Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future

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GREEN HYDROGEN CATAPULT

RMI

Contents

Executive Summary

Action is needed now if nations are to align the steel sector, which currently produces 11% of global CO_2 equivalent emissions, with a 1.5°C outcome.[1] To reduce emissions and co-pollutants yet meet new demand, producers must shift their approach to making iron and steel.

According to leading steel sector roadmaps, demand in 2050 could increase between 12% and 36% from current production, and meeting this new demand while reducing emissions hinges on ramping up green hydrogen–based ironmaking during this decade.

One of the key hurdles producers face in transitioning to cleaner iron and steel production using hydrogen-based direct reduction of iron is the availability and cost of green hydrogen, because up to 50% of the cost of green steel (near-zero-emissions steel) comes from the hydrogen production.

Historically, iron and steel have been produced in large integrated facilities colocated with access to cheap coal and iron ore. Greener production methods, however, will develop in new geographies rich in renewable resources. It could prove cost-effective to split up the typically integrated ironmaking and steelmaking processes. This would mean relocating a share of green iron production to regions with optimal renewable energy and access to iron ore, and relocating steelmaking to regions that have strong manufacturing capabilities and are close to demand. We call these potential export–import routes *green iron corridors*. Beyond achieving cost savings along the supply chain, green iron corridors can offer significant benefits:

- Maintenance of domestic steel production in import countries, responsible for up to 75% of the sector's direct jobs,
- Investment in local clean energy infrastructure and opportunity to scale a new, higher-value product for export countries, and
- Efficiency savings along the supply chain achieved by transporting a more finished product of green iron, rather than hydrogen and iron ore separately, securing supplies of both commodities and helping importers reach their energy and climate targets.

This report, by RMI and the Green Hydrogen Catapult, evaluates import and export contenders against an assessment framework and outlines opportunities, challenges, and recommendations to help leading green iron corridors become a reality.

Top six takeaways

1. **Iron ore quality will not constrain shifting to the direct reduction of iron (DRI) in the next decade.** A combination of utilizing high-grade ores, upstream beneficiation, and downstream smelting technologies will pave the way for the transition. Easier-to-upgrade magnetite ores will be prioritized for the first wave of pellet production. Hematite ores that are more difficult to upgrade will rely on collaboration along the supply chain to optimize the amount of beneficiation versus downstream process adjustments (via the DRI, smelter, or electric arc furnace [EAF]) in order to avoid unnecessary iron losses. In the long term, as costs for renewables and hydrogen decline, additional smelting steps for low-grade ores will become more cost-effective.

2. **Green iron trade can allow traditional steelmaking countries to maintain large parts of their skilled workforces into the future,** given that up to 75% of the sector's direct jobs sit downstream (associated with steelmaking and manufacturing). However, it will be critical to plan for workforce transition support on a subregional level, as changing trade patterns will influence how countries decide to move in the value chain.

3. **Restructuring half of primary steelmaking to use green iron could save >$25 billion annually across the 10 highest priority importers at today's prices.** This translates to a savings of $80–$125 per ton (t) of steel due to the higher capacity factors in the exporter regions, which reduce the needed renewables build-out by 20–50 gigawatts (GW). The additional re-heating required for green iron after transport is small, representing only ~3% of the total steelmaking energy, and is partially offset by lower transport energy due to the reduced volume compared with transporting iron ore.

4. **First mover producers and buyers, coupled with strong policy support, will drive initial green corridors** by incentivizing supply in export candidate countries through hydrogen and renewable energy subsidies, working in tandem with import candidates that have strong demand-driving policies such as mandates and carbon pricing. International collaboration alongside specific green iron targets will be necessary to fully realize these policy benefits.

5. **Emerging economies possess strong opportunity to move into this market given their resource endowments,** which ultimately will position them as cost-competitive producers. Measures to mitigate risks and reduce the cost of capital are needed to support project deployment at scale. Multilateral development banks can play a role in reducing financial barriers and developing the required infrastructure to support these promising exporting contenders. A strong emphasis on accountability must be placed on emerging trade relationships and agreements to avoid extractive relationships and ensure that sustainable industrial activities thrive in these regions.

6. **Fast-tracking corridor opportunities between existing and emerging iron exporter regions to the EU and Asia** could abate an annual ~30 million tons (Mt) CO_2 by 2030 (>50% of Germany's steel sector emissions today). Of the 50 importer/exporter options evaluated, more than 10 key corridors emerged as high contenders. Paving the way for global green iron trade will require bilateral political action to recognize the net benefits.

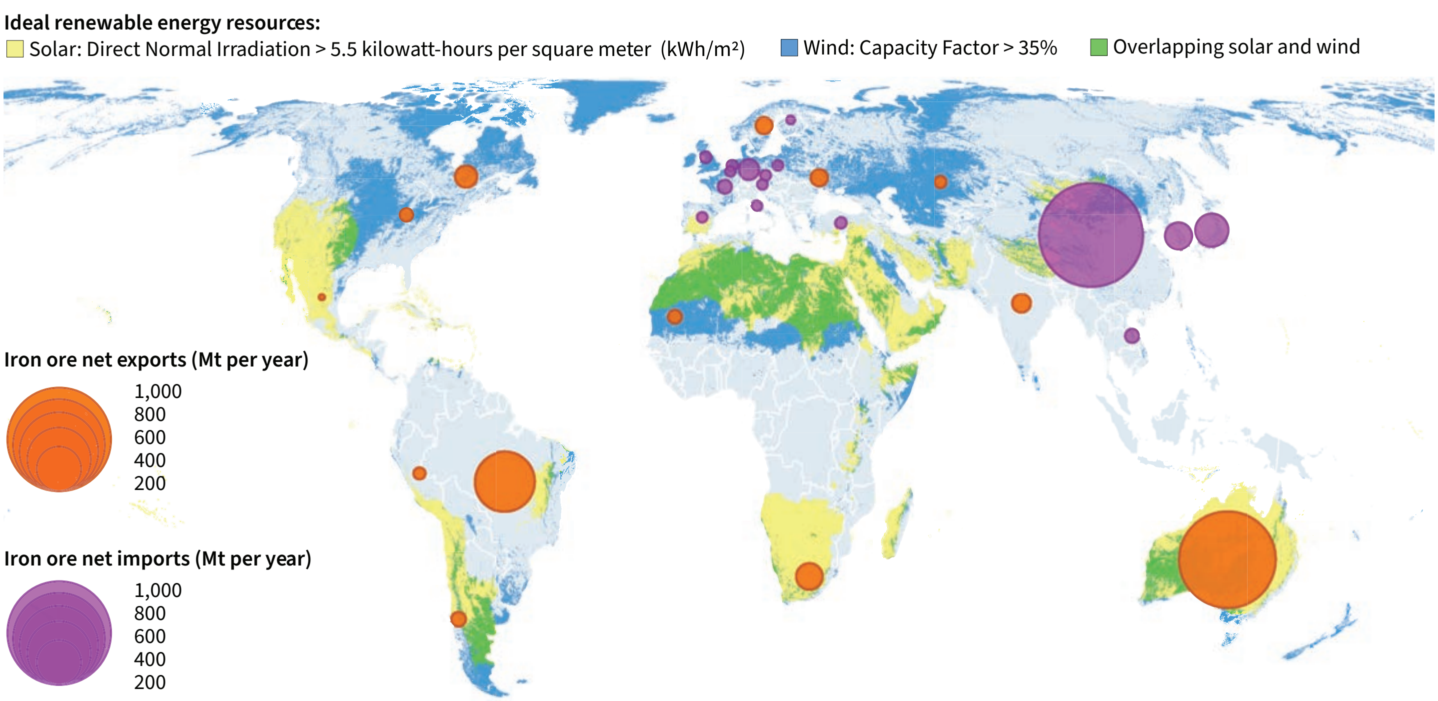
I. Introducing Green Iron Trade Corridors to Decarbonize the Steel Industry

Historically, steel has been produced in large integrated facilities that include both the ironmaking process, which uses coal to reduce mined ore from an oxide to iron in a blast furnace (BF), and the steelmaking process, which uses a basic oxygen furnace (BOF) to refine and alloy the iron into steel. Because of this, access to cheap coal resources drove the geographic locations of ironmaking and steelmaking in the past century, and advantages accrued over time to those that moved fastest to integrate into highly optimized facilities with economies of scale. With the transition to greener production methods, however, ironmaking will be drawn to new geographies.

Under the new energy economics driven by low-cost renewable energy, DRI, an alternative to the BF, will play an increasing role. Traditionally, the DRI pathway has used natural gas to reduce iron ore with approximately half the CO_2 emissions of the BF–BOF process. However, green hydrogen can play the same role as natural gas in reducing the iron oxide with minimal greenhouse gas emissions, offering a commercially viable pathway to near-zero-emissions iron and steel production.[2] With H_2–DRI production, up to 50% of the final steel cost comes from the green hydrogen, so the cost-competitiveness of steel will be driven by renewable energy availability and scalability.

Because cost-competitive green hydrogen will play a significant role in the global energy transition beyond just steel, countries are establishing hydrogen import and export strategies, depending on their resources and needs. Regions such as Northern Africa and Australia are emerging as promising green hydrogen exporters.[3] Others, in contrast, will rely on imports to supplement their domestic production capabilities, such as the EU Hydrogen Strategy target of importing importing 10 million tons per year (Mtpa) of green hydrogen by 2030.

Exhibit 1: Green iron corridors split up the ironmaking and steelmaking processes, with ironmaking in locations with abundant ore and renewable energy potential and steelmaking in other regions with strong manufacturing capabilities and existing reliance on iron ore imports



RMI Graphic. Source: Global Solar Atlas, https://globalsolaratlas.info/map; Global Wind Atlas, wind: https://globalwindatlas.info/en; World Steel, https://worldsteel.org/data/world-steel-in-figures-2023/; RMI analysis

When these export and import regions overlap with existing iron ore trade flows, transporting green iron results in both cost and energy savings compared with transporting hydrogen and ore separately. It could prove a win-win to split up the steel production processes: ironmaking would take place in one location with abundant ore and accessible renewable energy, and steelmaking would occur in regions that have strong manufacturing capabilities — and demand — already in place (see Exhibit 1, previous page). We call these potential export–import routes *green iron corridors*.

II. Iron Ore Quality and Management

Although the cost and availability of energy — now renewable energy — needed for ironmaking will remain the single largest driver in decarbonized production, iron ore quality and management will also play a significant role.

Historically, DRI plants have preferred iron ore pellets with an iron content of at least 67% and lower concentrations of key impurities such as silica, phosphorus, and alumina.[4] This both improves the economics of the DRI facility and allows the resulting reduced iron product to be used directly in an EAF, which has less ability to reject impurities to slag compared with a BF-BOF.

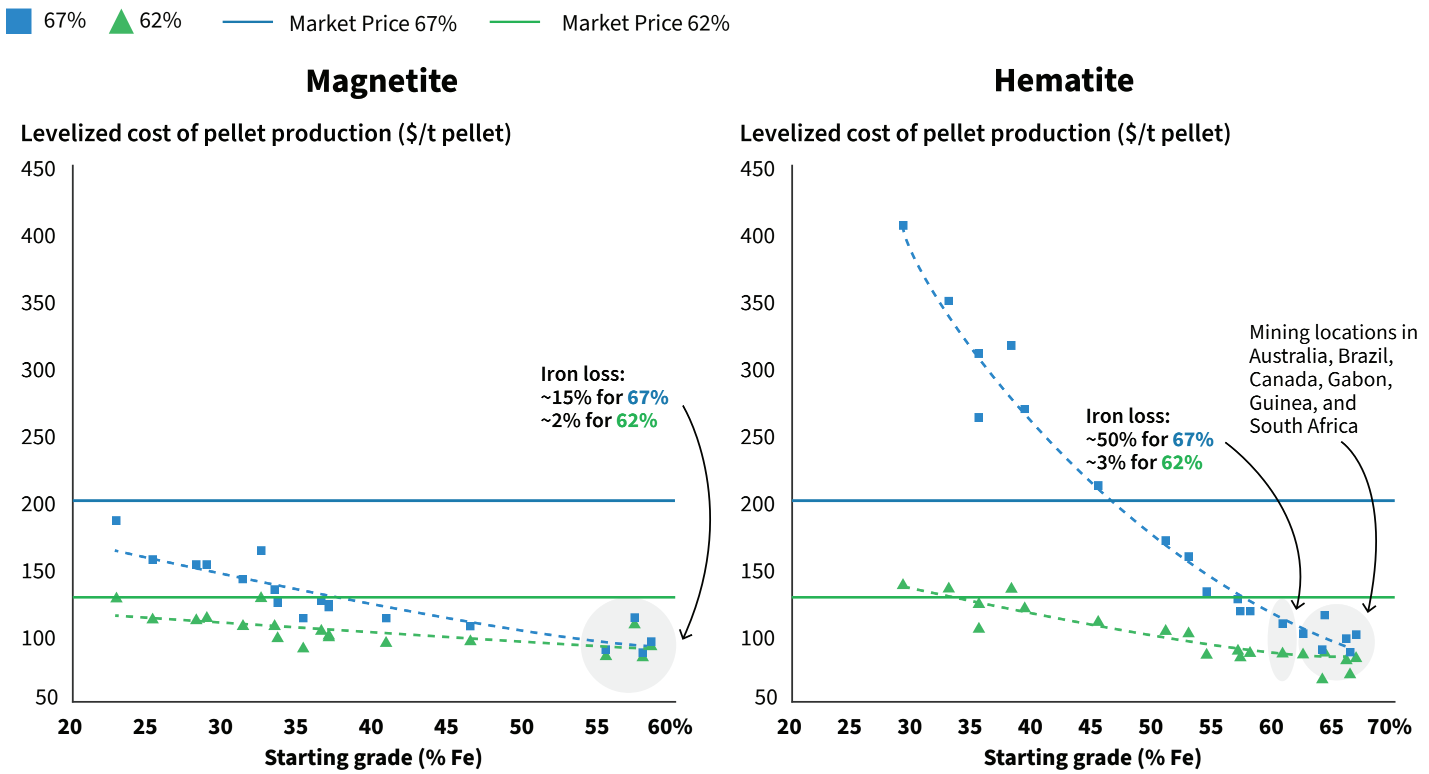
To meet the DRI grade requirement, ores must be upgraded, or beneficiated, to a concentrate that is then pelletized. Iron ore beneficiation is routinely done globally through processes such as magnetic and gravity separation. Specific aspects of each ore, such as iron-bearing mineral type (e.g., magnetite and hematite) and impurity composition, affect the efficiency (iron and mass loss) of the beneficiation process.

By creating average grade-recovery curves from several mining examples, RMI modeled the cost of producing various grades of pellets from existing mining resources around the world (see Exhibit 2, next page). According to this analysis, cost-competitive pellet production will differ based on specific ore characteristics: magnetite ores offer the most economical route to direct-reduction-grade (DR-grade) 67% Fe (iron) pellets, whereas low- to mid-grade hematite ores see improved margins with less beneficiation (e.g., producing 62% pellets instead).

Even though higher-grade hematite ores (>50% Fe) can be used to produce cost-competitive DR-grade pellets, comparing the levelized cost of production with current market prices, the iron and mass loss from the beneficiation process will drastically decrease the final product volume compared with direct shipping ore (DSO) and lower-grade pellets. This limits the attractiveness for existing DSO operations to switch to producing higher-grade pellets. For example (as shown in Exhibit 2, next page), upgrading this type of ore to 67% Fe pellets would result in losing around half of the iron (and mass), significantly reducing output volume (and total revenue) compared with DSO, and could lead to oversized downstream infrastructure (e.g., port, rail). These considerations are not captured by the levelized cost and market price comparison but will play into companies' portfolio investment decisions.

Conversely, a middle-ground approach, in which the ore is upgraded to only 62% Fe pellets (and the receiving DRI is optimized for lower grades) results in only ~3% iron loss at the mine, limiting the impacts to the operation while still shifting to a higher-value product more suitable for green steelmaking. At a systems level, for any ores that result in significantly higher iron losses, less mined iron will be lost by choosing to beneficiate to 62% Fe pellets versus 67% Fe pellets, and investment is instead placed in necessary downstream adjustments.

Exhibit 2: Cost-competitive pellet production routes differ based on ore specifics: Magnetite ores offer the largest profit margins for DR-grade 67% Fe pellets while low- to mid-grade hematite ores see improved profit margins with less beneficiation



RMI Graphic. Source: RMI analysis

For ores that are difficult to upgrade to DR-grade economically given the extensive iron losses that would occur, the alternative approach is to produce DRI from lower-grade pellets (e.g., BF-grade 62%–65% Fe). The additional impurities in these pellets pose some challenges along the supply chain, notably in (1) the DRI furnace, (2) shipping (discussed further below), and (3) steelmaking.

For the DRI furnace, there are some concerns about higher impurities resulting in a lower metallization. However, work is ongoing to find the optimal conditions to maximize metallization in the presence of impurities, with some lab-scale studies able to achieve reasonable yields with low-grade ores.

For steelmaking, higher impurities in the DRI will result in more slag production, which current EAFs are not equipped to handle. Work is under way through pilot testing for the electric smelting furnace (ESF) to overcome this challenge.

The ESF functions to remove the additional impurities that the DRI contains due to the lower-grade pellets, while also further reducing and melting the iron; it is based on technology proven in other industries (e.g., ferroalloy production).[5] The ESF produces a hot metal that can be either fed directly into a BOF or EAF or packaged into granules similar to pig iron and shipped to the final steelmaking locations.

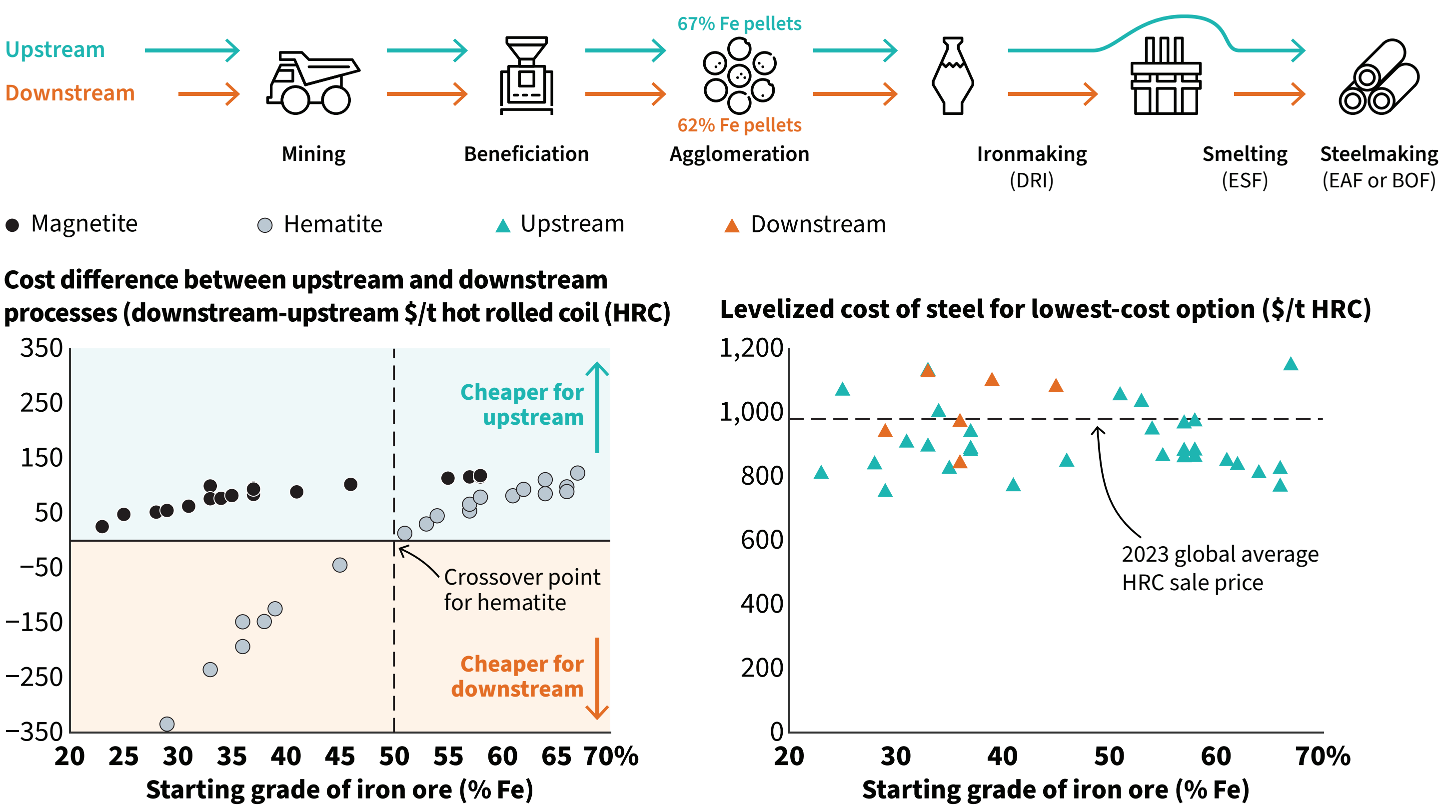
For shipping, the iron product can be shipped as several different products: DRI, hot briquetted iron (HBI), or granulated pig iron (the latter as the output from the ESF). Direct shipping of DRI poses some material handling risks, specifically autoignition (as the reoxidation reaction in the air releases heat) or generation of an explosive atmosphere (through a reaction with water that generates hydrogen). These risks led to the International Maritime Organization (IMO) setting shipping requirements for safe transport of DRI (requiring <5% oxygen environments during shipping) as well as the development of HBI.[6]

The HBI process involves compressing the porous DRI pellets into larger, higher-density briquettes. This reduces the surface area and significantly lowers the reactivity of the product to enable safer shipping. To quantify this, the IMO set a density requirement (as a proxy for surface area) of 5,000 kilograms per cubic meter (kg/m^3) to qualify as HBI, a specification based on the assumption that high-grade pellets would be fed to the DRI.

It is likely that HBI made from lower-grade pellets will not meet the same density requirement (due to the presence of lower-density impurities, as opposed to higher porosity). To address this, work is under way investigating whether the less dense product is still safe for maritime transport.[7] As an alternative, an ESF colocated with the DRI would produce a pig iron product that could then be shipped safely to stand-alone EAFs. If HBI from lower-grade pellets can be safely shipped, colocating the ESF with BOFs or EAFs would provide the necessary melting step to feed a hot metal into the BOFs or EAFs, replacing the emissions-intensive BFs and utilizing lower-grade HBI.

HBI or pig iron production from lower-grade pellets in conjunction with an ESF has yet to be proven at commercial scale, but several companies are investing in research, pilot projects, and full-scale projects.[8] Using the average grade-recovery curves, RMI modeled the cost of producing steel via two scenarios: (1) upstream using 67% Fe pellets for DRI-EAF production, and (2) downstream using 62% Fe pellets for DRI-ESF-BOF production (see Exhibit 3).

Exhibit 3: Cost-competitive options exist for meeting direct reduction supply requirements through a combination of iron ore beneficiation and downstream process additions. Magnetite ores should be prioritized for upgrading to DR-grade pellets, whereas many hematite ores will benefit from less beneficiation and the addition of a smelter after the DRI



RMI Graphic. Source: RMI analysis

This analysis indicates that magnetite ores see cost savings with the upstream scenario, whereas hematite ores see a crossover point for starting grades around 50% Fe between the two scenarios. Generally, the downstream option using the ESF with low-grade pellets is more expensive by levelized cost, based on the average grade-recovery curves, but this option also offers flexibility for ironmakers and steelmakers to adjust processes based on iron ore market dynamics and the available supply of pellets.

Ultimately, choosing between upstream and downstream approaches will require careful optimization, considering factors such as iron losses specific to each mine, company-wide asset management, and the trade-off between the cost of renewable energy and capital at the mining and steelmaking locations. Among major iron ore miners, investments are being made for both options. For example, Vale, Rio Tinto, and Fortescue are increasing DR-grade production via upstream beneficiation, and Rio Tinto, BHP, and Fortescue are investing in downstream ESF pilot facilities.[9]

In 2022, DR-grade iron ore consumption made up 5.3% of the total iron ore produced, and the widening gap between announced DR-grade supply and forecasted demand under net-zero scenarios demonstrates a market opportunity.[i] Geographically, the majority of DR-grade iron ore today is produced in Brazil, Canada, Sweden, and the Middle East from both hematite and magnetite ores, and new production capacity is coming online in various regions including Australia, Canada, and the United States.[10] RMI analysis indicates that the forecasted supply of DR-grade pellets in 2030 (40 Mt) could fall short of projected demand under International Energy Agency's net-zero scenario by approximately 117 Mt. However, the 18 magnetite mines included in this report could, on their own, more than close that supply deficit through 2030 from proven mineral resources, from a technical basis considering the mass loss from beneficiation. And these numbers leave out other magnetite and the hematite ore reserves around the world, which can be used to also produce DR-grade pellets or lower-grade pellets to feed into a DRI plant in conjunction with an ESF.

Taken together, there is enough global iron ore to support the clean energy transition in the steel sector, but action is needed now to shift toward beneficiation projects to produce pellets that can be used in a DRI plant either with or without an ESF, as these types of projects can take anywhere from two to six years for construction and another two to six years to reach full scale.[11]

III. Systems-Level Assessment: Green Iron Corridor Evaluation Framework

An understanding of competitive iron reduction locations requires a combined view of several key factors: renewable resources, iron ore quality and management, shipping distances, subsidies, and enabling environments.

To identify promising export and import regions, RMI developed a two-part assessment framework:

- A techno-economic model for identifying the lowest-cost option (considering the entire value chain) of producing HBI at existing mining sites, taking into account location-specific inputs such as cost of energy, labor, and capital (and assuming the global average of location-specific inputs on the steelmaking side). Modeling details, inputs, and assumptions are included in the Appendix for reference.
- A qualitative evaluation of key enabling-environment factors from a system level, including geopolitical, social equity, and policy. These factors are detailed in the Appendix for reference.

i This percentage is based on iron ore production reported by the US Geological Survey and DRI production reported by *World Steel in Figures*, assuming consumption rate of 1.43 t pellets/t DRI.

Export Locations

Our analysis shows that with recent market prices for pig iron and HBI, green iron production is cost competitive in regions with a combination of optimal renewable resources (leading to lower cost of hydrogen), high-quality iron ore, and enabling policies (see Exhibit 4). These costs are associated with a 67% direct reduction pellet production at the mining location. The enabling policies in the United States and Canada (clean hydrogen and renewable energy tax credits) have a significant impact on the levelized cost of producing HBI, making these countries leading export contenders.

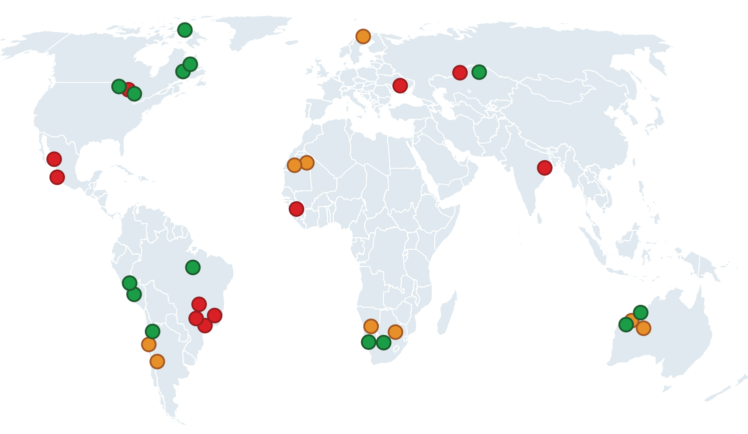
Although many other countries offer low mining costs thanks to the prevalence of high-grade iron ore there, locations such as Australia, Brazil, Canada, and South Africa offer cost-competitive HBI production due to their strong renewable resources and favorable financing environments (purely considering cost factors). Conversely, although Guinea has ~67% Fe ore, leading to highly competitive mining and pelletizing costs, its higher cost of capital (~18% weighted average cost of capital) and lower wind and solar capacity factors contribute to significantly higher capital and hydrogen costs on a levelized cost of HBI basis. However, creative financing can help mitigate risks and high costs of capital for promising projects.

Although this analysis investigates green iron corridors between single export and import locations, market interest is growing in corridors connecting three locations. Depending on the trade-offs between renewable resources, shipping logistics, and cost and efficiency of transporting a more finished product, the hydrogen production and iron reduction could occur either at the mining location or at a secondary location where the renewable energy is particularly competitive. These secondary green iron production hubs would connect iron ore export locations with iron ore import and steelmaking demand locations by producing and shipping an intermediate green iron product from where green hydrogen production is exceptionally cost competitive. These regions will likely be either (1) optimal renewable energy regions near iron ore production centers, such as Argentina or Finland, or (2) optimal renewable energy regions located along existing iron ore trade routes, such as Oman, Saudi Arabia, and the UAE.

Exhibit 4: Green iron production is cost-competitive with recent market prices in regions with optimal renewable resources, high-quality iron ore, and enabling policies

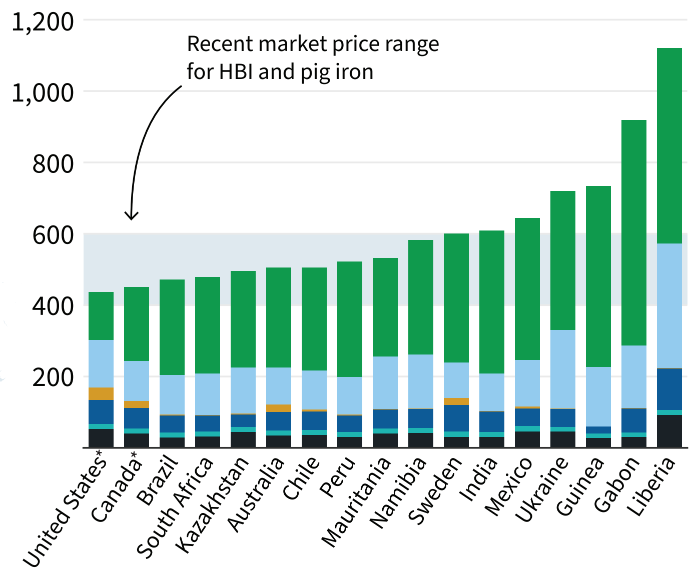
400–525 526–600 600+

Levelized cost of green iron at existing iron ore mine locations ($/t HBI)



Hydrogen Capital Labor Energy Transport Operations and maintenance

Lowest-cost option for each country: levelized cost of green iron at existing iron ore mine locations ($/t HBI)



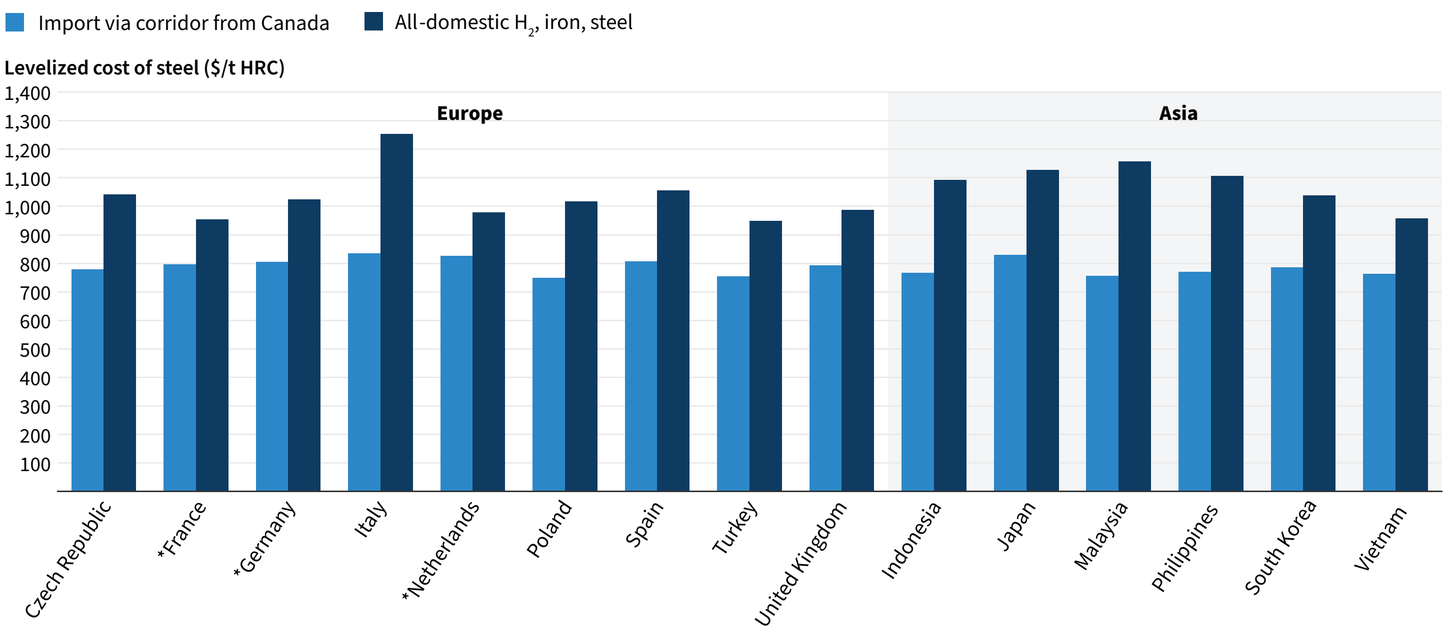
**US and Canada hydrogen costs include relevant subsidies (detailed in the Appendix).*

RMI Graphic. Source: RMI analysis

Import Locations

The techno-economic model was also used to evaluate the preferred iron reduction pathway for selected importer countries. The levelized cost of producing steel in importer countries was modeled via two options: (1) the corridor option — importing green iron and producing steel domestically, and (2) the integrated option — importing DR-grade iron ore at a starting price of $150/t and producing hydrogen, iron, and steel domestically. As an example, these comparisons are shown in Exhibit 5 with Canada as a green iron exporter; producers in importer countries would see cost savings of 15% to 35% by importing green iron rather than integrated domestic production, over half of the cost differences attributable to the improved hydrogen cost. These cost savings can be achieved while still keeping up to 75% (and in some cases as high as 95%) of the iron and steel direct jobs by maintaining existing steelmaking production lines and expertise in the import countries, a priority for producers.[12]

Exhibit 5: For key steel-producing countries, importing green iron via a cost-competitive export region like Canada results in cost savings compared with all-domestic production



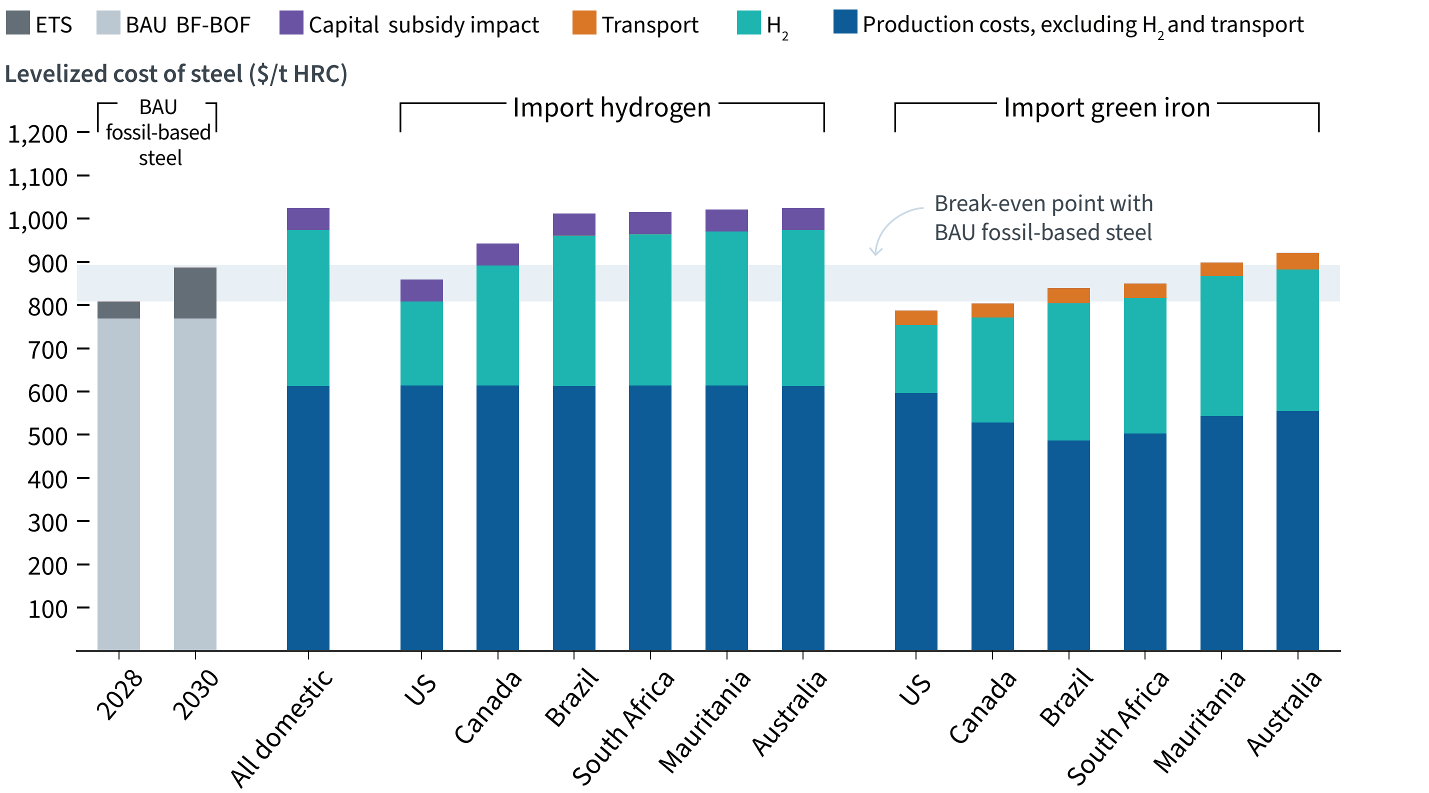
**The costs of domestic hydrogen production in these countries may fluctuate higher than those shown, given the significant constraints on land availability in Central European countries adding to the costs of deploying large-scale renewables and hydrogen infrastructure.*

RMI Graphic. Source: RMI analysis

Importing green iron provides a cost-competitive advantage over other options for producers in import countries. Looking closer at Germany, a key steel producer in Europe, our analysis indicates that importing green iron will cost less than importing hydrogen for domestic decarbonized iron production, seeing average cost savings of 8%, even with an $800 million capital subsidy for the domestic iron production (see Exhibit 6, next page).

Considering that European governments would have to spend an estimated $40 billion to continue subsidizing the decarbonization of integrated facilities, the business case for green iron corridors grows stronger without those capital subsidies, seeing cost savings averaging 13% (ranging from 8% to 17%). As free allocations for ironmaking and steelmaking allowances phase out between 2026 and 2034 in Europe, our analysis indicates that importing green iron could compete with domestic fossil-based steel production as early as 2028, with savings reaching over 10% by 2030. As carbon prices under the EU's Emissions Trading System (ETS) and Carbon Border Adjustment Mechanism (CBAM) are expected to continue increasing past 2030, the green iron import cost savings will only continue to grow, making the business case for European producers to decarbonize ironmaking and steelmaking sooner rather than later.

Exhibit 6: As an example, producers in Germany can see significant savings by importing green iron and combing it with domestic steelmaking rather than importing hydrogen for domestic iron and steel or producing domestic hydrogen, iron, and steel



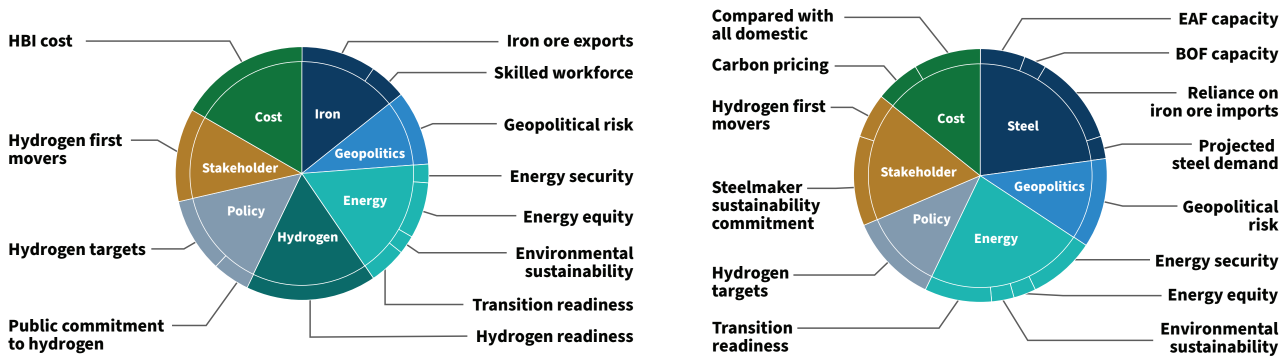
RMI Graphic. Source: RMI analysis

It is important to note the market realities not necessarily captured in this analysis. Early projects may face additional costs due to current challenging market conditions, including the recent increases in inflation and cost of capital globally. Installed renewable and electrolyzer systems, as well as DRI plants, may see elevated capital costs in some markets, depending on specific project characteristics. Site-specific infrastructure characteristics and requirements can also dictate additional project costs and complexities that will need to be considered on a case-by-case basis to determine the viability of a corridor. Furthermore, this analysis does not account for the seasonal variability of hydropower for locations with a high percentage of hydropower in the electricity mix (e.g., Brazil). Full site optimization and design of a renewable energy system, electrolyzers, and the iron production plant may offer variations in costs and benefits not captured in this analysis.

Systems-Level Assessment

Cost is important, but it is not the only variable when evaluating the potential of green iron corridors. Combining cost with an assessment of enabling-environment factors allows for a systems-level assessment of top corridor options. The factors included in this analysis are shown in Exhibit 7, with key distinctions (e.g., skilled workforce within iron) broken down and with the weighting of each factor indicating its significance to a successful green iron corridor (detailed in the Appendix).

Exhibit 7: Qualitative assessment of the enabling environment for green iron corridors within exporter and importer countries enables a systems-level assessment of top corridor options



	Exporter Assessments	Importer Assessments
Iron & Steel	**Iron ore exports:** net exports of iron ore **Skilled workforce:** workforce available for new iron production	**Steelmaking capacity:** steelmaking capacity: EAF and BOF capacity and utilization **Reliance on iron ore imports:** ratio of net imports to total steel production **Projected steel demand:** 2030 demand based on recent growth rates
Geopolitics	**Geopolitical risk:** strikes, riots and civil commotion, terrorism, war, country economic risk, currency inconvertibility and transfer risk, sovereign credit risk, expropriation, contractual agreement repudiation, legal and regulatory risk	
Energy	**Energy security:** reliance on energy imports, diversity of electricity generation, and ability to meet demand considering infrastructure, storage, and refining capabilities **Energy equity:** percentage of population with access to electricity and prices of fuel/electricity **Environmental sustainability:** energy consumption, ratio of generation to GDP, CO_2 emissions per capita **Transition readiness:** regulations and political commitment, education and human capital, innovation, infrastructure, and finance and investment	
Hydrogen	**Hydrogen readiness:** business environment, infrastructure experience, strategic intent, renewable energy potential	N/A
Policy	**Public commitment to hydrogen:** national public investment committed to hydrogen production **Hydrogen targets:** national green hydrogen strategy maturity	**Hydrogen targets:** national green hydrogen strategy maturity
Stakeholder	**Hydrogen first movers:** Green Hydrogen Catapult projects and current operations in country	**Hydrogen first movers:** Green Hydrogen Catapult projects and current operations in country **Steelmaker sustainability commitment:** level of climate commitment from major steelmakers
Cost	**HBI cost:** levelized cost of HBI from RMI techno-economic model	**Carbon pricing:** commitment to carbon pricing, based on current policies **Compared to all domestic:** difference in cost of steel between all domestic hydrogen, iron, and steel vs. imported green iron and domestic steel

RMI Graphic. Sources: USGS, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-ore.pdf; Jasansky et al., 10.1038/s41597-023-01965-y; Global Energy Monitor, https://globalenergymonitor.org/projects/global-steel-plant-tracker/; IEA, https://www.iea.org/reports/iron-and-steel-technology-roadmap; BNEF, Rystad, World Steel, https://worldsteel.org/data/world-steel-in-figures-2023/GEM; RMI analysis

Using this framework, front-runners and emerging contenders were identified, and are shown in Exhibit 8. The full ranked list of exporters and importers by category is shown in the Appendix. Within the exporters, the front-runners — Australia, Brazil, Canada, Chile, Sweden, and the United States — have a combination of strong policy support, ambitious hydrogen first movers, and transition readiness in addition to existing infrastructure and trade routes for iron ore exports. Targeted policy support to reduce the cost of hydrogen production in Australia and Chile could enable accelerated business cases in these locations.

The next group of emerging contenders — Mauritania, Mexico, Namibia, Peru, and South Africa — see promising renewable energy capacity and hydrogen first movers making on-the-ground investments, but as they are countries with emerging economies, they could benefit from transitional financing, workforce training programs, and investment in energy and infrastructure. Some countries such as India may prefer to leverage green iron for domestic production given increasing steel demand and their economic development goals.

Within the importers, the front-runners — Germany, Netherlands, Poland, South Korea, Spain, and the United Kingdom — have strong national hydrogen targets and requirements as well as an existing reliance on iron ore imports, and low geopolitical risk in addition to carbon pricing mechanisms for the EU nations. Introduction of demand-driven policy mechanisms that address any labor issues and incentivize green imports could improve the enabling environment for domestic steelmakers. China has significant steel demand and national decarbonization ambition, which may

Exhibit 8: Using the systems-level assessment framework, front-runners and emerging contenders for both export and import can be easily identified, along with their strengths and areas of growth

		Front-runners	Emerging contenders
Exporters	Countries	▪ **Australia** ▪ **Brazil** ▪ **Canada** ▪ **Chile** ▪ **US** ▪ **Sweden**	▪ **Mauritania** ▪ **Mexico** ▪ **Namibia** ▪ **Peru** ▪ **South Africa**
	Strengths	▪ Combination of strong existing policies, hydrogen first movers, and transition readiness ▪ Existing infrastructure and trade routes for iron ore exports	▪ Promising renewable energy capacity and hydrogen prices ▪ Hydrogen first movers making on-the-ground investments
	Growth areas	▪ Increased policy support in Australia,* Brazil, and Chile ▪ Workforce training programs in Brazil and Chile	▪ Creative financing, workforce training programs, and investment in energy and infrastructure
Importers	Countries	▪ **China**** ▪ **Germany** ▪ **Netherlands** ▪ **Poland** ▪ **South Korea** ▪ **Spain** ▪ **UK**	▪ **Czech Republic** ▪ **France** ▪ **Italy** ▪ **Japan** ▪ **Malaysia** ▪ **Turkey**
	Strengths	▪ Strong hydrogen targets, reliance on iron ore imports, and low geopolitical risk ▪ Carbon pricing mechanism in EU ▪ Current steelmaking expertise and supply chains	▪ Strong existing steelmaking capacity and reliance on iron ore imports ▪ Strong EAF capacity in Turkey
	Growth areas	▪ Demand-driven policy mechanisms to incentivize green iron imports	▪ Carbon pricing in Southeast Asia to create more incentive to decarbonize ▪ Increasing steelmaker climate commitments and product differentiation

*Note: Countries are listed alphabetically. *Australia has announced a production tax incentive that would support hydrogen/HBI competitiveness if passed into law. **China has significant steel demand and decarbonization ambition that may present an opportunity to import a more finished product vs. DSO.*

RMI Graphic. Source: RMI analysis

present opportunities to import a more finished product (more discussion of this in Case Study 3 below). The emerging contenders — Czech Republic, France, Italy, Japan, Malaysia, and Turkey — have robust steelmaking capacity, supply chains, and expertise, with a particular emphasis on EAF capacity in Turkey. Stronger carbon pricing regimes and domestic steelmakers' climate commitments could improve their financial environments and the business case for importing green iron via a corridor.

Several factors will play a determining role in shaping successful green iron corridors moving forward: understanding how policy can drive supply and demand, overcoming any challenges with establishing projects in emerging economies, and grasping the nuances of iron ore beneficiation. To better understand these factors, three case studies were developed between possible corridor locations.

- **North America and EU:** How policy can drive supply and demand
- **Mauritania:** Challenges and opportunities for emerging economies
- **Australia:** Nuances of iron ore beneficiation

IV. Case Studies

1. North America and EU: How Policy Can Drive Supply and Demand

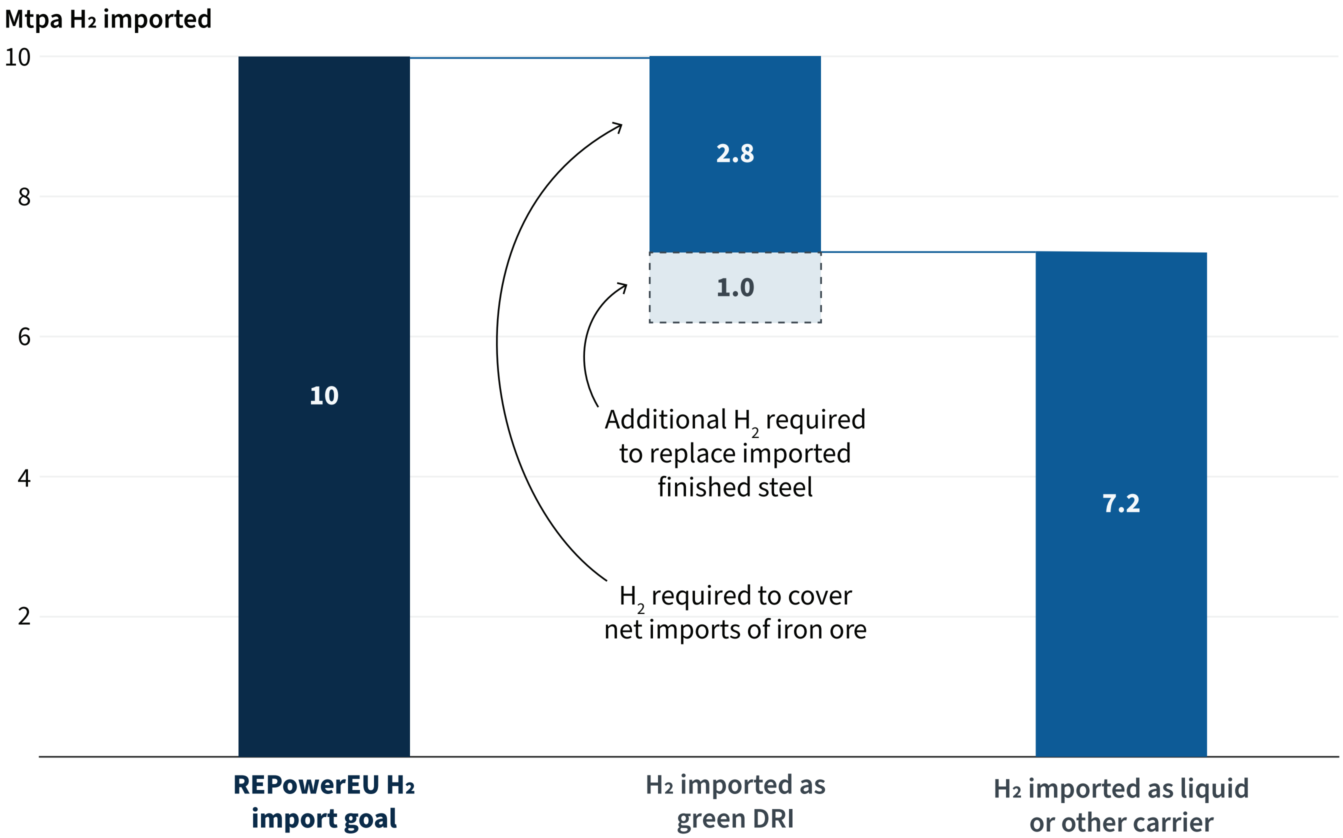
To understand how policies affect a potential North America–Europe green iron corridor, it is necessary to consider a broad landscape of both critical policies along the steel value chain and policies supporting renewable energy and hydrogen development. A robust policy framework for exporter countries involves incentives to support the production of hydrogen and the deployment of renewable energy. In contrast, importer countries have strong demand drivers for green iron and steel, including policies regulating the price of carbon pollution.

European Outlook

The European Commission has recognized that to meet climate and energy security targets, it will need to import hydrogen, as demonstrated by its ambitious REPowerEU import target of 10 Mtpa by 2030. This target is generally considered an overestimate unlikely to materialize by 2030; however, it remains a significant public recognition from the European Commission that Europe *cannot* meet its hydrogen demand without imports. Green iron imports have an opportunity to complement these targets by offsetting the amount of hydrogen needed via import. Exhibit 9 (next page) indicates that if the EU were to replace its net imports of iron ore with green iron imports (from a H_2-DRI process and in the form of DRI, HBI, or granulated pig iron, which is the product from the ESF after the DRI), this would be the equivalent of importing 2.8 Mtpa of hydrogen, nearly a third of the bloc's hydrogen import goal.

Within the EU, 57 primary BFs (at 27 sites) representing ~100 Mtpa production capacity are responsible for most of the industry's 190 Mt CO_2 equivalent emissions annually.[13] To date, EU member states have offered capital subsidies (of ~€500 million–€850 million) for four of these BFs to switch to DRI using natural gas.[14] Extending this strategy to the entire fleet would require €20 billion–€50 billion in capital subsidies and would result in a primary steelmaking fleet consuming ~7% of the EU's natural gas (or approximately three to five liquefied natural gas import terminals capacity) at a time of critically constrained supply. Leapfrogging to hydrogen DRI could alleviate this challenge, and Europe has several supply-side incentives for hydrogen, but the current mechanisms do not have the same scale of funding as does North America (e.g., the European Hydrogen Bank in its first round yielded an average subsidy of €0.46/kg of hydrogen).

Exhibit 9: Green DRI potential to offset hydrogen import goals



RMI Graphic. Source: European Commission, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483; World Steel, https://worldsteel.org/data/world-steel-in-figures-2023/; RMI analysis

To deliver on climate commitments, Europe has deployed several robust demand-side policies through strong mandates and carbon pricing mechanisms. The EU's Renewable Energy Directive (RED III) requires member states to integrate a minimum of 42.5% renewables into their energy systems and use 42% renewable fuels of non-biological origin (RFNBO)-certified hydrogen as part of their total hydrogen use in industry by 2030. RED III will greatly strengthen the prevalence of hydrogen-based products within industry, and although it does not directly affect the iron and steel industry, its mandates could serve as a framework for consuming green iron within the steel industry.

The EU's main demand lever for decarbonized iron and steel is the ETS, which utilizes a cap-and-trade mechanism to price carbon emissions. Currently, the iron and steel industry receives most of its carbon emissions allowances free, but as free allowance allocations are phased out between 2026 and 2034, the industry will be increasingly exposed to carbon costs.[15] Additionally, the EU is accelerating the reduction of the ETS emissions cap (from an annual rate of 2.2% to over 4% from 2024 onward). These reforms will limit the supply of allowances and could push carbon prices up. Assuming this results in an aggressive increase in the carbon price of $130 per allowance, steel made with imported green iron will begin to outcompete conventional domestic steel as early as 2028.

North American Policy Environment for Exports

The United States and Canada have passed and proposed policies that offer significant supply-side subsidies to produce green iron, mainly in the form of tax credits for hydrogen production — green iron's primary cost driver. These tax credits — 45V ($3/kg green hydrogen) in the United States and the proposed Canadian clean hydrogen investment tax credit (ITC) of up to 40% — mean that green hydrogen can be cost competitive with natural gas in ideal renewable energy locations looking toward 2030 (see Exhibit 10).

Exhibit 10: Policy landscape across the green iron value chain for the North American–EU corridor

		EU Incentive	EU Regulation	United States Incentive	United States Regulation	Canada Incentive	Canada Regulation
Upstream	Components and equipment	***Various grants and funds***		45X: Advanced manufacturing production credit 48C: Qualifying advanced energy project credit		Clean tech investment tax credit Clean tech manufacturing investment tax credit	
	Renewable electricity generation		Renewable Energy Directive III	45Y: Clean electricity production credit/ 48E: Clean electricity investment credit	***State-level renewable portfolio standards***	Clean electricity investment tax credit	Greenhouse Gas Pollution Pricing Act
	Green hydrogen production	European Hydrogen Bank	Emissions Trading System	45V: Credit for production of clean hydrogen H2Global (EU Policy)		Clean hydrogen investment tax credit Clean Fuels Fund H2Global (EU Policy)	
	Green hydrogen imports	H2Global	Carbon Border Adjustment Mechanism				
Production and procurement	Green iron production	Carbon contracts for difference (Germany)	Emissions Trading System	48C: Qualifying advanced energy project credit			Greenhouse Gas Pollution Pricing Act
	Green iron imports		Carbon Border Adjustment Mechanism				
Downstream	Green steel production		Emissions Trading System				Greenhouse Gas Pollution Pricing Act
	Green steel end use				Federal Buy Clean Initiative		

RMI Graphic. Source: RMI analysis

Clean Trade Policies

A new form of tariff has been introduced by the EU: the Carbon Border Adjustment Mechanism (CBAM), which places a tariff on the embedded carbon within imports of key sectors, including iron and steel. This measure is designed to prevent “carbon leakage,” which is defined as the potential reallocation of EU-based production, which is exposed to high carbon prices, to countries with fewer emission constraints (this was previously addressed via free allocation of allowances to domestic installations). Hydrogen-produced DRI has a greatly reduced emissions footprint, and the EU’s current import of un-agglomerated iron ore is not covered under CBAM, indicating that the biggest impact of CBAM will be on existing trade of agglomerated iron ore or carbon-intense finished steel products. As CBAM phases in and carbon prices increase, green iron has the opportunity to offset the carbon-intense imports as they incur the adjustment cost.[ii]

Similarly, the United States and the EU have been exploring the Global Agreement on Sustainable Steel and Aluminum (GASSA), which aims to shield the partners from emissions-intensive steel and aluminum imports and oversupply by establishing clean standards for trade. GASSA reflects the concept of a “climate club,” which eases trade barriers for products following emissions standards. Currently, talks on GASSA have stalled, but it remains an option in the future. Regardless of its status, the consideration of the climate club reinforces willingness on both sides of the Atlantic to establish clean trade. Refocusing these efforts on a green iron corridor that provides strong benefits to the exporting and importing parties offers an opportunity to make further progress. The passage of GASSA on this basis would strengthen a North America–Europe corridor — one that is already emerging with strong North American supply incentives working in tandem with European demand policies.

Decarbonizing Steel in Countries without Iron Ore

Europe’s status as a net importer of iron ore combined with a growing need to decarbonize steel production leaves the region with three pathways to meet its green steel demand goals:

Option 1: Importing iron ore and domestically producing green hydrogen, green iron, and steel

Option 2: Importing iron ore and green hydrogen for domestic production of green iron and steel

Option 3: Importing green DRI/HBI for domestic production of steel

Option 1: Domestic Hydrogen Production

The first option poses significant challenges. Europe has lower renewable energy capacity factors than the United States and Canada, and only 3.3%–7.4% of land is suitable for new wind and solar development, necessitating prioritization of renewable energy for uses that cannot be supplemented by imports.[16] Within Europe, competition for hydrogen will grow, especially as the RED III mandates are deployed, which require 42% of hydrogen consumed within industry to be RFNBO certified by 2030, and 60% by 2035. Current hydrogen use is dominated by refining, ammonia, and other chemicals sectors.

If Europe is to build a robust domestic hydrogen supply, current supply-side subsidies appear to be insufficient. The EU’s main supply policy driver under this scenario is the European Hydrogen Bank. The recently announced winners of European Hydrogen Bank’s pilot funding round were awarded nearly a total of €720 million (US$772 million).[17] Winning projects are slated to receive an average of €0.46/kg of hydrogen (US$0.49/kg) produced for 10 years.[iii] This results in a volume of roughly 0.16 Mtpa of hydrogen, vastly short of EU’s REPowerEU total hydrogen demand target of 20 Mtpa by 2030.

The auction results demonstrate that the fund total must be increased to avoid a bottleneck on the total amount of hydrogen funded. Although the European Hydrogen Bank will supply an additional €2.2 billion (US$2.36 billion), a further significant increase in funds would be needed to bring about substantial volume of domestic hydrogen. However, given the cost-competitiveness of green iron imports, such an increase may risk using funding unnecessarily.

ii CBAM carbon prices are tied to ETS prices, which are expected to rise in coming years, as discussed above.

iii Average subsidies weighted by production volume.

At the same time, the ETS has the potential to provide a subsidy to installations producing green iron within the EU through free allowance allocation. In recently updated free allowance benchmark rules, sponge iron exiting a DRI plant is now included under the hot metal benchmark, sintered ore has been revised to agglomerated iron (including pellets), and hydrogen production has been expanded to include electrolysis. Free allowances are based on the production volume of each individual benchmark, meaning an installation whose emissions are under the benchmark level will receive excess allowances and can sell those back into the market for profit. A green iron producer would receive a significant number of free allowances that could be sold and turned into a subsidy for each ton of steel produced.

Average estimates are that ETS allowances in 2030 (when hydrogen-based DRI facilities would be expected to come online) would allot a subsidy of approximately $100/t steel while costing traditional BF-BOF integrated facilities approximately $125/t steel. The narrowing of the green premium brings domestic green steel prices to a comparable level with incumbent BF-BOF steel, but notably, as shown in Exhibit 6 (page 12), steel manufactured with imported green iron could outcompete both, making it potentially the most cost-effective route for steel producers. As free allowances are rapidly reduced to zero by 2034, the subsidy will also be eliminated, strengthening the cost advantage of green iron imports and signaling a long-term business case for green iron corridors.

Option 2: Importing Green Hydrogen

Given the limited supply of renewable energy, importing green hydrogen to locally produce DRI and steel could emerge as an alternative. The German policy instrument H2Global, which is open to all EU members, seeks to address this situation directly through the creation of a two-way international auction for hydrogen and hydrogen-based commodity supply and offtake. International suppliers bid for long-term agreements, with the lowest bid winning, and EU domestic off-takers bid on short-term agreements, with the highest bid winning — closing the green premium gap. As currently structured, the mechanism is not open to domestic hydrogen-based iron, limiting this mechanism to enabling domestic iron production via imported hydrogen.

However, importing hydrogen for domestic iron production comes with its own difficulties. With the domestic supply bottlenecked by renewables availability, and imports requiring time to ramp up with infrastructure deployment, green hydrogen supply will face competing demands from other sectors in addition to steel that are looking to decarbonize or meet RED III targets. The current issues with deliverability and asset readiness will limit many current production sites' use of imported hydrogen. This leaves a third choice for steel producers: importing green iron.

Option 3: Importing Green Iron

Importing green iron emerges as a strong contender to kick-start the decarbonization of the EU's steel industry. Imports can be seen as complementary to the EU's broader transition, providing a cost-effective early route to green steel as Europe builds upon its processes (see Exhibit 11, next page). By leveraging early-mover markets with strong hydrogen production incentives, such as those in the United States and Canada, Europe can procure cost-effective green iron without significantly changing its supply chains.

This alternative can be effective in the short term because it requires the least building out of facilities and infrastructure in Europe. It would give the bloc's hydrogen and renewable industries time to mature and build upon previous methods of acquiring green steel. The EU's mechanisms, such as H2Global, could easily be retooled by opening specific tenders for imported green iron. Compared with importing both iron ore and hydrogen, it increases system efficiency by reducing resources used for shipping multiple products.

It should be noted that green iron imports are suited as a complement to EU industry, allowing the transition to scale while maintaining existing industrial capabilities and offsetting early costs.

Exhibit 11: European Union pathways to green steel

Viability increases as hydrogen technology matures, processes build upon previous configuration

	Imported green DRI		Domestic DRI production			
			Imported H_2		Domestic H_2 production	
	Enabling Conditions	**Status**	**Enabling Conditions**	**Status**	**Enabling Conditions**	**Status**
Natural Resources	Renewable energy, land availability, iron ore for exporter	**US:** strong wind and solar in Gulf Coast, iron ore **Canada:** hydro, wind, substantial iron ore	Renewable energy, land availability for exporter	**US:** strong wind and solar in Gulf Coast **Canada:** hydro, wind	Renewable energy and land availability	Limited renewable energy and land use, inducing heavy early prioritization
Infrastructure Deployment	Dry bulk import	Mature processes and existing infrastructure	Dry bulk import H_2 import terminal H_2 reconversion H_2 transportation	Requires large buildout of infrastructure	Dry bulk import H_2 transportation	Requires buildout of H_2 network
Technology Deployment	EAF	Mature technology, benefits from additional deployment	DRI EAF	Requires deployment of DRI facilities	H_2 production DRI EAF	Requires large-scale deployment of H_2 production
Enabling Policy	Supply incentives for exporter	**US:** 45V **Canada:** Clean H_2 ITC	H_2 import subsidies Iron production subsidies	H2Global CCfDs (Germany) IPCEI Hy2Infra	H_2 production subsidies Iron production subsidies	EHB CCfDs (Germany) IPCEI Hy2Use

Note: Carbon Contracts for Difference (CCfDs) are variable-price subsidization mechanisms that cover the gap between a renewable production process and its fossil alternative, fluctuating in response to the ETS carbon price. Important Project of Common European Interest (IPCEI) is an EU designation that a project is of high importance and is therefore allowed to receive direct Member State funding aid. IPCEI Hy2Infra focuses on hydrogen infrastructure, and IPCEI Hy2Use focuses on hydrogen use.

RMI Graphic. Source: RMI analysis

Creating an Environment Conducive to Green Iron Import

The North American and EU policy landscapes showcase blueprints of how to support and facilitate green iron corridors for exporters and importers, respectively. Beyond incentives within exporting countries, international collaboration and national targets for green iron are imperative in providing certainty to first movers that there is an early market for these goods. Current policies and incentive instruments such as RED III, European Hydrogen Bank, H2Global, and Carbon Contracts for Difference (CCfDs) have laid the groundwork for hydrogen deployment. However, to fully realize the systems and cost benefits of hydrogen-based iron import, an explicit integration of green iron with hydrogen targets, price support mechanisms, and bilateral green trade partnerships between the EU and iron-abundant countries, are needed for a quick ramp-up of green iron trade.

Recommended policy actions for Europe:

- Ensure the longevity of the existing workforce by expanding funding to reskilling and upskilling programs such as those within the Net-Zero Industry Act,[iv] with a focus on upstream and iron-related transitions specifically for equitable industry change and direct consultation with sector labor leaders.
- Set binding targets for the usage of green iron within steelmaking, akin to hydrogen deployment targets under RED III.
- Encourage the development of methodologies to define green iron, compatible with current steel sector standards (the most robust voluntary and compliance-based standards), and to establish expedited customs procedures for certified iron.
- Strengthen international partnerships with green iron corridor export candidate countries, incorporating green iron into broader frameworks for green trade.
- Expand hydrogen-based policy instruments such as the European Hydrogen Bank and H2Global to include international procurement of green iron.

2. Mauritania: Challenges and Opportunities for Emerging Economies

Emerging economies of varying maturity are identified as potential green iron production regions, which comes with both challenges and opportunities in establishing a new export market. In this second case study, we look more closely at one country, Mauritania. Ongoing feasibility studies on producing HBI exports provide clarity on what some of these specific challenges and opportunities are.[18]

Mauritania has just over 1 million square kilometers and 754 kilometers of coastline, and a population of 4.8 million.[19] It also features high solar irradiation and wind speeds that can be harnessed to install capacities of up to 457 GW solar and 47 GW wind, respectively.[20] With renewables accounting for ~70% of the levelized cost of hydrogen of green hydrogen (and ~40% of the levelized cost of HBI), the combination of vast land areas with a high renewable energy potential and low population densities suggests a strong potential for competitively priced green hydrogen and its derivatives.[21] The colocation of significant renewable potential with rich high-grade iron ore reserves (>67% Fe) also makes Mauritania a strong emerging contender to source competitive green HBI.

The country already exports approximately 14 Mtpa of iron ore, with reserves in the range of 4 billion tons. This prospect has attracted project developers to assess the feasibility of four green hydrogen projects. If the pipeline of projects is realized, it would position Mauritania as Africa's top green hydrogen producer.[22]

As shown in Exhibit 12 (next page), Mauritania, like many other emerging markets and developing countries (EMDCs), faces challenges associated with iron production, geopolitics, energy access, and its policy environment.

Although it is Africa's second-largest exporter, Mauritania does not have any steel production and thus has a limited domestic workforce skilled in ironmaking. Training workforce programs sponsored by the government or corporate partners could fill this gap, with the potential to add thousands of new jobs, over $4.5 million in wages for local economic growth, and over $650 million in revenue, which would be a 6% growth in national gross domestic product.[23]

iv The Net-Zero Industry Act is a regulation to strengthen EU net-zero industry. It includes provisions for reskilling and upskilling of workers for this purpose.

Exhibit 12: Mauritania's landscape in iron, geopolitics, energy, hydrogen, policy, cost, and stakeholders creates challenges and opportunities for development of a new export market

Landscape readiness: High / Moderate / Low

	Current landscape	Potential recommendation
Iron (Low)	▪ No current steel production, iron ore is largest export for country at 14 Mtpa	▪ Training workforce programs sponsored by government or corporate partners
Geopolitics (Moderate)	▪ Higher risk of strikes, civil commotion, and legal, economic, and credit risks ▪ 4.8 million people, $10 billion GDP, 29% of GDP in industry ▪ 19% of jobs are currently in industry, 29% in agriculture	▪ Creative financing to unlock lower cost of capital
Energy (Low)	▪ One state-owned electricity utility: SOMELEC ▪ 549 MW total capacity, 180 MW gas, 30 MW wind, 37 MW solar, 300 MW diesel ▪ 30% access rate to electricity: 56% in urban and <5% in rural	▪ Community or utility scale wind and solar development to grow domestic energy access with H_2 and HBI development
Hydrogen (Moderate)	▪ Potential: 50 GW green H_2, over 380,000 jobs by 2050	▪ National or local subsidies toward renewable energy and H_2 development
Policy (Moderate)	▪ Tax breaks and customs exemptions for H_2 developers ▪ Has a low carbon H_2 strategy without defined electrolyzer targets, but with goals to develop skilled jobs and build access to domestic basic services	▪ National or local subsidies toward renewable energy and H_2 development
Cost (Moderate)	▪ Promising potential for low H_2 costs due to higher capacity factor solar and wind close to the iron ore mines ▪ Cost of capital as high as 24% contributing to higher costs	▪ Creative financing to unlock lower cost of capital ▪ Public subsidies
Stakeholders (High)	▪ Announced projects in recent years by three Green Hydrogen Catapult members	▪ Securing offtake agreements to help reach final investment decision

RMI Graphic. Source: IEA, https://iea.blob.core.windows.net/assets/64c7f915-a7a2-4ede-a971-89e1203c3bf6/RenewableenergyopportunitiesforMauritania.pdf; public announcements; RMI analysis

Political and regulatory risks influence the cost of capital, which is generally higher in EMDCs than Organisation for Economic Co-operation and Development (OECD) countries. Few data points on capital cost for green hydrogen projects are publicly available. However, as a comparison, the average cost of capital for utility-scale renewable energy projects in the Middle East and Africa lies at 8.3%, compared with 4.4% in Europe and 5.4% in North America.[24]

In the case of Mauritania, owing to the higher risk of strikes; civil commotion; and legal, economic, and credit risks, the cost of capital can be as high as 24% for project development.[25] However, depending on the financial structure of the project, lower weighted average cost of capital figures are feasible in Mauritania. Mauritania's draft hydrogen law includes exemptions from taxes on loan repayment interest for hydrogen developers — an effort to reduce financial interest rates — but it remains unclear how this will affect the cost of capital. A combination of risk-mitigation mechanisms, such as political risk insurance, public equity investments, and guarantees, would strengthen the confidence of investors and therefore lower the capital costs of green iron production projects. The additional national or local policies that incentivize and ease deployment for renewable energy, hydrogen, and industrial developments could further strengthen Mauritania's cost-competitive positioning and speed the rate at which projects break ground.

The economic opportunity of green hydrogen and its derivatives has prompted Mauritania to build an environment conducive to green hydrogen investments. The government of Mauritania is strategically positioning itself through various ventures and actions:

- It is included in the Northwestern African Hub, poised to export green hydrogen and its derivatives to Europe.
- It has established goals of growing its hydrogen production alongside developing skilled jobs and building access to basic domestic services, and it has recently announced a variety of tax breaks for green hydrogen developers.
- Now a partner in the Team Europe Initiative, Mauritania is in a strong position to receive technical and financial assistance in order to expedite the necessary enabling environment to deploy renewables and green hydrogen at scale.[26]
- The Ministry of Petroleum, Energy, and Mines in Mauritania has signed agreements for three significant projects, two of which are spearheaded by Green Hydrogen Catapult members CWP-Global (AMAN) and ArcelorMittal (Green Steel).[27]
- The government is investing $660 million for the build-out of clean energy resources and the mining sector, with $100 million support from the World Bank (IDA), to be rolled out in 2025.[28]

With the development of green hydrogen projects, Mauritania stands to gain retained earnings from its abundant resources (wind and solar), reduced reliance on oil imports, green jobs, increased access to clean affordable electricity, and the opportunity to engage in an evolving global market.

It is worth noting that with projects in EMDCs generally and Africa in particular, critics have raised concerns that prioritizing renewable energy exports such as green hydrogen can lead to re-creating extractive relationships without benefiting local communities. A strong emphasis and accountability measures must be placed on emerging trade relationships and agreements to not only attract early investments but also ensure that sustainable industrial activities thrive in these regions.[29]

3. Australia: Nuances of Iron Ore Beneficiation

The third case study seeks to more deeply explore iron ore quality and beneficiation. The techno-economic modeling conducted here aims to better understand the trade-offs in meeting DRI quality requirements using average grade-recovery curves based on several mining examples. However, in practice, that trade-off point will vary with individual mines depending on ore specifics.

Certain ore specifics are not captured in this analysis, including (1) the amount and type of impurities, (2) the in situ grain size of the impurities, (3) how the impurities are bound to the iron oxides, and (4) the specific iron-bearing mineral amounts in the ore (hematite, magnetite, goethite, etc.). These factors will play a role in determining the trade-off point between upstream DR-grade pellet production and downstream ESF process addition.

Among iron-bearing mineral types, magnetite is strongly preferred over hematite for producing DR-grade pellets for two main reasons. (1) Magnetite can be separated from the impurities via low-intensity magnetic separation, a more efficient process than gravity separation, and (2) magnetite oxidizes during the pelletizing process in an exothermic reaction, providing up to 60% of the required heat for pelletizing.

Hematite is weakly magnetic. The iron particles in many hematite deposits can be of very fine grain, with finely distributed impurities disseminated throughout the hematite matrix, leading to challenges in beneficiation processes that rely only on physical separation. To separate the fine-grained iron particles from impurities, a combination of methods including crushing, grinding, gravity separation, and high-gradient magnetic separation can be employed (depending on the ore specifics). Generally, hematite ores require additional grinding and processing steps, leading to higher costs and larger iron losses than magnetite. However, the design and performance of the beneficiation process is very specific to the ore characteristics, and there are already mines currently producing high-quality pellets from hematite.

Among impurities, phosphorus, silica, and alumina have the largest impact on beneficiation and downstream processing. Generally, silica and alumina can be removed via physical separation techniques such as magnetic and gravity separation, and their removal to ~3% combined is necessary to achieve DR-grade pellets,[30] but can be limited by the economics driven by the associated iron losses. Phosphorus removal, on the other hand, requires chemical techniques such as acid leaching. These impurities can be very fine-grained, requiring many grinding steps for effective separation, also leading to significant iron losses. Depending on how the impurities are distributed throughout the ore, traditional physical methods of beneficiation can be unsuccessful at removing them, as is the case with phosphorus in some Australian hematite goethite ores. In Australia, most of the mining is currently focused on using the low-phosphorus ores, but those are projected to be almost depleted by 2030, so efficient methods of beneficiating high-phosphorus Australian ores are needed.[31]

Approaches such as heat treatment followed by acid leaching or alkaline leaching have been demonstrated at laboratory scale but would need to be scaled up to support wider production.[32] Downstream, the EAF is currently not as efficient as the BOF at removing any remaining phosphorus, so today's EAFs have stricter impurity thresholds than BOFs. Taken together, high phosphorus, silica, or alumina hematite with lower iron content ores may see cost savings through less upstream beneficiation and adding an ESF to remove the excess gangue before processing with a BOF or EAF.

Further examining the trade-offs between upgrading to pellet production and continued direct shipping ore (DSO) operations for high-grade hematite sheds light on some of the challenges and potential solutions faced by current iron ore miners. Australia, producing 37% of the world's iron ore and exporting 95% of that, mines mostly mid- to high-grade ore that is a mix of hematite and goethite with high concentrations of impurities that are difficult to separate from the iron ore.[33] Most of these exports are shipped as a DSO product to China, where the product is sintered and then reduced to iron in BFs. To support the transition to green iron production, pellets must be produced because DSO cannot meet the quality and content requirements for use in current DRI shaft furnaces.

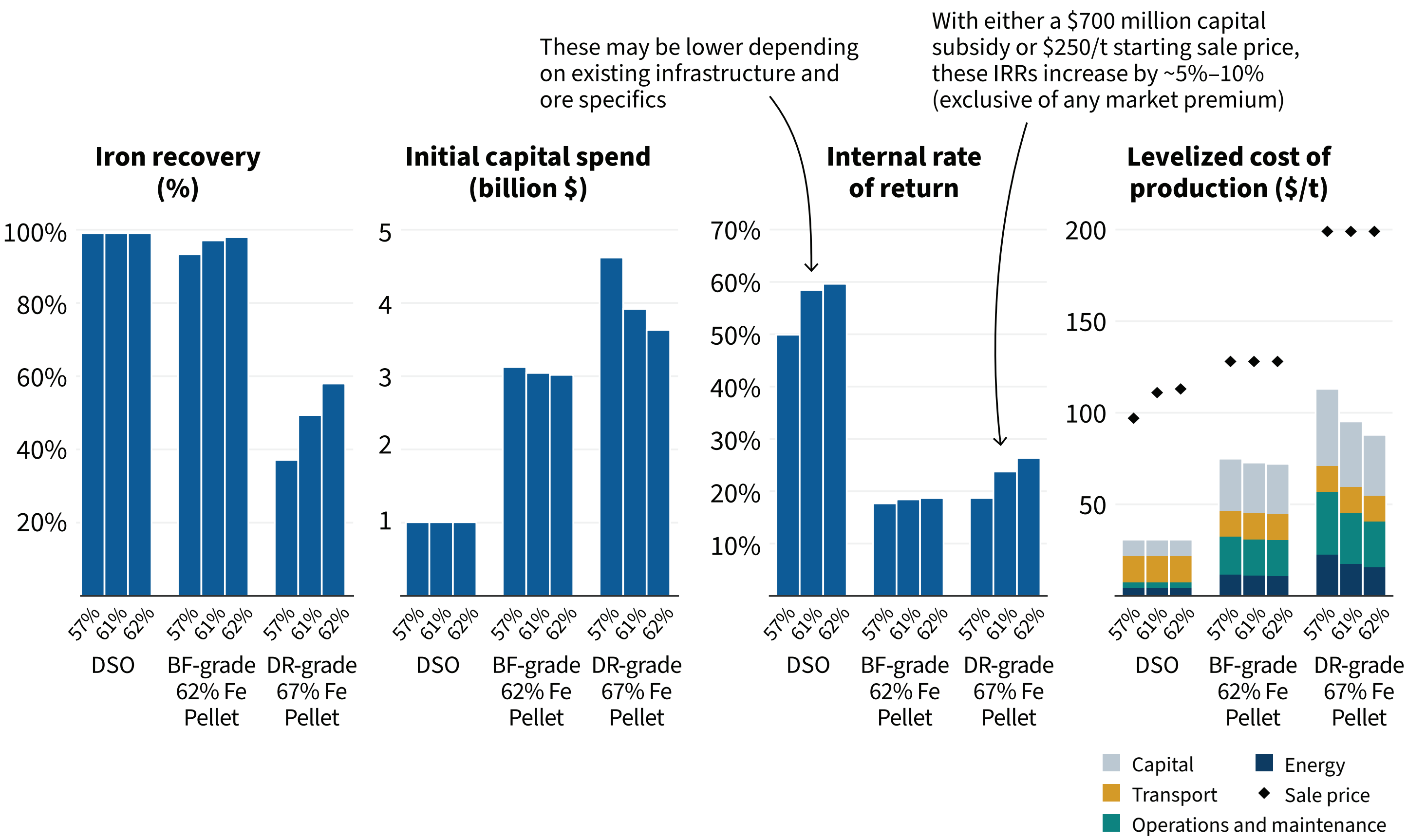
Looking closer at an Australian mining case study, we see positive business cases for several options but with different specifics (see Exhibit 13, next page). One is a DSO mine expansion; another is a mine expansion with new beneficiation and pellet plants to support a DRI facility with 62% Fe pellets (referred to as *BF-grade* and in need of an ESF or other downstream adjustments); the final is same as the prior but with 67% Fe pellet production (referred to as *DR-grade*). For hematite ores ranging from 57% to 62% iron content, the iron recovery is near 100% for DSO and BF-grade pellet options, but it drops significantly to reach DR-grade pellets, ranging from roughly 40% to 60% iron recovery.

Interestingly, for the highest starting grade of 62% Fe ore, the shift from BF- to DR-grade pellet production increases the initial capital and levelized cost of production by only about 20% while the expected sale price increases by over 50%, resulting in a higher internal rate of return for DR-grade pellets. This makes a strong business case for producing DR-grade as compared with BF-grade pellets for these ores with higher starting grades on a levelized cost basis, if considering the transition from DSO to pellet.

Transitioning existing production from DSO to pelletizing will likely be driven by changes in demand, as the business case alone is not enough to incentivize the transition. For example, if China — Australia's largest export market — introduces carbon taxes that incentivize faster transition from BFs to DRI plants, demand for Australia's DSO will see a rapid decrease. Globally, as the steel sector transitions to more DRI production, it is likely that magnetite mines will be used first, with hematite to follow, for two main reasons. (1) As discussed earlier, magnetite ores see efficiency savings in beneficiation and pelletizing processes, and (2) because the majority of global magnetite ores have iron contents in the mid- to low range, they must be beneficiated to produce a usable product for ironmaking. High-grade hematite, on the other hand, like the Australian ores, has the option of DSO or pellets.

In the case of Australia, magnetite makes up only ~3% of total production and and 38% of reserves; the remaining ores are a mix of hematite and goethite, with high amounts of phosphorus, silica, and alumina.[34] Although magnetite mines will likely be prioritized for the first investments in DR-grade pellet production, as demonstrated by such recent investments as the Iron Bridge Magnetite project, there are opportunities for beneficiation innovation and supply chain optimization to minimize iron losses, energy, and costs for hematite ores as well.

Exhibit 13: The transition from DSO operations to pellet production using higher-grade hematite Australian ores will not be driven only by financial outcomes and will likely require demand-side shifts to support the case (ores range from 57% to 62% iron content and all scenarios shown produce 8.8 Mt product per year)



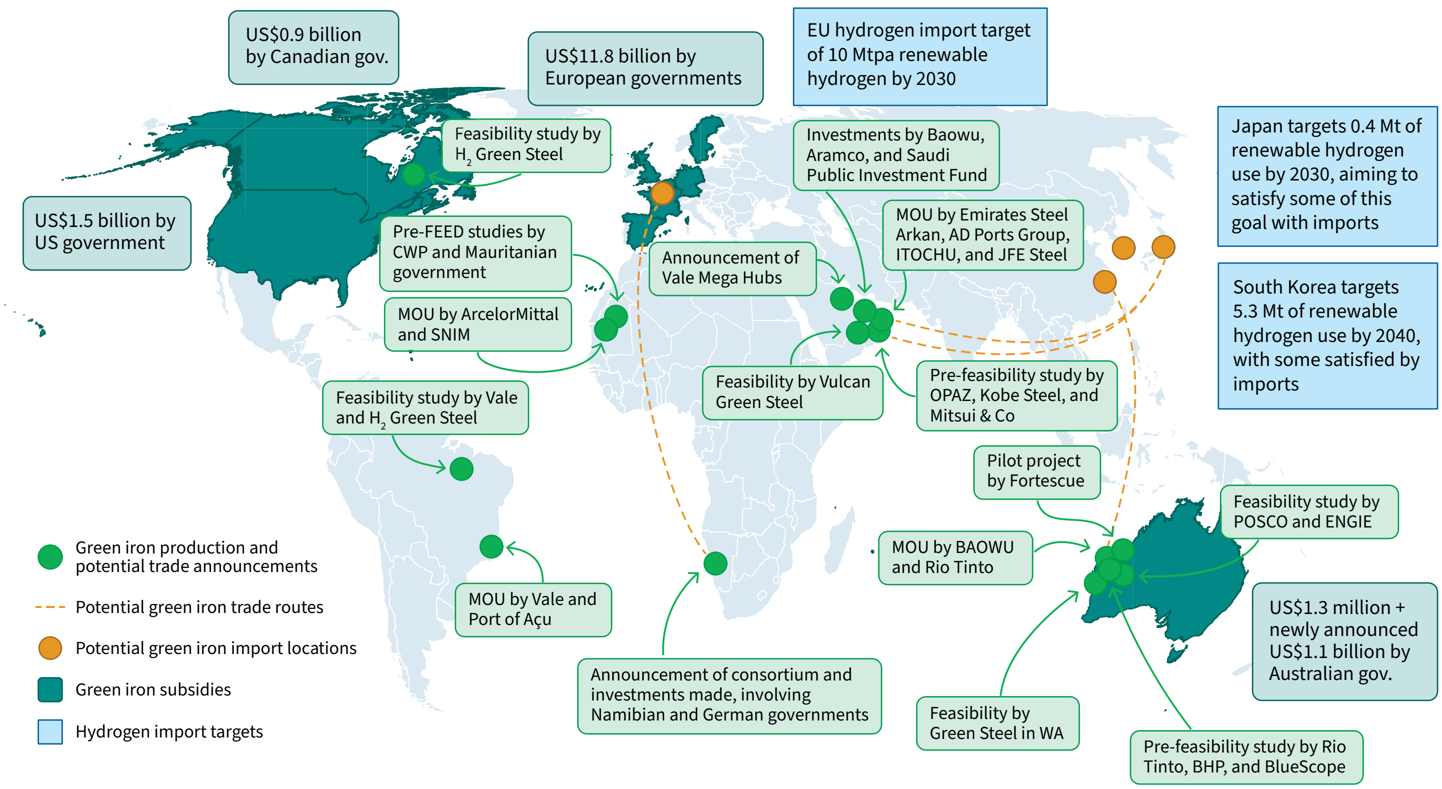
RMI Graphic. Source: RMI analysis

V. The Emerging Green Iron Landscape

As evidenced by the landscape of policies and recent project announcements, a global green iron economy is starting to emerge (see Exhibit 14, next page). Policies worldwide look to support elements of the value chain and spur domestic investment and trade. Australia, Canada, Europe, and the United States offer various levels of subsidy for green iron and steel projects. Europe has provided close to $12 billion to promote DRI projects and clean steel technologies in places including Belgium, France, and Germany.[35]

Similarly, the US Department of Energy recently announced over $1 billion (through the Industrial Demonstrations Program) in prospective funding for two new DRI projects.[36] Companies have also announced explorations and projects related to green iron production; multiple projects are being explored via memorandums of understanding or even pre-feasibility studies in Australia, Brazil, and Mauritania — locations with strong mining and renewable energy profiles. On the other hand, numerous countries across Europe and Asia have announced hydrogen import strategies, varying in maturity; the EU's 10 Mtpa by 2030 import goal is the most advanced.

Exhibit 14: Global green iron trade offers improved systems efficiency and economic growth to the broader hydrogen economy, benefits that can be realized sooner with targeted policy support and trade corridor consortium formation



Note: MOU is memorandum of understanding; Pre-FEED is pre-front-end engineering design

RMI Graphic. Source: Public announcements, RMI analysis

Despite the emerging landscape of support mechanisms and demand drivers, uncertainty remains about green iron corridors' role in the global hydrogen economy and proof points are needed to showcase supply chain partnerships. Green iron corridors are not a silver bullet for industry decarbonization, but rather a part of the solution sets needed to holistically meet mutually beneficial economic and environmental goals.

VI. Next Steps to Advance Green Iron Corridors

Green iron corridors create significant win-win opportunities. For importing countries, these corridors can help decarbonize domestic steel industries more cost-effectively while meeting energy and climate targets and contributing to energy security. For exporting countries, these corridors provide opportunities to scale higher-value iron products, develop local clean energy industries, and create new jobs.

To take advantage of the benefits to both exporter and importer regions through green iron corridor partnerships, RMI has identified these key action areas that will help create the sociopolitical conditions to drive domestic and international momentum into project development.

- **Undertake bilateral negotiations and diplomacy efforts**

  Front-runner export and import regions can look to establish joint targets at the national level related to green iron supply chains as a signal for establishing the market, considering importer fleet and transition plans.

- **Clarify green iron as a vector for hydrogen import**

  Many import policies lack clarity on whether hydrogen-produced iron will qualify as a vector for hydrogen import. This sets up a key area of opportunity for policymakers seeking to import hydrogen to clarify and leverage this concept to meet their country and regional goals in national policy.

- **Recognize green iron with credible carbon accounting frameworks**

  Agreement and standardization on how the emissions reduction impact of hydrogen-produced iron is accounted for within the emissions reduction inventory and nationally determined contributions of both parties (companies, countries, etc., on either side of a corridor) would help reduce uncertainty in corridor formation efforts. Development of a green iron standard and certification can be accelerated through voluntary pathways, utilizing existing and agreed-upon cradle-to-gate methodologies and boundaries, coupled with progressive climate-aligned thresholds.

- **Provide certainty needed for green iron technology deployment**

  Many elements of the technology stack needed for green iron trade corridors are mature, but some still require further development and integration, which poses risks to first-of-a-kind projects. Policymakers and intermediates can help accelerate these projects by providing financial mechanisms to de-risk, such as price floors, volume backstops, and credit guarantees.

- **Increase viable financing options for emerging economies**

  For “emerging contender” production regions with favorable fundamentals, a majority of which are non-OECD members, enhanced financing options to reduce risk and cost of capital are necessary. Multilateral development banks, for example, can play a role in reducing financial barriers and developing the required infrastructure to support promising exporting contenders.

- **Demonstrate technologies**

  Demonstration of key technologies along the value chain, including in green iron production, transport, and steelmaking, will further de-risk this pathway, improving access to finance for developers. First-mover projects supported by collaboration among companies with clearly established technology development targets can provide this increased certainty and spurring of market growth by demonstrating viability, learnings, and competitiveness of green iron trade corridors.

Collaborative intent and action along the supply chain between exporter and importer policymakers and corporations are necessary to launch a global green iron trade economy. Green iron corridors provide the steel industry with an economic and environmentally viable strategy. It is now time for leading regions to come together and make the new era of green steel a reality.

Appendix

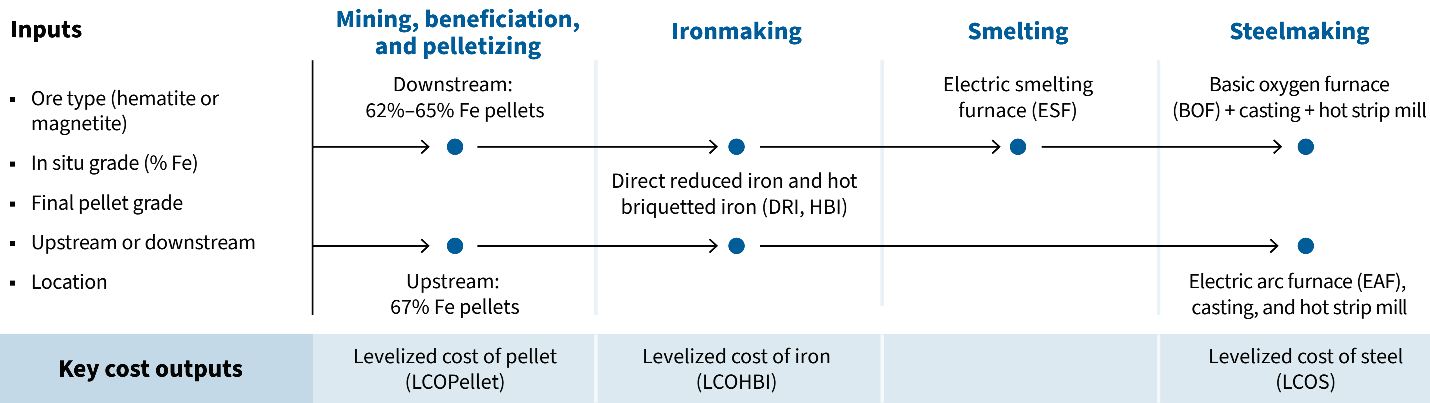
Exhibit A1: Qualitative assessment ranking—Full list

Exporters	Iron	Hydrogen	Energy	Geopolitics	Policy	Stakeholder	Cost	Total
Australia	68	88	90	94	28	75	85	75
US	27	100	90	74	60	50	100	72
Canada	7	75	91	51	31	100	92	64
Chile	1	63	81	68	67	75	83	63
Sweden	3	50	98	100	53	50	70	61
South Africa	2	38	61	31	67	100	87	55
Brazil	38	38	77	48	13	75	86	54
India	35	63	55	31	29	75	70	51
Namibia	0	38	52	40	40	75	73	45
Peru	1	38	60	50	13	25	82	38
Mexico	6	38	63	38	0	50	66	37
Mauritania	1	25	31	18	27	75	80	37
Kazakhstan	2	25	72	34	0	25	86	35
Ukraine	4	38	13	0	13	50	52	24
Gabon	0	0	53	16	0	25	26	17
Guinea	0	0	31	6	0	0	50	12
Liberia	0	0	31	11	0	0	0	6
Lower quartile	1	25	52	18	0	25	66	35
Upper quartile	7	63	81	51	40	75	86	61
Median	2	38	61	38	27	50	80	45
Average	0	0	13	0	0	0	0	44

Importers	Steel	Energy	Geopolitics	Policy	Stakeholder	Cost	Total
Germany	45	91	91	100	100	56	80
UK	38	84	77	80	90	47	70
Netherlands	36	75	95	80	41	41	61
Poland	18	58	77	80	59	67	60
Spain	19	78	65	80	48	63	59
Italy	24	69	64	80	16	100	59
France	31	85	76	80	37	42	59
Japan	77	64	100	40	35	34	58
Finland	18	98	97	60	19	45	56
Czech Republic	36	71	92	40	33	65	56
South Korea	67	67	90	40	30	28	54
Malaysia	56	56	75	20	11	56	46
Turkey	35	45	15	80	32	54	44
Oman	12	29	54	40	44	23	34
Saudi Arabia	29	43	48	20	44	15	33
Vietnam	28	48	56	20	11	12	29
Philippines	35	32	35	20	11	42	29
Argentina	30	51	16	20	22	34	29
Indonesia	11	46	35	20	11	40	27
Algeria	45	28	15	20	5	15	21
Egypt	28	31	17	20	22	0	20
Mozambique	35	4	0	0	0	47	14
Lower quartile	25	44	35	20	12	29	29
Upper quartile	38	74	87	80	44	55	59
Median	33	57	64	40	31	42	50
Average	33	56	58	46	33	41	45

RMI Graphic. Source: RMI analysis

Exhibit A2: Techno-economic model set up



Note: Location-specific cost assumptions include cost of energy (electricity, natural gas [for pelletizing], H_2, coal, and diesel) and labor.

RMI Graphic. Source: RMI analysis

Exhibit A3: Weighting for each factor and category used in systems-level framework

Importers Category	Category Weight	Individual Factor	Individual Factor Weight
Iron	14%	IO exports	10%
		Skilled workforce	5%
Geopolitics	10%	Geopolitical risk	10%
Energy	17%	Energy security	2%
		Energy equity	7%
		Environmental sustainability	2%
		Transition readiness	5%
Hydrogen	17%	Hydrogen readiness	17%
Policy	14%	Public commitment to hydrogen	5%
		Hydrogen targets	10%
Stakeholders	12%	Hydrogen first movers	12%
Cost	17%	HBI cost	17%

Exporters Category	Category Weight	Individual Factor	Individual Factor Weight
Steel	23%	EAF capacity	6%
		BOF capacity	3%
		Reliance on IO imports	11%
		Future steel demand	3%
Geopolitics	11%	Geopolitical risk	11%
Energy	23%	Energy security	9%
		Energy equity	3%
		Environmental sustainability	3%
		Transition readiness	9%
Policy	11%	Hydrogen targets	11%
Stakeholders	17%	Steelmaker sustainability commitment	11%
		Hydrogen first movers	6%
Cost	14%	Carbon pricing	6%
		Compared to all domestic	9%

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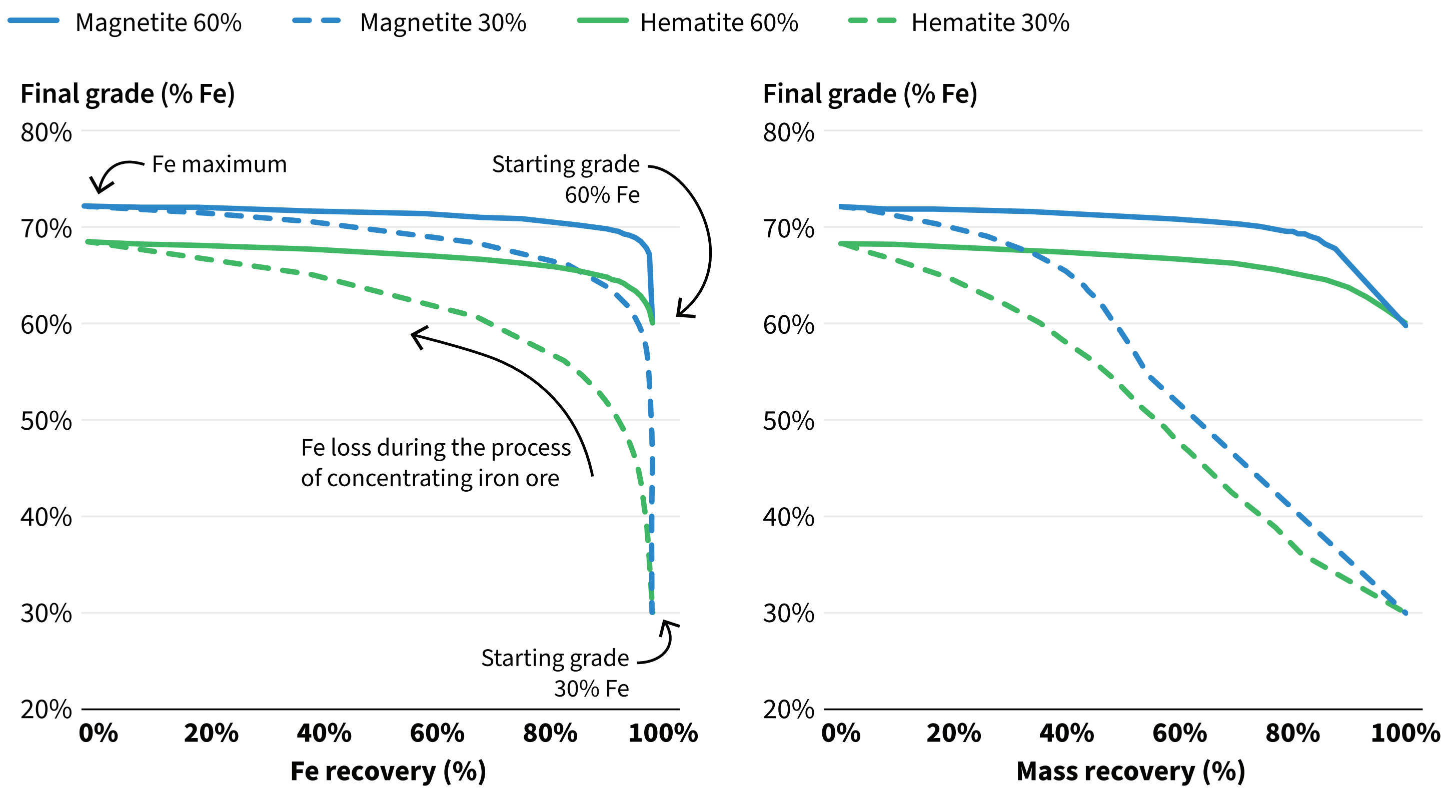
RMI Graphic. Sources: USGS, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-ore.pdf; Jasansky et al., 10.1038/s41597-023-01965-y; Global Energy Monitor, https://globalenergymonitor.org/projects/global-steel-plant-tracker/; IEA, https://www.iea.org/reports/iron-and-steel-technology-roadmap; BNEF, Rystad, World Steel, https://worldsteel.org/data/world-steel-in-figures-2023/GEM; RMI analysis

Exhibit A4: Grade recovery curves



Final grade = A x ln(-b(Fe recovery) + B) + C

A = (Fe maximum – starting grade) / ln(B)

Logarithmic relationship used to calculate grade recovery curves for concentrate from starting grade and ore type

b=360,743 for magnetite and 301 for hematite (average of 4-6 mining examples on right), B=b+1, C=starting grade

Fe maximum = 72.4% for magnetite, 68.5% for hematite

$$\textit{Mass recovery} = \textit{Fe recovery} \times \frac{\textit{Starting grade}}{\textit{Final grade}}$$

Mining examples used for curve fitting

	Start grade (%Fe)	Final grade (%Fe)	Fe recovery
Hematite	18.6%	60.8%	60.2%
	27.9%	64.8%	64.8%
	50.7%	65.1%	71.9%
	34.3%	63.1%	70.5%
Magnetite	36%	65.0%	90.0%
	36%	65.0%	75.0%
	22%	65.0%	89.3%
	33.9%	65.0%	65.3%
	28.9%	68.0%	90.7%
	31.7%	66.8%	78.7%

RMI Graphic. Source: RMI analysis based on data from various company reports

Exhibit A5: Cost assumptions

Capex			Opex	Labor
Equipment	**Size, Mt**	**Cost, 2023 US$**	**Cost, 2023 US$**	**FTE**
Mine	8	$85/t ore	$1/t ore	20 FTE*/Mt ore
Rail	2	$1/t pellet		
Beneficiation plant	2.9	$62/t ore	$3/t ore	10 FTE/Mt ore
Upgrade beneficiation to DR grade	2.9	$41/t pellet	NA	NA
Pellet plant	2.9	$208/t pellet	$6/t pellet	27 FTE/Mt pellet
DRI	2	$337/t DRI	$10/t HBI	74 FTE/Mt HBI
ESF	2	$294/t hot metal (HM)	$16/t HM	227 FTE/Mt HRC
EAF	1.7	$294/t liquid steel (LS)	$50/t HRC	227 FTE/Mt HRC
BOF	1.7	$248/t LS		227 FTE/Mt HRC
Casting	1.7	$108/t crude steel (CS)		100 FTE/Mt HRC
Hot strip mill	1.7	$227/t hot rolled coil (HRC)		120 FTE/Mt HRC

Additional capital expenditure (Capex) costs:

- Engineering: 10% of total equipment cost
- Site prep: 11% of total equipment cost

Operating expenditure (Opex) costs not including labor or energy

Financial assumptions for iron and steel plants:

- 60% debt
- 40% equity
- Cost of debt 7%–16.6%*
- Cost of equity 11%–20.6%*
- 1% of installed Capex for sustaining capital per year
- 25-year plant
- 2%/year rate of inflation

*Note: Country-specific financial inputs: Project capital structure includes a country-specific risk premium based on credit rating; *FTE is full time equivalent*

RMI Graphic. Source: RMI analysis based on data from various company reports

Exhibit A6: Heat and energy assumptions

	Units	Magnetite	Hematite	Hematite DSO
Drilling (diesel)	MJ/t crude ore	1	1	1
Blasting (explosives)	MJ/t crude ore	3	3	3
Loading and hauling (diesel)	MJ/t crude ore	92	92	92
Crusher (electricity)	kWh/t crude ore	4	4	4
Concentrator (electricity)	kWh/t crude ore	28	28	10
Pelletizing (fuel)	MJ/t pellet	424	1059	0
Pelletizing (electricity)	kWh/t pellet	41	41	0

Pelletizing heat for magnetite is 60% less than hematite, under the assumption that the magnetite oxidation to hematite exothermic reaction supplies 60% of the heat needed (Best Available Techniques Reference Document for Iron and Steel Production, European Commission, 2013).

RMI Graphic. Source: RMI analysis based on data from literature, various company reports and asset data

Exhibit A7: Iron and steel consumables assumptions

Direct Reduction of Iron, DRI

- 1.4 t pellet/t DRI
- 94% metallization
- Total Fe output:
  - 93% Fe for 67% Fe pellets
  - 89% Fe for 65% pellets
- Reduction from hydrogen
  - 55 kg/t DRI for 67% Fe pellets
  - 53 kg/t DRI 65% Fe pellets
- Heating: 1.6 GJ/t DRI (450 kWh/t DRI) from electricity
- Electricity requirement:
  - 450 kWh/t DRI heating
  - 95 kWh/t DRI
  - 10 kWh/t HBI for briquetting

Electric Smelting Furnace, ESF

- Electricity requirement:
  - 600 kWh/t hot metal for cold DRI
  - 480 kWh/t hot metal for hot DRI
- Fe output: 95% Fe

Electric Arc Furnace, EAF

- Electricity requirement:
  - 600 kWh/t liquid steel for cold DRI
  - 480 kWh/t liquid steel for hot DRI
- 1.07 t Fe/t liquid steel metallic feed requirement

Basic Oxygen Furnace, BOF

- NG requirement:
  - 0.1 GJ/t liquid steel
- Electricity requirement:
  - 138 kWh/t liquid steel
- 1.06 t Fe/t liquid steel metallic feed requirement

RMI Graphic. Source: RMI analysis based on data from literature, various company reports and asset data

Exhibit A8: Hydrogen model assumptions

100% renewable energy build

- **Subsidies:**
  - **United States**
    - Hydrogen: 45V Hydrogen Production Tax Credit $3/kg for 10 years
    - Renewable Energy: 45Y Renewable Energy Production Tax Credit $27.50/MWh for 10 years or 30% Investment Tax Credit
  - **Canada**
    - Hydrogen: 40% Clean Hydrogen Investment Tax Credit
    - Renewable Energy: 30% Investment Tax Credit
- **Hydropower**
  (Modeling does not account for interannual seasonality differences, supply contract specifics, or competitive pressure on hydro prices. Modeling estimates that 30% of electricity is bought at $30/MWh and 70% comes from a behind-the-meter renewable system. Contract/supply availability and externalities/potential environmental impacts of hydropower not analyzed in this report but would be critical in pre-feasibility study.)
  Canada, Brazil, and Sweden use 30% of electricity for iron/steel processes and hydrogen production from hydropower grid at $30/MWh
- **Future (Late 2020s) proton exchange membrane electrolyzer assumptions:**
  - $804/kW uninstalled Capex (stack + balance of plant)
  - $443/kW indirect Capex (engineering, procurement, and construction, construction, land)
  - 63% electrolyzer efficiency
  - 53 kWh/kg system energy requirement
- **Future (Late 2020s) renewable energy assumptions:**
  - Wind Capex: $1150/kW
  - Solar Capex: $930/kW
- **Storage assumptions:**
  - $516/kg capital cost for hydrogen storage in pipelines

RMI Graphic. Source: RMI analysis based on data from literature, various company reports and asset data

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GREEN HYDROGEN CATAPULT

The Green Hydrogen Catapult aims to expedite the global adoption of green hydrogen by increasing production capacity 50-fold, deploying 80 GW of renewables-powered electrolyzers, and cutting costs by 50% to less than $2 per kg of green H2. This coalition, supported by the UN High-Level Climate Champions and RMI, brings together leaders in the green hydrogen market to address the challenge of decarbonizing hard-to-electrify sectors. It encourages collaboration across the green hydrogen value chain, inviting new members to join its mission to scale a green hydrogen economy. For more information please visit **www.greenh2catapult.com**

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