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The Abating high emissions narrative explores the use of CCS technology and retirement opportunities of BOF capacity, with a focus on high demand regions like India.
Steel production has been growing steadily in the last decade—a rapid turnaround in emission intensity would be required to stop emission growth.

**Recent increases in emissions intensity are expanding the gap to 2030 targets**

<table>
<thead>
<tr>
<th>Emissions intensity of steel (kg CO2 / t crude steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
</tr>
<tr>
<td>1,500</td>
</tr>
<tr>
<td>1,000</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

- Emissions intensity has grown by 0.5% annually since 2010
- More than a 3% annual reduction in emissions intensity is required to meet 2030 targets
- Projected trend (based upon the last 5 years)
- Trend needed to meet 2030 and 2050 targets
- Historical trend

**Commentary**

- **Steel production grew by 20% in the last decade,** from 1,547 Mt in 2012 to 1,885 Mt in 2022
- **Hydrogen and natural gas technologies** for direct reduction of iron and electric arc furnace, cut emissions intensity by **70-95%**, compared to traditional blast furnaces
- Despite their potential, **high costs and limited offtake commitments** limit the deployment of such technologies to the U.S. and EU, with **emerging markets still expanding blast furnaces capacity**

Source: Systems Change Lab; World Steel Association - Environmental Sustainability Indicators; Climate Action Tracker - Paris Agreement Compatible Sectoral Benchmarks
Less than 15% of global steel market is reports in line with CDP. Of those reporting, nearly half are on track to exceed Breakthrough targets.

**STEEL OVERVIEW**

- **<15% of global steel market is covered by emissions targets**
  - Global steel revenue (in $B)
  - Global mix of 2021 steel production (in Mt)
  - Mix of companies reporting ambitions to CDP

- **45% of steel companies are on track w/ Breakthrough guidance**
  - Share of companies on track to exceed 3.5% Breakthrough targets (%)
  - Share of company targets exceeding 3.5% Breakthrough targets (%)

**Legend**
- Company performance vs. Breakthrough
- Missed target (<80%)
- Near miss (80-100%)
- Hit target (+100%)

**Note:** (*) US, Mexico, and Canada; Annual reduction ambition shows the % reduction a company will need per year in order to reach their target from the base year (includes underway, new, or revised targets); near-term defined as target year before 2030; Priority countries selected based upon highest emission countries from 2022 Global Carbon Project Data; % reduction refers to an annual percentage and does not take into account compounding; Breakthrough Agenda goals account for Scopes 1+2 only.

Source: 2022 CDP Climate Questionnaire Data; 2022 Global Carbon Project; World Steel Organization
There are three mainstream methods used to produce steel - each varying in operating procedures, required inputs and equipment, and emissions intensity.

### Blast Furnace - Basic Oxygen Furnace (BF-BOF)

- **Emissions intensity**: ~2.1 (t CO₂ / t crude steel)
- **Key inputs**:
  - Coking coal
  - Iron ore (Iron content 56-66%)
  - Steel scrap (up to 50%)
  - Limestone (or other calcium-rich material)
- **Production process**:
  - Coking plant: Metallurgical coal is processed and heated to 1200°C for use as reducing agent
  - Sintering plant: Iron ore fines (iron content of 56-66%) are mixed with limestone, dolomite, and heated to form larger ore pieces
  - The blast furnace heats to ~1600°C, activating coke to remove oxygen from iron ore, producing high-impurity pig iron and slag waste
  - Pig iron is sent to a basic oxygen furnace, heated to ~1600°C with scrap and limestone, producing primary crude steel and slag waste

### Direct Reduced Iron - Electric Arc Furnace (DRI-EAF)

- **Emissions intensity**: ~0.1-1.2 (t CO₂ / t crude steel)
  (from Hydrogen and Natural Gas respectively)
- **Key inputs**:
  - Natural gas / Hydrogen
  - Electricity
  - Iron ore (Iron content 66-68%)
  - Steel scrap (up to 100%)
  - Limestone (or other calcium-rich material)
- **Production process**:
  - Pelletizing plant: Iron ore fines are mixed with limestone and dolomite, moistened, then rolled into small pellets for direct reduction processes
  - Direct reduction of iron (DRI) uses gaseous agents to remove oxygen from iron ore at ~1000°C, producing impure sponge iron and slag waste
  - An electric arc heats a mixture to ~1800°C, melting DRI and scrap together, producing primary crude steel and slag waste

### Scrap - Electric Arc Furnace (Scrap-EAF)

- **Emissions intensity**: ~0.1-0.5 (t CO₂ / t crude steel)
  (dependent on electricity supply)
- **Key inputs**:
  - Electricity
  - Steel scrap (up to 100%)
- **Production process**:
  - Scrap recovery: Steel scrap is collected, inspected, and separated based on purity before it can be used in steel production
  - Ironmaking is not required when converting scrap into secondary steel
  - An electric arc heats the mixture to ~1800°C, melting recycled steel scrap into secondary steel and slag waste

### Notes:
The emissions intensity values are global averages. They can vary by geography - high volumes of scrap have driven growth in EAF capacity in North America; Europe and China primarily use BF-BOF steel production route and locations with abundant and low-cost natural gas, such as the Middle East, see DRI-EAF technology play a larger role; lower limit of the emission intensity values assume renewable energy use.

Source: World Steel Association, Mission Possible Partnership
Hydrogen and natural gas can replace coal/ coke via new processes for end-to-end steel production, which can result in up to 95% reduction in emissions intensity.

**Source:** Mission Possible Partnership – Making Net Zero Steel Possible

Note: Carbon emission figures are not inclusive of coal mine methane leakage
Over 70% of global steel is produced using basic oxygen furnaces, with high demand regions like India expected to further add high-emission production capacity.

World crude steel production by process (Mt, 2022)

<table>
<thead>
<tr>
<th>Process</th>
<th>Share of production (2022)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Oxygen Furnace</td>
<td>71.5%</td>
</tr>
<tr>
<td>Electric Arc Furnace</td>
<td>28%</td>
</tr>
<tr>
<td>Open Hearth Furnace</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Note: Global production includes both primary and secondary steel production volumes
Source: World Steel Association, World Steel in Figures 2023

Regions like India plan on meeting growing demand with high-emission production capacity - e.g., In India, BF-BOF capacity accounts for majority of planned additions by 2030.
Deploy near-zero emission tech

Near-zero emission production capacity will emerge as a viable solution to satisfy demand sustainably.

Investment in near-zero emissions capacity is accelerating to enable a shift from blast furnace into electric arc furnace production by 2050.

While H2-DRI production costs remain >20% higher than conventional production (depending on the grade of iron ore pellets), they’re expected to come down as green hydrogen technology scales.

European governments are incentivizing green steel, but the focus of decarbonization needs to be on the new capacity emerging in countries from the Middle East, North Africa and Asia.

Ensure access to key inputs

Increased availability of key inputs that support the transition to near-zero emission steel production.

Major steel consuming nations are promoting scrap utilization - e.g., China’s scrap supply is expected to double by 2030, supporting expansion of its electric arc furnace capacity.

For DRI, limited supply and high costs of green hydrogen and renewables is a key constraint, but costs are expected to decline and innovative solutions (e.g., using alternative inputs) are underway.

In the longer term, availability of high-grade iron will be key to ensure scaled deployment of DRI, which is particularly challenged in some growing markets like India.

Abate high-emission capacity

Advancing CCS and other abatement technologies de-risks future investments in emerging markets.

Given the ~30-year lifespan of steel plants, early retirement of new blast furnace lines will be challenging given the risk of stranded costs.

A portfolio of technology solutions (e.g., DRI-Smelt, CCS etc.) is under development to achieve decarbonization in the longer term, especially in U.S. and EU.

Deploying CCS technology in emerging markets with growing demand will need financial support, CCS infrastructure and adequate regulation.
The Sector Overview section provides context on the of the global steel production capacity and key barriers to decarbonization of the sector.

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~75% of business leaders from the U.S., Canada, and Europe believe that the firms can completely shift away from blast furnace production by 2050.

In what year do you expect your company will stop adding new blast furnace production capacity?

In what year do you expect your company will retire all remaining blast furnace production capacity?

Commentary

- The majority of steel producers in the US, Canada, and EU responded they will stop adding new BF capacity by the end of 2030.

- Although it may take some time, steel producers in these regions believe that they will be able to retire all remaining blast furnace capacity.

Note: Chart includes responses from respondents with expertise in the steel sector from the U.S., Canada, and Europe (N = 38) - respondents had the opportunity to answer each question across regions where they had expertise; The survey findings and emerging insights are based on the views of a subset of these companies and thus do not represent a universal view on the steel industry transition.

Source: Bain / WMBC Global Stocktake Survey (N = 215)
"Steel mills are making huge investment to change their technologies to produce low carbon steel - it's the only way to produce decarbonized steel"

Investment decisions and announcements show an increased uptake in near-zero emission steel production, but still fall short of 2030 target

Global near-zero emission primary steelmaking capacity (Million tonnes p.a.)

- Announcements total 83 Mt of H2 ready DRI capacity by 2030
- DRI projects recently surged, averaging 33 Mt/year in 2021 and 2022
- High cost of green hydrogen production may cause announced capacity to rely on blue hydrogen
- Estimated capacity from engineering and construction firms stands at 70 Mt by 2030, suggesting a bottleneck

“There is no question that there is early demand, but there are very few projects available that have investment decisions and a timeline to come online soon and are green enough.”
Manager of Climate Action, Auto manufacturer #1

Note: Title quote from Environment Manager, Auto manufacturer #2; The 2030 targets refer to the near-zero emissions primary steelmaking capacity that would be needed to be on a 1.5C compatible pathway based on IEA, IRENA, UN 2022, and Agora Industry scenarios
Source: Agora Industry (2023); Global Steel Transformation Tracker (2023)
Investments are being driven towards building large-scale green steel plants

<table>
<thead>
<tr>
<th>Overview</th>
<th>Targets</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description:</strong> Innovative steel manufacturer that is deploying a giga-scale electrolyzer to create green hydrogen to be used in primary steel production</td>
<td><strong>2025</strong></td>
<td>Partnership with Thyssenkrupp Nucera to create a 700 MW electrolyzer facility using highly efficient 20 MW modules</td>
</tr>
<tr>
<td><strong>Founded:</strong> 2020</td>
<td><strong>2026</strong></td>
<td><strong>H₂ Green Steel plans to produce green hydrogen leveraging onsite hydro and wind electricity and use it for steel production in the Boden plant</strong></td>
</tr>
<tr>
<td><strong>Headquarters:</strong> Stockholm, Sweden</td>
<td><strong>2030</strong></td>
<td>- Boden steel plant expects to produce up to 95% lower carbon emissions than standard blast furnace routes</td>
</tr>
<tr>
<td><strong>Ownership:</strong> Private</td>
<td></td>
<td>- Integrating Midrex direct reduction ironmaking (DRI) technology to leverage 100% green hydrogen at launch</td>
</tr>
<tr>
<td><strong>Series C Funding Round (2023): ~$1.64B</strong></td>
<td></td>
<td><strong>H₂ Green Steel is continuing to sign customers to purchase commitments in key markets</strong> like automobile manufacturing and shipping</td>
</tr>
<tr>
<td><strong>Technology deployed:</strong> H-DRI-EAF primary steel production powered by renewable energy</td>
<td><strong>2025</strong></td>
<td>- Agreements in 2023 alone include industry leaders such as Cargill, Anglo American, Mercedes-Benz, and Scania</td>
</tr>
<tr>
<td></td>
<td><strong>2026</strong></td>
<td><strong>Outside of green steel production, H₂ Green Steel plans to provide green hydrogen to other hard to abate industries like shipping</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Gotland Company has agreed to use green hydrogen provided by H₂ Green Steel in their Horizon fleet’s gas turbines by 2030 at the latest</td>
</tr>
</tbody>
</table>

Source: H₂ Green Steel company website and press releases, Thyssenkrupp press releases; Pitchbook

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**Case Study: H₂ green steel**

<table>
<thead>
<tr>
<th>Activities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Becoming an industry leader in green steel production</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Leveraging green hydrogen production capabilities to serve other sectors</strong></td>
<td></td>
</tr>
</tbody>
</table>
Efforts to develop innovative solutions to drive down emissions further are also underway

<table>
<thead>
<tr>
<th>Overview</th>
<th>Targets</th>
<th>Activities</th>
</tr>
</thead>
</table>
| **Description:** Global steel manufacturer that is fully transforming its traditional blast furnace steel-making to brand new fossil-free DRI-EAF production | 2021 (Completed) | SSAB fine-tuned its proprietary fossil-free steel made from hybrit sponge iron  
- Carbon emissions include purchased energy and iron ore (scope 1-2 and iron ore of scope-3 upstream) |
| Founded: 1978 | 2022 (Completed) | 
- Launch of SSAB Zero - made from recycled scrap, 0.0 kg Co2e emissions per kg steel |
| Headquarters: Stockholm | 2026 | 
- Launch HYBRIT demo plant (DRI) and a brand new EAF for large scale fossil-free steel production |
| Ownership: Public | | 
- Fully transform Nordic system with two brand new state of the art mini-mills |
| Founding: Debt free since 2021 | | 
- Plans to replace blast-furnace in Oxelösund and demonstration plant for Hybrit technology (2026) and build two state of the art mini-mills based on Hybrit DRI-EAF (by around 2030) |
| Technology deployed: | | 
- EAF scrap based production with fossil-free energy inputs (in the US) |
- Fossil-free hydrogen DRI-EAF based production with fossil-free inputs (in the Nordics) | | 
- Targeted partnerships with strategic fossil-free steel partners, e.g. Volvo group, Mercedes-Benz, Polestar, Autoliv, Volvo cars, Epiroc, PEAB, etc. |

Targeted partnerships with strategic fossil-free steel partners, e.g. Volvo group, Mercedes-Benz, Polestar, Autoliv, Volvo cars, Epiroc, PEAB, etc.

Source: H2 Green Steel company website and press releases, Thyssenkrupp press releases; Pitchbook
But DRI plant engineering and construction capabilities are highly concentrated, creating a potential constraint to the pace of global deployment

<table>
<thead>
<tr>
<th>DRI technology</th>
<th>Business model</th>
<th>Current pilot projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midrex Flex (using natural gas)</td>
<td>Relies on a licensing model with companies like SMS Group and Primetals to implement DRI technology into steel plants</td>
<td>Thyssenkrupp steel is integrating MIDREX Flex technology at its Duisburg, Germany site to use 50% H₂ for reduction by 2026 until sufficient H₂ supply is available</td>
</tr>
<tr>
<td>Midrex H₂ (using up to 100% hydrogen)</td>
<td>Designs and constructs ENERGIRON direct reduction plants for major steel manufacturers</td>
<td>Baosteel Zhanjiang steel plant in the Guangdong province will be the largest hydrogen-based DRI plant in China expecting to begin production as early as 2024 using ENERGIRON ZR technology</td>
</tr>
<tr>
<td>MX COL (using coal)</td>
<td>Innovative manufacturers are researching low-emission smelting technology to leverage conventional grades of iron ore</td>
<td>Metso’s DRI smelting furnace is capable of handling BF-grade iron ore by enabling high slag volumes</td>
</tr>
</tbody>
</table>

• ENERGIRON ZR (primarily using natural gas with modifications enabling a high ratio of H₂)

• Companies are working to deploy novel H₂-based DRI plants leveraging fluidised bed reactors (commercially ready by 2030)

### Share of construction additions (since 2011)

- **80%**
- **17%**
- **<3%**

### Total combined DRI construction capacity of ~70 Mt by 2030, suggests that additional solutions will be required to realize announced capacity in the pipeline

Source: H₂ Green Steel company website and press releases, Thyssenkrupp press releases; Pitchbook
"It will be difficult for companies to fully commit to green steel without some intervention to push cost parity"

<table>
<thead>
<tr>
<th>Low-emission production methods currently carry a premium to the traditional BF-BOF process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Levelized cost of steel production (2023, USD/metric ton of liquid steel; indexed)</strong></td>
</tr>
<tr>
<td><strong>Cost premium (vs. BF-BOF)</strong></td>
</tr>
<tr>
<td><strong>Industrial gas</strong></td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
</tr>
<tr>
<td><strong>BF-BOF</strong></td>
</tr>
</tbody>
</table>

| Average CO2 emissions (metric tons) | 2.1 | 1.2 | 0.6 | 0.5 | 0.1 |

**Commentary**

- **BF-BOF** is the lowest cost method of production.
- **Lower-emission technologies will become cheaper** as input costs (renewable electricity and green hydrogen) decline.
- **Fossil-dependent production technologies (e.g., BF-BOF, NG-DRI)** may increase with broader adoption of carbon pricing.

"Decarbonisation of steel is a cost issue - in both Capex and Opex terms. There isn’t really a technical barrier, though clearly innovation can bring costs down. Reality is that low emission steel is going to be more expensive - except for very rare exceptions" - Head of Strategic Projects & CO2 strategy, Steel manufacturer #3

Note: Title quote from Manager of Climate Action, Auto manufacturer #1; ‘Other costs’ include costs associated with labor, CAPEX, and other raw materials; ‘Natural gas’ costs are inclusive of other industrial furnace gasses used in the process; CCS cost per ton of CO2 based on a 90% capture rate system for retrofitting an average 2.5ML capacity BF-BOF facility; Average carbon emissions for H-DRI-EAF production route assumes access to a supply of renewable electricity and green hydrogen. Source: World Steel Association; Mission Possible Partnership - Steeling Demand Report; Morgan Stanley - Green Steel 2.0; Steel on the Net - EAF/BOF Cost Structure Summary; St. Louis Fed - Natural Gas and Iron Ore prices; Primetals - Outline of MIDREX DRI process; National Energy Technology Lab (DOE) - Cost of Capturing CO2 from Industrial Sources.
"The cost premium will come down as we scale, get more efficient and share cost more effectively. HDRI will become cost competitive with blast furnace"

The cost of low-emission steel production is expected to approach BF-BOF over time

Note: Title quote from Chief Technology Officer, Resource provider #2; Assuming the cost of BF-BOF will not change over time; Green premium is defined as the cost premium of H-DRI-EAF production over BF-BOF; Price of steel based on historical hot rolled steel indexed back to 1/1/2015 using annual averages

Commentary

- There are over 3,500 different grades of steel that manufacturers create using varying levels of alloying elements (e.g., nickel, chrome, etc.)
- Exact steel production costs can vary across geographies due to material, energy, transport, and labor costs
- Market conditions can have major impacts on the cost of production and the price of steel

Cost of green hydrogen ($ / kg) 8.5 5.3 3.5 2.4 2.2 2.0 1.9 1.9

Estimated green hydrogen costs based on consensus estimates from the IEA, IRENA, BNEF, Goldman Sachs, NETL, and DNV Global
Across North America and Europe, business leaders report that debt financing interest rates for BF-based projects are higher than low-emission alternatives.

Note: Chart includes responses from directors, vice presidents, and C-level executives with from steel companies in the U.S., Canada, and Europe (N = 18); Chart excludes 9 participants that responded “I don’t know” to this survey question; The survey findings and emerging insights are based on the views of a subset of these companies and thus do not represent a universal view on the steel industry transition

Source: Bain / WMBC Global Stocktake Survey (N = 215)
Most business leaders in the U.S. and EU steel sectors expect to leverage green hydrogen for steel production by 2030

What share of your company’s total steel production do you expect to leverage green hydrogen by 2030 in each of the following regions?

Share of total steel production leveraging green hydrogen (%)

<table>
<thead>
<tr>
<th>Region</th>
<th>Share of Production Leveraging Green Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU</td>
<td>50</td>
</tr>
<tr>
<td>U.S.</td>
<td>30</td>
</tr>
<tr>
<td>Rest of world</td>
<td>20</td>
</tr>
</tbody>
</table>

Note: Regional figures were calculated using the median response for each country; Rest of world includes China (N=7), India (N=9), Southeast Asia (N=4), Africa (N=2), Middle East (N=4), Oceania (N=1), Other Europe (N=1), Other North America (N=4);

The survey findings and emerging insights are based on the views of a subset of these companies and thus do not represent a universal view on the steel industry transition.

Source: Bain / WMBC Global Stocktake Survey (N = 215)

Commentary

- Producers across regions anticipate green hydrogen to become a significant input to production by 2030
- Developed markets (EU and U.S.) aim for higher share of inputs than rest of world
- The Middle East, which has a high share of DRI production may more easily transition to using hydrogen
- China, world’s top steel producer, expects the lowest share of production with green hydrogen by 2030

“In steel, we have various option to decarbonise - we can use green electricity either via green hydrogen through direct reduction, or in the future, we may be able to make steel through the direct electrolysis of iron as we do with aluminium today. But in the next 10-15 years, it will be through green hydrogen” - Head of Strategic Projects & CO2 strategy, Steel manufacturer #3

“One of the challenge is the likely costs for DRI. One of the big issues is going to be the ramp-up rates, [...] and how you compress that timeframe is a key question” - Manager of Sustainability, Resource provider #1
"The voluntary demand route is a red herring. In term of total impact, policy will be what moves the needle - through pricing, subsidies, or a combination"

The EU Emissions Trading System (ETS) will increase the cost of BF production

- ETS applies the 'cap and trade' principle, setting a total GHG emission limit, divided into tradeable allowances for steel producers
- Producers must buy extra allowances if emissions surpass the annual benchmark
- As this benchmark lowers, continuing BF operations becomes costlier - alternatively producers can invest in low-emission capacity to stay below the limit
- The Carbon Border Adjustment Mechanism (CBAM) offers an alternative, fostering a market for decarbonized steel and incentivizing investment in low-emission capacity

EU funding and subsidies for green H₂ increases the supply for steelmakers

<table>
<thead>
<tr>
<th>Direct Funding</th>
<th>Funds supporting the CAPEX of novel tech have accelerated deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>€10.6B of funding under IPCEI Hy2Use¹ and Hy2Tech² for 76 green H₂ industrial projects</td>
<td>Important Projects of Common European Interest (IPCEI)</td>
</tr>
<tr>
<td>Several European countries are establishing funding and specific targets to facilitate industry adoption</td>
<td>IPCEI funding covers the construction of hydrogen production facilities, transportation infrastructure, and the development of near-zero emission technologies for the steel sector</td>
</tr>
</tbody>
</table>

- ArcelorMittal has received nearly $800M in financial support for deploying 3 demonstration projects for H₂-DRI production across Europe³

Subsidies

- The European Commission introduced the EU Hydrogen Bank, allocating €3B in subsidies for green H₂ producers
- Launched in December 2022, Germany’s H₂ Global² provides €900M in subsidies to support the production and import of H₂ from countries outside EU

EU Innovation Fund

- Funded by the EU ETS, the aim is to introduce cost-competitive net-zero technologies for transitioning the energy and industrial sectors
- HYBRIT Initiative⁴, driven by SSAB, LKAB and Vattenfall, has received €143M from Innovation Fund in April’22 for demonstration of a complete value chain for H₂ based steelmaking, replacing BF with DRI

Important Projects of Common European Interest (IPCEI)

- IPCEI funding covers the construction of hydrogen production facilities, transportation infrastructure, and the development of near-zero emission technologies for the steel sector
- ArcelorMittal has received nearly $800M in financial support for deploying 3 demonstration projects for H₂-DRI production across Europe³

Germany’s Carbon Contract for Difference (CCfD)⁸

- Offers €50B of funding to make climate-friendly production processes competitive in energy-intensive industries (e.g., steel, cement, chemicals) to offset differences in the cost of green technologies over conventional energy sources
- CCfD can accelerate the transition from natural gas-based DRI to green H₂ based DRI by covering a portion of the cost premium associated with near-zero emission steel production

Note: Title quote from Head of Strategic Projects & CO2 strategy, Steel manufacturer #3
Source: 1) European Hydrogen Bank; 2) H₂ Global Subsidies; 3) IPCEI Hy2Use; IPCEI Hy2Tech; 5) Arcelor Mittal Projects: Spain, Germany, Belgium; 6) HYBRIT Initiative; 7) Research Fund for Coal and Steel 8) German carbon CfD
Additional capacity will emerge in the Middle East, North Africa, and Asia, as some regions are poised to adopt lower emission technologies.

Notes: 1) Countries with annual production >2Mn MT in 2022 selected for the analysis (~1% of global production of 1,900Mn MT in 2022); 2) Countries planning to cut or not planning to expand steel production have been eliminated from the analysis; 3) Different ranges for CAGR have been used for various countries based on availability of market reports; 4) Growth forecasts for Iran are not available but production is expected to expand: Iran; 5) Share of EAF in total production is for 2021 except for UAE, Pakistan, and Oman for which the data is for 2018 – however government statements and news article do not indicate any BF/BOF expansion.

Sources: 1) Steel Statistical Yearbook, 2019; World Steel Annual Production Data, 2022; Lit search.
Algeria and Egypt have expanded DRI steel production due to abundant natural gas; efforts towards green H2 expansion could enable shift to H2-DRI capacity

**Algeria**

With world’s third lowest natural gas prices, large iron ore reserves, and incentives for FDI and private investment, Algeria is growing NG-DRI-based EAF production

- Steel production (Mt, 2022): 3.5M
- Growth rate (2018-2022 production CAGR): 15%
- NG-DRI capacity (Mt, 2022): 5M
- Blast Furnace capacity (Mt, 2022): 1.5M
- Announced NG-DRI capacity (Mt): 2.5M

**Egypt**

Leveraging abundant, low-cost natural gas, Egypt is expanding DRI capacity using tax incentives in dedicated industrial zones

- Steel production (Mt, 2022): 9.8M
- Growth rate (2018-2022 production CAGR): 5.9%
- NG-DRI capacity (Mt, 2022): 8M
- Blast Furnace capacity (Mt, 2022): 0.5M
- Announced EAF capacity (Mt): 4M

**Supporting policies**

- Algeria has created investment incentive policy providing benefits that could be applied to support regional steel projects including:
  - Partial or total refund of expenditure relating to infrastructure works under the zone exemption arrangements
  - Concession of land under forward contract, over periods of 33 years
  - 5-year exemptions from corporate income tax
  - 3% interest rate subsidies boosting FDI and private investment
  - Algeria has the intent to export H2
  - Algeria is targeting 25GW of domestic power from green and blue hydrogen by 2050

- Egypt's green H2 Policies
- SCZone Benefits
  - Incentives for the Ain Sokhna Industrial Zone covering heavy industry projects may attract foreign investment into new steel production capacity
  - Similar incentives exist for RE manufacturing in Suez Canal Economic Zone
  - Policy provides a favorable location for international trade
  - Financial incentives such as 0% Customs Tax and VAT, and up to 50% of investment amount from net profits for taxation purposes
  - Proposed tax credit of up to 55% on revenues made from production of green H2 can potentially enable scaled H-DRI
  - Other incentives for green H2 include VAT exemption on equipment, waiver on land related charges, and credit facilities and mortgages; ambition to cut average thermal energy consumption in steel by 10%

Reducing the cost premiums associated with green steel requires demand commitments to unlock investment in zero-carbon primary production technologies.

**Commercial viability**

- Direct Reduction of Iron (DRI) using green H₂ has been proven to result in ~95% lower emissions.
- But DRI steel is currently ~25-40% more expensive than conventional blast furnace ironmaking methods, creating cost-competitiveness issues in a commoditized market.
- Early-stage demand through green steel procurement commitments is allowing steel producers to de-risk investments in zero-emission technology. Scaling near-zero-emission production capacity will be challenging within the existing market context.

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**Deployment of capacity**

- Engineering companies developing DRI technology are limited by the pace at which they can build and install new ironmaking equipment, potentially delaying final investment decisions for near-zero emission projects.
- H-DRI-EAF primary steel production capacity is currently in the demonstration stage, with commercial scale plants planned for 2030.
- Absent more rapid deployment of electrolyzer capacity to scale green H₂ production and bring it down the cost curve, producers will rely on natural gas / coal to ensure commercially viable ironmaking.

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“It will be difficult for companies to fully commit to green steel without some intervention to push cost parity.”
Head of Climate Action, Auto manufacturer #1

“There is no question that there is early demand, but there are very few [production] projects available that have investment decisions and a timeline to come online soon and are green enough.”
Head of Climate Action, Auto manufacturer #1
Procurement policies, pricing mechanisms, and international coordination will help the industry overcome capacity deployment challenges as it climbs down the learning curve.

Expanding niche demand for green steel

- Creating niche demand for green steel is critical for enabling early stage H2-DRI to be further developed, as well as reduce costs and technology risks.
- Early-stage adoption of net zero steel production can be kickstarted through carbon contracts for difference, public procurement initiatives (such as through the Green Public Procurement Pledge), sector specific green steel mandates, and private sector procurement.

Enabling broader adoption

- As DRI technology comes down the learning curve and green hydrogen becomes more readily available, pricing and subsidy mechanisms can create a level playing field for green steel.
- Policy options include incentives such as tax reliefs or grants to manufacturers, or carbon pricing mechanisms like the Emissions Trading System (ETS).
- Transition at scale will require much stronger international policy coordination, given the inherent challenges of such a competitive and strategic sector.

International coordination

- Decisive action across developed, emerging, and developing markets will be needed to ensure the next series of capacity additions and replacement for steel is low-carbon.
- Ideally, this transition would involve the alignment of regulation and standards of steel production, technology transfer mechanisms, and international support for the adoption of lower carbon production methods.
- Absent this scenario, coordinated measures by a coalition of willing actors may be the next best approach, which could include coordinated carbon border adjustments or broader trade policy approaches.
The Sector Overview section provides context on the of the global steel production capacity and key barriers to decarbonization of the sector.

The Zero emissions tech narrative explores the commercial viability and deployment opportunity in zero-carbon primary production technologies.

The Key inputs narrative explores the state of the availability and opportunity of raw inputs, including scrap, energy inputs and high-grade iron ore.

The Abating high emissions narrative explores the use of CCS technology and retirement opportunities of BOF capacity, with a focus on high demand regions like India.
Sector leaders identify inputs availability as the key barrier to decarbonizing along with technical feasibility, commercial viability, and infrastructure.

Note: Chart includes data from respondents with expertise in the steel sector (N=44); The survey findings and emerging insights are based on the views of a subset of these companies and thus do not represent a universal view on the steel industry transition; About half of the responses represent the EU and US, one-third represent India and China, and the rest of the responses represent the rest of the world. A respondent is tagged to a region based on the region they are responsible for overseeing (represents at least 30% of their time). One respondent can thus answer for multiple regions.

Source: Bain / WMBC Global Stocktake Survey (N = 215)
"Governments are pushing towards scrap steel production [...] It’s the quickest way of decreasing emissions across the product portfolio"

The European Union is increasing domestic scrap availability through export restrictions, standards and funding for scrap recycling.

- **Circular Economy Package**: Enables usage and recovery of scrap via Extended Producer Responsibility (EPR) and increased recycling targets.
- **Waste Shipment Regulation**: Ensures availability of high-grade scrap within the EU, by restricting exports of EU-origin scrap to countries that don’t have EU waste treatment standards.
- **Steel Action Concept of Germany**
- **Clean Steel Partnership**: Provides €700M in funding from the EU Commission over 10 years to increase the share of low-quality scrap recycling to 50% in '27.

The United States is indirectly incentivizing scrap collection by promoting domestic production, which is 70% EAF.

- **Build America, Buy America Act**: Set of domestic preference laws requiring that 55% of steel used in federally funded projects should be domestically manufactured as of 2022.
  - Increases to 75% requirement in 2029.
- **Buy Clean Initiative**: Covers 98% of government purchases to prioritize products with lower emissions.
  - Expected to increase use of low-emission construction materials including steel made with higher scrap percentage.

China is promoting expansion of domestic EAF production capacity and restricting the quality of scrap imports.

- **Capacity Replacement Program**: Favors new EAF capacity by allowing a 1:1 replacement ratio for scrap-based EAFs while replacing ratio for other technologies is 1.5:1.
  - China’s 14th Five Year Plan roadmap set a target for EAFs to reach 25% share of production by 2025.
- **Higher quality scrap import norms**: In 2021, the government revised quality standards for ferrous scrap imports.
  - Specified impurity levels to be below 0.3%, 0.8%, 1% for 3 different grades, impacting the use of imported scrap due to limited availability of compliant material in global markets.

India is directly promoting scrap collection through standards and guidelines.

- **Steel Scrap Recycling Policy**: Ministry of Steel’s policy focused on enhancing the availability of domestically generated scrap, providing guidelines for collection, dismantling and shredding activities in an organized, safe and environmentally sound manner.
  - Automobile Fitness Certification Policy to prevent plying of unfit and polluting vehicles.
  - Extended Producer Responsibility requires vehicle manufacturers to incentivize scrapping of unfit vehicles in exchange for price discounts for purchase of new vehicles.
  - New manufacturing companies and scrapping centers can pay income-tax at 15% (a subsidy of 15% and avoids requirement to pay the Minimum Alternate Tax).

In addition, the EU Commission is providing €700M in direct funding over 10 years for lowering steel energy intensity by 10% and increasing the share of low-quality input scrap recycling to 50% by 2027 by progressively increase the uptake of post-consumer scrap grades.

Source: 1) Waste Shipment Regulation; 2) Steel Action Concept, Germany; 3) Clean Steel Partnership; 4) Build America, Buy America Act; 5) Buy Clean Initiative; 6) China’s Capacity Replacement Program; 7) Steel Scrap Recycling Policy, 2019; Title quote from Sr. VP, Business Development, Technology provider #2.
~70% of business leaders in the steel sector believe that transportation costs and inconsistent quality are significant barriers to maximizing supply of scrap.

Note: Chart includes data from respondents with expertise in the steel sector (N = 44); The survey findings and emerging insights are based on the views of a subset of these companies and thus do not represent a universal view on the steel industry transition; About half of the responses represent the EU and US, one-third represent India and China, and the rest of the responses represent the rest of the world. A respondent is tagged to a region based on the region they are responsible for overseeing (represents at least 30% of their time). One respondent can thus answer for multiple regions.

Source: WMBC Sector Survey (N = 215)

**Commentary**

- High transportation costs limit the amount of scrap that steel producers can move to production facilities or import from international sellers.
- Additional costs associated with purifying contaminated scrap can be a significant barrier to maximizing recovery rates.
- Growing dependence on scrap for emerging EAF production combined with policies limiting the export of scrap may exacerbate these barriers in the future.
Leveraging growth in domestic scrap, China - world’s leading steel producer - will transition production toward low-emission electric arc furnaces.

China will benefit from increasing scrap availability over the next decade

- In regions with low-carbon grids, the EAF method is the least emissions-intensive for producing secondary steel from scrap.
- China produces ~53% of the world’s steel but only ~10% through EAF (vs. 28% of global production).
- China expects a ~70% by 2030 in scrap supply based on historical production, steel lifecycles, and enhanced recycling.
- China’s Capacity Replacement Program encourages new EAF capacity to replace old blast furnace capacity.
  - By 2030, more than 70% of China’s BF-BOF capacity will be due for relining.
  - It also incentivizes replacement with larger, more efficient blast furnaces.

Commentary

Note: Growth in scrap supply was averaged across 2023-2030 at a CAGR of 7.7%; Decrease in steel production was averaged across 2023-2030 at a CAGR for demand of -1%; Growth in share of EAF was taken between ‘22-’25 and averaged across 2025-2030 to model growth.

China’s Capacity Replacement Program favors new EAF capacity, while also supporting larger BFs to increase productivity

Recent policy will drive the transition of...

- Aligned with China’s 14th 5-year plan (2021-2025), the Chinese Ministry of Industry and IT (CMIIT) announced that EAF would make over 15% of steel production in 2025 and 20% in 2030
- China’s Capacity Replacement Program sets stricter requirements for new capacity, consolidating smaller BF plants and encouraging EAF additions
- China’s ETS system, launched in 2021, could increase the cost of BF operation if steel is covered in future phases
- The Action Plan for Carbon Peaking outlines the ambition to increase the supply of scrap metals to be used for low-emission secondary steel production

...a fragmented, blast furnace-oriented sector...

- Smaller, privately-owned mills quickly expanded lowering utilization rates and undermining steel margins
- Larger blast furnaces have lower coke usage, lower emissions of waste gas, limit the production of slag, and require lower inputs of energy sources (e.g., coal, electricity) per tonne of hot metal produced
- Incentives to replace BF/BOFs with EAFs will allow China to leverage its growing domestic scrap supply

...that is highly carbon intensive...

Steel sector emissions intensity by region (t CO2 / t steel)

<table>
<thead>
<tr>
<th>Region</th>
<th>Emissions Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>2.4</td>
</tr>
<tr>
<td>China</td>
<td>1.8</td>
</tr>
<tr>
<td>Global Average</td>
<td>1.7</td>
</tr>
<tr>
<td>Middle East &amp; Africa</td>
<td>1.5</td>
</tr>
<tr>
<td>OECD APAC</td>
<td>1.5</td>
</tr>
<tr>
<td>South America</td>
<td>1.4</td>
</tr>
<tr>
<td>CIS &amp; Other Europe</td>
<td>1.4</td>
</tr>
<tr>
<td>EU</td>
<td>1.3</td>
</tr>
<tr>
<td>Other APAC</td>
<td>1.2</td>
</tr>
<tr>
<td>North America</td>
<td>1.0</td>
</tr>
</tbody>
</table>

...and uses a relatively low share of scrap

Scrap ratio, 2019 (scrap usage as % of crude steel production)

<table>
<thead>
<tr>
<th>Country</th>
<th>Scrap Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkey</td>
<td>83%</td>
</tr>
<tr>
<td>US</td>
<td>69%</td>
</tr>
<tr>
<td>EU-28</td>
<td>56%</td>
</tr>
<tr>
<td>Russia</td>
<td>42%</td>
</tr>
<tr>
<td>S.Korea</td>
<td>40%</td>
</tr>
<tr>
<td>Japan</td>
<td>34%</td>
</tr>
<tr>
<td>World</td>
<td>34%</td>
</tr>
<tr>
<td>India</td>
<td>26%</td>
</tr>
<tr>
<td>China</td>
<td>22%</td>
</tr>
</tbody>
</table>

Source: Energy Transitions Commission; Lit. search
National approaches to restricting scrap exports could end up slowing the decarbonization of the global steel sector

Scrap export restrictions...

• 43 countries - largely in Africa, Middle East, and Asia - set scrap export restrictions to promote local recycling

• By 2024, the EU will modify its Waste Shipment Regulations, to promote domestic scrap utilization and monitor sales to non-OECD countries
  - Expected to impact most heavily China, India, Bangladesh, and Pakistan
  - With EU's new rules, the number of countries with such restrictions might rise to ~70

• Other top scrap exporters (US, UK, Canada, Japan) have refrained from such measures

...risk distorting markets for scrap collection and deployment of clean production

Reduce total scrap collection

- Export restrictions will lower scrap prices for domestic consumers, undermining price incentive driving recovery efforts
- Export restrictions hinder efficient scrap distribution to high-demand regions

Disincentivize new clean capacity

- Export restrictions will prevent export of scrap to non-OECD countries
- A shortage of scrap in these countries will limit their ability to expand DRI-EAF production and further incentivize BF-BOF production

Inhibits equitable development

- Scrap export restrictions risk sharper trade diversion and more trade among developed countries
- Only developed countries would have sustainable waste treatment processes in line with EU standards

Downcycling of high-quality scrap

- Scrap export restrictions may cause high-quality scrap to be downcycled and used in end-products that do not require it
- A lack of high-quality scrap in regions where it is required may lead to an increased reliance on primary steel production routes resulting in higher carbon emissions

Sources: 1) 43 countries globally have restricted the export of ferrous scrap; 2) EU avoids scrap export ban, monitors non-OECD exports; 3) EU scrap metal export curbs would be backwards step in global decarbonization
“Iron ore grades are one of the constraints to the deployment of DRI that often gets overlooked”

Multiple things must occur in parallel for ore supply to meet scaled DRI-based steel production

Mining companies and steel producers may be able to address this shortage by:

- Developing new deposits of high-grade iron ore (with >66% iron content)
  - Conventional blast furnace production currently uses iron ore with iron content as low as 58%
  - Only ~3% of iron ore shipped today is of a suitable grade to be used in DRI-EAF steelmaking

- Advancing and expanding iron ore beneficiation to improve the quality of low-grade ore and meet DR-grade iron ore demand
  - Expanding pelletizing capacity to convert high-grade ore and pre-processed low-grade ore into DRI-suitable pellets

- Developing new melter technologies (e.g., DRI-Smelt-EAF) that enable lower-grade ores to be utilized in DRI-based steelmaking

- Even considering actions to expand DR-grade ore supply, CCS technology will be necessary to abate remaining BF capacity

Note: Title quote from Manager of Sustainability, Resource provider #1; Net-zero target based on 1.5C compatible target for 2030 as stated in the Breakthrough Agenda 2022; Expected demand based on current DRI-EAF project pipeline; Lower bound of expected supply is based on high-grade iron ore mining projects for which realization by 2030 is highly probable or probable, whereas the hashed upper bound estimate reflects the IIMA projection if all possible projects were built; The survey findings and emerging insights are based on the views of a subset of these companies and thus do not represent a universal view on the steel industry transition

Source: Agora Industry; Wuppertal Institute; IEEFA; Wood MacKenzie; IIMA
In India, the sourcing of iron ore compatible with DRI operations is challenging, and would significantly drive-up costs for transitioning to DRI operations. 

“The issue is not that there is no iron ore for DRI pellets in India, but that the operational efficiency of DRI goes down a lot without high grade iron ore – so either you need to spend money improving the iron ore grade or ensure that the DRI process is adapted to lower operating parameters

The question is can you get the regulatory environment and policy incentives to make this shift – the cost is 80$ more per tonne. I will be out of business in a week if I have to take this on as a producer. This is the broader decarbonisation question – in the end, somebody has to pay”

Head of Strategic Projects & CO2 strategy, Steel manufacturer #3
“The renewable and hydrogen demand that the steel sector will drive is not going to other sectors where it may be more efficiently and productively used”

Green steel is forecasted to use up to 30% of global supply for green hydrogen

Project global green hydrogen capacity (Mt p.a.)

<table>
<thead>
<tr>
<th>Year</th>
<th>Supply of green H2</th>
<th>Demand for green H2 by steel sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>0.5</td>
<td>24%</td>
</tr>
<tr>
<td>2030</td>
<td>24</td>
<td>21%</td>
</tr>
<tr>
<td>2050</td>
<td>195</td>
<td>30%</td>
</tr>
</tbody>
</table>

Commentary

- **Global supply of green hydrogen is expected to grow to ~200Mt p.a. by 2050**
- **Global demand for green hydrogen** for steel production is expected to reach ~60Mt p.a. in 2050 assuming net-zero steel targets are met
  - EU policy like the Renewable Energy Directive 3 is driving hydrogen demand across sectors, increasing the need for sufficient supply
- To meet projected demand in the steel sector, and ensure a sufficient supply for other major sectors, hydrogen producers may be able to address this shortage by expanding:
  - **Renewable energy and electrolyzer capacity** to produce green hydrogen
  - **Transport infrastructure** to move hydrogen to demand centers

"There is also a scalability challenge. Even if we made a decision tomorrow to shift to green hydrogen, the scale of green hydrogen required would be massive"

- Head of Strategic Projects & CO2 strategy, Steel manufacturer #3

Note: Title quote from Manager of Sustainability, Resource provider #1; Green hydrogen supply figures based on consensus estimate from DNV, Goldman Sachs, Credit Suisse, IEA, and Ember; Supply figures exclude hydrogen produced as a process by-product, Demand figures for 2030 and 2050 based on 1.5C compatible steel decarbonization scenarios from Agora Industry and the IEA

Source: DNV Global, Goldman Sachs, Credit Suisse, IEA, Ember, Agora Industry - Global Green Iron Scenario
Alternative steel production technology solutions are being developed that don’t rely on hydrogen or high-grade iron ore.

### Overview

- **Description:** Global metal technology company intended to commercialize molten oxide electrolysis for high-volume steel production.
- **Founded:** 2013
- **Headquarters:** Massachusetts, USA
- **Ownership:** Private
- **Funding:** Raised $240M as of May 2023
- **Technology deployed:** Molten Oxide Electrolysis (MOE) ironmaking powered by renewable energy

### Targets

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>Launch demonstration plant capacity showcasing the molten oxide electrolysis process. Deploy first commercial-scale MOE steel production plants.</td>
</tr>
<tr>
<td>2030</td>
<td>Develop zero-emission production. Deploy first commercial-scale MOE steel production plants.</td>
</tr>
</tbody>
</table>

### Activities

- Molten Oxide Electrolysis (MOE) replaces fossil fuels with renewable electricity to convert low- and mid-grade iron ore fines directly into high-purity molten iron.
- MOE eliminates multiple steps in the conventional steelmaking process like coke production, iron ore sintering and pelletizing, blast furnace reduction, and basic oxygen furnace refinement.
- Boston Metal’s modular MOE cells can be scaled up to meet production capacity targets from thousands to millions of tons of steel output. Roughly the size of a school bus, MOE cells contain an electrolyte solution that is heated to excite electrons that split the bonds in the iron ore.
- MOE production process can reduce capital expenditure needed to construct new production capacity by eliminating the need for coke ovens and sintering plants that would otherwise be required for blast furnace facilities.

Source: Boston Metal company website and press releases.
Limited availability of raw inputs restrict companies’ ability to advance low-emission production.

- Steel producers are dependent on scrap for cost-effective and low-emission steel production which in turn decreases the need for raw materials such as coke and iron ore.
- Purifying steel scrap can be labor-intensive and may require specialized equipment to properly separate impurities, contaminants, and non-ferrous material before it can be used.
- Existing infrastructure and a region’s historical manufacturing rates directly drive the pool of available scrap as steel products reach the end of their life.
- Steelmakers require access to renewable energy to power EAF capacity and produce green H\textsubscript{2} to use as a reducing gas in low-emission ironmaking (e.g., DRI), but the volume of renewable capacity and high-voltage distribution infrastructure varies between regions.
- Leveraging green H\textsubscript{2} in the DRI process can enable up to a 95% reduction in carbon emissions compared to conventional blast furnace routes, but many steel producers opt for fossil dependent fuel sources due to lower costs and wider availability.
- Until now, ore with >66% iron content has not been specifically needed in steel production which has deterred mining companies from pursuing new deposits or purifying low-grade ore, further limiting the supply of inputs required for low-emission DRI processes.
- While there is enough high-grade iron ore to serve near-term DRI capacity additions, other low-emission methods of ironmaking (e.g., HI-smelt) that leverage conventional grades of iron ore will need further development to replace BF capacity.

Iron ore grades are one of the constraints to the deployment of [DRI] that often gets overlooked... You get a significant shortfall if there’s rapid expansion of hydrogen based DRI.”

Mngr. of Sustainability, Resource provider #1

-70% of business leaders consider transportation costs to be a barrier to securing a sufficient supply of scrap.

-60% of business leaders consider availability of inputs to be a top barrier to the decarbonization of the steel sector.
Increasing the availability of raw inputs is key in advancing low-emission production.

**Promote Circular Economy for Scrap Steel**
- Champion recycling and collection of scrap steel, by allocating funds to recycling initiatives for scrap following examples like the EU’s Clean Steel Partnership, or by adopting standards such as those highlighted in India’s Steel Scrap Recycling Policy.
- Impose recycling standards for steel production, through mandates on the percentage of raw materials to be sourced from recycled steel.
- Provide support to enterprises investing in cutting-edge recycling technologies, such as tax credits, to encourage innovation and efficient recycling practices.

**Invest in green hydrogen infrastructure**
- Lower cost green hydrogen production is critical for the development of greener steel.
- Alongside supply-side policy, which enables the development of the broader hydrogen industry, industry-specific demand-side policy can also help increase investor certainty, with options such as industry-specific mandates for the adoption of green hydrogen, or more technology-neutral approaches such as carbon standards.

**Promote international cooperation on critical inputs**
- Greater coordination across major economies will be needed to ensure efficient access to essential inputs like high-grade iron ore and scrap steel and mitigate recent policies banning scrap metal exports.
The Sector Overview section provides context on the state of the global steel production capacity and key barriers to decarbonization of the sector.

The Zero emissions tech narrative explores the commercial viability and deployment opportunity in zero-carbon primary production technologies.

The Key inputs narrative explores the state of the availability and opportunity of raw inputs, including scrap, energy inputs and high-grade iron ore.

The Abating high emissions narrative explores the use of CCS technology and retirement opportunities of BOF capacity, with a focus on high demand regions like India.
Business leaders expect to increase R&D spend on CCS technology, and drive deployment of the technology by 2030, particularly in the U.S. and EU

I would expect my company's total R&D spend directed toward CCS technology for blast furnace production to ___ from now until 2030

What proportion of your company’s blast furnace capacity do you anticipate being abated using CCS technology by 2030?

Share of respondents (%)

<table>
<thead>
<tr>
<th>Change in R&amp;D spend on CCS technology by 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. &amp; EU N = 23</td>
</tr>
<tr>
<td>Grow by 11-20%</td>
</tr>
<tr>
<td>Grow by 0-10%</td>
</tr>
<tr>
<td>Shrink by 11-20%</td>
</tr>
<tr>
<td>Rest of world N = 9</td>
</tr>
<tr>
<td>Grow by 11-20%</td>
</tr>
<tr>
<td>Grow by 0-10%</td>
</tr>
<tr>
<td>Shrink by 11-20%</td>
</tr>
</tbody>
</table>

Share of respondents (%)

<table>
<thead>
<tr>
<th>Share of blast furnace capacity with CCS by 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. &amp; EU N = 26</td>
</tr>
<tr>
<td>26-50%</td>
</tr>
<tr>
<td>11-25%</td>
</tr>
<tr>
<td>1-10%</td>
</tr>
<tr>
<td>No CCS</td>
</tr>
<tr>
<td>Rest of world N = 10</td>
</tr>
<tr>
<td>1-10%</td>
</tr>
<tr>
<td>No CCS</td>
</tr>
</tbody>
</table>

Commentary

- Steel producers are confident they will increase their R&D investments to fast-track the commercial viability of Carbon Capture and Storage (CCS) technology
- Producers in the U.S. and EU believe this technology can be leveraged within existing blast furnace capacities to curtail carbon emissions by 2030
- Commercially viable CCS technology will be particularly impactful in emerging markets where rapidly increasing demand is being met with new blast furnace capacity
- Steel producers are partnering with mining companies in China to finance the deployment of CCS projects

"CCUS is the most cost effective in terms of scalability. Seems like a good option, but it depends on the specific economics of each region" - Head of Strategic Projects & CO2 strategy, Steel manufacturer #3

"It's difficult to expect that China will adopt CCS in their production facilities. - Chief Technology Officer, Resource provider #2

"Pragmatic view is to ensure that technologies that a region like India adopt are as clean as possible, and they can be converted to carbon neutral in the future. This might mean ensuring they're compatible with future deployment of CCUS. In our view, this is likely to remain the most cost-effective option" - Head of Strategic Projects & CO2 strategy, Steel manufacturer #3

Note: Chart includes data from energy consumers with expertise in the steel sector (N = 36) and excludes 3 "I don’t know" responses from the U.S. & EU, and 1 from the rest of world; The survey findings and emerging insights are based on the views of a subset of these companies and thus do not represent a universal view on the steel industry transition

Source: WMBC Sector Survey (N = 215)
"The investments sunk in blast furnaces is really significant [...] also a young investment well short of its payback”

Most iron and steel plants are relatively young

<table>
<thead>
<tr>
<th>Technology</th>
<th>Average furnace lifespan</th>
<th>Average refractory lining lifespan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast Furnace</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>DRI-Coal based</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>DRI-Gas based</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

**Commentary**

- Given the ~30-year lifespan of steel plants, early retirement of blast furnace capacity would impose stranded cost burdens on producers.

- However, ~70% of global blast furnace capacity will need relining before 2030 according to world steel association, presenting a window to retire high-emission capacity in areas with decreasing demand.

- ~50% of the current equipment inventory is in China; India accounts for an additional 5%

Notes: Title quote from Manager of Sustainability, Resource provider #1
Source: IEA: Iron and steel technology roadmap; World steel association
“India is a high growth market and they’re planning on building coal integrated BF plants [...] green technology is just not ready for the capacity they need”

Growing steel demand in India requires 162 Mt of capacity additions by 2030

Commentary

- By 2030, India’s steel making capacity is expected to triple, surpassing 300 Mt as they aim to become a net steel exporter
- India currently stands as the globe’s premier developer of coal-driven steel capacity, commanding 40% (153 mtpa) of the global BF-BOF steelmaking projects underway
- Given the ongoing projects, India appears poised to maintain high-emission steel production for about the next three decades until these facilities are phased out
- China, once at the forefront, now closely follows India, accounting for 39% (147 mtpa), with both nations contributing to over 75% of global BF-BOF development
- India is also a leader in the development of coal-based DRI-EAF production with 9.1% of total (26 mtpa), laying the groundwork for a potential shift to more eco-friendly H-DRI-EAF ironmaking, sans CCUS

Source: Global energy monitor petal to the metal 2023; Title quote from Sr. VP, Business Development, Technology provider #2
India is promoting BF/BOF expansion to achieve its ambition of being a net steel exporter

<table>
<thead>
<tr>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04 ABATING HIGH-EMISSIONS</th>
</tr>
</thead>
</table>

India is currently world’s leading producer of direct-reduced iron

- India produces 30% of global direct reduced iron (DRI), with 39 million tons of steel output from DRI in 2021
- Currently, ~80% of India’s DRI capacity is coal-based
- A transition toward H-DRI has the potential to cut India’s DRI emissions from ~2.8-3.2 tCO2/ton steel (via current coal-fired DRI) to ~0.4-0.5 tCO2/ton steel

While India has put in place recent policies to promote H₂ production...

- India’s 2022 National Green Hydrogen Mission aims to make India a leading producer and supplier of green hydrogen globally
  - ~$2.4B announced for the development of cost-competitive green H₂ at <$1 per kg with the aim to produce 5M tons of green H₂ by 2030
  - Of the proposed outlay, ~$2.1B is directed towards Production-linked Incentives (PLI) for green H₂ production (75% of fund) and electrolyzer manufacturing (25% of fund)
- While India has set targets to increase adoption of green H₂ across sectors (e.g., fertilizer, oil refineries, gas distribution networks), it has not set any specifications for steel to drive near-zero emission production

...India is advancing BF/BOF production to create a self-sustaining steel industry

India’s National Steel Policy 2017:

- Explicitly expects the BF-BOF route to contribute 60-65% of the crude steel capacity and production in 2030-31
  - Remaining 35 - 40% to come via EAF & IF route
- Aims to increase domestic steel output to ~300Mt by 2030
  - An ~$0.8M production-linked incentive for Specialty Steel is expected to drive additional ~$5B investment and add 25 MT of steelmaking capacity
  - Plans to generate demand for steel via infrastructure development projects and the National Rail Plan 2030
  - Expecting this demand to spur investment, India has set aside ~3M hectares of land for steel plants
  - 100% FDI allowed in steel, infrastructure, rail and automotive sectors
- Establishes India’s ambition to become a net steel exporter by 2025-26
- Promotes usage of low-grade iron ore at captive mine sites conducive to BF/BOF production in conjunction with the Ministry of Mines

Notes: BF/BOF - Blast Furnace/ Blast Oxygen Furnace, DRI - Direct Reduction of Iron, Source: 1) National Steel Policy, 2017; 2) India’s DRI Production; 3) India’s PLI schemes under the Green Hydrogen ecosystem; 4) World’s second-largest producer of Crude Steel
"I could not justify investment in anything like CCS. There's no market premium for the product. There's no regulatory push"

There are a few commercial-scale CCS projects planned

<table>
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<tr>
<th>Partners</th>
<th>Project type</th>
<th>Announcement</th>
<th>Operation</th>
<th>Project Status</th>
<th>Announced capacity (Mt CO2/yr)</th>
<th>Fate of carbon</th>
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<tr>
<td>France ArcelorMittal, IFP, Axens, Uetikon, Grassco, brevik, TotalEnergies</td>
<td>Capture</td>
<td>2019</td>
<td>2025</td>
<td>Planned ▲</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>France Arcelor Mittal, Air Liquide</td>
<td>Capture</td>
<td>2020</td>
<td>2030</td>
<td>Planned ▲</td>
<td>1 - 2.85</td>
<td>Dedicated storage</td>
</tr>
<tr>
<td>Norway Statkraft, Carbon Recycling International</td>
<td>CCU</td>
<td>2017</td>
<td>-</td>
<td>Planned ▲</td>
<td>0.3</td>
<td>Use</td>
</tr>
<tr>
<td>United States Dastur International Inc., ON Clean Energy, Inc., University of Texas</td>
<td>Capture</td>
<td>2020</td>
<td>-</td>
<td>Planned ▲</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>United States Board of Trustees of the University of Illinois, Voestalpine, Air Liquide</td>
<td>Full chain</td>
<td>2022</td>
<td>-</td>
<td>Planned ▲</td>
<td>Dedicated storage</td>
<td></td>
</tr>
<tr>
<td>United Arab Emirates ADNOC, Masdar</td>
<td>Full chain</td>
<td>2007</td>
<td>2016</td>
<td>Operational</td>
<td>0.8</td>
<td>EOR</td>
</tr>
</tbody>
</table>

Notes: Title quote from Manager of Sustainability, Resource provider #1; EOR - Enhanced Oil Recovery Sources: Materials Processing Institute, Agora EnergieWende, Bain analysis

Commentary

- Adding CCS on a blast furnace is a possible pathway to abating existing emissions, with up to ~70% direct CO2 emissions reduction
- Multiple cross-industry collaborations have been announced leveraging CCU/CCUS technology in BF/BOF
- However, 2030 pipeline for commercial-scale CS on the BF-BOF is slim, with other alternatives gaining more traction
  - Production of 1 Mt for CS projects vs 84 Mt for H2-ready direct reduced iron (DRI) plants in 2023
- Key barriers include preference for other alternatives, inability to address upstream emissions (e.g., coal mine methane leakage) and high CAPEX costs
  - £400-£500m CAPEX for 1mt of steel estimated as investment costs in the UK

“There’s a lot of discussion on CCUS but the project announcements have been limited”
- Sr. VP, Business Development, Technology Provider #2
“We are increasingly engaging with our customers on technology development pathways [...] CCS, CCUS is something we’ve been looking into recently”

<table>
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<th>Overview</th>
<th>Targets</th>
<th>Activities</th>
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<tr>
<td>• Description: HBIS Steel is the sixth largest steelmaker in the world, producing ~41M metric tons annually</td>
<td>2022 • Peak carbon emissions from steel production</td>
<td>• Invested in the development of carbon capture and utilization technology to enable integration into steel production processes and reduce CO₂ emissions</td>
</tr>
<tr>
<td>• Founded: 1943</td>
<td>2025 • Cut carbon emissions from steel production by 10% from the peak</td>
<td>- Using an alternative form of carbon capture in vacuum pressure swing adsorption (VPSA)</td>
</tr>
<tr>
<td>• Headquarters: Shijiazhuang City, China</td>
<td>2030 • Cut carbon emissions from steel production by 30% relative to the peak</td>
<td>- Two utilization technologies constituting slag mineralization and biological conversion to protein to sequester CO₂</td>
</tr>
<tr>
<td>• Ownership: State owned enterprise</td>
<td>2050 • Achieve carbon neutral steel production across the entire business</td>
<td>• Formed partnership with global mining company BHP to develop and implement absorptive desulphurization at the HBIS demonstration project in Xuanhua, Hebei</td>
</tr>
<tr>
<td>• Revenue (2022): $21.3B</td>
<td></td>
<td>- Absorptive desulphurization will allow HBIS to use nearly 60K metric tons of capture CO₂ per year in the food and industrial sectors</td>
</tr>
<tr>
<td>• Technology deployed: Trial carbon capture, utilisation, and storage (CCUS) technologies at conventional steel facilities</td>
<td></td>
<td>- The Hebei province accounts for ~20% of China’s reported steel production emphasizing the need for more CCUS initiatives</td>
</tr>
</tbody>
</table>

Source: HBIS and BHP press releases; title quote from Manager of Sustainability, Resource provider #1
Industry stakeholders call for a global carbon price to ensure the long-term viability of green steel

“The EU ETS helps to justify the green premium for carbon-zero steel, but this framework does not exist in other markets and makes green steel demand hard to aggregate”

Chief Technology Officer, Resource provider #2

“Ultimately, we need government intervention to create a level playing field. In the short term we have launched an internal carbon price to deal with this”

Stina Klingvall, Manager of Climate Action, Volvo Cars

“Steel accounts for 9% of global emission and the cost for the global economy to get rid of CO2 emissions is peanuts. But putting it all on steel makers makes it impossible – it’s a question of effort distribution. If we had decided to put a CO2 tax on the global steel industry some years ago, our collective investment plans would have been set by now”

Head of Strategic Projects & CO2 strategy, Steel manufacturer #3
Emissions from existing blast furnaces must be minimized, but carbon capture tech is expensive and in early development.

**Retire BF-BOF capacity**

- Given the ~30-year lifespan of steel plants, early retirement of blast furnace capacity would impose stranded cost burdens on producers.

- Roughly 70% of global blast furnace capacity will need relining before 2030, presenting a window to retire high-emission capacity in areas with decreasing demand.

- Insufficient infrastructure to enable transport and storage of carbon constrains the short-term commercial viability of CCS by limiting a producer’s ability to remove captured carbon from their facility.

- Producing steel from CCS-abated BF-BOF is ~5-20% more expensive than unabated BF-BOF production, making the technology unattractive to steel producers until there is a regulatory push from governments or if it can reduce its cost premium.

**Mature CCS technology**

- Growing steel demand in emerging economies like India has driven steel producers to continue investment in new fossil-dependent blast furnace capacity primarily to develop infrastructure, become self-sufficient, and leverage low-cost coal reserves.

- CCS on the blast furnace production route is possible, and would achieve a ~73% direct CO2 emissions reduction using existing tech.

- "The investment that has been sunk in blast furnaces...is obviously really significant. And we're talking about... young investment that is well short of its payback.”
  - Mngr. of Sustainability, Resource provider #1

- "I could not justify investment in anything like CCS. There's no market premium for the product. There's no regulatory push.”
  - Mngr. of Sustainability, Resource provider #1

- ~80% of business leaders believe that their companies will accelerate R&D investment into CCS technology by 2030.

**Abate existing BF-BOF capacity**

- Producing steel from CCS-abated BF-BOF is ~5-20% more expensive than unabated BF-BOF production, making the technology unattractive to steel producers until there is a regulatory push from governments or if it can reduce its cost premium.
Government support is needed to modernize steel capacity, and ensure international cooperation for a level playing field.

- In developed markets, the construction, retrofitting, and upgrading of existing blast furnaces can be enabled through a range of policy measures including standards, tax incentives, and carbon pricing.
- Developing countries will likely need support if the world is to move towards lower carbon production - whether that’s the move towards DRI plants or the upgrading of existing blast furnaces to CCUS; in either case, the early retirement or upgrading of high-emitting blast furnaces should be a priority for international finance initiatives in the coming decade.

- At a minimum, all major steel-producing economies should aim to ensure that any new or upgraded blast furnace facilities are as clean as possible and are compatible with future deployment of CCUS, even if policy support is not possible today.
- Established international standards would support the development of CCUS over the medium-term - including unified carbon sequestration regulations, on- and off-shore storage standards, and diverse transport method guidelines.
- Ultimately, businesses will need significant incentives to deploy CCUS at scale - whether that’s for R&D, infrastructure, or subsidies for operational facilities.

- Harmonized international standards and greater transparency can support the development of international trade in green steel: a unified and standardized methodology for quantifying and reporting greenhouse gas emissions and better labelling can enable stakeholders to validate sustainability claims, reinforcing consumer confidence.
- That said, CCUS at scale will be extremely challenging to achieve through voluntary demand or national approaches.
- Ultimately, the technologies for lower carbon steel are known - whether DRI or carbon capture makes more economic sense may vary by context; in either case, a giant leap forward in international governance will be required to enable the decarbonization of the steel sector, which may be through coordinated carbon pricing across major producer economies or common approaches to production standards.

- Provide financial support to retire or upgrade blast furnace

- Support CCS technology

- Ensure international coordination on green steel