natural gas in the EAF for heating or to inject a few percent carbon, which could add ~ 0.05 – 0.1 tCO₂. So EAF step might be ~ 0.3 tCO₂/ton. Cliffs’ Toledo HBI plus an EAF has been reported to achieve about 1.1–1.2 tCO₂/ton steel, roughly half the emissions of BF steel (carbonchain.com).

Hydrogen-Based Ironmaking (Future “Green Steel” Pathway)

The hydrogen-based route replaces fossil fuels with green hydrogen and renewable power to achieve near-zero emissions. The envisioned steps are:

Mining: Similar mining of iron ore in Minnesota (potentially the same taconite mines). The ore extraction processes remain (drilling, blasting, hauling), with diesel equipment unless electrified. In a true green end-state, mining trucks and drills could be electrified or hydrogen-fueled, further cutting emissions – but in the near term, assume mining emissions remain comparable to today’s (Scope 1 diesel CO₂).

DR-Grade Ore Processing

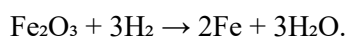
The ore is concentrated and formed into DR-grade pellets suitable for direct reduction. This involves additional grinding and flotation to achieve higher Fe purity (≥67% Fe). Minnesota’s ore processors may adjust chemistry (e.g. lower silica, add limestone or dolomite for metallization) and use existing pelletizers with some modifications (ceep.mit.edu).

The pelletizing step itself is similar, but a switch to renewable energy sources is anticipated. For example, indurating furnaces could use hydrogen burners or electrically heated furnaces instead of natural gas, eliminating CO₂ emissions from that step. (If hydrogen or biogas is used in the furnace, water vapor replaces CO₂ as the combustion product.)

Direct Reduction with Hydrogen

This is the core of the green ironmaking. Direct Reduced Iron (DRI) is produced by reacting the DR-grade pellets with 100% hydrogen gas (H₂) in a shaft furnace.

Hydrogen acts as the reducing agent:



The only reaction by-product is water vapor. The H₂ fuel is produced via electrolysis of water, powered by renewable electricity (wind, solar, hydro). This DRI step emits virtually no CO₂ on-site (Scope 1 is near zero – only water and heat). It does consume a large amount of electricity indirectly (Scope 2, for H₂ production and compression). In the “green” scenario, electricity is carbon-free, so the effective emissions from DRI are minimal. The solid product is sponge iron (~94–95% Fe) which can be used immediately or compacted into hot briquetted iron (HBI) for transport.

Shipping DRI/HBI: The metallic iron product would be shipped to an Electric Arc Furnace (EAF) steel plant. In a future Minnesota scenario, this could mean building an EAF on-site or nearby (e.g. at the mine or a port) or, more likely, transporting HBI to existing EAF mills elsewhere in the U.S. Because HBI is stable and much lower-volume than raw ore, transport emissions per ton of steel are small (and could be further reduced by electric rail or ships).

Electric Arc Furnace Steelmaking

The DRI (plus some scrap metal) is melted in an EAF to produce steel. The EAF is powered by electricity; when using renewable power, its direct CO₂ emissions are very low (primarily from graphite electrode consumption and any minor natural gas usage for supplemental heating). Steel refining and casting then proceed as usual. The EAF route’s emissions depend on the power source – with a zero-carbon grid, EAF steelmaking adds negligible CO₂. (In Sweden’s HYBRIT project, for example, the DRI-EAF route is supplied by 100% fossil-free electricity, targeting ~25–50 kg CO₂ per ton steel total emissions (Roosevelt Institute, 2022.)

Scope 1 Emissions – Direct Emissions in Minnesota

On-site fossil fuel use can be close to zero. There is no coal/coke, and natural gas is replaced by H₂. The only Scope 1 CO₂ in Minnesota might come from residual use of diesel in mining or backup systems. This could be on the order of ~0.01 tCO₂/ton steel or less. Essentially, Minnesota would have no significant new CO₂ sources from operating a hydrogen DRI facility. (By contrast, in the current system

Minnesota has ~0.1–0.15 tCO₂/ton steel in Scope 1 from pelletizing; the H₂ route could cut that by >90%.)

Scope 2 Emissions – Indirect Emissions from Electricity Use

Large increase in electricity demand, but if met with renewables, it adds little to CO₂ emissions. Hydrogen production and electric furnaces might draw 3–4 MWh per ton steel combined. This would likely be via new wind/solar farms in Minnesota or the region. Minnesota’s policy of 100% carbon-free electricity by 2040 supports this shift (Rocky Mountain Institute, 2023). If achieved, Scope 2 CO₂ beyond 2040 would be near zero. (If grid power in the interim has some CO₂, those emissions would mostly be counted in the power sector’s inventory).

Scope 3 Emissions – Downstream Emissions from EAF Steelmaking

Upstream, the production of green hydrogen is essentially just water and renewable power – no fossil supply chain like coal mining is needed, so upstream Scope 3 is minimal (manufacturing of electrolyzers, etc., which is very minor per ton). Downstream, the EAF steelmaking may be outside Minnesota, but its emissions are very low compared to a BF. For example, if an EAF in Illinois used a moderately clean grid, it might emit ~0.2 tCO₂/t. If it uses renewables, it could be <0.05 t. So the total Scope 3 from steel production is reduced by ~95% relative to the BF baseline (Roosevelt Institute, 2022). Also, transport emissions are small (shipping HBI is much less CO₂-intensive than shipping bulk ore or pellets).

10D: Emission by step (H₂-DRI): The hydrogen DRI-EAF pathway can achieve a 90–95% reduction in CO₂ emissions relative to the traditional BF route.

Key contributions at each stage:

Mining

If diesel equipment is unchanged, mining will still emit ~10 kg CO₂/ton. However, this becomes one of the largest remaining sources. In a true end-state scenario, companies may electrify mine fleets (using renewable electricity or green hydrogen fuel cells), cutting Scope 1 mining emissions to near-zero as well.

Ore Processing

Concentrating will still use considerable energy, but if Minnesota’s grid is carbon-free by 2040 (as targeted by state law (rmi.org)), the Scope 2 emissions for crushing and milling approach zero. Pellet induration is a challenge to fully decarbonize, but using hydrogen or biomass in the furnace can eliminate coal/gas usage. HYBRIT has tested using biogas and plasma heaters for pelletization to avoid fossil fuels. We assume any residual CO₂ from pelletizing is very small (on the order of <0.05 tCO₂/ton steel). The only inherent CO₂ source that may remain is limestone in the pellet mix – calcination of CaCO₃ to CaO releases ~30–40 kg CO₂ per ton of steel if used (mdpi.com). In a low-emission design even that could be minimized (using recycled slag or captured CO₂). Overall, Minnesota on-site emissions in mining+pelletizing would be a fraction of today’s, potentially under 5% of the BF-route’s emissions (mdpi.com).

Hydrogen Production

This is off-site but critical. Hydrogen DRI requires ~50–55 kg of H₂ per ton of DRI. Producing that via electrolysis demands about 2,500–3,500 kWh per ton of steel (midrex.com). If this electricity is renewable (wind/solar/nuclear), the associated CO₂ is near zero. If grid power with some fossil share is used, emissions would occur in the power sector (Scope 2 for the DRI plant). For instance, at 0.5 kg CO₂/kWh, H₂ production would cause ~1.25–1.75 tCO₂ – but the goal in a green scenario is to use clean power. (Projects like HYBRIT and H₂ Green Steel have dedicated renewable generation to ensure the hydrogen is truly low-carbon (rooseveltinstitute.org).)

Direct Reduction (H₂ DRI): Scope 1 at the DRI plant in Minnesota is ~0. The reduction reaction yields H₂O, not CO₂. Any fuel burned for heating is assumed to be hydrogen-fired or electric, so no fossil carbon is emitted. This is the fundamental advantage – by removing coal or natural gas from the reactor,

CO₂ emissions are eliminated. (In practice, some pilot hydrogen DRI units still use a small natural gas purge or for startup, but advanced designs aim for 100% H₂.)

EAF Steelmaking

If the EAF is located outside Minnesota, its emissions fall in Scope 3 for the Minnesota iron producer. An EAF using 100% renewable electricity would only emit on the order of 20–40 kg CO₂/ton steel from graphite oxidation and alloy additions. If the electricity has some carbon intensity, that adds accordingly (e.g. at 0.4 kg/kWh and ~600 kWh/ton, an EAF would emit ~0.24 tCO₂ – but we assume end-state decarbonized power). Steel mills may also inject a small amount of natural gas or carbon in the EAF for chemistry, but many designs are moving to eliminate that with oxygen or biomass. For this analysis, we consider EAF emissions negligible with green power.

Overall Emissions Reduction

The hydrogen DRI-EAF route is transformative in cutting CO₂. Several studies indicate roughly 0.1–0.2 tons CO₂ per ton of steel is achievable, versus ~2.0+ t/ton in the incumbent route (Roosevelt Institute, 2022). That is a ~90–95% reduction in carbon footprint. Essentially all carbon-bearing inputs are removed (only remaining carbon is in minor additives). HYBRIT in Sweden has demonstrated pilot sponge iron production with virtually zero fossil carbon, and estimates a 95% emissions reduction is feasible when scaled. (Roosevelt Institute, 2022). Table 1 summarizes and compares all the emissions in the ironmaking pathways discussed so far.

10C: Raw Material Availability

Water Use Estimates

A 2 million ton-per-year (2 MTPA) green iron plant requires approximately 3.4 to 5.6 million cubic meters (m³) of water annually, depending on system efficiency and recycling (Rocky Mountain Institute, 2023; HYBRIT, 2022). The majority of this water—about 2.1 to 3.2 million m³/year—is consumed in producing the ~106,000 tons of hydrogen needed annually, at an average of 20–30 liters of water.

Regional Water Availability

Conversations with regional water appropriation agencies confirm that the Iron Range has abundant groundwater and surface water resources available. Several legacy mine pits in the region lack natural outlets and could serve as additional water sources. Hence, the estimated water demand of 3.4–5.6 million m³/year is considered feasible and below the typical appropriations granted for existing taconite facilities (Dieter, C.A., 2020; Maupin, M.A., 2018)

Discharge and Recycling

Water discharge volumes depend heavily on the plant’s recycling design. Under conventional practices (with ~90% recycling efficiency), water losses due to evaporation, blowdown from cooling towers, and dust suppression would result in 340,000–560,000 m³/year of discharged water. However, modern green DRI projects—such as H2 Green Steel and HYBRIT—are incorporating Zero Liquid Discharge (ZLD) systems that recycle up to 99.9% of process and cooling water (H2 Green Steel, 2024; Société Générale, 2022; Energy Research Centre of the Netherlands, 2022). Under such advanced systems, net water discharge can be reduced to as little as 2,000 to 20,000 m³/year, limited mainly to evaporative and unavoidable losses. The ZLD system at H2 Green Steel’s Boden, Sweden facility, for example, includes ultra-pure water treatment, high-efficiency recovery systems, and closed-loop cooling—setting a benchmark for sustainable water practices in green steelmaking (H2 Green Steel, 2024).

Electricity

Electrolysis is highly energy-intensive. Depending on the type and efficiency of the electrolyzer, producing 1 kg of hydrogen consumes approximately 45–70 kilowatt-hours (kWh) (Midrex, 2023; IEA, 2020). Therefore, the production of 106,000 tons of hydrogen annually would require between 4.77 and 7.42 terawatt-hours (TWh) of electricity. At current electrolyzer efficiency, approximately 50.6–52.5 kWh electricity is needed (Rocky Mountain Institute, 2023). We envision that this energy should be

coming from low- or zero-carbon sources—such as wind, solar, hydro, or nuclear—to ensure that the hydrogen qualifies as “green” and that the DRI process remains climate-aligned. Additionally, auxiliary equipment such as hydrogen compressors, shaft furnace blowers, and electric drives also contribute to the plant’s overall electricity footprint, although these are secondary compared to electrolysis.

Minnesota Power is the primary electricity supplier to the taconite industry. Their 2025 Integrated Resource Plan (IRP) shows current annual energy sales of approximately 10 terawatt-hours across all sectors - residential, commercial, and industrial (Minnesota Power, 2025). To serve a 2MPTA green iron plant would mean increasing Minnesota Power’s supply of energy by 50-75%. Minnesota Power’s IRP contemplates several future significant load growth scenarios. In the most aggressive scenario, an increase in electrical output of 2 terrawatt-hours a year for approximately seven years is modelled. The IRP does not identify where this anticipated demand is coming from and it is likely several energy intensive industrial uses may be contemplated. From a raw material input perspective, the supply of electricity is likely a constraining element.

Natural Gas

Based on conversations with representatives from the regional natural gas industry, the natural gas supply is unlikely to be a constraint to intermediate-stage DRI development on the Iron Range. Based on a DRI facility built in Texas, we estimated a 2 MPTA DRI plant would consume 23 MMBTU of natural gas and used this as a basis for our discussion and analysis. The current natural gas pipeline system operates near capacity, and natural gas for a DRI plant would be an additional demand on the system. The existing system is extensive and robust based on the current industrial needs of the taconite plants. The current pipeline may be able to handle this increase with additional compression. If not, portions of the pipeline could be increased in size, or parallel pipelines could be installed. Once the precise demand is known, the system is analyzed, and a technical solution is identified. This technical solution then goes through a regulatory approval process before implementation. This process typically takes up to 24-36 months and would likely fall within other permitting timelines.

Iron Ore

Currently three taconite facilities have the ability to manufacture DR-grade pellets - U.S. Steel Keetac, Minorca Mine, and Northshore Mine. A fourth DR-grade taconite plant, Mesabi Metallics, is currently under construction. To support a 2 MTPA direct reduced iron plant would require approximately 3 MTPA of DR-grade pellets. Minnesota has abundant iron ore resources and DR- pellet making capacity to support this demand. While the resource itself is not a constraint, who controls the ore and who is willing to invest in a DRI plant may be. The DNR reports 107 active iron ore / taconite leases covering more than 9,000 acres (Minnesota DNR, 2024).. These leases are almost exclusively held by U.S. Steel and Cleveland Cliffs or their subsidiaries. Some smaller holdings by Magnetation, Mining Resources, and Ontario Iron Company comprise less than 400 acres. Other sources show holdings by MagIron, Scranton Holding Company, and Mesabi Metallics (Scranton, 2023). Private holdings also exist

10D: In-depth (IDI) Interview List

This is information on the interviewees with whom IDIs were conducted for the qualitative insights on social and political considerations in this paper.

<i>Interview Number</i>	<i>Number of Representatives Present</i>	<i>Sector/ Organization Type</i>	<i>Date of Interview</i>
1	1	Government (State)	February 24, 2025
2	1	Local Economic Development	March 3, 2025
3	2	Government (State)	March 7, 2025
4	2	Local Nonprofit	March 17, 2025
5	1	Local Electric Utility	March 17, 2025
6	1	Local Economic Development	March 21, 2025
7	1	University Research Center	March 21, 2025
8	1	Government (Local)	March 27, 2025
9	1	International DRI Technology Provider	March 28, 2025
10	1	Local Environmental Advocacy	March 31, 2025
11	1	International Nonprofit (Research)	April 1, 2025
12	2	Integrated Steel Company	April 11, 2025
13	2	Merchant Mining Company	April 17, 2025