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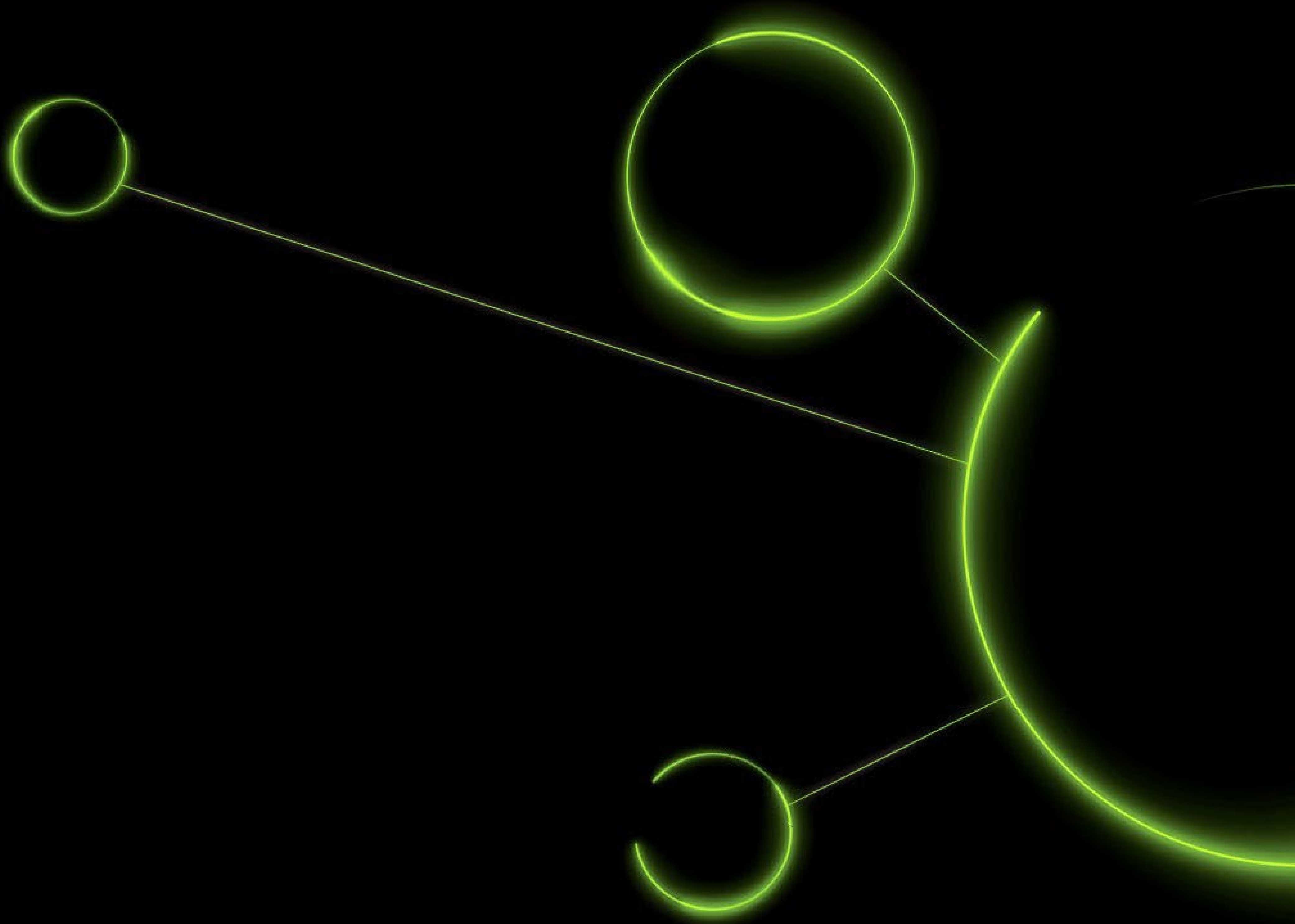

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Green steel

Technology and value chain shifts to tackle decarbonization challenges

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Steel production directly accounts for some 7% of global carbon dioxide (CO2) emissions.[1] With an eye on regulation and emission-conscious customers, major steelmakers are exploring greener production pathways.[2] The transition will take time and a lot of money. And the new pathways being explored face several challenges, including high costs and potential scarcity of raw materials and other inputs. Emerging technologies and steelmaking value chain changes could help overcome some of these hurdles.

Main pathways to green steel

Three main production processes account for practically all of the steel made today:[3]

1. Producing iron in a blast furnace and then converting the iron into steel in a basic oxygen furnace, a process known as Blast Furnace-Basic Oxygen Furnace (BF-BOF). Blast furnaces are the single largest source of emissions in the industry. Seventy percent of global crude steel is made this way.[4]
2. Producing direct reduced iron (DRI) from ore using a reducing agent, typically natural gas, or sometimes coal, and then turning the iron into steel in an electric arc furnace (EAF). This process is known as DRI-EAF.
3. Converting scrap steel into the desired steel product in EAF.

BF-BOF is the most prevalent and the most emissions-intensive. It produces 2.32 tons of CO2 per ton of crude steel (tCO2/t) and accounts for about 86% of all CO2 emitted by crude steel production. In comparison, scrap-EAF and DRI-EAF produce 0.67 tCO2/t and 1.65 tCO2/t respectively.[5] Therefore, decarbonizing the steel industry depends, in large part, on abating BF-BOF emissions and shifting toward clean DRI and EAF.

Steel producers around the world are pursuing a variety of paths to decarbonize the industry. Table 1 summarizes decarbonization approaches being pursued by the world's top 25 steelmakers, who account for 43% of crude steel production globally. How these approaches may play out across the seven main steelmaking regions, where 84% of the steel is made, is also noted.[6] (Some emerging technologies are described further below.) By 2050, the green shift could significantly reduce the share of crude steel produced globally by BF-BOF and increase the share of DRI-based and scrap-EAF steel. The carbon intensity of crude steel production overall could then decline from 1.4 tCO2/t to 1.1 or 0.6 tCO2/t, per International Energy Data (IEA) data.[7]

Table 1. Major technologies enabling green steel transition and their adoption

Main transition pathways	Major technologies	Tech readiness level (TRL)[8]	Carbon intensity (tCO2/t)[9]	% carbon reduction vs BF-BOF[a]	# of top 25 global steelmakers working with tech[b]	Plans or expectations in leading steel-producing regions[c,10]
Abating BF-BOF emissions	**CC[d]**	7-8	0.9	60%+	**9**	• **China: CC** important as BF-BOF assets still young to abandon • **India:** Energy efficiency through 2030 and **CC** post-2030 as BF-BOF assets still young to abandon • **Japan:** Energy efficiency through 2030, and **CC** and **H_2** post-2030
	H_2 to partially replace coal[d]	7	1.8–1.9	18%–23%	**8**	
	H_2 + CC	5	-	-	2	
	Scrap in BF	4–8[e]	-	-	1	
	Other: Low-basicity high-silica pellets, heat recovery, quality ore, etc.	-	-	-	6	
Shifting to clean DRI	**H_2 or H_2-NG blend[d]**	6–7	0.1–0.4 for H_2-DRI-EAF[f] 0.8 for NG-DRI-EAF	80%+ for H_2-DRI-EAF[f] 65%+ for NG-DRI-EAF, 10% H_2 blend cuts CO_2 by 3%[11]	**9**	• **China:** Slow shift to **H_2/NG-DRI** from BF through 2030 • **EU:** "Strong" shift to **H_2-DRI** with ~20 projects, **NG/H_2-NG** DRI in interim • **India:** Post-2030 shift to **H_2-DRI** given DRI experience and access to solar power for green H_2 production • **Japan:** Post-2030 shift to **H_2-DRI** starting with partial H_2 • **US:** Could pivot to **H_2-DRI** with federal H_2 incentives than extend life of aging BF-BOF assets • **Russia:** To more than double **DRI** production by mid-2025 • **South Korea:** Shift to 14 **H_2-DRI** assets from 11 BF by 2050
	H_2 + CC	-	-	-	3	
	CC	5–9[g]	0.5 for NG-DRI-EAF-CC	75%+ for NG-DRI-EAF-CC	1	
	Ore pre-treatment, enhancements	-	-	-	1	
Shifting to EAF	**Scrap-EAF[d]**	11[h]	0.4–0.7	70%+	**7**	• **China:** 43 new **EAFs** or 15%–20% of steel produced by 2025 vs 11% in 2021 • **India: Scrap/DRI-EAF** could remain >50% of steel production through 2050 • **Japan:** Energy efficiency for **EAF** through 2030, larger EAFs post-2040 • **US: Scrap-EAF** route to remain primary
	RE	-	-	-	4	
	CC	-	1.2–1.3 for BF/DRI-EAF-CC	44%+ for BF/DRI-EAF-CC	2	

H_2: Hydrogen, CC: carbon capture, NG: natural gas, RE: renewable energy

a. With respect to BF-BOF carbon intensity of 2.32 tCO2/t
b. Steelmaker activities are not exhaustive and are based on company documents and news published from 1 January 2020 to 15 May 2023, and company websites. One steelmaker can explore/adopt multiple technologies.
c. Seven leading regions by share of crude steel production, 2021: China (52.9%), EU (7.8%), India (6.1%), Japan (4.9%), US (4.4%), Russia (3.9%), and South Korea (3.6%)[12]
d. Technology explored/adopted by five or more (i.e., 20%+) top 25 global steelmakers
e. High-quality steelmaking with scrap use involving replacing primary raw materials with increased scrap usage
f. DRI is most frequently converted to steel in EAFs, hence 'DRI-EAF' variations are examined for carbon intensity
g. TRL = 9 for CC with chemical absorption and 5 for CC with physical absorption
h. Scrap-EAF is well established with proof of stability attained

The data suggest that traditional steelmakers' abatement of BF-BOF emissions could occur largely via **carbon capture and hydrogen use**. And their shift to clean DRI and EAF will likely center on **hydrogen-based direct reduction** and **scrap-based** steelmaking with EAF, respectively. Hydrogen-based direct reduction is the focus of two startup green steelmakers, whose collective funding of nearly US$4 billion demonstrates investor confidence in the technology.[13] These strategies face challenges, however.

Hurdles along the green transition routes

Each of the decarbonization pathways described in table 1 must surmount obstacles. The difficulties with carbon capture center on engineering and cost. The shift to the DRI-EAF pathway is complicated by access to raw materials and other inputs. Discussing carbon capture first: Technical challenges facing the use of carbon capture in steel production include the difficulties of integrating it into the production process due to the complex and variable steel plant infrastructure; diverse points of emission; and carbon capture technology's compatibility, scalability, and emitted gas composition requirements. Steelmakers may also confront a lack of nearby CO2 storage/use sites.[14] And until the price of carbon rises—thereby increasing traditional BF-BOF costs—steelmaking with carbon capture would be costlier, according to a report Deloitte produced with Shell on the steel industry's decarbonization.[15]

The DRI-EAF pathway faces different challenges, centering on access to raw materials and renewable energy. Direct reduced iron—the primary input, along with scrap, for steel produced in electric arc furnaces—requires high-grade iron ore. But supplies of high-grade ore are limited; two-thirds of the global ore supply is unsuitable.[16] In addition, direct reduction with hydrogen requires green hydrogen for low-carbon ironmaking. And renewable energy is required to produce green hydrogen and operate low-carbon EAFs. But affordable green hydrogen is not yet available, and renewable energy supplies accessible to steel plants may remain limited through 2030.[17] Multiple industry observers anticipate a shortage in scrap steel for scrap-EAF as well, with regions such as China, India, and Japan increasing demand.[18] Scrap export restrictions by many regions could exacerbate issues.[19]

Two noteworthy developments are intended to address these challenges: a reorganization of the steel production value chain, and the commercialization of new, lower-carbon technologies for making iron and steel.

Steelmaking value chain shifts

To secure scarce inputs, some **steelmakers are moving upstream**. For instance, at least three top 25 steelmakers intend to produce green hydrogen themselves and at least two plan to produce renewable power.[20] And two top 25 steelmakers have acquired scrap recyclers.[21] The Deloitte and Shell steel report also describes **closer collaboration between steelmakers and suppliers**.[22] For example, some are working with miners to expand access to high-quality raw materials for DRI. One steelmaker formed a green hydrogen-DRI-EAF joint venture with a miner and an energy company.[23] Further, Deloitte and Shell anticipate a **geographic splitting of ironmaking from steelmaking**.[24] To give an instance, some miners and steelmakers expect to produce DRI in Australia and the Middle East with their ore, renewable power, and hydrogen potential, then export the iron for steelmaking in regions closer to consumers, such as in the European Union.[25]

Some steelmakers are moving upstream

Emerging technology solutions

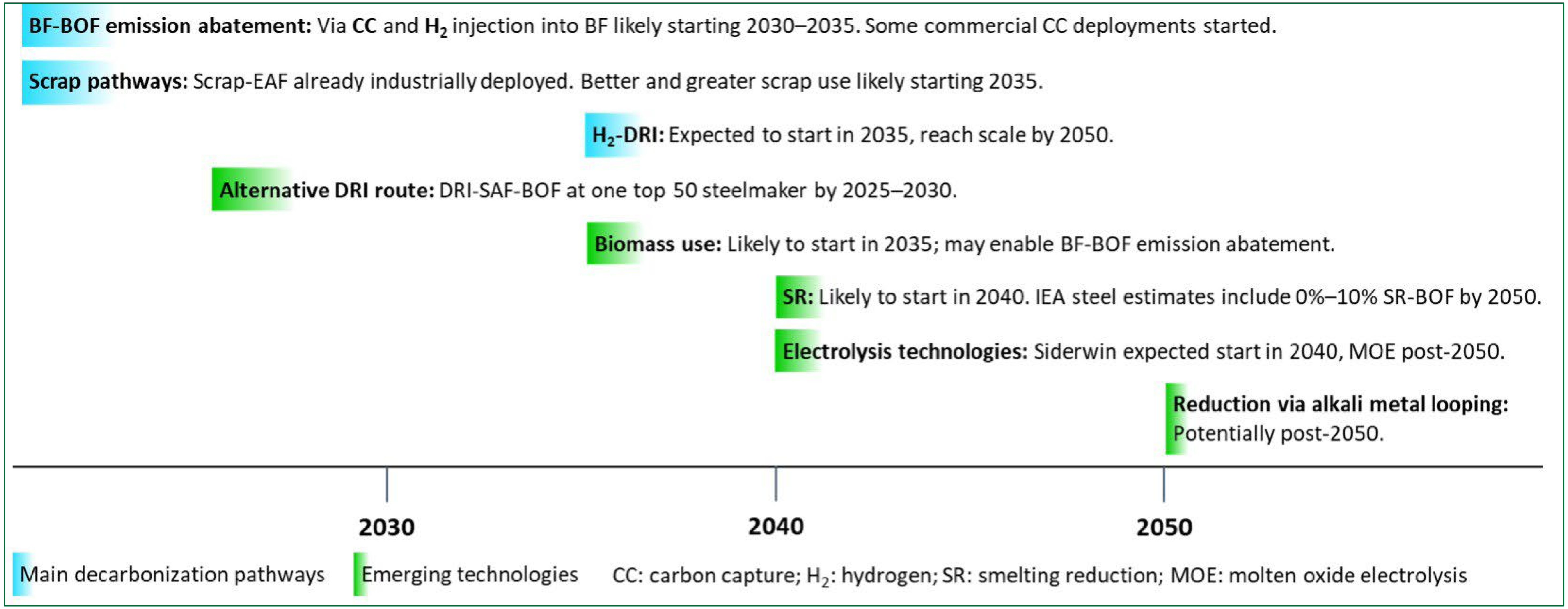
Multiple green ironmaking technologies are emerging. These focus on decarbonizing the most emissions-intensive part of the steelmaking process, reducing the need for carbon capture and avoiding the main decarbonization pathways’ raw material challenges. Some prominent ones are profiled in table 2.

Table 2. Select emerging green ironmaking technologies

Technology	Brief description	Technology Readiness Level (TRL)[26]	Adoption	Scarce inputs avoidable
Alternative to coal				
Biomass	Biogas or biochar derived from waste or purposely grown plant material used instead of coal in BF-BOF and EAF routes[27]	2–9	At least four steelmakers including three top 25 are exploring. One startup plans production in 2024. At least one steelmaker is using it commercially.[28]	Green hydrogen; high-grade ore and green power if BF-BOF is retained
Synthetic waste	Waste plastic, non-recyclable paper, and end-of-life rubber tires used instead of coal	3–9	Tire use is commercialized, with at least one steelmaker involved. Plastic and paper feasibility is being explored by at least two top 25 steelmakers.[29]	
Smelting reduction (SR) *[non-hydrogen plasma]*	Group of technologies that use carbon and oxygen directly to reduce ore into iron, requiring less energy than BF	7–9	At least one top 25 steelmaker is exploring, a mining giant is working on its first commercial plant, and one ironmaker has established multiple plants.[30]	High-grade ore, green hydrogen, and green power as SR iron tends to be routed to BOF
Electrolysis pathways				
Molten oxide electrolysis	High-temperature (1600°C) electrolysis of melted ore	5	Startup has received US$217 million in funding and backing from two mining majors and one top 25 steelmaker. Demo plant expected in 2024.[31]	High-grade ore, green hydrogen
Oxygen decoupled electrolysis	Low-temperature (60°C) electrolysis of aqueous-acidic solution with leached ore	4–5	Startup has received US$113 million in funding and backing from a mining major and one top 25 steelmaker. Pilot plant expected in 2023.[32]	
Siderwin (electrowinning)	Low-temperature (110°C) electrolysis of aqueous-alkaline solution with ore particles	4	Development efforts are led by a top 25 steelmaker, with funding of EUR€7 million.[33]	
Reduction via alkali metal looping	Ore heated at 400–700°C with sodium	4	Startup has received US$6 million in funding.[34]	High-grade ore, green hydrogen
Alternative DRI routes	Instead of the usual DRI-EAF route, DRI routed to submerged arc furnace (SAF), melter, or open slag bath furnace (OSBF) then to BOF	4–6	Multiple large steelmakers including at least one in top 25 and a leading equipment maker are exploring these routes.[35]	High-grade ore

Figure 1 lays out a potential timeline for the introduction of these technologies. These technologies could enable and coexist with the three main decarbonization pathways discussed above. In the long run, steel production will follow multiple paths to decarbonization.

Figure 1. Possible timeline of green iron–steel technologies industrial deployment



BF-BOF emission abatement: Via CC and H_2 injection into BF likely starting 2030–2035. Some commercial CC deployments started.

Scrap pathways: Scrap-EAF already industrially deployed. Better and greater scrap use likely starting 2035.

H_2-DRI: Expected to start in 2035, reach scale by 2050.

Alternative DRI route: DRI-SAF-BOF at one top 50 steelmaker by 2025–2030.

Biomass use: Likely to start in 2035; may enable BF-BOF emission abatement.

SR: Likely to start in 2040. IEA steel estimates include 0%–10% SR-BOF by 2050.

Electrolysis technologies: Siderwin expected start in 2040, MOE post-2050.

Reduction via alkali metal looping: Potentially post-2050.

CC: carbon capture; H_2: hydrogen; SR: smelting reduction; MOE: molten oxide electrolysis

Source: Estimates from ESTP, IEEFA, IEA[36]

The cost of the transition

The decarbonization of the steel industry will be costly, requiring capital investments of approximately US$800 billion by 2050, according to Deloitte and Shell's report.[37] Banks have begun supporting steelmakers in this regard, with six major banks even making a joint lending commitment of US$23 billion.[38] And some lenders have agreed to link the margin payable on a top 25 steelmaker's US$5.5 billion revolving credit to emissions and sustainability performance.[39] Sustainability bonds are a source of funds as well, and at least seven top 25 steelmakers have raised more than US$2 billion through green, sustainability-linked, and transition bonds since 2020.[40] However, significantly more funds are required. Government support and guaranteed green steel demand from enterprise customers are likely to remain crucial to encourage investments.[41]

Decarbonizing an industry

The steel industry is often referred to as "hard to abate." The interplay of technology, operations, supply chain, and capital required for progress are the reason for this. Players up and down the value chain as well as in policy and finance all have a role to play. Collaboration will be key to make the progress required, at the pace required, to decarbonize the industry.

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(2) Share in world crude steel in 2021 (%): (a) BF-BOF: 72; (b) DRI-EAF: 8; (c) Scrap-EAF: 20.
(3) Ton of steel by BF-BOF, DRI-EAF, and scrap-EAF = 1 x 2: (a) BF-BOF: 1,405; (b) DRI-EAF: 156; (c) Scrap-EAF: 390.
(4) CO_2 emissions per ton of steel in 2021 (tCO_2/t): (a) BF-BOF: 2.32; (b) DRI-EAF: 1.65; (c) Scrap-EAF: 0.67.
(5) CO_2 emissions (tons) = 3 x 4: (a) BF-BOF: 3,259; (b) DRI-EAF: 258; (c) Scrap-EAF: 261; (d) Total: 3,778.
(6) CO_2 emission share of BF-BOF: 86%.

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Together, we will connect climate technology innovation with industry to accelerate the solutions of the future.

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