Full Report

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# Smarter, Leaner, Cleaner

## Direct Reduced Iron and the Future of American Steel

Commissioned by Ceres
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# Executive Summary

We conducted a technical-economic analysis of the potential in the United States for Direct Reduced Iron (DRI), between February and June 2026, with the support and advice of the expert stakeholder group listed below. The study explores the feasibility of different iron- and steel-making technologies under different sets of economic conditions.

The timing matters. The U.S. steel sector is entering a near-term capital investment cycle in which a large share of existing blast furnace and coke oven capacity must either be refurbished, replaced, or retired. These decisions involve multi-billion-dollar commitments that will define the structure of the U.S. steel system for decades.

The report examines four regions that capture the diversity of American ironmaking: Minnesota's Iron Range, the Gulf Coast, Pennsylvania, and Northern Indiana. For each, we weighed the factors that actually determine what gets financed and built: the cost of raw materials, energy, and equipment; transport; and how each pathway compares with the alternatives available in that region. Because input prices such as natural gas, electricity, and iron ore are volatile, we did not rely on single best-guess figures. We ran the economics across a range of plausible prices, so the findings reflect how each option performs under both favorable and unfavorable conditions rather than at one convenient snapshot.

## Limitations

This analysis compares production pathways under a common set of commercial assumptions, focusing on relative cost and capital intensity. It is built to show how pathways perform under shared conditions rather than to assess project-specific feasibility, detailed engineering design, or how markets might evolve over time. The results therefore indicate relative positioning for new-build DRI across pathways and regions under stated conditions, rather than predicting realized project outcomes.

# Findings

## The investment case

Direct reduced iron (DRI) is the future of American steel, not because it can undercut the price of steel from a blast furnace that has already been paid off, but because it is the best place to put the next dollar of new capital.

The U. S. is entering exactly the moment when that capital gets committed. The country's aging blast furnaces and coke ovens are reaching the end of their lives, and keeping one running is not free: a blast furnace must be relined with heat-resistant bricks every 15 to 20 years at a cost that can run into the hundreds of millions of dollars. And at end-of-life, a coke-battery rebuild can increase the bill by more than a billion dollars per battery, simply to extend a legacy asset another 15 to 20 years.

At that decision point, new-build DRI is the most attractive investible solution. It is the lowest-cost, new-build option in every region we modeled, and it clears the 15% real rate of return typically sought by investors at today's tariff-supported U.S. steel prices. That result holds even when we tested a depressed steel-price year and at higher electricity prices that might come in the future. DRI can be swapped for the blast furnace to feed basic oxygen furnaces at existing integrated steel mills, which typically specialize in higher-end, automotive-grade steel. It also operates easily with state of the art electric mini-mill steel making. Here recycled scrap and new virgin iron from ore (as hot briquetted or pig iron) are flexibly mixed on a batch-by-batch basis for end consumers, allowing production of everything from structural steel, which normally has a high recycled content, to premium vehicle sheet steel. DRI also wins where the incumbent, blast-furnace technologies cannot follow: it operates "out of the box" at about 40% lower greenhouse-gas emissions and more than 80% lower local air pollution. With the flexibility to switch between gas and hydrogen, it can, in turn, provide a hedge against future energy and emissions costs. For a capital asset built to run for 40 to 50 years, the combination can add up to a compelling case.

**The Size of the Prize.** The DRI opportunity is best understood as two distinct things rather than one blended number. The first is a recurring cost. The U.S. imports roughly 4 to 6 million metric tonnes of merchant pig iron every year at a cost of $2 to $3 billion a year. Our analysis shows domestic gas-based DRI is cost-competitive with those imports in every region, an expenditure that could be value-captured at home. The second is the capital build-out. As the aging blast-furnace fleet reaches its reinvestment decisions over the coming decade and beyond, tens of billions of dollars of new capital will be deployed. DRI can compete for that investment furnace-by-furnace.

**Natural gas DRI is the lowest-cost new-build option in the four regions we examined.** On a new-build basis, DRI-based steelmaking runs about $610 to $628 per tonne of finished steel, against roughly $634 to $639 for a new blast furnace with basic oxygen furnace (Section 2.1, Figure 3). The most competitive configurations pair gas DRI with an electric arc furnace, or feed DRI through a submerged arc furnace into an existing basic oxygen furnace. Regional cost differences are small, so the mix of viable options is driven less by cost than by local differences in customer needs, feedstock access, infrastructure, and alternatives supplied by competitors.

**All four regions are attractive for investment.** Pennsylvania is marginally the cheapest on absolute cost, helped by ready access to natural gas, established supply lines, a skilled workforce, and proximity to customers. The Gulf Coast has a near-term siting advantage in deepwater port access, low-cost gas, and an emerging cluster of co-located gas-DRI and EAF operations. Minnesota's Iron Range leads on access to renewable electricity using wind from the Dakotas and the Southwest Power Pool, which is what unlocks DRI's lowest-carbon potential. Northern Indiana remains competitive on its legacy of high-quality primary steelmaking, strong transport links, a skilled workforce, and proximity to automotive customers.

**DRI achieves the 15% rate of return expected by investors, even under adverse market conditions.** At a 15% real target return, both new blast furnace steel and natural gas DRI are viable at today's US steel prices, which sit well above global prices because of tariffs (Section 2.2, Figure 4). Neither is, however, viable at internationally exposed benchmark prices, so the commercial case for new investment rests in part on continued trade protection. The DRI case is notably robust: it still clears the 15% bar stress tested against the worst U.S. steel-price year of the past fifteen and against a 20% jump in wholesale electricity prices (Section 2.6).

**Domestic DRI pig iron could compete with imports.** Modeled domestic DRI pig iron production competes on price with imported pig iron at roughly $414 to $503 per tonne (Section 2.3). In other words, domestic DRI pig iron could replace supply of a strategic material formerly sourced from Russia and Ukraine.

**DRI reduces exposure to energy-supply risk.** Flex-fuel DRI furnaces can swing between natural-gas-based and hydrogen-based operation, letting producers switch or blend fuels as prices, supply, and regulations change. At today's grid electricity prices, hydrogen-based DRI remains materially more expensive than natural gas, with a hydrogen premium on the order of $170 to $250 per tonne iron produced (Section 2.4). The gap closes only where very low-cost electricity, on the order of $20 per megawatt-hour, can be paired with hydrogen storage to capture low-price periods. These conditions are not typical of U.S. industrial power supply but are achievable in specific renewables-rich regions. We modeled green-hydrogen DRI in all four regions, and Minnesota's Iron Range is the standout: its near-term renewable potential, led by Great Plains wind and access to the Dakotas and Southwest Power Pool, gives it a competitive advantage in a carbon-constrained market, or where buyers specifically demand low-carbon iron. Closing the hydrogen cost gap in the near term would require durable support policies.

**DRI cuts pollution and regulatory risk.** Compared with the blast-furnace route, and using average US grid electricity, a natural-gas DRI furnace delivers more than an 80% reduction in local air contaminants and about a 40% reduction in greenhouse gas (GHG) emissions. Those figures improve further as green hydrogen becomes affordable. Beyond the downwind health benefits, lower emissions reduce a plant's exposure to tightening air-quality and climate regulation over its operating life.

**Increased domestic American iron trade will accelerate the shift to DRI.** As merchant pig iron, hot briquetted iron (HBI), and iron-ore pellets increasingly move dependably between regions within the United States, downstream EAF steelmakers will have more options to meet customer needs. Iron must be reheated when shipped to a second site, which adds some cost and emissions. But that penalty is outweighed by the improved batch-by-batch flexibility, for individual steelmaking sites and for the U.S. industry as a whole.

## Recommendations

**Based on the above analysis, we offer the following recommendations:**

**For steelmakers:** Our analysis is a starting point, not a site-specific blueprint. We encourage companies to use it as a baseline as they evaluate DRI projects at particular sites. Companies should continue to consult widely, inside and beyond the advisory group convened for this study, as they conduct analysis and weigh options.

**For investors:** The results point to near-term, new-build opportunities in flex-fuel DRI projects across all four regions. Siting decisions will be driven mainly by infrastructure, feedstock access, and downstream demand rather than by regional cost gaps.

**For policymakers:** Given that flex fuel DRI is cost-competitive in each region, state and local policymakers should engage steelmakers directly about the potential for DRI development projects in their own state. Given the performance advantages of DRI, additional plants are likely to be built. The major question is: where? Fortunately, state and local governments have a number of tools available to support industrial development, from development-forward permitting to tax incentives and more.

**For steel industry service and technology providers:** In the U.S., DRI will become a strategic component of iron supply, enabling a variety of new system configurations as outlined in this report. We recommend offering DRI site visits as a way to familiarize stakeholders with DRI 's potential to onshore iron production, modernize both steelmaking sites and the national steel production system, to onshore production of a critical material, to manage a variety of business risks, and to spur local economic development.

**Future of American Steel Study**

We wish to thank the business and academic professionals who generously shared their insights, time, and experience to shape this study. Their expert contribution was advisory only and does not constitute or imply endorsement of the study, its methodology, or its conclusions. These are the sole responsibility of Ceres, Dr. Bataille, and Dr. Li. Organizational names are provided below for identification purposes only and do to imply their endorsement of this report.

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## 1.0 The Case for Regional Analysis of Iron and Steelmaking in the United States

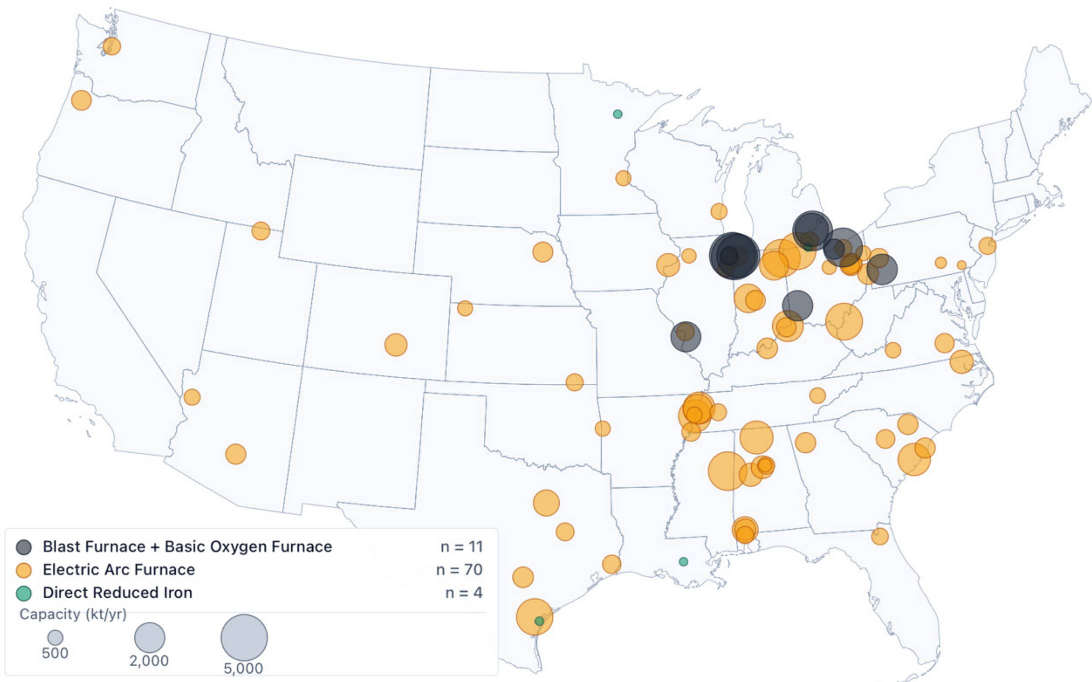
Industrial transitions in U.S. heavy industry are often framed as questions of technology choice: blast furnaces versus electric arc furnaces, natural gas versus hydrogen, carbon capture versus process redesign. While technological feasibility assessment remains highly valuable, that framing is incomplete. The U.S. iron and steel industry produced approximately 82 million tons of raw crude steel in 2025, with an estimated value of about $149 billion (1). The United States is also a major net importer: between 22% and 33% of total domestic steel demand has been met by overseas imports in recent years, with imports of around 29 Mt in 2022 making the U.S. the second-largest steel importer globally by volume (2,3).

What matters in practice is how the U.S. steel system reorganizes across regions, input chains, and business models as it responds to decarbonization pressure, trade exposure, cost volatility, and changing demand for both metallic inputs and end-use products. Steel is a particularly difficult transition case because the sector is both energy-intensive and process-emitting. The issue is not simply whether lower-carbon technologies exist, but whether they can be embedded in viable industrial configurations. Recent U.S.-focused analysis emphasizes that the primary barrier to steel decarbonization is economic rather than technical, with deep decarbonization pathways requiring substantial capital investment and lacking clear commercial returns under current market conditions (3,4).

This is not a distant question. A substantial portion of the remaining U.S. blast-furnace-based integrated steel fleet is approaching major reinvestment and asset-renewal decision points, including blast furnace relining cycles (5) and coke oven replacement cycles. Most of these blast furnaces are expected to come up for major relining and renovation over the next 5 to 7 years, with capital decisions typically prepared 3 to 5 years in advance. The present window is therefore the least-cost moment to shift to lower-emissions production rather than undertake routine refurbishment (3,6). The choice carries an outsized emissions footprint: U.S. integrated blast furnace steel production averages around 2.8 tonnes of $CO_2$ per tonne of steel, above the global integrated average of 2.2 tonnes and well above gas-based DRI pathways at roughly 0.7 to 1.4 tonnes, depending on how needed electricity is produced. Each relining decision therefore involves an emissions exposure that is both large in absolute terms and high relative to international peers running the same production route. The transition is therefore not only a long-term decarbonization challenge, but an immediate capital allocation problem in which lower-emissions options must compete directly with conventional reinvestment under real-world financial and strategic constraints.

The U.S. starting point is also distinctive. The industry is already structurally hybridized into two configurations. On one side sits the legacy integrated system built around domestically sourced iron ore, blast furnaces, pig iron, and downstream flat-rolled production. On the other sits a large minimill and electric arc furnace base, fed primarily by scrap but increasingly concerned with metallic quality, feedstock purity, and access to supplemental sources of iron. Electric arc furnaces accounted for about 71% to 72% of U.S. raw steel production in 2023 to 2024, while integrated production accounts for the balance and is concentrated in a much smaller set of facilities (7,8). By early 2025, pig iron and raw steel were being produced by two companies operating integrated mills in eight active locations, while raw steel from electric arc furnaces was produced by 47 companies at 102 minimills (1). Integrated and EAF capacity are not uniformly co-located across regions, reinforcing the importance of place-specific production dynamics. Figure 1 gives an overview of the geographical distribution of different steelmaking pathways in the continental United States.

**Figure 1 – Steel Manufacturing in the United States**

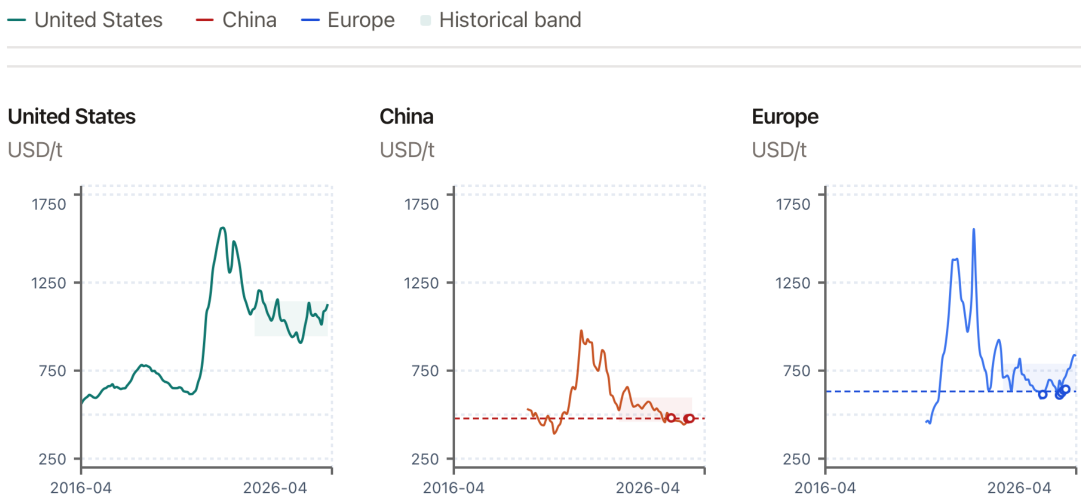



Source: Global Energy Monitor Iron & Steel Tracker; circle area scales with reported facility capacity (kt/yr).

That diversity is precisely why direct reduced ironmaking has become strategically important. DRI is not simply another process route, but part of a broader metallics strategy, meaning how steelmakers source and balance scrap and ore-based inputs to meet cost, quality, and emissions objectives. In industrial terms, DRI sits at the intersection of several pressures: the need to supplement scrap with cleaner sources of iron, the need to support higher-quality steel production in EAF-based systems, the option to transition from natural gas-based to hydrogen-based reduction over time, and the possibility of separating ironmaking from final steelmaking geographically. This flexibility allows investment decisions to be made under current fuel and cost conditions while preserving the option to transition toward hydrogen-based reduction over time (9–11). DRI is already widely used in gas-rich systems such as Mexico, is emerging on the U.S. Gulf Coast (12), and features prominently as a transition technology in international decarbonization pathway assessments (13). Its solid form also makes it readily transportable, opening the possibility of trade in intermediate iron units and potentially shifting ironmaking toward regions with structural energy advantages (14,15).

The U.S. question, then, is: what role can DRI plausibly play within the North American steel economy? Stakeholder discussions highlighted interest in DRI far beyond its role as a lower-emissions pathway. Priorities included its integration with smelting to produce pig iron, its potential to displace imports, its role in supporting higher-grade steel production, and the viability of merchant DRI and HBI markets. Stakeholders also emphasized that any viable pathway must be grounded in competitiveness and cash flow rather than in aspirational green steel narratives. This matters because green premiums are not widely observed across products and are typically linked to specific offtake agreements rather than general market conditions, while certification standards for green, low-emissions, or near-zero steel remain unsettled (16). Recent U.S. market conditions, including elevated domestic steel prices supported in part by reduced import competition caused by tariffs (see Figure 2), and extended order books at some mills (17,18), further reinforce the importance of evaluating pathways under realistic commercial assumptions rather than assuming stable market structures over multi-decade asset lives. Accordingly, this report does not assume that tariffs, subsidies, or green premiums persist over the full economic life of new assets. The more conservative posture taken here is intended to test which configurations remain commercially defensible if current support proves less durable than its statutory duration suggests (3).

**Figure 2 – Historical Benchmarks**




These dynamics translate directly into differences in business model. An integrated blast furnace/basic oxygen furnace route (BF/BOF), a scrap-based electric arc furnace (EAF) route, an integrated gas-DRI EAF facility, or a domestic merchant DRI briquetted iron or pig iron producer competing with imports are not simply alternative technologies, but distinct commercial propositions with different risk profiles, capital requirements, infrastructure dependencies, and exposure to trade. Geography plays a decisive role in determining that outcome. Energy prices, natural gas access, clean energy access, iron ore proximity and quality, port infrastructure, water availability, workforce capabilities, and proximity to end-markets vary materially across the United States, and these differences matter especially for DRI-based configurations, where the economics of reduction, transport, and downstream processing are highly location-sensitive (1). Stakeholder discussions highlighted a more specific set of binding siting constraints in practice, particularly deepwater port access, electricity cost and reliability, control over DRI-grade iron ore, seasonal transport logistics, and access to natural gas and water. These constraints are consistent with broader findings on ore-quality limitations and upgrading costs (16).

These structural differences are visible in metallics and product-quality requirements. The United States imports on the order of 4 to 6 million tonnes of pig iron per year, reflecting a structural gap between a predominantly scrap-based steelmaking base and limited domestic ore-based ironmaking outside the integrated segment (19). This reliance raises both cost and supply-security considerations and points to a potential role for domestic production as a substitute. Product quality also remains a binding constraint. Scrap availability and composition vary widely, and some applications, particularly those requiring tighter chemical control, limit the extent to which scrap alone can serve as a feedstock (20,21). As a result, scrap alone does not eliminate the need for ore-based sources of iron, and DRI matters not only for emissions, but for enabling new combinations of EAF production, quality control, and metallics supply (22,23).

For these reasons, this report treats the future of American steel as a regional and business-model question first, and a technology ranking exercise second. A large body of work has examined steel decarbonization from technology, policy, and market perspectives (see Appendix A). This report takes a different approach. Rather than evaluating pathways in isolation, it examines how they translate into region-specific, commercially viable configurations under real-world constraints. Differences in energy prices, resource access, infrastructure, and market exposure across U.S. regions are large enough to materially change which production pathways are viable in practice. A pathway that appears competitive in one region may not be financeable in another, and configurations that are infeasible in isolation may become viable when connected across regions. The transition therefore cannot be understood at a national level alone. The focus is not on identifying a single optimal technology, but on understanding which combinations of pathway, region, and business model can actually be financed and built within the U.S. steel system.

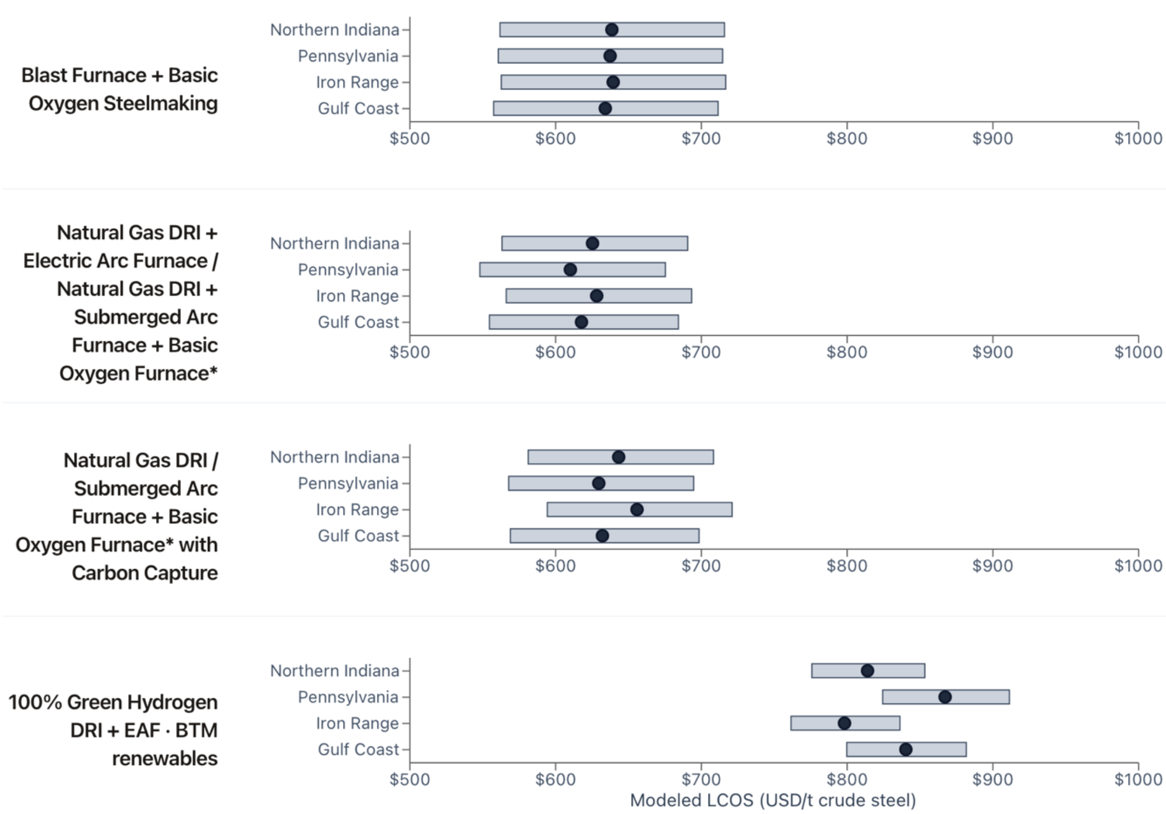
# 2.0 Comparative Results

## 2.1 Relative Technological Costs

Figure 3 summarizes levelized cost of steel (LCOS) across four production pathways: blast furnace–basic oxygen furnace (BF–BOF); natural gas DRI; natural gas DRI with carbon capture; and green hydrogen-based DRI. DRI configurations are shown for both electric arc furnace (EAF) and retrofit-compatible SAF–BOF (submerged arc furnace-basic oxygen furnace) routes. In this latter configuration, the blast furnace is replaced by a DRI-based reduction system, while existing BOF, casting, and finishing assets are retained. DRI is routed through a smelting step to produce a liquid iron stream compatible with BOF operation. This pathway potentially preserves site infrastructure, workforce, and both upstream and downstream integration, while shifting the emissions and cost structure of upstream ironmaking. While detailed cost data for smelting-based configurations is limited, available evidence suggests that capital requirements are broadly comparable to DRI-based new-build configurations when evaluated on a capacity-equivalent basis. As such, retrofit configurations should be understood as a variant of the DRI-based transition rather than a distinct technology pathway.

Results are presented for four regional archetypes: Gulf Coast, Iron Range, Pennsylvania, and Northern Indiana (see Appendix B for site selection and Appendix C for methodology). The BF–BOF costs reflect new-build facilities rather than relining or retrofit cases.

**Figure 3 – Levelized Cost of Steel by Technology Pathway and Region**




* DRI-SAF-BOF retrofit configuration requires existing BOF infrastructure.

Three findings stand out. First, cost ordering is consistent across regions. Natural gas DRI is the lowest-cost pathway in every region, followed by blast furnace steelmaking, with natural gas DRI with carbon capture and storage close behind. Hydrogen-based DRI remains substantially higher-cost in all cases. Median LCOS for natural gas DRI falls in a narrow band ($610–$628/t), while BF–BOF clusters slightly higher ($634–$639/t). The cost advantage of gas DRI over BF–BOF ranges from roughly $10–$30/t depending on region. Hydrogen DRI sits well above both, with median costs of ~$800–$870/t, or roughly $170–$250/t higher than gas-based DRI.

Second, regional sensitivity is pathway-specific. Blast furnace steelmaking costs vary little across regions, reflecting reliance on globally traded inputs rather than local energy conditions. Natural gas DRI also shows relatively tight variation ($18/t), reflecting some differences in regional natural gas prices. In contrast, hydrogen DRI exhibits the largest regional spread ($70/t), driven primarily by differences in electricity costs for behind-the-meter renewable supply. The Minnesota Iron Range has the lowest potential costs for hydrogen DRI of all the regions assessed.

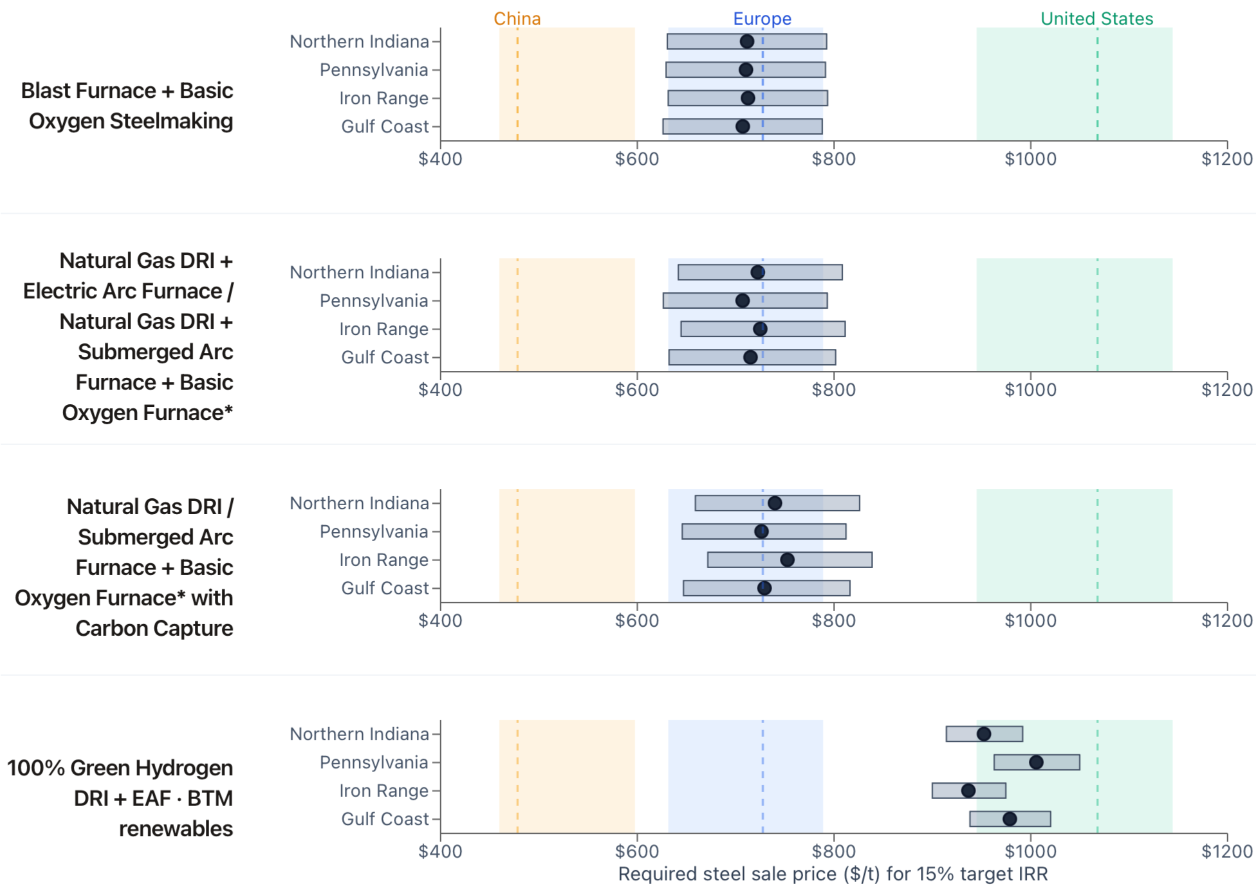
Third, uncertainty varies materially across pathways but does not alter the overall ranking. Blast furnace steelmaking shows the widest cost range (P10–P90 $155/t), reflecting exposure to iron ore and metallurgical coal volatility. Natural gas-based DRI pathways show somewhat narrower spreads ($130/t), driven by natural gas price variation. Hydrogen DRI has the narrowest spread (~$80/t), but its higher cost base means this tighter range does not close the gap with other pathways. The relative position of hydrogen DRI remains highly sensitive to electricity procurement assumptions, explored further in Section 2.4.

## 2.2 Commercial and Financing Implications: From Cost Competitiveness to Real-World Deployment

The results in Section 2.1 identify which pathways are competitive on a levelized cost basis. However, steel investment decisions are not made on cost alone: projects must also meet return thresholds consistent with real-world capital allocation. Figure 4 reframes the LCOS results in this context, showing the steel prices required to achieve a 15% real return for each pathway and region, alongside benchmark prices in the U.S., Europe, and China. Distributions are shown as Monte Carlo P10–P90 ranges, with reference lines indicating recent benchmark price levels (Figure 2). Technical details of the methodology used are provided in Appendix D. As with Section 2.1, blast furnace steelmaking results shown here are for new construction, not retrofits or relining, which we address in Section 3.0.

At a high level, natural gas DRI is the lowest-cost pathway across all regions, with Pennsylvania and the Gulf Coast sitting at the lower end of the gas-based range at roughly $700–$720/t. Differences between regions are small and within model uncertainty, but these two regions consistently appear among the most favorable configurations in the figure. The carbon capture DRI variant follows the same pattern and sits approximately $20–$30/t above the unabated gas DRI route. Hydrogen-based DRI operates at a distinctly higher cost level (~$940–$1,000/t) and shows greater regional variation, with the Iron Range at the lower end and Pennsylvania at the upper end. Under current electricity procurement assumptions, these configurations approach U.S. price levels but remain well above international benchmarks, indicating that they are not commercially competitive without materially lower input costs or additional policy support. Section 2.4 explores how these results shift under alternative power pricing conditions.

**Figure 4 – Investment Hurdle Analysis – Required Steel Prices at 15% IRR[1]**




* DRI-SAF-BOF retrofit configuration requires existing BOF infrastructure.

The gap between U.S., European, and Chinese benchmark prices reflects structural differences in market conditions. In the U.S., persistent trade protection, including Section 232 tariffs and a dense set of anti-dumping and countervailing measures, interacts with increasing market concentration following recent consolidation (i.e. Cleveland-Cliffs/Stelco, Nippon/U.S. Steel) among major producers (24). European prices reflect a more import-exposed market, greater producer fragmentation, and weaker industrial demand conditions since 2022 (25). In China, persistent overcapacity against a weakened domestic consumption base continues to push large volumes into export markets, with exports reaching ~117 million tonnes in 2024 (26), the highest in nearly a decade and rising (27,28), while state-linked producer access to low-cost capital, subsidized energy and land, and historically favorable export VAT treatment further depress export prices below the marginal cost structures faced by Western producers (29). This indicates that, under current conditions, both conventional reinvestment and gas-DRI-based configurations are commercially viable if the steel can be sold into the U.S. market.

Against the European and Chinese benchmarks, the picture changes. No modeled U.S. pathway at a 15% real return clears the Chinese benchmark. The European context is more complex. Exporting U.S. steel into Europe adds freight costs (Atlantic Ocean shipping) of approximately $35–$70/t from coastal sites such as the Gulf Coast (30–32), with inland regions (Iron Range, Northern Indiana, Pennsylvania) adding roughly $15–$55/t for rail movement to port (30). Beginning in 2026 and phasing in through 2034, the EU Carbon Border Adjustment Mechanism (CBAM) applies a charge equal to the EU ETS price (currently ~$70–$92/t$CO_2$ (31,33)) applied to embedded emissions (full passthrough as there's no federal U.S. carbon price). So once transport costs and tariffs are accounted for, no U.S. pathway under this assessment is commercially viable for selling into Europe, even at the top end of the recent European price range (3-year observations). This creates a central commercial insight: U.S. steel investment at a 15% real return is viable within the current domestic price environment, but not necessarily under internationally exposed conditions without continued price support, policy intervention, or materially lower capital intensity.

These results highlight a central feature of the U.S. steel transition: investment viability is shaped as much by market structure and capital discipline as by underlying production costs. Pathways that are technically feasible or even cost-competitive in isolation may not proceed unless they can meet return thresholds under real-world market conditions. The transition is therefore best understood as a process of selective deployment, where only a subset of configurations clears both cost and financing constraints within specific regional and market contexts.

## 2.3 Intermediate Products: Pig Iron and HBI

Intermediate products are central to understanding how the U.S. steel system can reconfigure in practice. While most techno-economic comparisons focus on integrated steel production routes, the ability to produce, trade, and use intermediate iron units such as pig iron, sponge iron, direct reduced iron (DRI) in lump or pellet forms, and hot-briquetted iron (HBI) determines how those routes connect across regions. These materials act as the link between upstream ironmaking and downstream steelmaking. They allow ore-based iron to be produced in locations with favorable energy and resource conditions and then transported to electric arc furnace (EAF) steelmaking facilities elsewhere. In doing so, they relax the need for co-located blast furnace ironmaking and enable a wider range of system configurations than would be possible under a strictly integrated model. As a result, the competitiveness of intermediate products is not only a question of standalone cost, but of how they reshape the feasible architecture of the steel system. The analysis below therefore evaluates pig iron and HBI not simply as products, but as mechanisms through which regional advantages can be translated into system-level change. Figure 5 illustrates merchant price benchmarks for imported pig iron and DRI, while Figure 6 compares modeled production costs for DRI-derived pig iron and HBI across the four regional archetypes against current merchant-price benchmarks.

**Figure 5 - Merchant Price Benchmarks for Pig Iron and DRI**

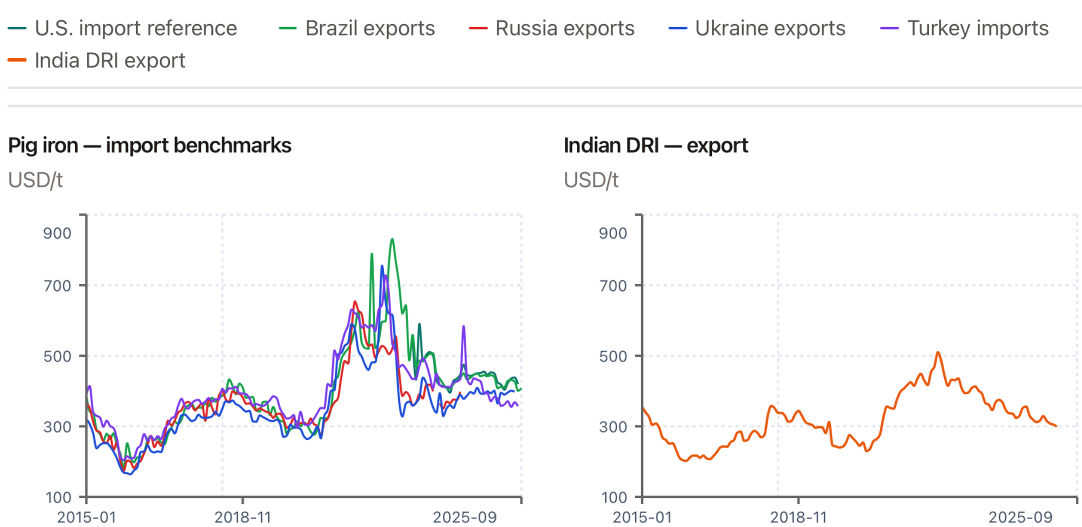
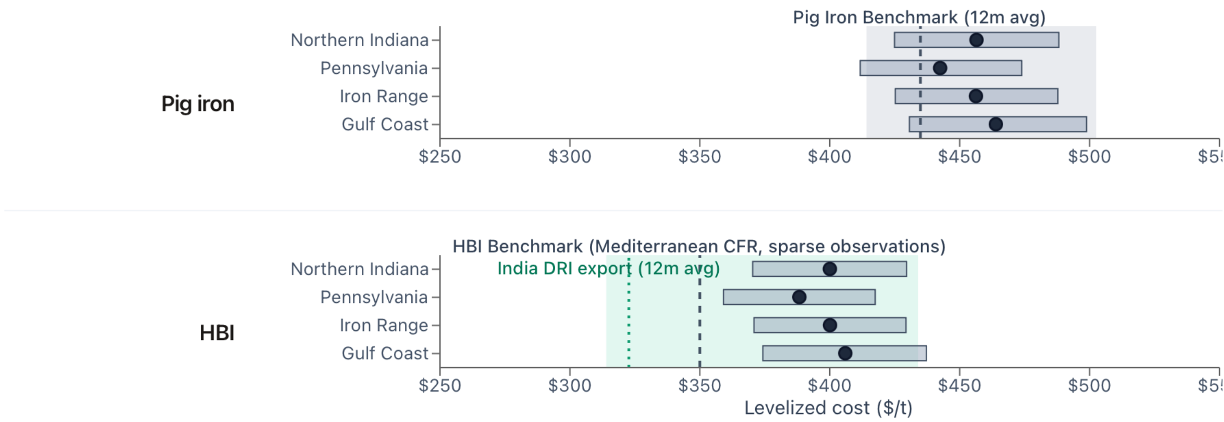


**Figure 6 - Intermediate Products Screening**




* DRI-SAF-BOF retrofit configuration requires existing BOF infrastructure.

The United States currently imports on the order of 4–6 million tonnes of pig iron per year, with imports in the most recent 12-month window reaching approximately 5.5 million tonnes (1). Supply is becoming increasingly concentrated: in 2022 Brazil accounted for roughly 42% of U.S. imports (~2.3 Mt), followed by Ukraine (~0.7 Mt), Russia (~0.6 Mt), and India (~0.4 Mt). Recent conflicts between two major producers (Russia and Ukraine), where up to 18 Mt per year of pig iron production capacity has effectively been destroyed, have led to a corresponding increase in supply from Brazil. This import flow reflects a structural gap between the predominantly scrap-based U.S. steelmaking base and limited domestic ore-based ironmaking outside the integrated blast-furnace segment - and it defines a potential addressable market for domestic merchant pig iron supply. The Russo-Ukrainian war has raised national domestic security of supply concerns for several commodities, including steel. It is a reasonable question to ask whether and how the US has the capacity to supply its own reduced iron in a reasonable time frame if necessary.

Domestic natural gas-DRI pig iron is competitive with current U.S. import prices across all four regions modeled. Monte Carlo cost ranges for Pennsylvania ($412–$474/t P10–P90), Iron Range and Northern Indiana (~$425–$488/t each), and Gulf Coast ($431–$499/t) all sit within the trailing 36-month P10–P90 envelope of Brazilian FOB New Orleans import prices ($414–$503/t). Regional cost differences are modest, with P50 production costs spanning ~$443/t (Pennsylvania) to ~$464/t (Gulf Coast).

The export-oriented HBI question is structurally different. Where pig iron is tested against a domestic import-replacement benchmark, HBI is tested against an export-destination benchmark. Against a Mediterranean CFR reference of ~$350/t (Europe is often identified in global decarbonization scenarios as a potential destination market for low-carbon iron units (14)), no U.S. configuration reaches parity: Pennsylvania is closest at ~$388/t (P50, ~$38 above parity), with Iron Range and Northern Indiana at ~$400/t and Gulf Coast at ~$406/t. But a broader international price envelope provides a second reference point. The trailing 36-month P10–P90 range of Indian DRI export prices ($312–$436/t) captures the range at which internationally traded merchant iron units have cleared in recent years. Against this envelope, all four U.S. gas-DRI HBI configurations sit largely or fully within the band: Pennsylvania ($359–$418/t P10–P90), Iron Range ($371–$429/t), and Northern Indiana ($370–$430/t) are fully inside, while Gulf Coast ($374–$437/t) is fully inside through its P10 and reaches the band's upper edge. So all four U.S. sites' modeled cost distributions sit within the envelope of prices a comparable merchant iron-unit market has realized as recently as 2022–2023. For domestic use, the relevant comparison is the landed cost of imports rather than FOB benchmarks. Indian DRI at ~$323/t FOB India over the past 12 months, plus freight to U.S. ports and the 25% Section 232 tariff, places imported material at or above the modeled cost range of any U.S. gas-DRI HBI configuration. Domestic gas-DRI HBI is therefore competitive across all four regions against the realistic alternative facing a U.S. EAF buyer.

There are two important caveats. First, the observable HBI benchmark reflects a thin merchant market, not the full strategic opportunity for U.S. low-carbon iron units. Global DRI production reached 141 million tonnes in 2024 (34), but the vast majority of that volume is consumed captively as hot DRI at co-located EAF operations rather than traded. The merchant segment, which is primarily HBI and cooled DRI, represents only a small single-digit share of global DRI output, and the Mediterranean CFR benchmark used in this analysis is constructed from a limited set of observable transactions within that narrow segment. The benchmark therefore indicates what current merchant HBI trades at, not what iron-units demand would support in a structurally different future merchant market.

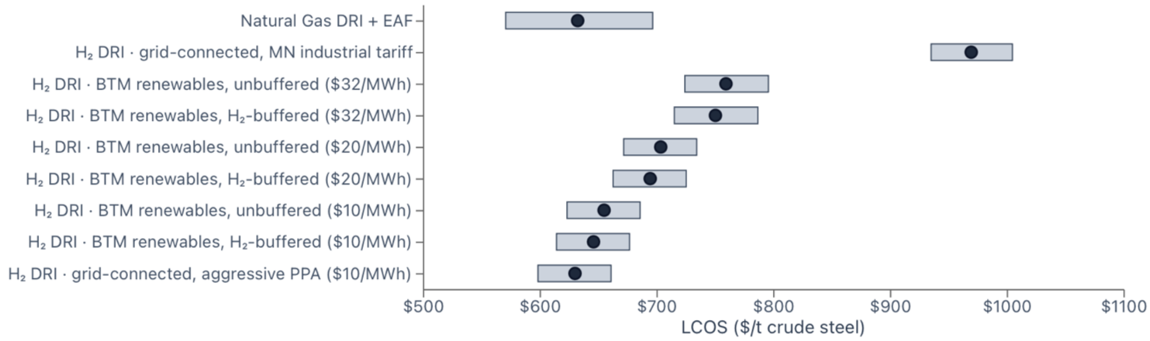
Second, several structural forces point to a materially larger addressable market for merchant iron units than the current benchmark implies. European blast-furnace retirements driven by energy costs and tightening carbon policy are creating demand for ore-based metallics that European scrap cannot satisfy: approximately 24 DRI projects totaling around 40–50 million tonnes of DRI capacity have been announced across Western and Northern Europe, and major European steelmakers have committed to DRI-based transition pathways (35). Scrap quality is a binding constraint on this transition: European prime (low-copper) scrap supply is materially insufficient to feed the new EAF flat-steel capacity being built, and producing quality-sensitive flat steel (for example, automotive sheet with copper content below 0.1%) from EAF routes requires a substantial ore-based metallics charge rather than scrap alone (12,35). Similar scrap-scarcity dynamics apply in other EAF-growth regions with limited domestic scrap generation, including parts of the Middle East and Southeast Asia. These dynamics suggest that a realistic forward view of merchant HBI pricing may diverge from the current sparse benchmarks - potentially upward, if European and other low-carbon steel transitions tighten global demand faster than supply.

## 2.4 Hydrogen DRI: competitiveness as an electricity procurement question

Section 2.1 and Section 2.2 established a clear headline: green hydrogen DRI sits roughly $170–$250/t above the cheapest incumbent pathway across all four regions under current assumptions, and required prices for a 15% target IRR place green hydrogen DRI as broadly uncompetitive in most regions in the near term. Those findings reflect the canonical operating configuration: behind-the-meter renewables paired with multi-day hydrogen storage, sized to maintain electrolyzer utilization despite intermittent renewable supply. Other operating configurations for the same pathway - different supply architectures, different storage sizes, different effective electricity costs - produce materially different economics.

Figure 7 compares nine operating models on a single levelized-cost axis. Each row is a distinct project configuration: a specific combination of hydrogen supply architecture (behind-the-meter renewables versus grid-connected), electrolyzer capacity factor, and effective electricity cost.

**Figure 7 – Electricity Pricing and Operating Model Effect on Hydrogen DRI Competitiveness with Natural Gas DRI**




* DRI-SAF-BOF retrofit configuration requires existing BOF infrastructure.

Figure 7 shows three configurations:

- **Behind-the-meter renewables, unbuffered (CF=0.45):** a dedicated wind/solar farm supplying an on-site electrolyser with no storage and no grid backup. When generation stops, the DRI plant stops.
- **Behind-the-meter renewables, $H_2$-buffered (CF=0.675):** the same ring-fenced architecture, but with multi-day hydrogen storage between electrolyser and shaft furnace. Real-project precedents (i.e. HYBRIT (36,37)) often include some element of onsite storage for $H_2$. The capacity factor used in this configuration is 0.675, set as an illustrative intermediate point between unbuffered (0.45) and grid (0.90). This is intended as a screening-level proxy for "materially improved but non-grid-like" utilization rather than a physically derived outcome of a specific storage sizing. The actual utilization a real buffered plant would achieve depends on how much storage is installed and how electrolyzer operation is tuned against intermittent supply. The conceptual basis for treating renewable electricity, electrolysis, and hydrogen storage as an integrated system for low-carbon primary iron is drawn from the literature (38,39).
- **Grid-connected (CF=0.9):** an electrolyser drawing from the transmission grid, running at a chemical-plant-like availability consistent with the central-case industrial assumptions in the literature (40,41). The procurement contract determines the effective $/MWh.

Within the behind-the-meter families, three price points are shown symmetrically: $32/MWh, the wind proxy for Minnesota (derived from Global Wind Atlas inputs (42,43) with NREL ATB 2024 cost anchors for 2030), $20/MWh as quoted in literature as an important illustrative benchmark for low cost hydrogen production (44,45), and $10/MWh which is illustrative of heavily renewable driven systems where power pool pricing can go very low or negative for extended periods (46).

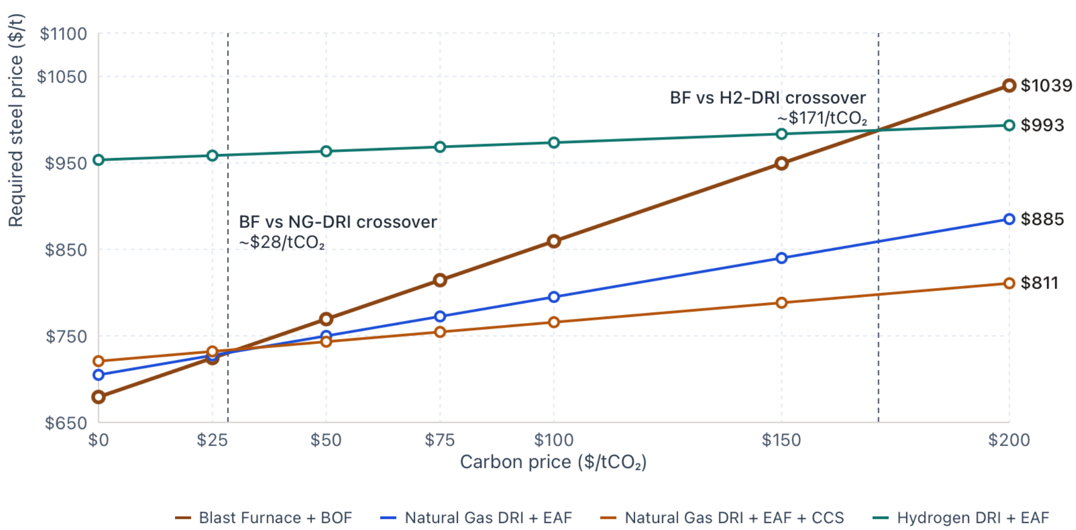
The competitiveness gap between hydrogen DRI and natural gas DRI (P50 of $632/t at Iron Range 2030) depends strongly on which operating model is assumed, not on the pathway itself. The naive grid-connected configuration is the worst case, not the baseline. An electrolyzer operating at the Minnesota industrial tariff (~$78/MWh in 2030) and running at 90% availability produces an LCOS of $969/t, which is $337/t above natural gas DRI. This is the configuration many readers implicitly picture when they hear "grid-connected electrolyzer". The behind-the-meter unbuffered configuration at $32/MWh produces an LCOS of $759/t, the modeled cost reported for Iron Range in earlier sections. At $20/MWh, the range of costs for hydrogen DRI starts to become competitive with the upper end of the range for gas DRI, while at $10/MWh the hydrogen DRI option would compete neck and neck with unabated natural gas. The buffering effect is small under the assumed CF uplift and storage CAPEX.

At all three price points, adding hydrogen storage and lifting the assumed electrolyzer capacity factor from 0.45 to the illustrative 0.675 changes LCOS by approximately –$9/t: the additional storage capital is largely offset by the assumed utilization improvement.

## 2.5 Carbon Pricing Sensitivity

The results presented in Sections 2.1 and 2.2 do not include explicit carbon pricing. However, the relative position of blast furnace and DRI-based pathways is highly sensitive to $CO_2$ costs, particularly in regions where baseline cost differences are small. Figure 8 illustrates this effect for Northern Indiana as a representative marginal region. Costs are adjusted as a function of emissions intensity, showing how production costs increase under rising carbon prices. Because blast furnace steel carries substantially higher emissions intensity than natural gas DRI, its cost rises more rapidly as carbon prices increase. The comparison shown is for new-build blast furnace steelmaking facilities, not retrofits or relining (which we address in Section 3.0).

**Figure 8 - Investment Viability Sensitivity to Illustrative CO2 Pricing (Northern Indiana, P50)**




* DRI-SAF-BOF retrofit configuration requires existing BOF infrastructure.

This leads to a clear crossover in investment viability. At baseline in the example above, blast furnace steel and natural gas DRI + EAF are close in required price, with blast furnace steel marginally competitive. As carbon pricing increases, the gap narrows and reverses. In the central case shown, natural gas DRI becomes competitive with blast furnace steel at approximately $28/t$CO_2$. – the preference for DRI in greenfield US reduction investments over the last generation indicates operators may be quietly pricing in a carbon premium, besides enjoying the flexibility enhancements. Beyond this point, the cost advantage shifts decisively toward DRI-based configurations. The magnitude of this effect is large relative to the baseline differences observed in Section 2.1. In Northern Indiana and similar inland regions, where blast furnace and natural gas DRI pathways are separated by differences on the order of $10-30/t, even moderate carbon prices are sufficient to change the relative ordering of pathways. This indicates that carbon pricing does not need to be extreme to affect investment decisions in these regions; it needs only to be sustained and material.

However, the same mechanism does not extend to hydrogen-based pathways under current assumptions. While carbon pricing compresses the gap between blast furnace and natural gas DRI, it does not close the gap to hydrogen DRI. Even at carbon prices well above \$100/t$CO_2$, hydrogen-based configurations remain above both blast furnace and gas-DRI pathways in required price. It is not until support policies are on the order of \$170/tCO2 that hydrogen DRI would start to be competitive with blast furnace steelmaking in this case study. These results highlight a key distinction between pathway transitions.

Carbon pricing can shift the relative competitiveness between incumbent and near-term technologies, particularly in marginal regions. It does not, on its own, bring forward hydrogen-based ironmaking under current cost structures (although provision 45V of the IRA would have materially addressed this issue (3,47,48)). The effect of carbon pricing is therefore to accelerate substitution within the existing technological frontier, rather than to immediately enable the next one. The same directional logic may also arise through trade exposure rather than domestic policy. In particular, the EU's Carbon Border Adjustment Mechanism creates increasing cost exposure for higher-emissions steel sold into the European market, reinforcing the commercial disadvantage of blast-furnace-based routes relative to lower-emissions alternatives.

## 2.6 Electricity Pricing Sensitivity

The baseline project inputs (see Appendix C) apply the EIA Annual Energy Outlook 2025 reference case for industrial electricity prices (49), which projects roughly flat real-term prices through 2050. Independent forecasters treat this baseline as conservative for the 2025–2035 horizon. NERC's 2026 Long-Term Reliability Assessment revised projected 10-year peak demand growth upward by 69% relative to its 2025 assessment, citing data centers as the dominant driver (50). PJM capacity auctions have cleared at or near the FERC-approved cap for three consecutive auctions, with data-center load accounting for 40% of the most recent capacity bill (51,52). Recent academic work projects that data-center growth could lift average US wholesale electricity costs by 8% by 2030, with regional outcomes exceeding 25% in data-center-concentrated markets, and with these costs typically passed through to retail and industrial customers (53).

Against this evidence, the sensitivity analysis applies a single calibrated +20% long-term industrial electricity price shock to the AEO 2025 reference case. The magnitude is set above the published central estimate of national wholesale-cost increase (approximately +8% by 2030 per Wade et al., 2025) but substantially below the year-on-year wholesale energy- and capacity-price moves now clearing in PJM. The implicit assumption is that industrial customers retain partial insulation through contract structure and forward-market hedging, and so absorb only a fraction of the wholesale and capacity-cost movement, while absorbing more than the national-average central estimate would imply over a 10–25 year plant investment horizon. This is a methodologically stronger position than picking either endpoint as it requires only that some of the published pass-through occur, not that wholesale-market-scale moves transmit fully to industrial customers. The core findings of the analysis hold steady under this +20% test case i.e. natural gas DRI retains its position as the lowest-cost new-build pathway in every region, with regional differences preserved, domestic pig iron remains within the trailing-36-month Brazilian import-price envelope, etc.

# 3.0 System Architectures and Transition Pathways

The results in Section 2 describe pathway-level cost and investment outcomes. However, these results do not translate into direct substitution between technologies. The U.S. steel system evolves through the interaction of existing asset constraints and the development of new supply relationships. In particular, the capital cycle of the blast furnace fleet and the emergence of tradable iron units determine how and where alternative pathways can be deployed. The transition is therefore not best understood as a sequence of plant-level technology switches, but as a reconfiguration of system architecture. New technologies do not replace incumbent systems simply because they are marginally more cost-competitive in isolation. Instead, system evolution depends on how new production routes interact with existing infrastructure, how intermediate products can be produced and moved, and how downstream steelmaking requirements are met.

Section 2 compared four integrated steel production routes across four regional archetypes and showed that relative competitiveness depends strongly on both region and operating model, with hydrogen-DRI competitiveness driven as much by electricity procurement as by the pathway itself. Interpreting these results at the system level requires moving beyond pathway rankings to consider how production, trade, and demand are connected. This section therefore introduces a set of system configurations that are already present in the U.S. steel system and that the component-level results suggest will remain relevant through the 2030s, and identifies the intermediate products (pig iron, DRI, and HBI) that form the connective tissue between them. A pathway-by-pathway ranking implicitly assumes that each region adopts its locally cost-optimal route. This is the implicit structure of most published steel decarbonization analyses and of the techno-economic model used in this report, and it is also a simplification. Several key features of the U.S. steel system are not captured if analysis remains at the pathway level.

First, iron units are transportable. Pig iron moves from Brazil to New Orleans at scale today. HBI moves from the Gulf to Europe in smaller volumes. Pellets move from Minnesota to Indiana on the Great Lakes. The Gulf Coast gas-DRI competitiveness result is therefore not only a statement about Gulf Coast steel production, but about the availability of a merchant iron-unit stream that could feed EAFs elsewhere. Second, customer-side requirements are heterogeneous. Automotive flat steel requires low-copper metallics that ferrous scrap alone cannot reliably supply, whereas long products and construction grades accept a wider metallics mix. A region's cost-optimal pathway is therefore shaped by the downstream demand it serves, not only by local energy prices. Third, the U.S. steel system is already hybrid. Approximately 70% of steel produced in the U.S. is produced via EAF, and a substantial share of that production depends on imported pig iron and DRI/HBI to meet quality specifications. Any forward view that treats the system as a collection of isolated integrated facilities misrepresents the current starting point.

The natural gas–fed, syngas reductant DRI-based pathway is dominant under most current pricing forecasts, and could be even more dominant if flex-fuel furnaces running autothermal reforming are standardized. These configurations allow the reduction system to operate initially on natural gas–derived syngas while retaining the ability to incorporate hydrogen over time, without requiring full process replacement. Autothermal reforming also produces a relatively concentrated $CO_2$ stream as part of normal operation, which can be routed to capture and storage infrastructure with comparatively limited additional process complexity. This creates a pathway in which carbon capture can be added incrementally to new-build DRI facilities using commercially available technology, rather than requiring a step-change in process design. Taken together, these characteristics change the investment profile of DRI-based systems. Instead of requiring a single forward commitment to a fully decarbonized configuration, they allow developers to potentially stage investments over time: deploying natural gas–based DRI under current cost conditions, adding carbon capture where infrastructure and policy support exist, and incorporating hydrogen as input costs and supply conditions evolve. In system terms, this flexibility reinforces the role of DRI as a bridging architecture. It enables new ironmaking capacity to be deployed under current commercial constraints while preserving optionality across multiple decarbonization pathways, reducing the risk that near-term capital decisions lock the system into a single long-term trajectory.

## 3.1 Key System Architectures

The component-level analysis, combined with stakeholder discussions during the study, points to a small number of system configurations through which the U.S. steel sector is likely to evolve. These configurations are not mutually exclusive, and each is already visible in the current system. The relevant question is not which one dominates, but how their relative weight shifts as investment decisions are made in the late 2020s and early 2030s. The results have described the economics of new-build facilities and therefore speak to forward-looking capital allocation rather than the operating cost position of existing plants. Existing integrated mills benefit from fully or partially depreciated capital and operate under fundamentally different cost structures. The comparative framing is therefore most relevant to forward-looking investment decisions and to the evolution of the system as replacement and expansion capital is deployed, not to the relative competitiveness of specific plants operating today.

## 3.2 Archetype 1: Regionally integrated production

The first configuration corresponds to regionally integrated production, in which ironmaking and steelmaking remain co-located within a single region using locally available energy, infrastructure, and feedstocks. The existing Great Lakes blast-furnace integrated mills are the canonical example, as are co-located natural gas DRI + EAF operations in regions with favorable gas access. The analysis in this report shows that new-build natural gas DRI configurations are broadly cost-competitive across all four archetypes, with regional cost differences within roughly $20/t at the P50 - small enough that pathway choice rather than location dominates the cost picture. The siting case for regionally integrated production therefore rests less on regional cost advantages than on resource endowment, infrastructure, and downstream proximity. On those grounds, the Gulf Coast is the clearest case: deepwater port access, abundant low-cost natural gas, and an emerging cluster of co-located gas-DRI + EAF operations make it a natural location for new integrated production. The Great Lakes (Northern Indiana) and Pennsylvania regions retain regionally integrated production primarily through the existing fleet's depreciated capital and downstream customer proximity, not necessarily through a new-build cost advantage. The Iron Range, by contrast, has resource endowment that points away from integrated steelmaking and toward an upstream role: domestic iron ore, established pellet production capability, and gas-DRI pig iron costs competitive with imported Brazilian pig iron (Section 2.3). Iron Range is therefore potentially better positioned as an upstream iron production node feeding downstream EAFs elsewhere than as a location for integrated crude steel production.

This configuration becomes viable when regional energy and feedstock advantages align with integrated production economics, and where site-level constraints do not prevent redevelopment. Brownfield integration matters in this context. In addition to greenfield configurations, DRI-based pathways can also be deployed as retrofit configurations within existing integrated sites. In these cases, blast furnace ironmaking is replaced by DRI routed through a smelting step to produce a liquid iron stream compatible with BOF operation, allowing existing casting, rolling, and finishing assets to remain in use. This approach preserves site integration, workforce capabilities, and established logistics networks, while shifting the emissions and cost structure of upstream ironmaking. Modern gas-based shaft DRI configurations that integrate reforming and reduction within the reactor can, in some cases, avoid the need for large external reformers, reducing spatial requirements and allowing greater flexibility in fitting new process units into constrained existing sites. While footprint flexibility is not a primary driver in the techno-economic comparison, it is often a real constraint in Great Lakes and Pennsylvania contexts where site limitations might affect redevelopment options. The configuration weakens where regional input costs erode the competitiveness of integrated production or where physical and permitting constraints limit the ability to redevelop existing sites. In these cases, alternative configurations that separate ironmaking and steelmaking become more relevant.

## 3.3 Archetype 2: Domestic Iron Corridors

The second configuration corresponds to domestic iron corridors, which represent the primary mechanism by which the U.S. steel system can decouple ironmaking from steelmaking. In this configuration, ironmaking and steelmaking are separated across regions and linked through domestic trade in upgraded iron units: DR-grade pellets from the Iron Range, and merchant pig iron or HBI from regions such as the Gulf Coast, supplying EAF-based steelmaking in regions with scrap and market access but without local ore or low-cost gas. Iron Range pellet production is an established capability. The analysis in Section 2.3 shows that both the Gulf Coast and Minnesota Iron Range regions have the potential to produce gas-DRI pig iron at costs comparable to observed prices for imported Brazilian pig iron over the last 3 years. Both regions could therefore be credible candidates for supplying merchant iron units into the broader U.S. steel system, particularly if structural changes in the international merchant pig iron system (e.g. destroyed legacy production capacity from the Russo-Ukrainian conflict) persist for the foreseeable future. This configuration becomes viable as merchant iron supply scales and as transport, contracting, and offtake arrangements develop to support inter-regional trade.

Two structural observations affect the viability of domestic iron corridors. First, near- to medium-term DRI deployment is highly pellet-dependent. Commercially proven and bankable DRI systems remain overwhelmingly pellet-based, and fines-based routes under pilot and demonstration have not yet established the reliability, throughput, and utilization rates required for large-scale industrial deployment. Domestic iron corridor configurations are therefore conditional on the scale and cost trajectory of U.S. beneficiation and pelletization capacity. Second, if high-grade pellet supply proves constrained, the downstream configuration may need to shift toward DRI combined with a smelting step, such as submerged arc furnaces or other smelters producing pig iron, rather than DRI feeding EAFs directly. This represents a strategic branch in the system configuration: not only how ironmaking is decarbonized, but how the downstream steelmaking system is structured under evolving raw material constraints.

The strength of this configuration derives from the combination of regional cost asymmetries and the tradability of iron units. It is most strongly supported where merchant iron production is competitive with imports, as shown in Section 2.3 for Gulf Coast and Iron Range gas-DRI pig iron, and where downstream EAF-based steelmaking has both access to scrap and a structural need for supplemental ore-based metallics. Under these conditions, the ability to separate ironmaking from steelmaking allows regions with energy or resource advantages to specialize upstream, while downstream production remains located close to end markets. The configuration is further reinforced when differences in input costs across regions are large relative to transport costs, creating a persistent economic incentive for inter-regional iron-unit trade rather than co-located integrated production. The configuration weakens where raw material constraints, logistics bottlenecks, or insufficient scale in merchant iron production prevent reliable supply. Its pace of development depends directly on the expansion of domestic ironmaking capacity, the build-out of transport and contracting infrastructure, and the willingness of downstream producers to rely on externally sourced metallics rather than integrated production.

## 3.4 The Existing System Constraint: Blast Furnace Capital Cycles

Most of the remaining U.S. blast-furnace capacity, concentrated in Indiana and Pennsylvania and held by a further-consolidated group of producers after the 2024–25 Cleveland-Cliffs/Stelco and Nippon/U.S. Steel transactions, comes up for major relining in the late 2020s (3,5). A reline is a multi-hundred-million-dollar capital decision (often on the order of $300m (54)) that extends the furnace by 15–20 years. At captive coke-supply sites where coke batteries match blast furnaces approximately one-to-one, end-of-life convergence between reline and battery rebuild can stack the integrated capital decision to $700 million-$1.3 billion per blast furnace ($500M-$1B per modern coke battery rebuild (55,56) on top of the $200-300 million reline), meaningfully closing the gap to a DRI-based retrofit at the next reinvestment cycle. But at sites that have already migrated to merchant coke supply, the reline decision might be completely decoupled from coke-plant capex. The operative choice at each site is reline as-is, convert to a natural gas DRI configuration, or retire.

On the component economics alone, the default is likely to be refurbishment, at least for sites that do not have coke batteries to replace. The regionally integrated production analysis in Section 2.2 treats each pathway as a new-build comparison, which is not the decision the existing integrated fleet actually faces. Operating blast furnaces carry partially or fully depreciated capital and run under lower effective cost structures than the new-build screens show; a reline is cheaper on a whole-of-capital basis than a new-build conversion. Relining a blast-furnace is only the order of one-third to one-half of the cost of constructing a new one (54), whereas a retrofit to replace the blast furnace with new DRI shaft furnace and a submerged arc furnace (SAF) feeding the existing basic oxygen furnace, is likely to require investment on the order of several billion USD per site. Blast furnaces with carbon capture and storage, which would allow retrofit rather than replacement, is at TRL ~5 with no active 90% capture pilots at industrial scale and it is unfortunately not a live technology option for the current wave of refurbishments (3). So while new blast furnaces may not look that attractive on the economics, blast furnace steelmaking facilities in Indiana and Pennsylvania are likely to reline in the late 2020s and operate into the early to mid 2040s, absent any external pressure. Two mechanisms will determine whether that default position persists in future.

**System-level: domestic iron corridors at scale.** If the Domestic Iron Corridors described in Section 3.3 develop to scale, Indiana and Pennsylvania EAFs able to source competitive merchant pig iron or HBI from the Gulf Coast or the Iron Range have less reason to keep an on-site blast furnace running. The integrated-mill architecture does not get dismantled by retiring individual furnaces on cost. It gets dismantled when the downstream steelmaker no longer needs the ironmaking step attached to the steel mill. That is a decade-scale shift driven by the downstream side of the system, not by the reline economics of any individual furnace, and its pace depends directly on how quickly domestic merchant iron capacity scales and on the contracting and logistics infrastructure for inter-regional iron-unit trade.

**Policy-level: carbon pricing and carbon exposure.** Section 2.5 shows that even moderate carbon prices materially alter the operating cost stack of blast furnace and natural gas DRI pathways in marginal regions. At an emissions intensity of roughly 1.8 $tCO_2$ per tonne of crude steel, a carbon price of ~$50/$tCO_2e$ adds on the order of ~$90/t to blast-furnace operating costs, compared to roughly half that for natural gas DRI. In the representative Northern Indiana case, the required-price crossover between blast furnace and natural gas DRI occurs at approximately ~$28/$tCO_2e$. This is large relative to the $10-30/t baseline cost differences observed in Sections 2.1 and 2.2, and would directly enter the capital allocation decision at reline.

This changes the interpretation of policy risk. The question is no longer whether carbon pricing might matter, but whether it will be present and durable at levels sufficient to enter the reline decision. Carbon exposure may arise through multiple channels, including explicit domestic carbon pricing, sectoral emissions standards, or trade-linked mechanisms that embed carbon costs in export markets (e.g. Europe (57,58)). The blast-furnace retention case therefore rests on the absence of sustained carbon pricing or equivalent signals. In the presence of such pricing, the reline-as-is default is no longer supported by the underlying cost structure.

Taken together, the implication is that the existing U.S. blast-furnace fleet is likely to reline through the late 2020s and operate into the 2040s unless one of two conditions changes: either the downstream side of the system develops a substitute supply of ore-based metallics at scale, or carbon costs or equivalent regulations enter the capital-allocation calculation with sufficient durability. New primary steel capacity over the same window will predominantly be natural gas DRI + EAFs, concentrated on the Gulf Coast and, contingent on the Domestic Iron Corridors scaling, at other sites (possibly Minnesota's Iron Range) fed by inter-regional iron-unit trade. Absent either of those two mechanisms, the integrated fleet decarbonizes through the retirement edge rather than the reline edge.

## 4.0 Implications for the Future of American Steel

**The U.S. system will reconfigure rather than substitute.** No single pathway dominates across regions, and no single configuration captures the system. Natural gas DRI + EAF emerges as the lowest-cost pathway in all four regions analyzed, with regional cost differences small enough that location decisions for new-build capacity are driven less by cost gradients than by resource endowment, infrastructure, and downstream proximity. Pennsylvania and the Gulf Coast have the lowest absolute modeled gas-DRI costs, with the Gulf Coast retaining the clearest siting case on infrastructure and gas-access grounds. Results are robust to reasonable variation in key input assumptions, particularly natural gas pricing, industrial electricity-price stress consistent with current data-center-driven demand forecasts, and capital cost uncertainty.

**DRI is central to every plausible configuration.** Gas-based DRI is competitive with blast furnaces in the regions where it is sited, can produce iron units usable as pig iron or HBI for merchant markets, and provides the feedstock EAFs require to mix with secondary scrap to serve quality-sensitive downstream demand. Its role is not confined to a specific decarbonization scenario, but reflects its position within the broader metallics balance of the system.

**The near-term investment case for DRI rests on the elevated U.S. domestic price environment.** At a 15% real target IRR and realistic capital costs, blast furnace and natural gas DRI configurations are commercially viable under current U.S. prices, but sit above international benchmarks for European and Chinese steel markets. Current U.S. prices are themselves at the upper end of their historical range ($945–$1,144/t over the last three years), implying that an investment thesis based on present conditions is also a thesis on the durability of trade protection and market concentration.

**Green hydrogen DRI is primarily a question of electricity procurement.** Under the central operating model, it sits $170–$250/t above gas-based DRI across the four regions today, narrowing somewhat at the 2030 horizon as electrolyser CAPEX declines. This premium closes only under very low electricity prices, on the order of $10/MWh, which are not typical of U.S. industrial supply but may be achievable in specific regions. The most credible candidates are the Great Plains and Upper Midwest, where high renewable resource quality and a power pool that increasingly clears at low (and occasionally negative) marginal cost could combine to support hydrogen production at industrial scale. Outside those geographies, and outside that procurement story, green hydrogen DRI would not compete on the modelling shown here in the near term without additional policy support.

**DRI-based metallics compare favorably with imports across all four regions modeled.** Natural gas-DRI pig iron costs align closely with observed costs for imported Brazilian pig iron. Domestic gas-DRI HBI is also shown to be competitive against merchant DRI/HBI that would otherwise serve U.S. EAFs, especially when freight and tariff costs are layered on.

The implications of these results are straightforward but important. In the absence of a material change in policy or market structure, the existing integrated blast furnace fleet is likely to continue along its current capital cycle. Relining remains the default decision at the plant level, extending the operational life of these assets into the 2040s. At the same time, new-build primary steel capacity in the United States is unlikely to take the form of additional blast furnaces. No new blast furnaces have been built in the U.S. since 1980.

Across the configurations examined, natural gas–based DRI paired with EAF steelmaking emerges as the most commercially viable pathway for new investment under current conditions. The result is not a sudden replacement of the existing system, but a gradual reweighting, with new capacity entering through DRI-based routes while legacy assets persist until displaced by either economic or policy pressures.

A central feature of this transition is the flexibility embedded in modern DRI systems. Flex-fuel DRI furnaces, particularly those based on autothermal reforming, can be deployed today using natural gas–derived syngas while retaining the ability to incorporate hydrogen over time. In the near term, this enables meaningful emissions reductions relative to blast furnace steelmaking, on the order of ~35–70% depending on electricity inputs to the EAF.

At the same time, these systems produce relatively concentrated $CO_2$ streams, allowing carbon capture to be added incrementally using commercially available technology. Over longer time horizons, the same assets can transition toward higher shares of hydrogen as input costs, infrastructure, and supply conditions evolve. In this sense, DRI functions not only as a production pathway but as a platform for staged decarbonization, reducing the risk that near-term capital decisions lock the system into a single long-term configuration.

The role of DRI also extends beyond direct steel production. As shown in Section 2.3, gas-based DRI can produce merchant iron units, including pig iron and HBI, at costs that are competitive with imports in certain regions, particularly along the Gulf Coast. This creates the possibility of a domestic metallics supply base capable of supporting a predominantly EAF-driven steel system. In this configuration, DRI combined with downstream smelting or briquetting can supply high-purity iron units for either on-site use or inter-regional trade. This is particularly relevant for quality-sensitive applications where scrap alone is insufficient, and suggests that the evolution of metallics markets may be as important as the evolution of steelmaking technologies themselves.

Taken together, these dynamics point toward a system in which ironmaking and steelmaking are increasingly decoupled. Rather than replacing blast furnaces one-for-one, the U.S. steel system is more likely to evolve through the expansion of domestic iron corridors, in which upstream iron units are produced in regions with structural advantages and transported to downstream EAF-based production. This configuration allows new capacity to enter where it is most cost-effective, while enabling the gradual displacement of integrated ironmaking as alternative sources of metallics become available at scale. The pace of this transition will depend on the development of logistics, contracting, and supply relationships, as well as on the evolution of demand for higher-quality EAF steel products.

The key uncertainty is not technological feasibility, but the conditions under which these configurations can scale. The analysis shows that moderate carbon pricing or equivalent policy signals are sufficient to shift investment decisions at the margin, but are not required for DRI to enter the system as new capacity. Conversely, hydrogen-based DRI remains highly sensitive to electricity procurement conditions, and is unlikely to play a major role in the near term outside of regions where sustained low-cost power can be secured. Demand growth, trade policy, and the structure of metallics markets will therefore play a decisive role in determining how quickly the system reconfigures.

The central conclusion of this report is that the future of American steel will be determined less by a single technological breakthrough than by how a set of already-available pathways are combined in practice. Natural gas DRI, flex-fuel capability, carbon capture, and merchant iron-unit production together form a coherent and commercially grounded transition architecture. The question is not whether these elements exist, but how they are deployed, and at what scale. The decisions made over the next decade will not produce a single national outcome, but they will define the structure of a more flexible, regionally differentiated, and potentially lower-emissions steel system for decades to come.

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# Technical Appendix

## Appendix A: Positioning Within Existing Analysis and Literature

Recent analysis of steel decarbonization spans multiple domains, including technology roadmaps, policy and transition strategy, market design and demand formation, and emerging perspectives on the trade and geography of ironmaking. Together, these strands establish a broadly shared understanding of the main pathways and structural challenges facing the sector. In particular, there is now strong agreement that near-zero emissions steel production is technically feasible, that direct reduced iron (DRI) and scrap-based production will play central roles, and that infrastructure, policy, and market conditions will be critical to enabling transition (13,16).

Technology-focused analyses, including those produced by the International Energy Agency and research groups such as Material Economics, primarily address technical feasibility. These studies evaluate the emissions reduction potential of alternative production routes - DRI, electric arc furnaces (EAFs), carbon capture and storage (CCS), and hydrogen-based processes - and outline long-term pathways to near-zero emissions at the global level (13,59). A second body of work, including recent analyses by Rocky Mountain Institute and U.S. federal agencies, focuses on policy and transition strategy. These studies examine reinvestment decisions in existing assets, the role of federal and state incentives, and the enabling conditions required to deploy lower-emissions technologies, including access to clean electricity, hydrogen development, carbon transport and storage infrastructure, permitting timelines, and workforce transition (5,60,61). Taken together, these strands define what is technically possible and what is institutionally required, but generally treat regional variation and commercial constraints in a stylized or secondary way.

A third strand focuses on market formation and demand-side mechanisms, including procurement strategies, certification schemes, and buyer coalitions such as the First Movers Coalition (62). This work addresses revenue uncertainty and early-stage investment risk, but does not in itself resolve how production structures evolve across regions or how supply-side competitiveness differs under real-world conditions. In parallel, a growing set of studies integrates techno-economic, trade, and system-level perspectives. Industry-aligned pathway work and scenario analysis highlight the potential for coordinated global transitions, including DRI deployment, green iron trade, and coal phase-out (63,64). More detailed modelling approaches show that geography, trade, and cost heterogeneity materially influence decarbonization pathways (3,6). Related work on green iron corridors and steel hubs suggests that ironmaking may shift toward regions with structural advantages in energy or feedstocks, while steelmaking remains closer to demand centers (14,15,65). However, these approaches are typically global or national scale and do not provide detailed, region-specific comparative evaluation within the U.S. context i.e. at the level of states, regions and municipalities.

The existing literature provides a strong foundation for understanding how steel decarbonization may unfold at global and national scales. However, relatively little work evaluates these questions at the sub-national scale where investment and siting decisions are actually made. Because energy prices, resource endowments, infrastructure availability, logistics constraints, and proximity to markets vary substantially across regions, these differences can materially shape the relative competitiveness of alternative production pathways.

This study addresses that gap. It builds on established technology and policy insights, incorporates emerging perspectives on market structure and trade, and extends them through a comparative, regionally explicit techno-economic framework. Rather than focusing on a single pathway, region, or enabling condition, it evaluates multiple steel production pathways across distinct U.S. regional archetypes, incorporating variation in energy prices, resource access, infrastructure conditions, and logistics, and linking these to uncertainty analysis, market benchmarking, and project finance screening. In doing so, it does not prescribe a single transition pathway. Instead, it clarifies how different combinations of technology, region, and business model produce differentiated outcomes, and under what conditions those configurations appear commercially plausible within the U.S. steel system.

## Appendix B: Regional Analysis Approach

### Regional Archetypes

To support interpretation - particularly for readers not directly engaged in steel production - this section provides a concise overview of how each region functions within the broader U.S. steel system. The objective is not to catalogue assets, but to clarify the role each geography plays in feedstock supply, production, and emerging configurations. The relative feasibility of steel production pathways in the United States is shaped fundamentally by regional conditions. Differences in energy costs, natural gas availability, iron ore access, infrastructure, logistics, water resources, and proximity to end-use demand define the baseline within which steel manufacturing operates. These factors are not secondary considerations; in many cases, they act as binding constraints on what can be built, at what cost, and at what scale. To capture these effects in a structured and comparable way, the analysis that follows is organized around a set of regional archetypes. Each archetype represents a distinct combination of input conditions and industrial structure.

The purpose is not to describe individual locations exhaustively, nor to recommend specific sites for development, but to provide a consistent lens through which pathway performance can be evaluated across different parts of the U.S. steel system. Existing U.S. production already shows clear regional clustering: integrated  blast furnace capacity is concentrated in the Midwest and Northeast, gas-based

DRI facilities are clustered on the Gulf Coast, and EAF capacity is distributed across most of the country (3). The four regional archetypes used here are designed to mirror that geography rather than to disaggregate it further.

### Minnesota Iron Range: Upstream Iron Supply

The Minnesota Iron Range functions primarily as an upstream resource and processing region. Its role is anchored in the mining and beneficiation of iron ore, which is converted into pellets and shipped to steelmaking facilities, particularly in the Great Lakes region. While historically oriented toward blast furnace-grade pellets, there is increasing attention to direct reduction-grade pellets and higher-value intermediate products such as hot-briquetted iron (HBI). State-level procurement materials also distinguish among steelmaking pathways, including integrated production based on iron ore or iron ore pellets and secondary production based primarily on scrap in electric arc furnaces (66).

Upgrading iron ore into higher-value intermediate products such as DR-grade pellets, HBI, or pig iron expands the feasible transport radius and enables participation in downstream steelmaking systems beyond the immediate region. In this sense, the Iron Range is best understood as a strategic feedstock base within the U.S. system, with relevance to DRI-centered configurations occurring primarily through its ability to supply ore-based iron inputs rather than through local steel production.

### Gulf Coast (Louisiana): Energy-Linked Ironmaking

The Gulf Coast, and Louisiana in particular, represents the most developed U.S. environment for gas-based direct reduction. The region combines abundant natural gas, deepwater port access, and established industrial infrastructure, making it well suited to DRI-based configurations. This role is visible in current industry practice. DRI facilities in Louisiana form part of vertically integrated raw materials strategies, supplying ore-based iron to downstream steelmaking operations and, in some cases, supporting merchant production (67). This allows DRI to function either within vertically integrated systems or as a merchant product, depending on configuration. The combination of energy access and logistics enables both domestic integration and potential export-oriented configurations, making the Gulf Coast potentially the strongest candidate in the United States for energy-linked ironmaking and merchant DRI or HBI production.

### Indiana / Great Lakes: Integrated Steel Core

The Indiana / Great Lakes region remains the center of integrated steel production in the United States. It contains a high concentration of blast furnace capacity and is closely linked to downstream manufacturing, particularly automotive production. The regional system is characterized by large-scale, capital-intensive facilities, established supply chains, and proximity to both raw materials and end-use markets. Regional planning and economic development materials underscore this concentration, identifying northwest Indiana as a highly specialized primary metals and manufacturing hub, even as the sector has declined overall in recent years (68). This existing asset base provides scale and industrial capability but also creates path dependence. As a result, emerging pathways such as DRI are more likely to appear initially as supplements to existing production systems rather than as wholesale replacements. This reinforces the continued importance of feedstock quality and process integration in this region.

### Pennsylvania: Mixed and Transitional System

Pennsylvania occupies a more mixed position within the U.S. steel system. Historically central to steel production, the region today reflects a combination of legacy integrated assets, EAF-based production, and broader manufacturing activity. Its steel ecosystem is less concentrated than the Great Lakes core and less clearly aligned with a single production model. State-level and statewide industrial strategy materials frame Pennsylvania as a significant manufacturing base pursuing advanced-manufacturing competitiveness while facing transition challenges around technology integration, capital, and workforce capability (69). This mixed structure makes the region analytically useful as a transitional case. It highlights the challenges of integrating new pathways into existing industrial contexts where infrastructure, energy conditions, and asset configurations are not strongly aligned with a single emerging production model.

### Implications for Interpretation

Taken together, these regional archetypes illustrate that the U.S. steel system is composed of distinct but interconnected industrial ecosystems. For example:

- The Iron Range functions primarily as a feedstock platform, with growing relevance to DRI through DR-grade pellet production.
- The Gulf Coast represents the leading U.S. environment for energy-linked ironmaking and merchant DRI/HBI production.
- Indiana anchors the integrated steel core, with strong ties to automotive demand and existing blast furnace capacity.
- Pennsylvania reflects a hybrid and transitional system, where legacy assets and emerging pathways interact under less clearly aligned conditions.

These differences are not incidental. They are central to interpreting the analysis that follows. Pathway feasibility is shaped not only by technology and cost, but by how those pathways interact with existing regional conditions, infrastructure, and industrial roles. The comparative results should therefore be understood as conditional on these regional contexts, rather than as uniform conclusions applicable across the entire U.S. steel system.

## Appendix C: Analysis Approach

This study uses a comparative techno-economic framework to compare alternative steel production pathways across a set of U.S. regional archetypes. The analysis covers multiple production routes, including integrated blast furnace pathways, scrap-based electric steelmaking, and gas- and hydrogen-based direct reduction configurations, evaluated under a common set of regional input conditions. Pathways are compared on a levelized cost basis using a standardized cost framework that incorporates capital, energy, raw materials, labor, and other major cost components. Results are presented across multiple time horizons to show how relative pathway performance changes under different regional and market conditions.

To distinguish robust findings from assumption-sensitive ones, the study incorporates sensitivity analysis and Monte Carlo simulation over key cost drivers, including capital costs, commodity inputs, and energy prices. These uncertainty results are used to show how pathway rankings and cost ranges vary under plausible alternative conditions. The analysis also compares modeled costs against selected market reference points to provide a directional view of relative competitiveness. These comparisons are intended as screening tools rather than forecasts of realized margins at specific plants or in specific markets. Finally, the study applies a simplified project investment screen to test whether pathways that appear competitive on cost also appear viable under a common set of commercial assumptions. This finance layer is indicative rather than bankable and is intended to support early-stage strategic interpretation, not project-specific investment decisions. Full methodological detail is provided in the technical appendix.

The model evaluates a fixed set of integrated crude-steel and intermediate product production routes, including scrap-based electric arc furnace (EAF) steelmaking, blast furnace–basic oxygen furnace (BF–BOF) production with and without carbon capture, natural gas–based direct reduced iron (DRI) feeding EAF steelmaking with and without capture, and hydrogen-based DRI feeding EAF steelmaking as a distinct pathway. These pathways are constructed from engineering-economic data derived primarily from the International Energy Agency technology roadmap and related literature, including energy and material intensity benchmarks for EAF and DRI systems (13,70,71), blast furnace process characterization (72–74), and hydrogen-based ironmaking (75,76). Carbon capture is incorporated using literature-based estimates of incremental capital and energy penalties where relevant (77,78), with additional transport and storage costs applied (79,80). Gas-based DRI is represented as a generic shaft-furnace route aligned with literature benchmarks rather than vendor-specific configurations, while hydrogen-based steelmaking is modeled as a distinct pathway with electrolyser costs informed by published cost trajectories (39,81). Electric arc furnace pathways include alternative metallic charge configurations to reflect different balances between scrap and ore-based inputs.

Capital costs in the techno-economic model are converted into per-tonne values using a standard capital recovery formulation based on a real discount rate, asset life, and utilization rate defined at the regional archetype level, such that levelized costs reflect annualized capital charges rather than explicit project cash flows. A real weighted average cost of capital on the order of ~8% is used as a representative screening value, consistent with common practice in industrial techno-economic analysis (13). A separate screening-level finance layer is then applied to assess investment viability under simplified commercial assumptions. This layer reconstructs project-level economics using a representative plant scale and benchmark-based revenue proxies, evaluates performance using standard financial metrics such as net present value and internal rate of return.

### Key Inputs

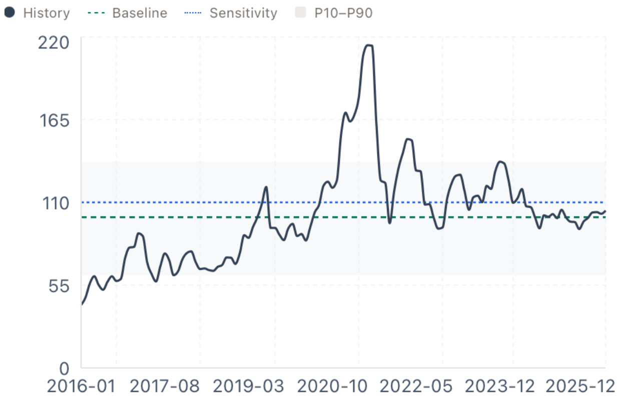
Raw materials and energy costs often dominate steelmaking economics. Figure 9 highlights a range of key model inputs such as data on iron ore, ferrous scrap, and industrial electricity and natural gas pricing. Iron ore prices are taken from the World Bank's Commodity Markets Outlook monthly Pink Sheet series (82), and ferrous scrap prices from the USGS Iron and Steel Scrap monthly statistics (83,84). Industrial natural gas and industrial electricity are represented at the state level using EIA monthly series (49) for the four archetype regions that anchor the regional cases: Louisiana (Gulf Coast), Minnesota (Iron Range), Pennsylvania, and Indiana. Figure 10 illustrates solar and wind resources used for assessing renewable energy potential and the economics of producing hydrogen from renewable electricity (42,43,85).

Figure 11 shows how industrial energy prices are projected across the modelled time horizon using EIA data (49). In our modelling the variation is used as growth factors applied to each regions energy prices, so for example, a Gulf Coast plant inherits the same gas-price uncertainty shape but starts from Louisiana's lower current price rather than the national average. The model uses three Annual Energy Outlook (AEO) 2025 price paths - the EIA's Reference Case, plus a high and a low case that bracket it (chosen from 11 AEO scenarios). The bracket pair are AEO's Low Oil and Gas Supply and High Oil and Gas Supply scenarios, which push gas and electricity prices furthest apart and so give the widest credible spread to stress-test against. By 2050 the scenarios vary significantly depending on the fuel. Electricity prices stay in a fairly narrow band of around \$77–94/MWh, and metallurgical coal barely moves at all (every scenario lands within \$7.4–7.5/MMBtu). Natural gas is where the uncertainty really shows up in EIA's analysis: against a Reference Case of \$5.4/MMBtu, the low-price case falls to \$3.9 and the high-price case climbs to \$10.4 - about a 2.5× spread.

**Figure 9 – Historically Benchmarked Energy and Raw Material Inputs**

### Iron Ore

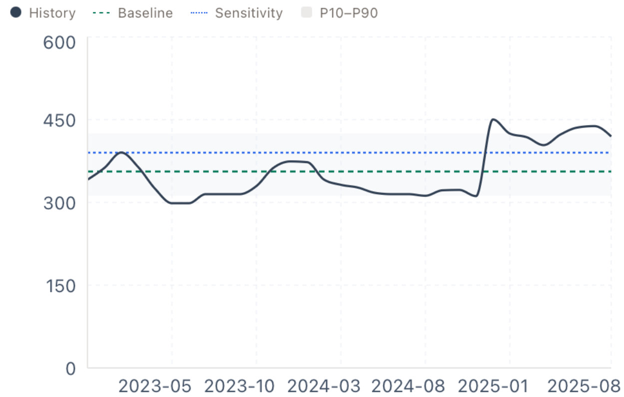
USD/t dry




Baseline: **100 USD/t dry** · P10–P90: **61.7–137 USD/t dry**

### Ferrous scrap

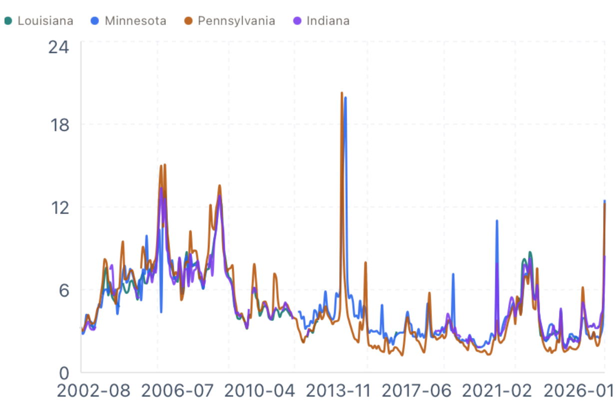
USD/t




Baseline: **356 USD/t** · P10–P90: **312–425 USD/t**

### Industrial natural gas

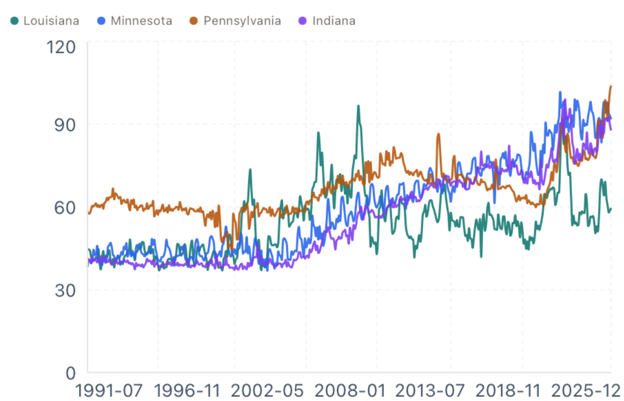
USD/MMBtu




Recent range (2024–2025): **1.50–6.18 USD/MMBtu**

### Industrial electricity

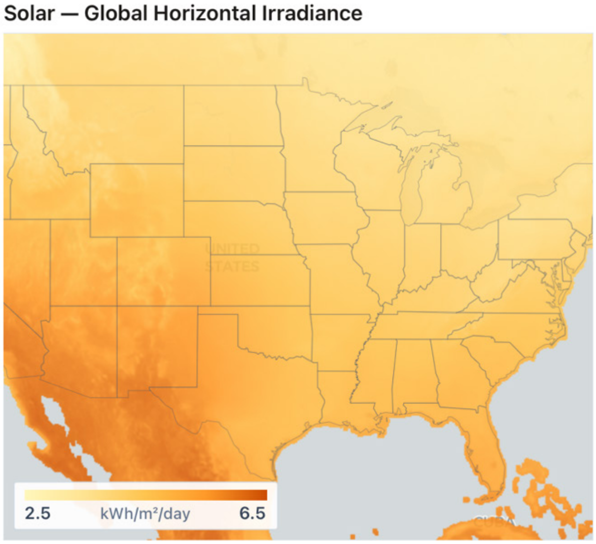
USD/MWh




Recent range (2024–2025): **50.5–104 USD/MWh**

**Figure 10 - Solar and Wind Resources**

### Solar — Global Horizontal Irradiance




### Wind — Capacity Factor (IEC Class 2)

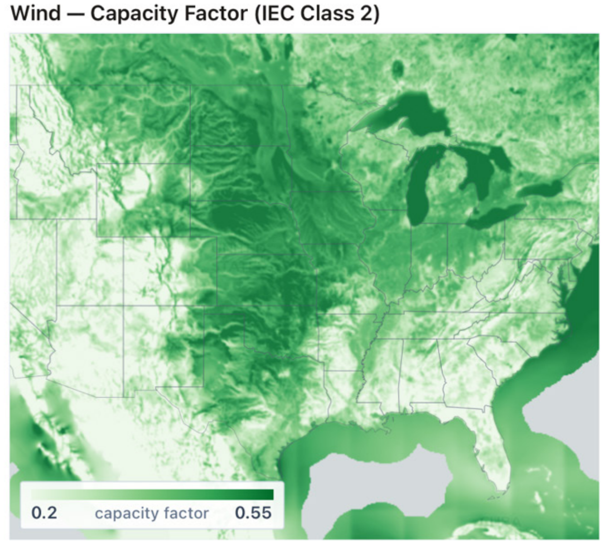
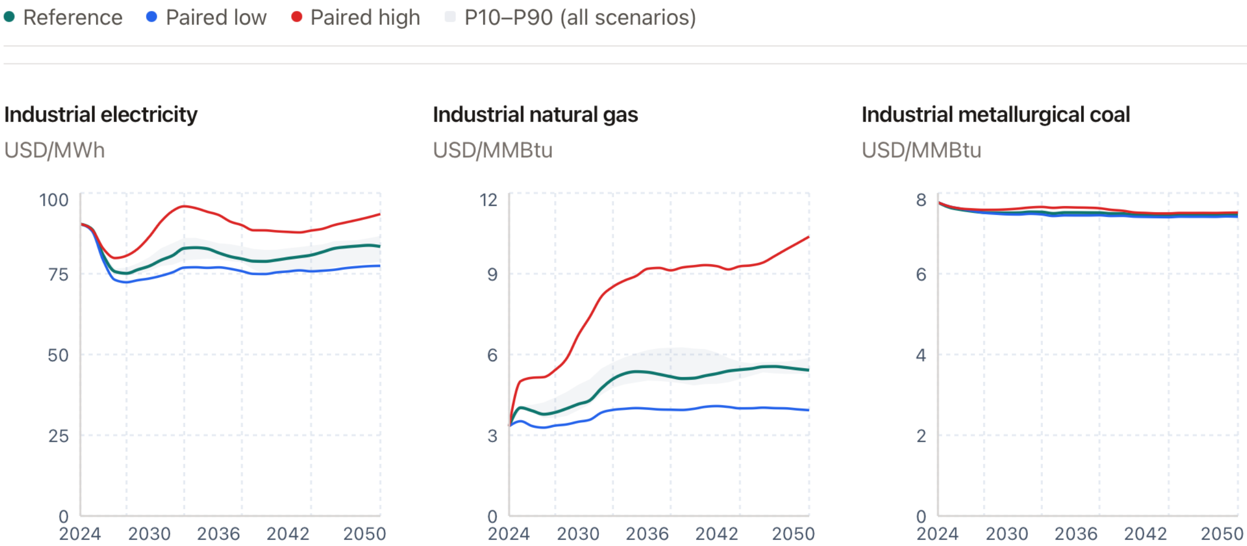


**Figure 11 – Energy Price Trajectories**

2024–2050 · 11 scenarios. AEO: reference + paired low/high; faint band = all scenarios.



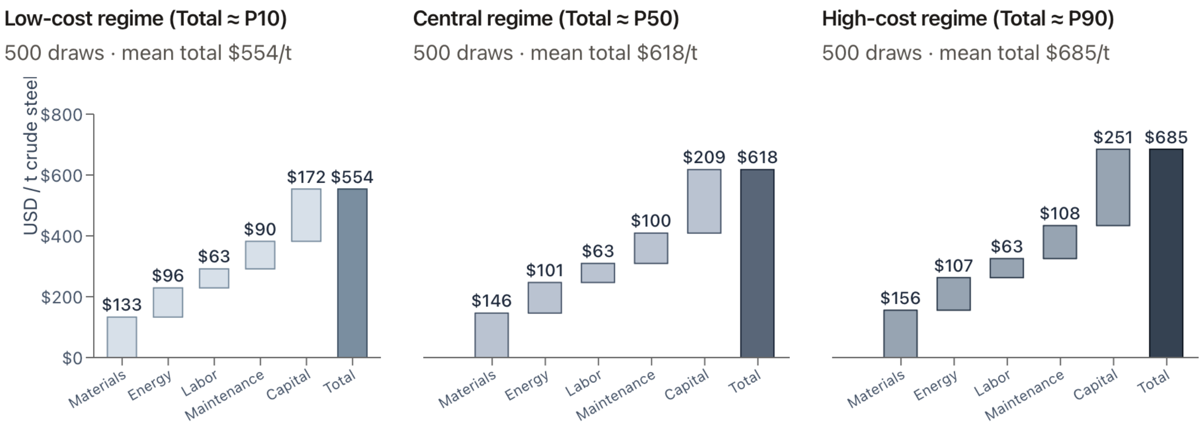

Scenario bands apply to energy costs; steel revenue uses separate benchmarks.

## LCOS Construction and Uncertainty Treatment

The levelized cost of steel (LCOS) is defined as the minimum plant-gate price required for a new facility to cover all costs of construction and operation over its lifetime, expressed per tonne of output. The analysis constructs LCOS by building up costs across major components including capital recovery, maintenance, labor, energy, and raw materials for each pathway. Capital costs are converted to per-tonne values using a capital recovery approach based on a real weighted average cost of capital, asset life, and utilization rate. Uncertainty is incorporated using a Monte Carlo simulation framework. For each pathway and region, the model samples documented uncertainty ranges across key inputs, including capital costs, energy prices, and raw material prices. The cost build-up is repeated across 5,000 simulation runs, generating a distribution of outcomes for each pathway. Modeled BF-BOF and EAF costs are within range of independent plant-level cost data published in the Global Steel Cost Tracker ((86), 2018-2020 vintages, n=39 US plants)

To illustrate the structure of these results, Figure 12 groups simulation outcomes into low, central, and high bins based on total cost for an example gas-based DRI unit feeding an electric arc furnace in the Gulf Coast region. Each panel represents the average cost breakdown of runs within that bin. This approach avoids constructing outcomes based on all inputs simultaneously taking extreme values, which would imply unrealistic combinations of conditions. Instead, it reflects coherent combinations of input variation observed across the simulation space.

**Figure 12 - Illustrative LCOS cost breakdown at low, central, and high stochastic outcomes (natural gas DRI, Gulf Coast)**




* DRI-SAF-BOF retrofit configuration requires existing BOF infrastructure.

Variation across outcomes in this example is driven primarily by capital costs and raw material inputs. Labor costs are held constant and are not subject to uncertainty sampling in the current implementation. Energy and maintenance costs vary across simulations but contribute less to total variation than capital and raw materials. Results are summarized using standard distributional metrics, including median (P50) values and percentile ranges (P10–P90). These distributions are used to compare pathways across regions and to assess the robustness of relative cost positions under varying input conditions.

## Appendix D: Investment Screening Methodology

The investment analysis presented in Section 2.2 is implemented as a screening-level financial framework designed to interpret techno-economic results under consistent commercial assumptions. It does not represent a full project finance model. Levelized cost of steel (LCOS) is calculated using a capital recovery approach based on a real weighted average cost of capital (WACC), asset life, and utilization rate. This converts capital expenditure into an annualized cost per tonne of output. Investment viability is evaluated using a target internal rate of return (IRR), set at 15% real. This value is intended to approximate hurdle rates applied in practice when firms evaluate major capital investments under uncertainty. WACC determines the cost of capital embedded in levelized costs, while IRR represents the return threshold required for project approval within corporate capital allocation processes.

For each pathway and region, the analysis assumes a representative plant configuration and estimates the steel price required to achieve the target IRR over the project lifetime. This is calculated by combining modeled operating costs with capital expenditure and solving for the revenue level that produces the specified return. Where Monte Carlo cost results are available, this calculation is applied across the distribution of outcomes to generate ranges of required prices. These ranges reflect variation in key cost inputs including capital costs, energy prices, and raw materials.

Revenue is represented using benchmark-based price proxies rather than plant-specific contract structures. These benchmarks are held fixed and are not modeled as stochastic variables. As a result, uncertainty in the investment results reflects variation in costs rather than variation in market prices.

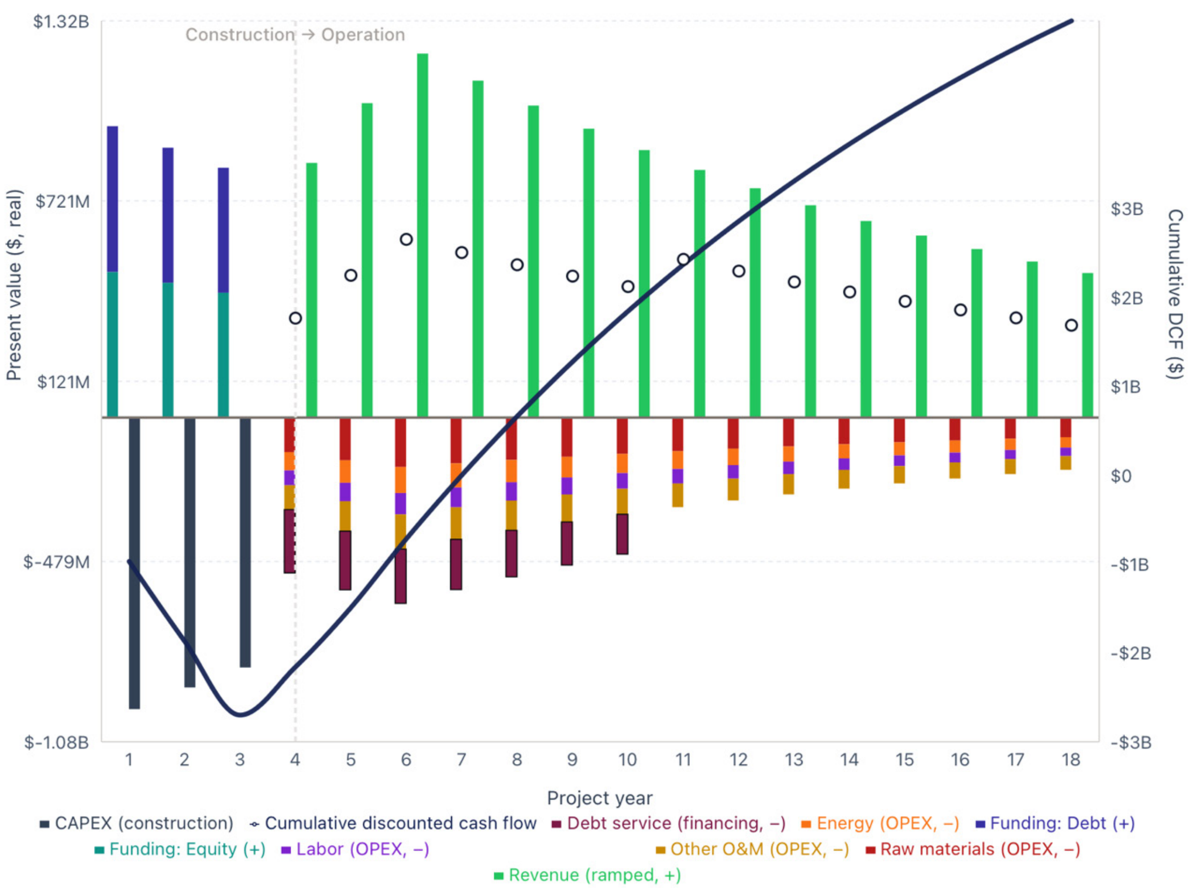
Uncertainty is applied to cost inputs only. Variation in market prices, policy conditions, and demand is not modeled within the simulation framework. The framework does not include detailed capital structure, debt financing, taxation, depreciation, or policy incentives, and does not model firm-specific financing conditions. Results should therefore be interpreted as indicative screening outputs rather than bankable project evaluations.

To illustrate how these screening-level financial metrics map onto underlying project economics, Figure 13 presents an indicative discounted cash-flow structure for a representative gas-DRI + EAF configuration in the Gulf Coast. The figure decomposes annual cash flows into capital, operating, and financing components on a present-value basis, alongside the cumulative discounted cash-flow trajectory used to derive NPV and IRR. The purpose is not to represent a specific project, but to make transparent the structure linking levelized costs to investment outcomes.

**Figure 13 – Illustrative Archetype Annual Cashflow Structure**

Illustrative discounted cash-flow structure for Gulf Coast Natural Gas DRI + Electric Arc Furnace / Natural Gas DRI + Submerged Arc Furnace + Basic Oxygen Furnace*, today. Bars show annual components in **present value**; the line shows **cumulative discounted cash flow** used to derive NPV and IRR. Screening-level case.

NPV $7.37B · IRR 38.8% · discount 8.0% real · 15 yr life.




* DRI-SAF-BOF retrofit configuration requires existing BOF infrastructure.

Based on stakeholder input and observed market conditions, the WACC corresponds to a value in the low-teens range, incorporating both debt and equity financing. Investment feasibility is evaluated against higher equity return thresholds, on the order of ~15% real IRR, which more closely represent the hurdle rates applied by sponsors when making capital allocation decisions. This separation ensures that levelized costs reflect realistic financing conditions while still capturing the stricter investment discipline that governs whether projects proceed in practice.

Investment decisions in the steel sector are made under more stringent conditions than those typically assumed in academic technoeconomic analyses. Capital allocation occurs within a broader portfolio of competing uses of funds, including maintenance capital, capacity expansion, balance sheet management, and strategic investments. As a result, even projects that appear viable under standard financial metrics may not proceed if they are not competitive within this internal capital allocation framework. While major steel producers are unlikely to rely on pure project finance, drawing instead on balance sheet funding, export credit facilities, subsidies, and bond issuance, the screening framework serves as a proxy for the level of performance required to compete for capital under real-world corporate decision conditions.

The analysis focuses on comparative cost signals and capital intensity rather than detailed project finance structuring or system-wide optimization. It does not model debt structuring (e.g., tenor, DSCR, or export credit arrangements), endogenous financing strategies of different sponsor types, or dynamic capital allocation decisions over time. Similarly, while intermediate products such as pig iron and hot briquetted iron are evaluated on a cost and competitiveness basis, the model does not optimize cross-regional trade flows or determine equilibrium sourcing patterns. Technology evolution is represented through discrete scenarios rather than fully endogenous transition dynamics, and uncertainty in emerging pathways, particularly electrolysis-based ironmaking, is not comprehensively captured in the Monte Carlo framework. These limitations are intentional and reflect the study's focus on comparative cost signals and capital intensity; they do not materially affect the primary conclusions regarding the relative positioning of major production pathways under commercially realistic conditions.

[1] Stakeholder discussion questioned whether the trailing 3-year US steel price benchmark used as the revenue series in sits at the upper end of historical experience and may flatter the investment-hurdle result. To test this, we ran a 15-year stress-year backcast: for each calendar year 2010–2024, we deflated the year's average US steel price to real USD2024 via BLS CPI-U and treated it as the locked-in revenue for a 15-year project at today's plant cost structure, then computed IRR for each pathway and region. Natural gas DRI, blast furnace steelmaking, and natural gas DRI with carbon capture all clear the 15% IRR hurdle in 15 of 15 historical years in every region modeled; even the worst year on record (2016, $761/t in real USD2024) produces gas-DRI IRRs of 17.9–20.2%, above the hurdle in every region. The investment thesis for natural gas DRI is therefore robust to the realized historical price regime and does not depend on the 2022–2024 elevation in current benchmarks.