Rhodium Group

Energy & Climate

Forging a Global Clean Steel Economy: Leveraging Trade to Reduce the Green Premium

May 5, 2026
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Since the start of the Iran war, the vulnerabilities of the global fossil economy have been brought into sharp focus. Critical energy infrastructure has been damaged or destroyed, trade has been disrupted, and daily energy price volatility has become the norm. The importance of resilient energy supply chains is as clear as ever, and an electrified economy supported by domestic clean power generation is rightfully central to this conversation. However, sources like solar and wind are not immune from supply chain pressures themselves—they too depend on a range of raw inputs. One of the most important raw inputs is steel, which is not only essential for the build-out of electrification infrastructure but also for construction, vehicle manufacturing, and a vast array of durable goods, and is itself highly reliant on fossil fuels to manufacture. In order to build the backbone of a truly resilient, clean energy economy, securing a clean, sustainable steel supply will require reducing the steel industry's dependence on fossil fuels.

As the current conflict highlights, global resources are deeply interconnected, and developing robust, diversified trade networks is crucial to avoid overreliance on individual resources. For countries with limited clean energy supply, electrifying energy-intensive industrial processes like steel production is likely to remain prohibitively expensive for the foreseeable future. However, in steel production, fossil fuels are consumed primarily in the ironmaking step, while most of the economic value is created downstream in steelmaking. With electric arc furnaces and modern direct reduction—an alternative pathway to make steel without a traditional blast furnace, using natural gas or hydrogen instead of coal to process iron ore into iron—the ironmaking step can be completely decoupled from steelmaking, providing supply chain flexibility and opportunities to co-locate the most energy-intensive steps of the process in regions with abundant clean power resources and low production costs. Doing so will require building a diverse set of bilateral trade partnerships to obtain clean inputs at competitive prices, while avoiding overreliance on individual resources. In this note, we examine the major cost drivers of clean iron production and assess which countries are best positioned to produce it at low cost.

Pathways to steel decarbonization

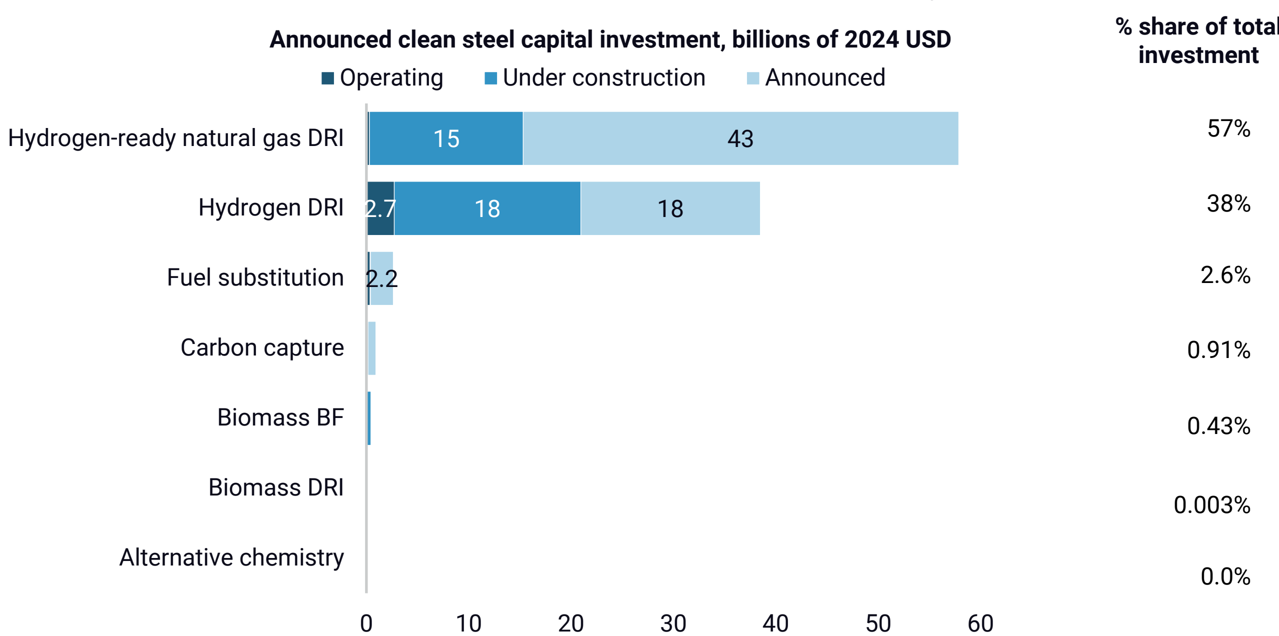
Steel serves as a bedrock of the global economy, and is highly carbon-intensive to manufacture, accounting for about 7% of global CO_2 emissions. Decarbonization thus far has mainly come from two methods: scrap recycling and direct reduced iron. Steelmaking typically occurs in two steps, with the initial ironmaking step (converting iron ore to iron) traditionally requiring large quantities of fossil fuels. Electric arc furnaces, which mainly require electricity and have lower emissions, are utilized in the second step, converting iron to steel. These furnaces are extremely flexible and can also process inputs of up to 100% steel scrap into new products, reducing demand for the carbon-intensive ironmaking step. However, steel is already highly recycled, quality scrap is scarce, and many end uses, such as vehicles, require high-purity steel, which can rarely be made from scrap alone and often depends on virgin iron inputs. With scrap recycling—a mature but limited option—reducing emissions from ironmaking will be the most important factor for further decarbonizing the sector.

To understand the evolving landscape of clean steelmaking across the range of technologies aimed at decarbonizing ironmaking, the Clean Investment Monitor, a joint project by Rhodium Group and MIT-CEEPR, tracks quarterly investment and project status of all clean steel facilities across the world by technology type (including hydrogen-ready direct reduced iron (DRI), hydrogen DRI, fuel substitution, carbon capture and bio-based blast furnaces, among others). Figure 1 breaks down the current pipeline of over $100.3 billion of announced investments in clean steel projects.

FIGURE 1

Direct reduced iron (DRI) dominates clean steel investment to date

Announced clean steel capital investment, billion 2024 USD, and share of total global investment



Source: Clean Investment Monitor, Rhodium Group

Note: The values here vary slightly from Clean Investment Monitor data due to the original dataset using a looser definition of "Hydrogen-ready natural gas DRI" in the United States, which includes all natural gas DRI facilities—not strictly those with stated intentions to transition to hydrogen.

The primary option for decarbonizing ironmaking is using a process called direct reduced iron (DRI), which is typically produced in a vertical shaft furnace, where methane is split into CO and H_2, both of which serve as reductants on the iron ore. Today, this process primarily relies on natural gas, which reduces emissions from ironmaking by about 40% compared to a coal-based blast furnace.

Fully decarbonized ironmaking is the natural extension of this process: instead of utilizing natural gas, green hydrogen produced via electrolysis can serve as a reductant alone. This can be achieved in the same vertical shaft furnace setup as natural gas DRI, where high-temperature hydrogen rises through the furnace, reducing ore pellets. Other hydrogen-based technology options under development include fluidized bed H_2-DRI, hydrogen plasma DRI, and hydrogen-based rotary kilns, which aim to utilize lower-grade iron ore fines but are not yet as widely deployed. Among clean ironmaking projects that've broken ground or been announced in recent years, hydrogen DRI accounts for 56% of investment under construction or operating and 38% of all announced investment (Figure 1).

There are a number of additional methods under development to decarbonize ironmaking aside from direct reduction—such as biomass substitution, electrochemical processes, and carbon capture—but these other solutions account for only 4% of total announced investment. Each of these methods comes with its own set of challenges. To date, biomass substitution has been limited to specific high-supply regions, and investment in carbon capture has fizzled out as early trials resulted in poor capture rates and no economic gain in the absence of strong policy support. Novel electrochemical approaches like Boston Metals' molten oxide electrolysis, Electra's chemical-based electrowinning, and Helios's sodium reduction of ore show promise but are in very early stages and will likely take time and significant investment to move out of the lab and deploy at scale. To date, there have been no announced investments in commercial-scale facilities utilizing these technologies.

Despite the availability of a number of viable hydrogen-based ironmaking technologies, the majority of global clean projects tracked by the Clean Investment Monitor (CIM) are typical shaft furnaces that can operate on natural gas in the interim until hydrogen is readily available (aptly referred to as hydrogen-ready natural gas DRI). Technologies utilizing shaft furnaces like Midrex Flex and Energiron can also immediately operate on up to 100% H_2. These fossil-based, hydrogen-ready facilities account for 57% of the total investment tracked by CIM.

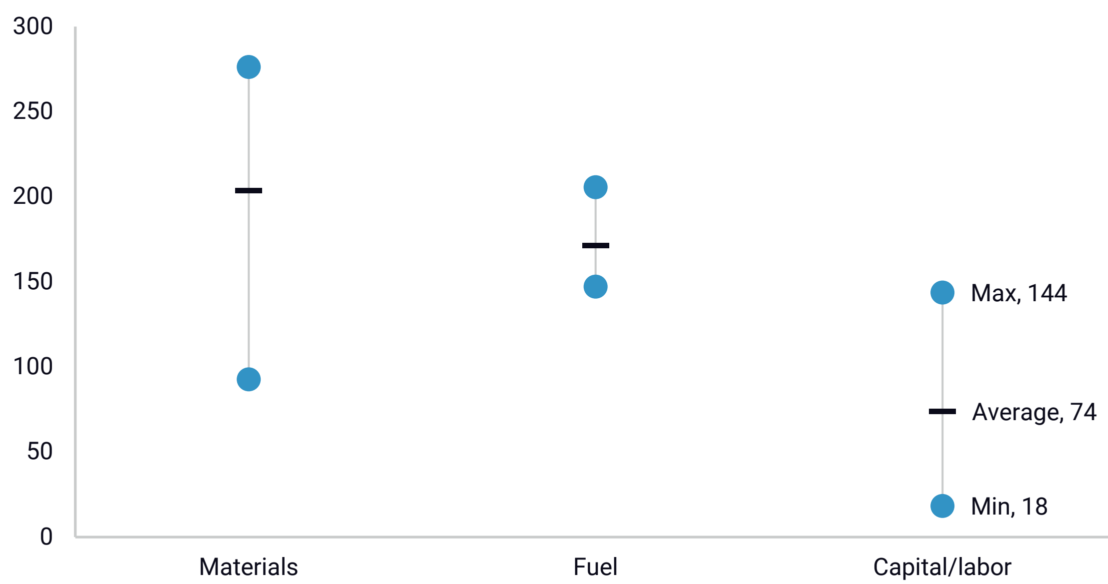
Although these facilities are not immediately fully decarbonized, they serve as an important transitional technology. Direct reduction facilities, no matter the fuel they use, are a major share of the capital investment required to eventually decarbonize, setting up steel infrastructure for a much easier eventual transition to hydrogen and reducing emissions by up to 40% compared to blast furnaces in the interim. Replacing blast furnaces with direct reduction or other alternatives as quickly as possible is crucial to scaling the long-term infrastructure for steel decarbonization. Blast furnaces require periodic large capital investments, but have very long lifetimes between maintenance periods. Without a transition away from traditional blast furnaces, countries risk locking in emissions for decades, whereas natural gas-based DRI does not have the same risk—facilities utilize H_2 and CO produced in a methane reformer and can almost immediately pipe in electrolyzer-produced H_2 instead, without requiring replacement of the entire facility.

In a competitive, globally traded industry, input costs matter

Like many manufacturing industries, steelmakers operate on thin margins and must contend with volatile raw material markets and high price competition, making costs crucial to clean steel viability. About 10% of announced investment in hydrogen-only DRI facilities was canceled in 2025 due to concerns over hydrogen availability and costs, Notably, 87% of canceled capacity came from ArcelorMittal projects that had received significant state funding, with the company citing hydrogen market conditions as the reason for not moving forward. Steel infrastructure is long-lived, and without a strong forward outlook for clean steel input costs, the large capital investments required are a hard sell. Even if clean steel input costs reach cost parity with traditional steelmaking—reducing the green premium to zero—the transition could take decades unless clean steel can clear the even higher bar of motivating the early retirement of blast furnaces, which can have decades-long lifetimes. Although natural gas DRI is already cost-competitive and accounts for about 40% of new infrastructure, it only makes up approximately 10% of global steel production due to slow industrial turnover.

Producing a ton of clean steel with hydrogen is fuel- and material- intensive. The cost of raw inputs, including primarily iron ore pellets, hydrogen, and small amounts of lime, accounts for the majority of the levelized cost of production, with labor and capital making up a much smaller share. Rhodium modeling of steel costs across multiple countries in 2030 shows that materials account for the largest source of variability and the biggest share of costs, while fuel costs come in a more consistent second (Figure 2).

FIGURE 2
Material and fuel costs drive the majority of hydrogen DRI production costs
2023 USD per ton of iron in 2030



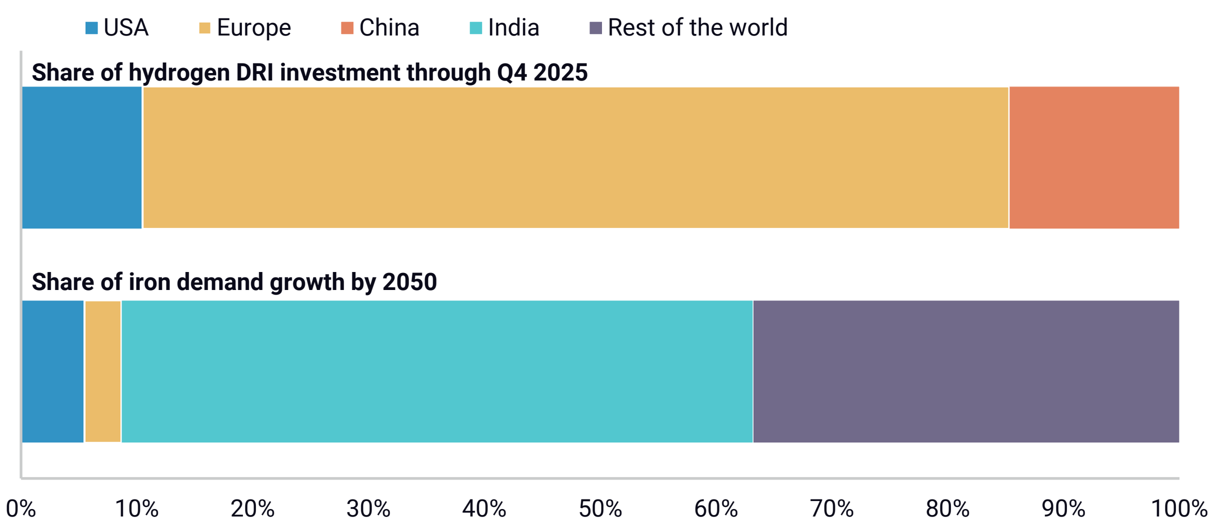
Source: Rhodium Group
Note: Cost ranges based on analysis of the outlook for hydrogen DRI costs in 2030 in a limited set of countries

Direct reduced iron plants (both natural gas and hydrogen-based shaft furnaces) typically require a higher-grade supply of ore than traditional blast furnaces, and often additional processing into agglomerated pellets. Such high-grade ore is generally high in iron content and low in impurities. The supply of such ore is limited to specific regions, and a consistent supply can provide a significant cost advantage, reducing the need for additional processing and the need to compete on the volatile open market. On the fuel side, cheap hydrogen is dependent on abundant and cheap clean electricity resources, which are also highly regional. Reducing the two most significant costs of clean steel—fuel and materials—will be crucial to reducing the green premium for clean steel. One way to do that is to import these inputs from regions with large, high-quality endowments of clean fuels and materials to lower costs for clean steel producers.

Analyzing regional advantages

To date, Europe has dominated investment into hydrogen DRI, but the region will likely see relatively little demand growth for iron over the coming decades. As a result, there is a misalignment between current investment in clean steel production and likely overall demand growth for iron (clean or traditional). According to modeling from the Rhodium Climate Outlook, growth in iron demand will occur in India and the rest of the world (including Africa, South America, and Eurasia), but minimal clean investment has been allocated there (Figure 3). This means that in the fastest-growing regions, most new demand is being met with traditional, fossil-based ironmaking technologies, which risks locking in emissions for decades.

FIGURE 3
India dominates iron demand growth but lags investment in clean production
Share of hydrogen DRI investment through Q4 2025 and total (clean + traditional) added iron demand by 2050



Source: Rhodium Group

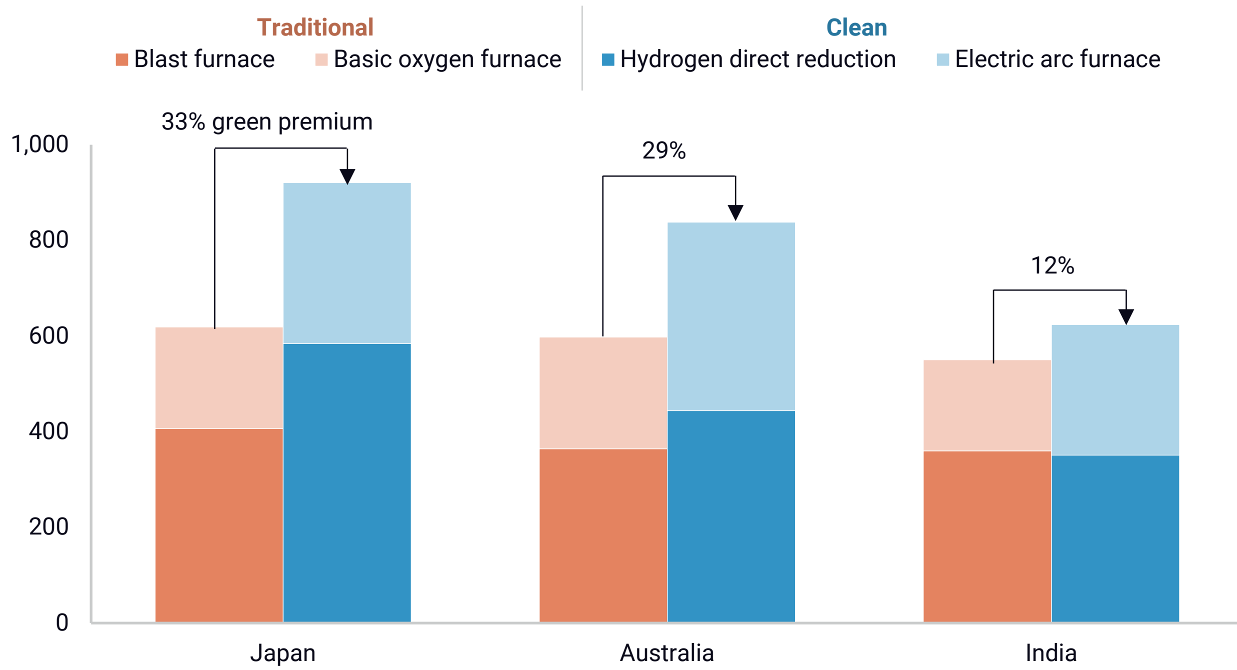
Given the resource intensity of hydrogen DRI, countries with access to key resources have a distinct competitive advantage. Supply chains for traditional blast furnace ironmaking inputs are well established and globally distributed, and modeled costs vary minimally between countries. By comparison, modeled hydrogen DRI costs vary more dramatically between countries with distinct resource and economic conditions, as shown in Figure 4 below. Three representative countries are shown—Japan, historically a major steel producer with minimal resources for clean steel, Australia, a developed economy with large clean steel resources, and India, an emerging economy with growing demand and significant resources.

In the push to decarbonize steelmaking, countries with resource and cost advantages represent the best opportunity for early investment and strategic trade partnerships for more resource-constrained nations. For traditional steelmaking countries, this can be an opportunity to reduce carbon intensity cost-effectively while retaining most jobs and the economic value of steel production.

FIGURE 4

The green premium for DRI steelmaking narrows in resource-rich emerging economies

Steelmaking levelized cost of production for select countries in 2030, 2023 USD per ton of iron



Source: Rhodium Group

In order to identify potential leaders of steel decarbonization, we have analyzed countries along five distinct pillars: cost factors, including cost of fuel, raw material resources and labor/capital costs, and non-cost factors (i.e., policy support and DRI readiness). Identifying the relative strengths of countries along these axes can help build robust supply chains and trade partnerships that are cost-effective while reducing overreliance on the advantages of any one region.

For each of the pillars considered, raw data for multiple criteria were normalized and weighted against each other based on relative contribution to the global average cost of iron production. The normalization is designed to identify regions that are strong across all variables considered rather than leaders in a single category. The pillars and their relevance to the final rankings are outlined below:

- **Fuel costs**: Energy costs account for about 40% of the levelized cost of hydrogen DRI, and the economic feasibility is heavily driven by the availability and cost of solar and wind. Regions with significant solar and wind resources and high potential for cheap and abundant renewables are the obvious choice of location for new hydrogen DRI facilities.

- **Material resources**: Aside from fuel, the primary input for direct reduced iron is iron ore. One major challenge for direct reduced iron is the quality of ore required. While blast furnaces can typically use fines (processed into sinter) with lower iron content as the liquid phase makes it possible to remove more impurities, direct reduction in a typical vertical shaft furnace generally requires high-quality pellets with >67% iron content. In addition, trade of DR-grade pellets is limited, and the majority of pellets tend to be consumed domestically. Approximately 48 million metric tons (MMT) of DR-grade ore was supplied as merchant pellets—processed iron ore that serves as the feedstock for a direct reduction furnace—in 2024, accounting for only 22% of total DR-grade ore demand and 3% of global ore trade. Securing supply is a major challenge, and countries with large domestic ore reserves (especially those with high iron content), infrastructure for concentration and processing, and significant existing exports have a distinct advantage when it comes to expanding DRI production.

- **Cost factors**: Capital expenditure and labor costs make up a smaller but variable share of the iron levelized cost of production. These factors are often in opposition; stable, developed economies that can offer lower interest rates and cost of capital typically have higher labor costs, and vice versa. This may make countries with low financing costs more attractive for early demonstration plants with high capital costs, but low-labor-cost economies more attractive as the clean steel economy scales and the cost curve is brought down.

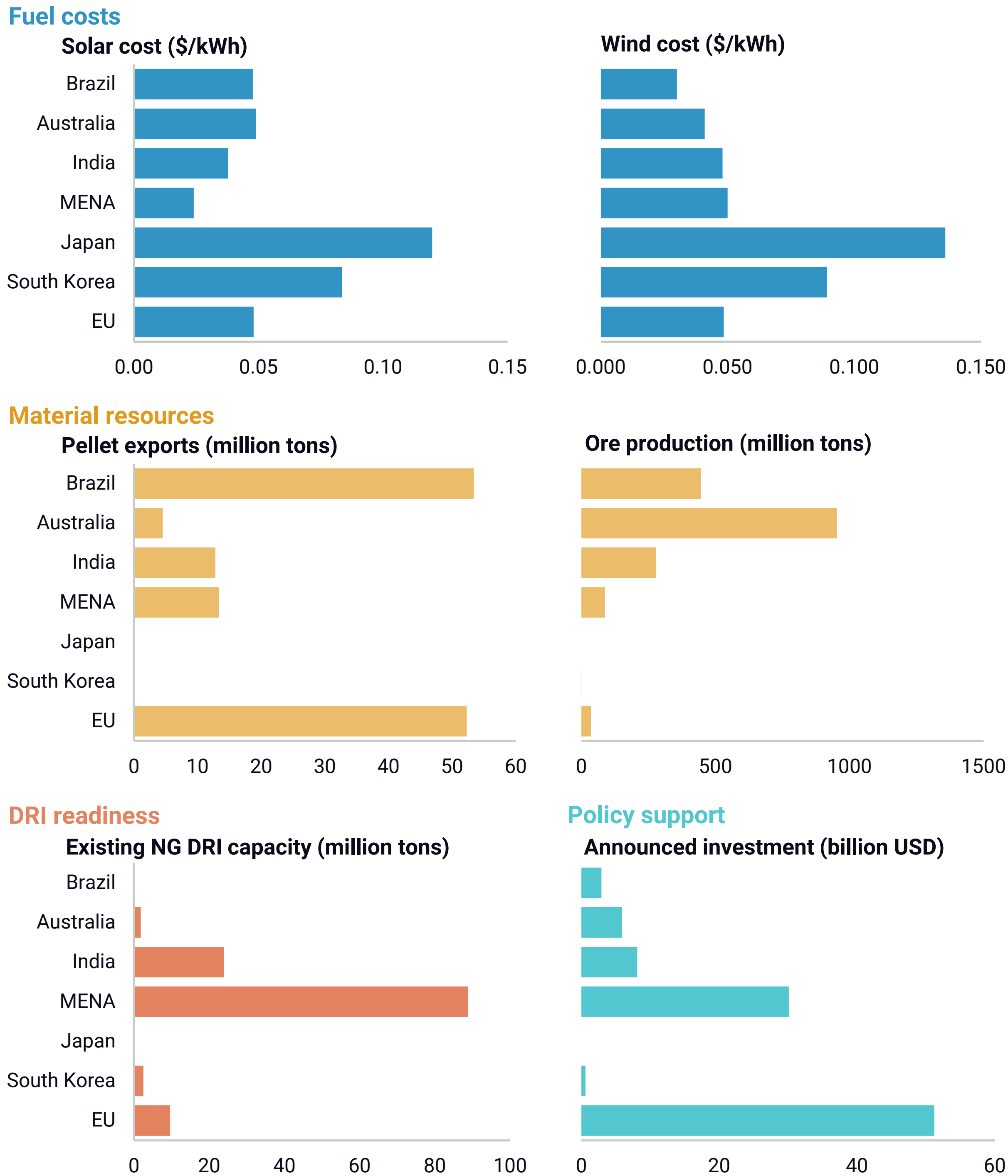
- **DRI readiness**: This pillar attempts to capture the benefits of existing infrastructure and conditions conducive to implementing direct reduction ironmaking beyond direct cost factors, including how much existing fossil DRI capacity a country has and the age of the blast furnace fleet. Countries with aging iron infrastructure are primed for a transition, given the impending need for major capital investment, either to extend the life of fossil capacity or replace it with modern alternatives. Existing DRI capacity also potentially offers an advantage, due to both institutional knowledge around region-specific technology development and operation, and the possibility of retrofitting existing natural gas facilities to use hydrogen at lower costs than greenfield development.

- **Policy**: This pillar captures how friendly the policy environment in a country is to clean steel by considering policy for green hydrogen and clean steel supply and investment to date into clean steel (both public and private). Subsidies and government grants directly lower the costs for early projects, while carbon pricing policies such as the EU's Carbon Border Adjustment Mechanism (CBAM) help increase domestic competitiveness of clean technologies. Overall investment indicates early adopters and helps provide a measure of where clean steel is getting the most support, from private players as well as from governments.

FIGURE 5

Pillar data for select variables and countries

Countries with high clean steel supply potential or high clean steel demand



Source: Rhodium Group

Scoring across these criteria, a few potential leaders emerge, each with slightly different advantages and drawbacks. We dig into country examples below. The same criteria highlight the challenges some countries are likely to face in decarbonizing their domestic steel sectors. Japan and South Korea have exceptionally high renewable costs, minimal ore resources, and robust automaking industries that require high-quality steel. While renewable costs aren't quite as high in Europe, many EU member countries are also highly dependent on both ore and iron imports and must contend with high labor costs and inefficient, aging infrastructure while trying to meet the goals of their own decarbonization policy. For these nations, partnering with advantaged suppliers to import iron would provide a more cost-effective way to meet goals while retaining higher value steelmaking.

Brazil

Resource rich, DRI poor

Brazil is exceptionally rich in all the ingredients required for hydrogen DRI. Renewables are cheap and rapidly expanding, and it is one of the leading producers and exporters of DR-grade ore. Labor is relatively affordable, and the bond yields—a proxy for infrastructure financing costs—are lower than in many peer countries. However, domestic DRI production is currently nonexistent in Brazil, and most technology development to date has focused on replacing fossil fuels with biomass (which also exists in abundance) in the blast furnace and pelletizing processes.

The states of Minas Gerais and Pará in the "iron quadrangle" boast exceptionally high-quality ore reserves, including the Carajás mine, one of the largest in the world, which regularly produces ore with >66% iron content. However, much raw material from this region is destined for export, with Brazil serving as a major pellet source for Europe and East Asia, as well as a major source of direct shipping ore, which is processed into pellets elsewhere (i.e., Oman and Bahrain). For Brazil, the upside of developing a domestic clean steel economy is significant—onshoring production of iron itself would allow it to capture a greater share of the value chain, while continuing to export to partners in the EU and South Korea/Japan at likely lower costs than those countries could achieve themselves, given challenging resource conditions. Partnership with Europe is especially synergistic, with the EU-Mercosur agreement now in place, allowing for tariff-free trade corridors.

Australia

Leader in need of a pivot

Australia is the uncontested current leader of iron ore exports, accounting for over half of shipments worldwide. Although it lags Brazil in total renewables share, Australia leads in wind and solar deployment, with massive potential. However, current ore production is heavily geared towards the incumbent technology, with most shipments destined for blast furnaces in China and DR-grade pellets making up less than 1% of total exports. That could change, given Australia's supportive market and policy environment, which provides subsidies for green hydrogen production and state funding for clean iron decarbonization, creating a strong pipeline of announced clean steel projects. Demonstration projects like Zesty and NeoSmelt are also underway, which aim to utilize electric smelting furnaces and novel processes to produce DRI from the lower-grade ores found in the Pilbara region.

In addition, potential bilateral partnerships are already forming in Australia. South Korean-based Posco is one of the largest consumers of Australian resource exports and has partnered with Australian mining company BHP on the development of their hydrogen-based fluidized-bed DRI technology HyRex. The project aims to utilize lower-grade Pilbara ores, with a demonstration project underway in Pohang, Korea. Posco is also backing the planned Port Hedland hydrogen-ready natural gas DRI project in Western Australia. The massive 12 MMT plant will produce pellets and hot briquetted iron exports destined for Korean steel mills. The project received environmental permits in 2025 but has yet to take a final investment decision, and whether labor and capital costs can be kept competitive remains to be known.

India

Low costs, high growth

Similar to Brazil, India has the advantage of cheap and abundant renewables and low labor costs, and is the world's third-largest ore producer after Australia and Brazil. The state-backed National Green Hydrogen Mission aims to make India a leader in clean hydrogen production, and other initiatives are in the works to specifically support clean steel totaling over $2 billion, with direct funding of three pilot H_2 DRI projects approved thus far and additional fiscal incentives for broader decarbonization planned.

India is already a significant producer of fossil DRI, but the industry has some unique attributes that make it difficult to decarbonize. Much of the direct reduction capacity is small, coal-based rotary kilns, which are optimized to use low-quality ores. Although India produces significant ore and is a major exporter, it increasingly imports high-quality ores from Brazil and Oman, amid growing domestic demand and shortages of high-quality pellets, a major challenge to the implementation of vertical shaft furnaces for decarbonization. Other nascent technologies that could be adopted in India are showing promise—the recently launched Oshivela project in Namibia utilizes an enclosed rotary kiln developed by HyIron to reduce iron ore fines with hydrogen, which could potentially be well-suited to India's ore resources. In addition, India has underutilized beneficiation capacity (only 40% in use) that could potentially be ramped up to produce higher-concentration ore, given a stronger market.

The announcement of a 10 MMT natural gas DRI plant in Salav from JSW (equivalent to 40% of India's current gas-based DRI capacity) offers a glimpse of the potential for bilateral partnerships in India. This plant is intended specifically to export lower-emission iron to Europe in response to the EU's CBAM and will be constructed with flexible technology that can more easily transition to hydrogen in the future.

Middle East and North Africa (MENA)

The elephant in the room

Saudi Arabia, Oman, Bahrain, Egypt, and other MENA countries are also prime candidates for establishing bilateral low-carbon steel trade partnerships. Unlike much of the rest of the world, natural gas DRI is already the dominant, incumbent technology, and MENA accounts for 44% of global DRI production. Iran is by far the world's largest producer of DRI steel and meets ore demand fully through domestic sources. Other MENA countries like Saudi Arabia, Egypt, UAE, Qatar, Libya, and Algeria have already established strong supply chains for DR-grade pellets. While the industry in MENA is currently reliant on dependable, cheap gas resources, costs for renewables in the region are also among the lowest in the world.

While most capacity in MENA is fossil-based, new project announcements have indicated an intention to transition to hydrogen as it becomes economically feasible. The world's largest DRI complex—the 8.1 MMT Tosyali SULB project in Benghazi, Libya—has commenced construction of a Midrex Flex shaft furnace, which could eventually utilize 100% hydrogen. The existing Tosyali facility in Algeria utilizes the same technology, and multiple projects underway in Oman use Energiron DR, which can similarly operate on up to 80% hydrogen. With this infrastructure already in place, cross-border partnerships and investment from nations with strong decarbonization goals could provide the incentive to make the transition to hydrogen, at a lower cost than greenfield development.

Geopolitical tensions, like those currently underway in the Middle East, can introduce volatility and uncertainty for those dependent on critical inputs for steelmaking. Similarly, Ukraine, once a major source of high-grade pellets for Europe, has reduced exports multiple times in the past several years due to logistical challenges from the ongoing war with Russia. On the precipice of further conflict, cooperation to develop clean ironmaking in places like India and Brazil can offer Europe resource security and diversification, while giving those countries an opportunity to grow domestic clean industries. For Japan and South Korea, deepening ties with Australia while expanding partnerships offers the chance to hedge against potential high costs and slow transition.

No supply without demand

Despite the solid technological promise of clean steel pathways, the sector faces an uphill battle to commercial viability. Investment to date has been concentrated in Europe, where mature capital markets and supportive government policy have driven early-stage development. However, other regions may hold stronger resource advantages and a clearer path to cost competitiveness. Existing direct reduction infrastructure is centered in the Middle East, a region subject to the same uncertainties roiling the global fossil supply. However, a broad and relatively geopolitically stable set of countries has the resource potential to cost-effectively produce clean iron to help diversify the clean steel supply chain and build long-term resilience of low-cost inputs.

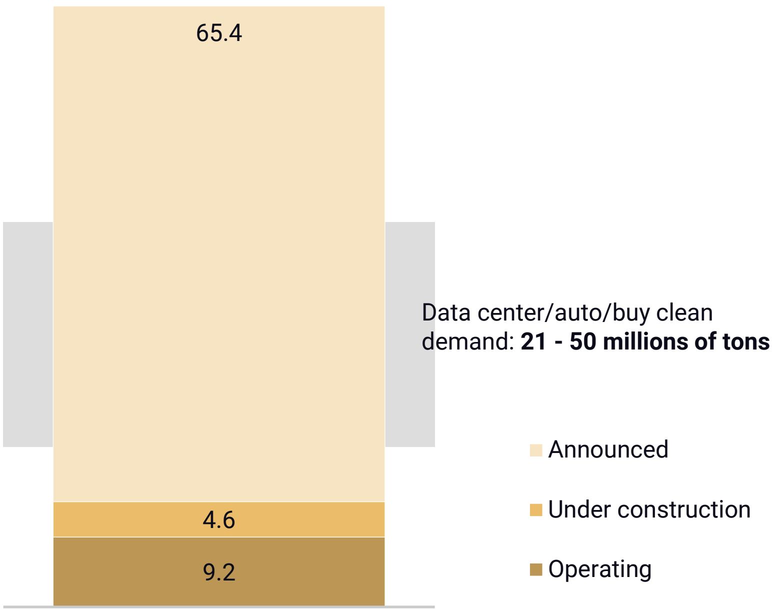
Resource potential is not enough, however, and a strong demand signal is needed to justify expanding investment into clean steel. As long as clean iron comes at a cost premium, regions like Brazil and India will meet rising steel demand with cheaper traditional technologies—meaning the market for clean iron will depend heavily on foreign buyers. To date, most demand for clean steel has come from voluntary commitments, especially from the auto and high technology sectors. Policy-driven demand to date has been limited to the United States and Europe, with some state-based buy-clean programs in the former and policies that favor low-carbon materials like CBAM in the latter.

Based on the current pipeline, the supply of clean steel is likely to outstrip demand for clean steel over the coming decade, based on current policy and voluntary-demand drivers (Figure 5). If all projects come to fruition, clean steel capacity will exceed demand by a factor of 1.8-4.3x by 2030, with a similar mismatch in 2035. This risks a collapse of the nascent industry, where existing projects cannot find buyers and scale production to drive down costs. Cross-border partnerships—particularly those that include long-term purchase agreements—can play a crucial role here, bolstering demand, reducing costs, and sparking further investment.

FIGURE 6

Full pipeline of clean steel investment supply outstrips likely demand

Clean steel supply and demand projections in 2030, millions of tons



Source: Clean Investment Monitor, Rhodium Group

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ACKNOWLEDGMENTS

This nonpartisan, independent research was conducted with support from Sequoia Climate Foundation. The results presented reflect the views of the authors and not necessarily those of the supporting organization. The authors would like to thank Rhodium Group colleagues Jaspreet Sohal and Maggie Young for their review and contributions.

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