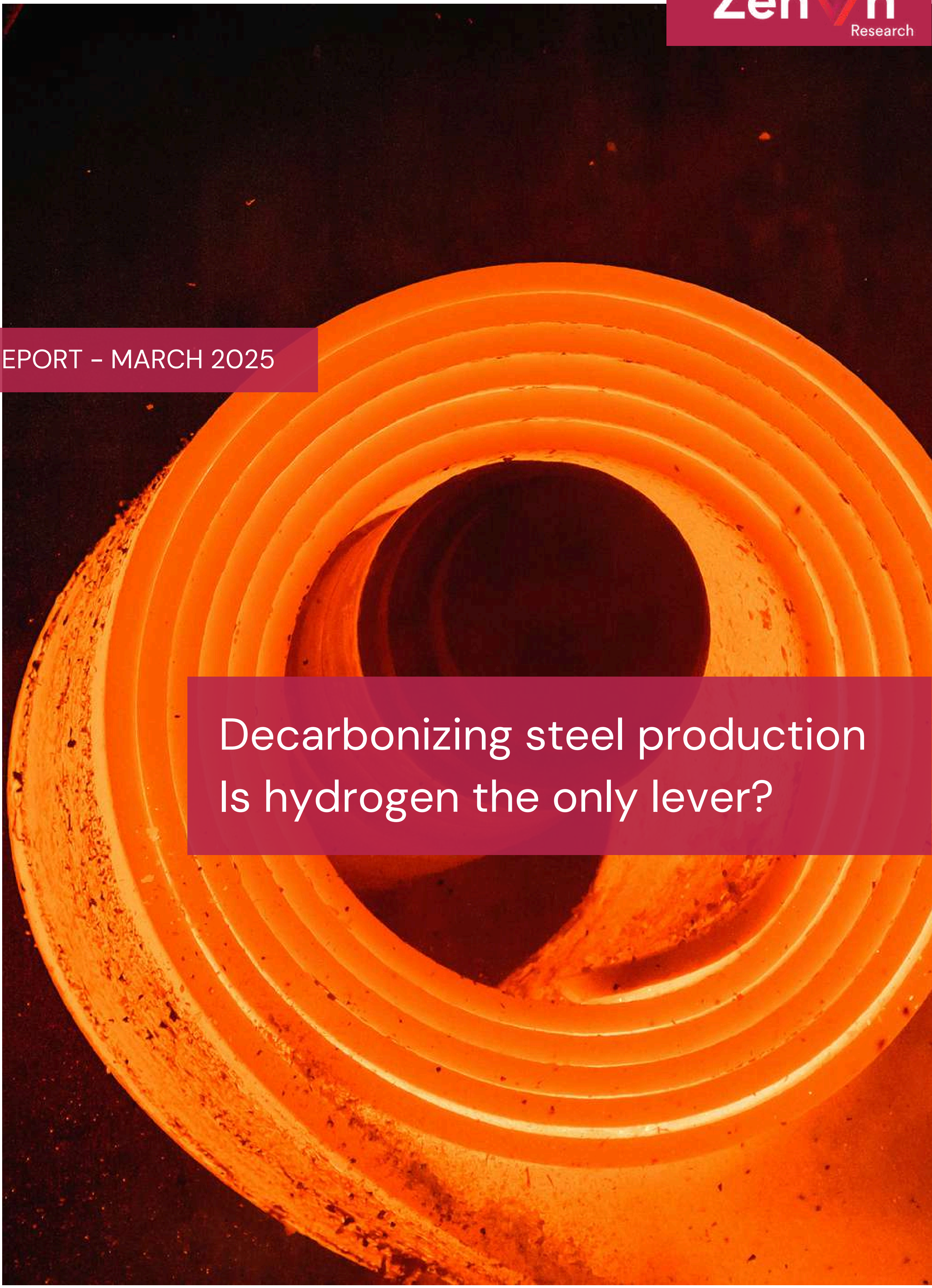

REPORT - MARCH 2025

Decarbonizing steel production
Is hydrogen the only lever?

SUMMARY

Introduction

Steel is by far the most used metal, and the single most climate-impactful raw material. Due to its strength and low cost, it is the backbone of modern civilizations. Its primary production relies heavily on coal, and is realized in very large-scale units, whose decarbonization requires in all cases to implement breakthrough technologies (carbon capture and storage, hydrogen or electrolysis) that all lack maturity today and whose deployment at scale still entails deep and complex challenges on the industrial, commercial, and policy sides.

Facing a difficult context of high energy costs, fierce international competition, and the policy urge to decarbonize, the EU steel industry stands at a crossroads, between the ambition of pioneering climate transformation, and a possible existential threat. This report synthetizes the current knowledge about present technologies and emerging low-carbon ones, and provides a critical, yet prudent overview of proposed decarbonization pathways, summarizing potentials as well as constraints, trade-offs and knowledge gaps. It intends to help policymakers, stakeholders and civil society navigate the steel decarbonization transition.

Executive Summary

Steel has a major climate impact, and is hard to abate. With a yearly production of 1.9 Gt, and a market value of about 2 Tn USD, steel is systemic, and by far the most widely used metal. Composed mostly of iron, it is strong, cheap for a metal, and thus widely used in buildings, infrastructure, machines and consumer goods. With a total carbon footprint of 3.6 Gt CO_2 emissions in scope 1 and 2,[1] i.e., 10% of global energy-related CO_2 emissions, it is considered not on track to reach climate goals (IEA, 2023a), and notoriously hard to abate, as 90% of primary production relies on the coal-based blast furnace-basic oxygen furnace (BF-BOF) route, involving very large scale assets in highly capital-intensive units.

Secondary production (end-of-life scrap recycling) is very energy efficient and should be maximized, but has limited potential. Scrap recycling needs 8-10 times less energy than primary production, and uses electric arc furnaces (EAF), so the already low emissions are also easier to reduce. End-of-life scrap availability shall increase as global economies age, from about 24% of global production today to 35% in 2050 in highest estimates, but it is fundamentally limited by the long residence time of steel in the economy. About 85% of end of-life products are already recycled, so recycling cannot even meet a stabilized future demand. Decarbonizing primary production is thus anyways needed, and requires breakthrough technologies.

Carbon capture and storage (CCS) on primary steel production is possible, but has lost momentum, and is now struggling to convince. Widely presented until recently as the most promising solution, CCS is possible on modified coal-based blast furnaces and gas-based Direct Reduction (DR) plants, but implementation has been lagging, **innovations have been discontinued, and the project pipeline is depleted.** The main issues in the on BF-BOF route are the multiplicity of CO_2 sources, which makes on-site emissions reductions difficult beyond 70%, the upstream methane leaks in coal mining,

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[1] Emissions scopes are as in the GHG Protocol. Scope 1 covers direct fuel-burning and process emissions, scope 2, the indirect emissions from power and heat consumption, and scope 3, all other indirect emissions considered.

and the mostly inexistent CO_2 infrastructure. This adds to the general skepticism towards CCS solutions, as strategies that are fundamentally extrinsic, reversible (e.g., following policy shifts), and entail non-zero risks of CO_2 instability in storage sites. CCS on gas-based DR plants is more feasible, but unattractive for countries with low gas supply security, and projects show little progress.

Hydrogen, currently presented as the main solution, is facing bottlenecks and delays. Clean hydrogen for direct reduction of iron ore (H_2-DRI) followed by an electric arc furnace (EAF) is technologically proven a pilot scale, but not mature commercially, and faces two important bottlenecks. **Firstly, the iron ore used in blast furnaces is of too low quality for the DRI-EAF route, and the appropriate DR-grade ore is scarce,** representing only 3% of globally traded iron ore.[2] Deploying H_2-DRI at scale would require a global reconfiguration of the iron mining and processing value chains, either adding more beneficiation stages to increase the ore´s Fe content, or deploying additional processes after the DR, such as electric smelters (of yet low technological maturity), followed by BOF - both pathways bringing additional steps and costs.

The second and probably nastier obstacle to H_2-DRI deployment is the cost of supplying clean hydrogen at scale and continuously, probably requiring costly storage. This has been the game-killer for first-mover European projects (except in Sweden due to the outstanding availability of domestic high-grade ore, and cheap clean power). Possible cost reducing strategies include to relocate the most energy-intensive ironmaking step in countries having abundant and cheap renewables, and developing green iron trade, implying deep changes to the industrial geography. Natural hydrogen, if it becomes cheap and abundant, could also help unlocking the hydrogen pathway, but this remains highly hypothetical.

Direct electrolysis of iron ore may be the technological game-changer, so strong support seems very relevant. Despite low current maturity, this strategy is gaining momentum. It has 10-20% less consumption than the H_2-DRI route and appears cheaper and simpler, avoiding any expensive hydrogen production, transport or storage. Ores of any grades may be usable in principle and the processes allow for flexible coupling to variable power supply from cheap renewable sources, especially for the low temperature variants. Being fundamentally modular, such electrowinning technologies may also be able to be deployed faster, with decentralized units and low upfront costs, for example in developing countries, and enjoy fast learning rates.

Policies are strongly needed to accelerate technology deployment, enable the coordination of actors and share the costs fairly. In all cases, near-term abatement costs, estimated to 100-500 USD/t CO_2, are substantially higher than current carbon pricing levels, so strong policy support, and a readiness to pay for green premiums will be needed if climate targets in the sector ought to be met. Direct subsidies for investments and operation (e.g., the EU hydrogen bank), carbon pricing, including border adjustment mechanisms (CBAM), but also green public procurement, certifications and incorporation quotas, must be coordinated and implemented wisely.

An integrated, lucid transition strategy for the steel sector is strongly needed, but so far largely missing. The steel industry being of systemic scale, its decarbonization implies profound reconfigurations of value chains and infrastructure, in particular concerning raw materials and clean energy inputs (and even also, as a major feedstock supplier to the construction industry). Mines, ports, ships, trains and railways, but also, massive clean power supplies, high-capacity grid connections, and eventually, hydrogen and/or CCS infrastructures need to become available where relevant. Moreover, the most energy-intensive ironmaking stage could partly relocate to renewables-rich locations, bearing deep additional geopolitical considerations and implications on labor force reconfigurations. A shared, well-informed and pragmatic transition strategy is thus strongly needed to align all stakeholders towards well-defined goals, despite the many remaining uncertainties. This is perhaps the largest challenge.

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[2] Or about 7% of global iron ore production, by iron content, assuming all DR production uses high quality iron ore, except the coal-based rotary kilns in India, that have about 37 Mt operating capacity (BNEF, 2024)

01

OVERVIEW OF GLOBAL AND EUROPEAN STEEL INDUSTRY

Global production and trade
Steel in the global economy
Global energy consumption
European steel industry

1.1 Global production and trade

Global production of crude steel (before shaping in final products such as coils, bars, etc.)[3] reached 1.89 Gt in 2023 (about 280,000 Eiffel towers), strongly concentrated in China, with 1019 Mt (55% of global production) and other major Asian economies: India 141 Mt (8%), Japan 87 Mt (5%), for a total of 76% in Asia, while EU-27 countries all together produced only 127 Mt (7%), and North America, 110 Mt (6%), as shown in Figure 1 and Table 1. The global steel industry has a market value near 2,000 Bn USD and employs directly more than 6 million people, and indirectly, over 50 million (Worldsteel, 2022).

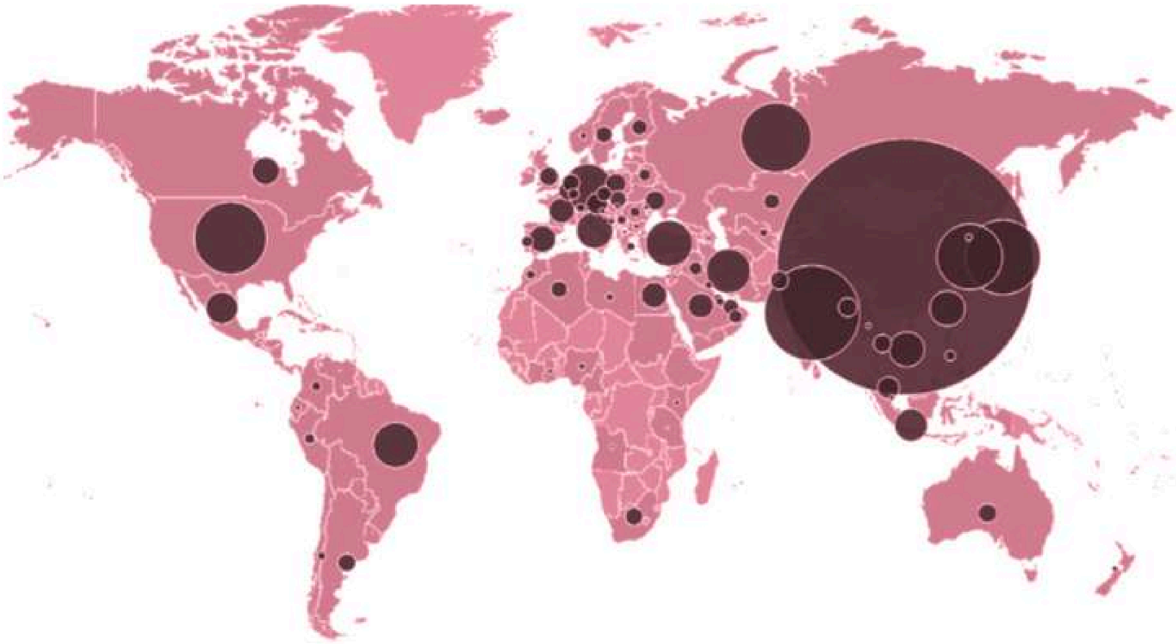

Figure 1: Global production by countries, in 2023. Source: (Worldsteel, 2024)

Since World War II, global steel production has had two periods of fast growth, as seen in Figure 2. The first period, until 1973, (almost quadrupling from under 200 Mt to over 700 Mt), dominated by OECD countries, and the second period, from 2000 to 2020, with another tripling, impressively dominated by China.

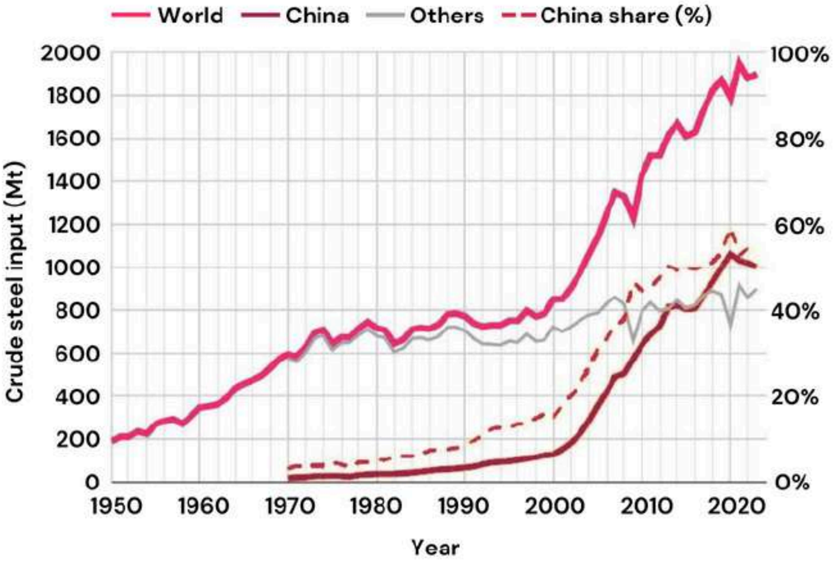

Figure 2: Global and Chinese crude steel production since 1950. Source: (Our World in Data, 2024)

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[3] Crude steel is used in this report as the by-default end gate of analysis, as it is the last step common to all routes, after which the energy intensities vary depending on the processes applied to obtain the different products.

Steel products are widely traded. The total production of finished or semi-finished products was 1763 Mt in 2023 (93% of crude steel production), and 434 Mt were traded internationally, thus representing 25% of the apparent consumption of final products (Worldsteel, 2024). Table 1 shows that the first gross exporter 2023 was China by far, and the first importer, the EU-27 taken as a bloc.[4]

Rank	Production	Mt	Total exports	Mt	Total imports	Mt
1	China	1 019.1	China	94.3	EU-27	39.2
2	India	140.8	Japan	32.2	USA	26.4
3	EU-27	127	South Korea	27	Germany	18.7
4	Japan	87	EU-27	26	Italy	18.7
5	USA	81.4	Germany	22.5	Türkiye	18
6	Russia	76	Italy	16.1	Mexico	17.5
7	South Korea	66.7	Belgium	14.6	South Korea	15
8	Germany	35.4	Russia	13.9	Vietnam	14
9	Türkiye	33.7	Türkiye	12.7	Thailand	13.7
10	Brazil	31.8	Brazil	12.3	Indonesia	12.4
11	Iran	31	Iran	11.9	France	11.8
12	Italy	21.1	Netherlands	11.8	Belgium	11.6
13	Vietnam	19.2	France	9.9	Poland	11.6
14	Taiwan	19.1	India	9.9	China	11
15	Indonesia	16.8	Indonesia	9.6	Spain	10.2
16	Mexico	16.2	Taiwan	9.5	India	9.8
17	Canada	12.2	USA	8.9	Netherlands	9
18	Spain	11.4	Vietnam	8.6	Canada	8.6
19	Egypt	10.4	Spain	7.8	Taiwan	7.5
20	France	10	Malaysia	7.6	Malaysia	7.1

Table 1: Production, total imports and total export by countries in 2023. NB: total internal trade between EU-27 countries is 93.1 Mt. Source: (Worldsteel, 2024)

In terms of players, the steel industry has a low level of concentration. The largest producer in 2023 (Baowu) only accounted for 7% of global output, and the top 50, for only 56%.

Rank	Company	Headquarters	(Mt)	(%)
1	China Baowu Group	China	130.8	6.9
2	ArcelorMittal	Luxembourg	68.5	3.6
3	Ansteel Group	China	55.9	3.0
4	Nippon Steel Corp.	Japan	43.7	2.3
5	HBIS Group	China	41.3	2.2
6	Shagang Group	China	40.5	2.1
7	POSCO Holdings	South Korea	38.4	2.0
8	Jianlong Group	China	37.0	2.0
9	Shougang Group	China	33.6	1.8
10	Tata Steel Group	India	29.5	1.6
Top 10			519.2	27.4
Top 25			823.9	43.5
Top 50			1106.6	58.5
Total			1892	100%

Table 2: Production, total imports and total export by countries in 2023. NB: total internal trade between EU-27 countries is 93.1 Mt. Source: (Worldsteel, 2024)

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[4] Internal trade between EU-27 member countries amounted to 93.1 Mt in 2023, representing 77% of total exports and 70% of total imports of EU-27 countries considered separately.

1.2 Steel in the global economy

Because of its strength, durability, and low cost, steel is by far the most used metal, by far outnumbering aluminum, the second most used metal at 108 Mt in 2022. Steel products contain about 97% iron, which is the second most abundant metal in the earth crust (5% by weight) after aluminum (8%), together with some carbon at various levels (0.05% to >1%), several possible alloying elements, and impurities. Alloying can strongly enhance the properties of iron regarding resistance to mechanical stress or corrosion. In particular, stainless steel, which makes up 3% of steel production, bears 10-18% chromium, often nickel, and others, it has excellent cleanability and is widespread in food or medicine related applications.

As the ubiquitous structural metal, steel is the backbone of industrial civilizations, and has a long residence time in the economy, of 40 years in average (Worldsteel, 2021). Its per capita consumption is thus quite correlated to the first stage of industrial development of countries. As shown in Figure 4, steel demand reaches a plateau and decreases once a GDP level of about 10,000 USD/capita/year (1990 reference value) is reached since, at this point, most of the infrastructure has already been built.[5]

Steel is 3 times heavier than aluminum (7.8 g/cm³ versus 2.7 g/cm³), and requires much less energy for its primary production from natural ore, typically 20 GJ/t for primary steel, versus 75 GJ/t for primary aluminum production (BNEF, 2021). Because of its relatively low energetic cost to mine and produce, steel is also the cheapest metal to produce, at about 500 USD/t for crude steel, versus about 1500-2000 USD/t for aluminum (IEA, 2020). This explains that steel is the most used metal in infrastructure (buildings, bridges, etc.), but also, for heavy machinery, transport devices (cars, ships, trains), and many other equipment and consumer goods.

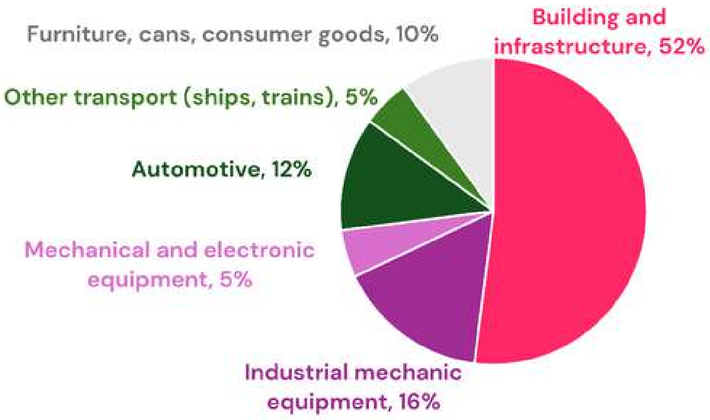

Figure 3: Steel uses by sectors. Source: (Worldsteel, 2024)

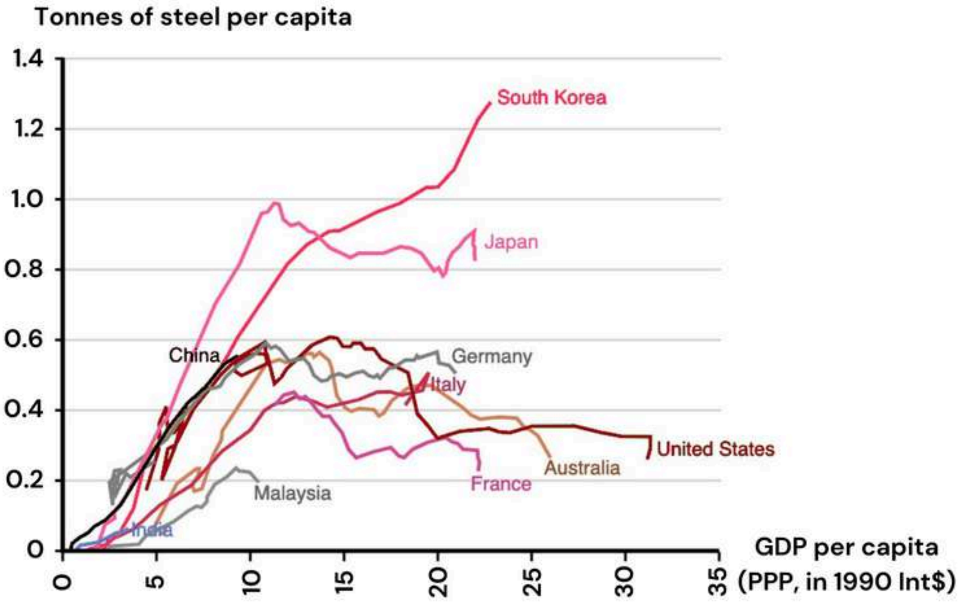

Figure 4: Steel production per capita as function of country's GDP (5-year sliding average, in thousands of 1990 USD/y). Source: (Roberts et al., 2016)

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[5] Interesting outliers are Japan, presenting a higher plateau, and South Korea, where no plateau is yet visible by 2016. Those economies are strongly oriented towards exports of industrial goods, for example, Korea was South Korea, in particular, was until recently the 1st exporter of ships before China. Korea reached its plateau soon after 2016, stabilizing at an apparent steel use of about 1 t /capita/year over 2018-2023 (Worldsteel, 2024).

1.3 Global energy consumption

Steel production is the single most energy intensive and CO_2 emitting industry. Its specificity is to be heavily based on coal, which accounts for 74% of its direct energy supply. The steel industry thus represents directly 15% of the global coal demand (not counting its indirect demand via electricity), and 55% of coal demand for industry. The global footprint of steel production was 35 EJ in final energy demand in 2018, that is, 8% of the global total, only in direct consumption (e.g., not counting upstream coal and iron mining activities).

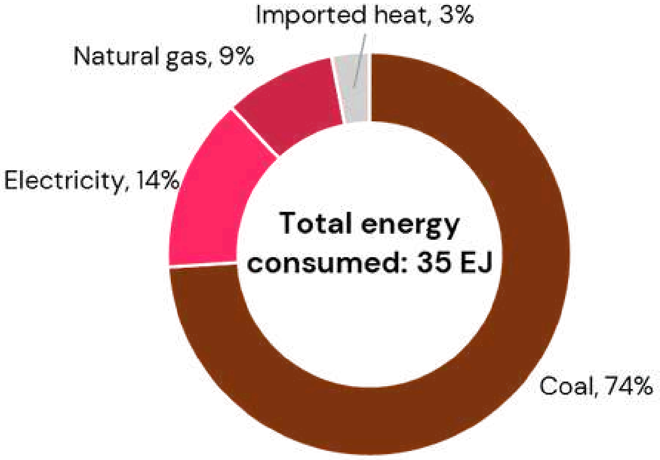

Figure 5: Global direct energy consumption for steel production in 2018. Source: (BNEF and CTC, 2024)

1.4 European steel industry

In 2023, the EU-27 produced 127 Mt of crude steel, emitting 147 Mt CO_2 (5% of its total emissions). About 50% of EU steel production uses the integrated BF-BOF route, with very large units of typically 2–5 Mt per year capacity (see Figure 6), versus many smaller EAF recycling units, with typical capacities of 0.1–1 Mt. Germany was the first producer in 2020 (36 Mt), followed by Italy (20 Mt), then France (12 Mt). Overall, the EU steel industry employs 300,000 people directly, and 2.6 millions when including indirect and induced jobs (Eurofer, 2024).

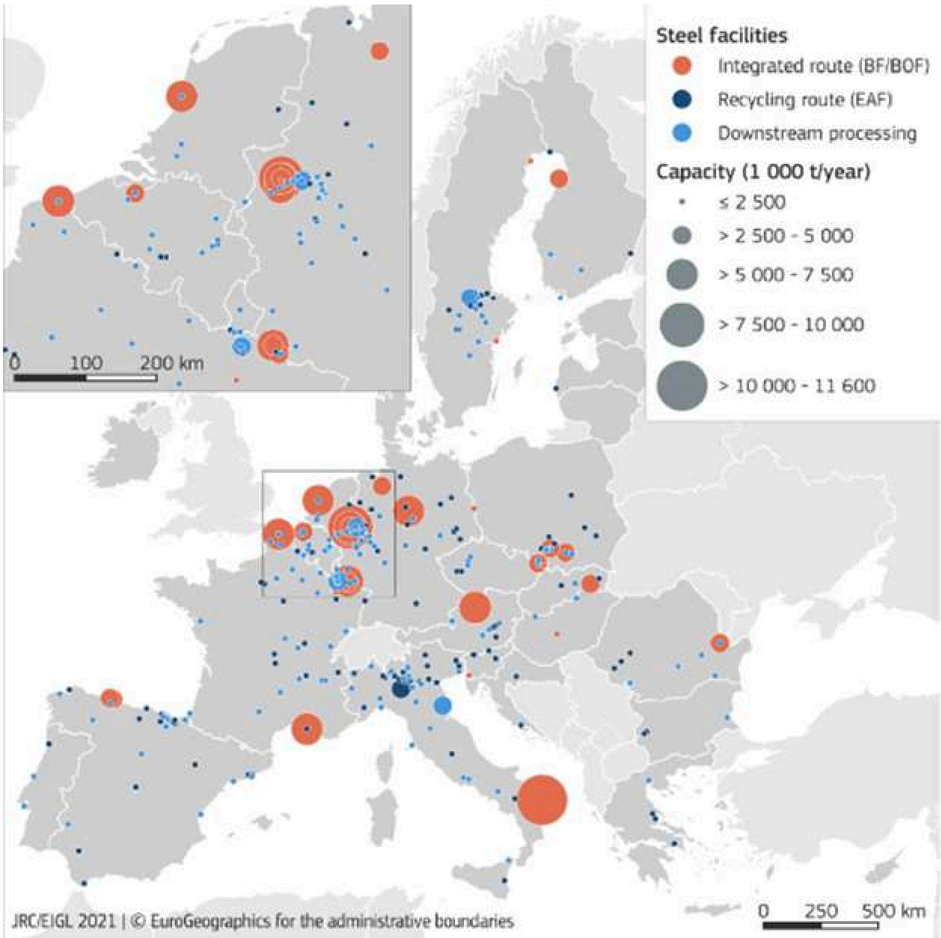

Figure 6: EU steel production sites showing integrated BF-BOF, recycling EAF, and downstream processing sites. Source: (JRC, 2022)

02

CURRENT TECHNOLOGIES

Main technologies for iron and steel making
Inputs, by-products and products
The BF-BOF route
The DR-EAF route
The secondary EAF route
Energy consumption and CO_2 emissions

2.1 Main technologies for iron and steel making

There are three main routes for iron and steel making. Primary production of steel starts from iron ore, which is found naturally as oxides, mostly Fe_2O_3 (hematite) and Fe_3O_4 (magnetite), that needs to first be converted to metallic iron in the ironmaking phase, which carries about ¾ of the energetic cost, after which, the steelmaking phase allows to purify the iron, and produce varieties of steel.

- In the **Blast furnace – basic oxygen furnace (BF-BOF)** route, the ore is mixed with coke, heated to about 1550°C, and reduced (i.e., oxygen is removed from it) to produce liquid pig iron (or "hot metal"), which is then sent for steelmaking in a BOF.
- In the **Direct reduction – electric arc furnace (DR-EAF)** route, the ore, prepared as pellets, is reduced by a gas, producing solid direct reduced iron (DRI), which is then melted and purified in an EAF.
- **Secondary production of** steel consists in recycling scrap, using only an EAF.

Importantly: primary and secondary production are not separated. In the BOF, typically 10-20% of scrap is loaded, in first place, of course, home scrap (see below), while in the EAF, about any proportions of pig iron, DRI and scrap can be loaded, depending on the inputs locally available, and time-dependent economic optimization.

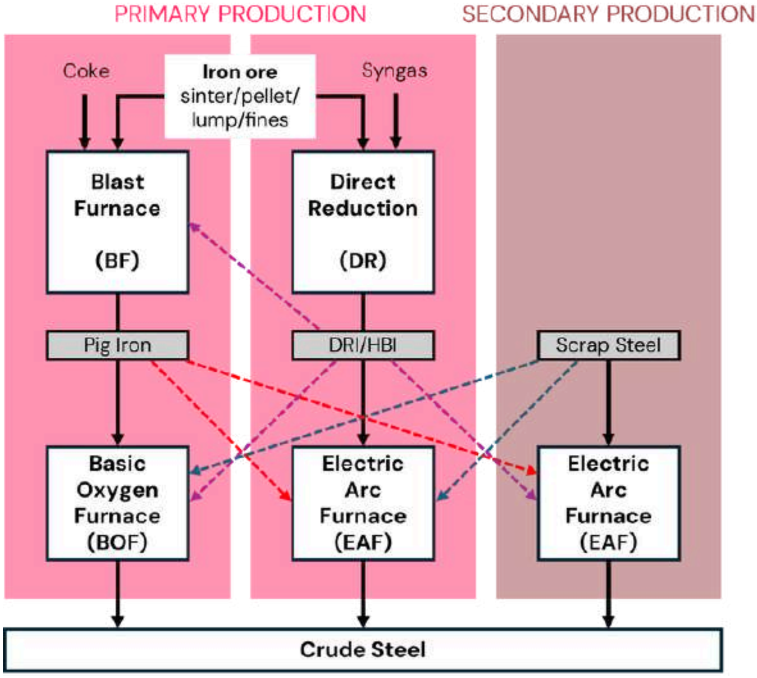

Figure 7: Main technological routes in iron and steel-making. DRI: Direct reduced iron. HBI: Hot briquetted iron. Source: (BNEF, 2019; Worldsteel, 2024).

2.2 Inputs, by-products and products

Iron ore is found in nature with Fe concentrations of 30-70%[6], and is commercialized as large lumps, fines (< 6mm), sinter or pellets. After being mined, the ore often needs some processing to be usable. Iron ore fines are usually agglomerated into sinter (an agglomerate of iron ore fines and binding materials) or pellets in dedicated sintering or pelletization plants, while lumps can be used directly in DR shafts, without further processing. To produce pellets, the raw mineral is first sorted grossly, using magnets to remove stones (which are not magnetic, unlike the iron), then crushed and grinded to smaller chunks, again magnetically sorted. A binder (usually bentonite, a clay material) is then applied to make the pellets (small balls of about 1 cm diameter) which are then dried and sintered at about 1300°C, and cooled (see, e.g., (HYBRIT, 2024a)).

Coke is a form of purified coal, suitable for the blast furnaces. Coking coal (a specific grade of hard coal with elevated carbon content) is heated to around 1100°C in a coke oven without oxygen to remove its volatile components, resulting in a mostly carbon-based substance.

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[6] Note that, since the Fe mass share in pure Fe_2O_3 is 69.9%, and in pure Fe_3O_4, 72.4%, some iron ore deposits are made of almost pure iron oxides

Scrap is of three types. Primary scrap represents about 22% of crude steel production (IEA, 2020), and includes the **"home scrap"** (also called internal, or semi-manufacturing scrap), obtained before making finished products, and the **"prompt scrap"** (also called industrial, or manufacturing scrap), which is produced by the steel users when cutting sheets, etc. Primary scrap is generally of high quality, with near zero contamination, and is virtually entirely recycled. On the contrary, **"end-of-life scrap"** (or "post-consumer"), comes from wasted goods or decommissioned infrastructure. It is a more diffuse resource, potentially more contaminated, requiring sorting and cleaning.

Fluxing agents, mostly calcium oxide (limestone) and sometimes dolomite or others, are introduced in the BF, the BOF, and the EAF to optimize the reduction or conversion processes, by lowering the temperature of fusion of the iron, and purge the impurities (Si, Al, S, P) which are extracted in the co-produced slags.

Slags are floating layers forming on top of liquid iron or steel, containing oxidized impurities "cemented" by the melted fluxing agents.,They that are extracted from the various furnaces as hot liquids and after cooling, become a valuable solid solid co-product. The production of 1 t of crude steel leads to about 400 kg of slag in the BF-BOF route (2/3 BF slag and 1/3 BOF slag) and 200 kg in the EAF route (Worldsteel, 2020). The steel industry produces in total over 600 Mt per year of slag. The , the BF slag isbeing a vita keyl input (substitute to clinker) for the cement industry (as substitute to clinker), while and the BOF and EAF slags arebeing less valuables products and rather used, e.g., to build routes.

Off-gases from the various BF, BOF and coke ovens are byproducts that often contain unburned fuels (CO, H_2, CH4) that can be either recirculated in the furnaces or, more generally, burnt on-site in heat and power plants.

Steel products. Crude steel is obtained by continuous casting, and delivered in large semi-finished products, mainly slabs, billets and blooms, and for to a smaller extent, ingots (<4%). Final products are obtained after further treatments (reheating, shaping, rolling, coating, etc.), andthey are mostly coils, sheets, bars, rods, tubes, and rails, whichand are sold to the customers[7].

Shares of the different routes. As shown in Figure 8, the dominant route for steel production in 2018 was BF-BOF, however 7% of the iron inputs were obtained as DRI, and 24% as scrap.

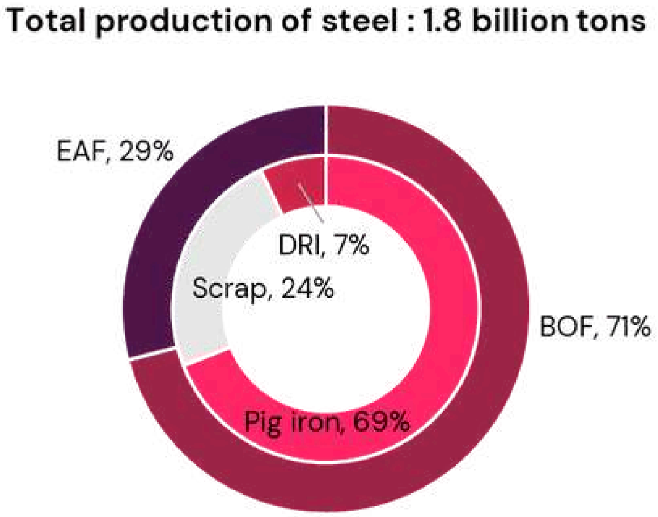

Figure 8: Share of inputs and of the different production routes, in 2022. Sources: (BNEF and CTC, 2024)

2.3 The BF-BOF route

The **blast furnace** is a large wide tower (up to 60 m high, and 15 m diameter), where sinter (ore agglomerates), iron ore lumps or pellets are added continuously from the top, together with coal coke (or, very rarely, biogenic charcoal,[8] or other fuels), and fluxing agents (several 100 kg per tCS). While moving down, the mixture faces a counter flow of gas of increasing temperature, as hot air is continuously re-injected at the bottom by pipes called tuyeres. As the coke is heated up, it is gasified, releasing CO and H_2 gases that progressively reduce the solid ore into metallic iron. Temperatures above 1600°C area reached at the bottom, well higher than the melting point of pig iron (about 1250°C). Off-gas, dense in CO_2, is removed at the top, while at the bottom, buoyant slag formed by the limestone and rock residues is removed, and liquid pig iron ("hot metal") is extracted at the lowest part.

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[7] Details of flows and losses at all stages are given, e.g., in (Cullen et al., 2012).

[8] Very rare today (about 10% in Brazil), but before the 18th century, all steel production was based on charcoal as the reducing agent and energy source.

The second stage is the **basic oxygen furnace**, where the hot metal is poured and converted to steel. The pig iron produced by the BF contains too much carbon (about 4-5%), which needs to be reduced to typically 0.02-2%, and still too many impurities like sulfur, phosphorus and silica, that make it brittle. Unlike the BF which is continuous, the BOF is a quite smaller, batch process working with up to 400 t of material at a time, charged and processed in about 30 minutes. Oxygen is blown into the liquid metal (usually with a vertical lance), to remove C and other impurities (Si, P) by decarburization and combustion, with the addition of some flux materials, which are chemical bases, to optimize the purification process and protect the lining of the vessel. The process is strongly exothermic due to the combustion of impurities, thereby requiring no fuel, the heat release making it actually preferable to add 10-20% of scarp.

The BF-BOF route is the dominant route today (71% of global production), with typical units having capacities of 2-5 Mt per year.

2.4 The DR-EAF route

The production of iron by direct reduction reached 136.5 Mt and represented 7% of the global steel production in 2023 (BNEF, 2024). It happens fully in the solid state, at temperatures typically < 1000°C (well below the melting point of pure iron at 1538°C). A DR shaft is a tall cylinder-like container 25-30 m high, 4-5 m wide (see e.g., (Hamadeh et al., 2018)), where iron ore pellets, a few cm in size, possibly with some lump ore, are continuously loaded from the top, without coal nor flux. The reducing agent is a gas injected from below, currently obtained from fossil gas or coal, containing the reducing molecules CO and H_2, that form H_2O and CO_2 when removing O from the ore.

The obtained product is called **Direct Reduced Iron** (DRI) or "sponge iron", as removing the oxygen takes about 30% of the mass off the pellets, creating porosity in the same time that their color turns from reddish to grey (see Figure 9). To avoid the porosity that could favor reoxygenation, especially if the DRI is stored outdoors or transported to another plant for further steelmaking, the DRI pellets are sometimes[9] pressed into **hot briquetted iron** (HBI), applying heat (approx. 750°C) and high pressure (up to 180 kN/cm2).

Figure 9: Left: Ore pellets on the left, and DRI pellets on the right (note the color change, from reddish to greyish). Right: Hot briquetted iron. Source: (HYBRIT, 2024a)

DR is a more recent technology that BF. As seen in Figure 10, it is developed mostly in countries having abundant and cheap natural gas (NG). The major exception is India, who produced 36% of the global DRI in 2023, but 80% of that using coal-based rotary kilns (Midrex, 2024), which are more traditional, smaller and rather inefficient systems. For the modern, gas-based shaft DR, Midrex is the dominant reactor technology, with 56% of the total DR market, and HYL/Energiron about 12%, while rotary kilns amount to 30% of global DR.

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[9] 9% of DRI was output as HBI in 2023, 11% as hot DRI to be fed rapidly to an EAF, to avoid energy losses, and the rest as cold DRI and 21 Mt of DRI were traded in 2023. (Midrex, 2024).

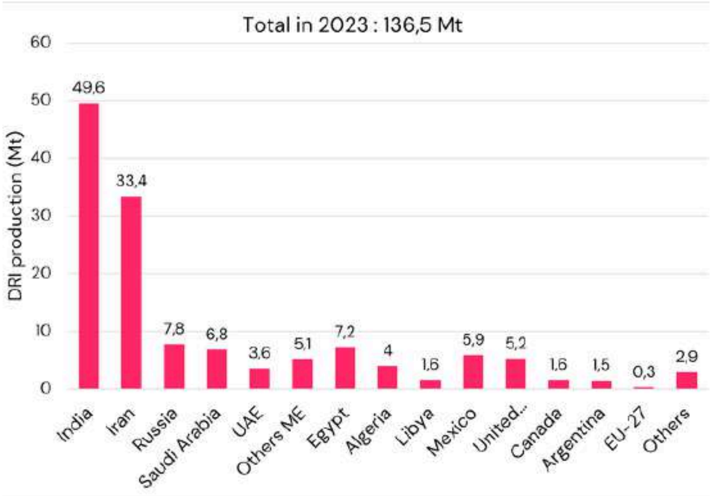

Figure 10: DRI production by countries in 2023. "Others ME" includes Oman, Qatar and Bahrein. Source: (Worldsteel, 2024)

The next step for steelmaking is to melt and purify the obtained DRI in an **Electric Arc Furnace**, which have a wide container shape, with usually three plunging electrodes, with capacities in the range 1– 400 t. The DRI or HBI are charged, generally with the addition of scrap, and fluxing agents to remove impurities and lower the temperature of fusion. The mixture is progressively melted by the application of strong currents, and oxygen is blown into the metal to remove the eventual excess carbon in the charged DRI, and burn impurities (Si, S, P, Al, Mn, Ca, etc.), removing their oxides to the layer of slag floating on top of the liquid iron. The slag layer is continuously removed, to avoid its accumulation that would harm the process.

2.5 The secondary EAF route

The secondary route for steelmaking consists in processing steel scrap into an EAF. It represented 24% of steel production 2022, considering end-of life scrap only, whose supply was about 460 Mt[10]. Due to the flexibility of the process, some primary pig iron or DRI can also be introduced.). In total, around 650 Mt of pre-consumer and end-of-life scrap was consumed in 2020 for steel production, 2/3 in the secondary route and 1/3 in the primary route. (Worldsteel, 2021).

Scrap availability is fundamentally limited by the rate at which steel products reach their end of life, and the average lifetime of steel in the economy is estimated to 40 years (Worldsteel, 2021). As seen in Figure 11, most of the increase in scrap supply towards 2050 is expected to come from China and other recently industrialized economies, whose steel demand is now flattening.

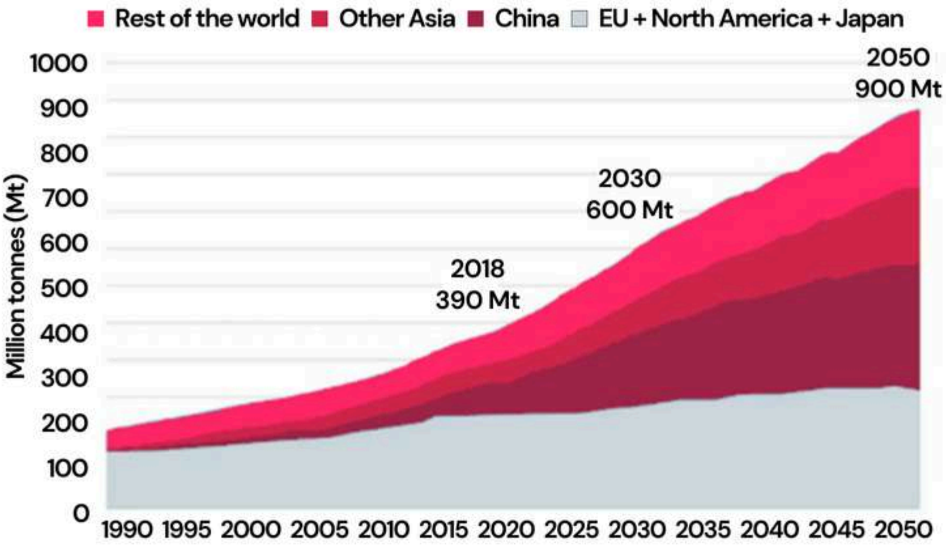

Figure 11: Estimated end-of-life scrap availability per countries. Source: (Worldsteel, 2021)

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[10] This estimate is the difference between total production of 1890 Mt and the sum of 1301 Mt of pig iron and 126 Mt of DRI (Worldsteel, 2024)

The scrap-based EAF route is by far the most energy-efficient route, requiring 8 - 10 times less energy than primary steelmaking (see Figure 13). It is a quite flexible, batch process that takes about 0.5 – 2 hours. EAF units have capacities of 0.1 - 1 Mt, smaller and much more distributed than BF or DR units (Global Energy Monitor, 2024).

Secondary steel is generally of lower quality than primary steel. It has higher levels of impurity ("tramp") elements such as copper and others (Cr, Ni, Sn) due to contaminated end-of-life scrap. Those metals, having a lower affinity for oxygen than iron, cannot be removed through oxidation in the EAF like the other impurities (see above), otherwise the iron itself would be re-oxidized. After being mixed in the steel, tramp elements are very difficult to remove, but diluting their concentration with virgin primary steel is possible. It is thus of high importance to control tramp presence by rigorous scrap sorting, which is feasible.

Lower quality has often limited the use of recycled steel to the production of long products, more often used for less quality-demanding applications (e.g., in construction), while flat products, where the presence of impurities is more problematic[11], are generally made from primary steel. Secondary production thus often leads to downcycling, but this can quite be avoided, as many techniques are available to improve the scrap quality and recycling technologies (see, e.g., (Ricardo, 2024)). High quality recycled steels are already available in several markets, for example, car manufacturing uses about 15% of recycled steel already.

The rate of end-of-life scrap recycling is estimated to 80-90%[12], i.e., close to the maximum, with a higher uncertainty than for other steel data (Bureau of International Recycling, 2023; Worldsteel, 2021)). This rate could be still improved, as well as the scrap quality, by better scrap dismantling and sorting, and product design that facilitate the sorting[13]. Steel recycling is fundamentally profitable, and scrap is a scarce and valuable resource[14]. Producing steel from scrap instead of iron ore saves about 80% in energy and typically costs 200 USD/t instead of 500 USD/t, leaving a 300 USD/t cost gap that fixes the equilibrium price of scrap, setting the threshold at which a given scrap resource is profitable to recycle (Gérardin and Ferrière, 2025; IEA, 2020). And because iron is magnetic, scrap is easy and affordable to recover from most waste streams.

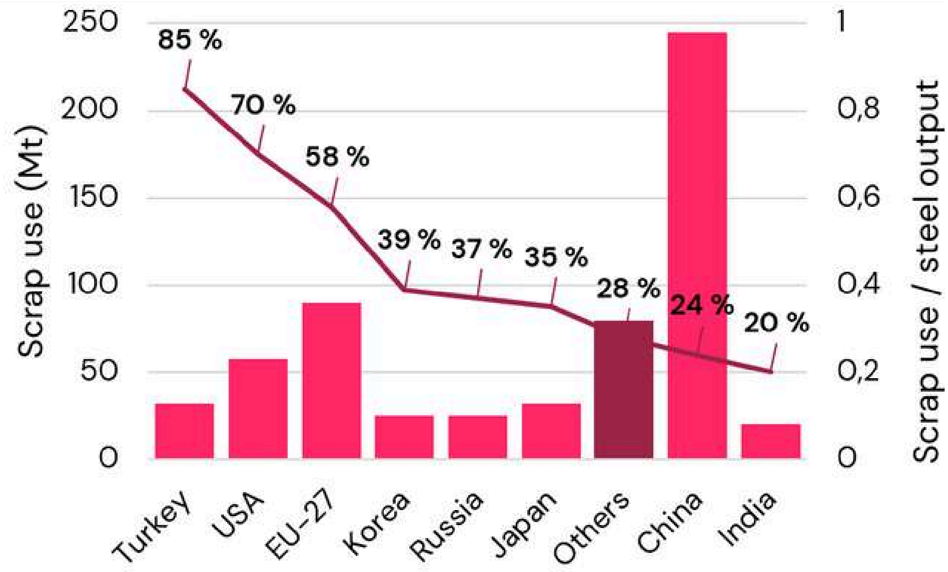

Figure 12: Scrap use in steel production by countries, in 2021, and share of scrap total metal input (right axis), with global average of 32%. Source: (GMK Center, 2022)

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[11] The most problematic scrap pollutant is copper, with a typical tolerance of 0.1% of copper in weight for flat products, versus 0.4% for long products (JRC, 2022)

[12] More precisely, at least 90% in the automotive and machinery sectors, at least 85% in construction, and at least 50% for electric and domestic appliances (Worldsteel, 2022)

[13] For example, policies to increase the use of recycled steel in the car industry could drive up the demand for recycled steels of higher quality, according to (World Economic Forum, 2023)

[14] It can even be considered strategic (GMK Center, 2022)

The share of total end of life + prompt scrap inputs in steel production, as seen in Figure 12, was 32% on average in 2021, higher in the older industrial economies, especially the EU-27 (58%) and the USA (70%), but also Korea, Russia and Japan, and was well lower in younger growing economies, such as China (24%) and India (20%).

Turkey is a special case as it has specialized in importing scraps and re-exporting recycled steel. The total international trade of steel scrap was about 98 Mt in 2022 (including 25 Mt between EU-27 countries), the EU-27 was the largest exporter, for 17.6 Mt while Turkey was the largest importer and its main buyer, for 10.6 Mt (Bureau of International Recycling, 2023).

2.6 Energy consumption and CO_2 emissions

The global average energy and CO_2 emissions intensities for the three routes are shown in Table 3 and Figure 13, for two estimates. The Worldsteel data are real world values in 2023 reported from the industry for CO_2 only and for finished products, whereas the IEA models are for crude steel only, and represent idealized routes (archetypes) with scrap inputs of either 0% or 100% (which is most often not the case in practice) that represent the two theoretical extremes in the “sliding scale” approach (see below). Figure 13 also allows to visualize the shares of different types of emissions in each route, from fossils consumption for energy and process, materials preparations (sintering, pelletization, coke preparation), and upstream methane emissions in coal and gas supplies.

In the BF-BOF route, most of the energy is provided as coal for heat and as reducing agent in the BF, making it the most emitting process besides being the most energy-intensive with 21.4 GJ/tCS[15]. The DR-EAF process is more energy-efficient, using 17.1 GJ/tCS. The secondary EAF route is way more efficient, using only 2.1 GJ/tCS, as most of the energy in primary steelmaking is for the ironmaking. CO_2 intensities are in the same order, however the Worldsteel and IEA methods differ due to the several above mentioned differences.

The CO_2 intensity per unit of energy is larger for scrap-based EAF, relying essentially on power, than for the BF-BOF, based mostly on coal. This is because the global electricity mix still strongly relies on fossil fuels, especially coal, and thus has an average direct CO_2 intensity of 440 gCO_2/kWh in 2022, which is 35% higher than the direct CO_2 intensity of 325 gCO_2/kWh of coal heat used directly (IEA, 2023b).

(tCO2/tCS)	BF-BOF	DR-EAF	Scrap EAF
Worldsteel	2.33	1.37	0.68
IEA reference models	2.95	1.48	0.29

Table 3: Carbon footprints of steel production routes. Wordsteel data are reported average CO_2 for finished products, while IEA modelled CO_2e footprints are for cast crude steel, but includes upstream emissions for ore and energy inputs. Sources: (IEA, 2020; Worldsteel, 2024)

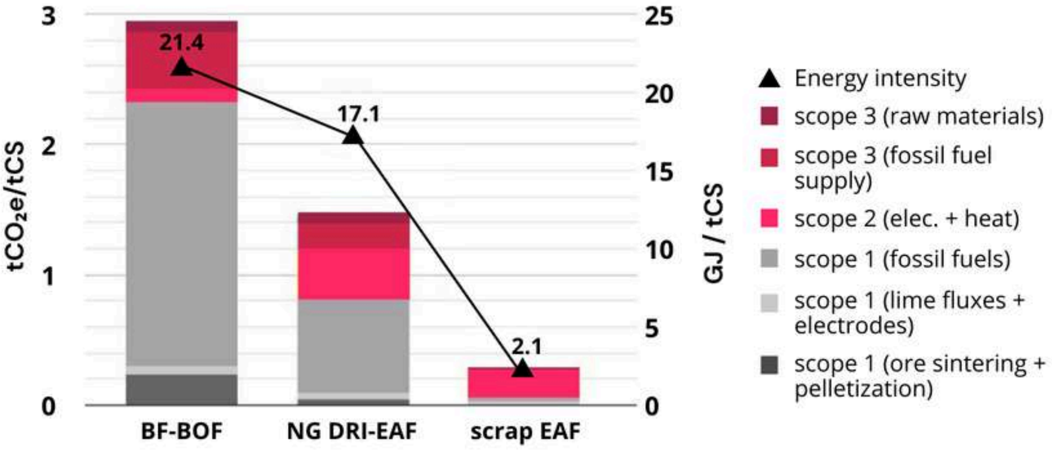

Figure 13: CO_2e emissions in scope 1, 2, 3 (left axis) and energy intensity (right axis) for IEA´s ideal model routes, with ether 0% or 100% scrap inputs. The assumed electricity carbon footprint is the global average of 440 $kgCO_2/kWh$ (direct emissions only). Source: (IEA, 2020a, 2022)

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[15] tCS denotes a ton of crude steel, before processing into final products

03

MAJOR DECARBONIZATION VISIONS AND PLANS

BF fleet reaching end of life:
the 2020s opportunity
Major scenarios: the recent dominance
of hydrogen-based DRI
Decarbonization projects pipeline

3.1 BF fleet reaching end of life: the 2020s opportunity

After 15-20 years of operation, blast furnaces need a complete relining (that is, a deep reconstruction of their inner surfaces), which requires substantial reinvestment and about 3-6 months down time, or they can be decommissioned. The global average lifetime for plants in operation before relining is 17 years (Vogl et al., 2021), which is quite shorter than the 35-40 years economic lifetime of whole plants (IEA, 2020).

As a consequence, 71% of current global coal-based BF capacity (total capacity 1090 Mt) would reach end-of-life before 2030, requiring substantial reinvestment, or decommissioning (Agora Industry and Wupperthal Institute, 2023), the largest share in China: This could make an opportunity to substitute them by low carbon steel assets (Agora Industry, 2021).

3.2 Major scenarios: the recent dominance of H_2-DRI

A number of scenarios for the evolution of the steel sector have been proposed by various organizations, within broader visions of future climate action, the most ambitious framework being a transition towards global net zero emissions by 2050, as, e.g. in (BNEF, 2023; Energy Transitions Commission, 2022; IEA, 2023a). Figure 14 shows the evolution of steel production in IEA´s Net Zero Emissions by 2050 scenario (NZE), supposedly compatible with 1.5°C of global warming, first developed in (IEA, 2021). There, by 2050, almost all steel production uses near-zero carbon technologies.

For comparisons, Table 4 shows the main features in IEA´s NZE, Bloomberg New Energy Finance (BNEF)´s NZ Scenario, and IEA´s latest Sustainable Development Scenario (SDS), described in (IEA, 2020), supposedly compatible with well below 2°C global warming, which was IEA´s most climate-ambitious scenario before the NZE was created in 2021.

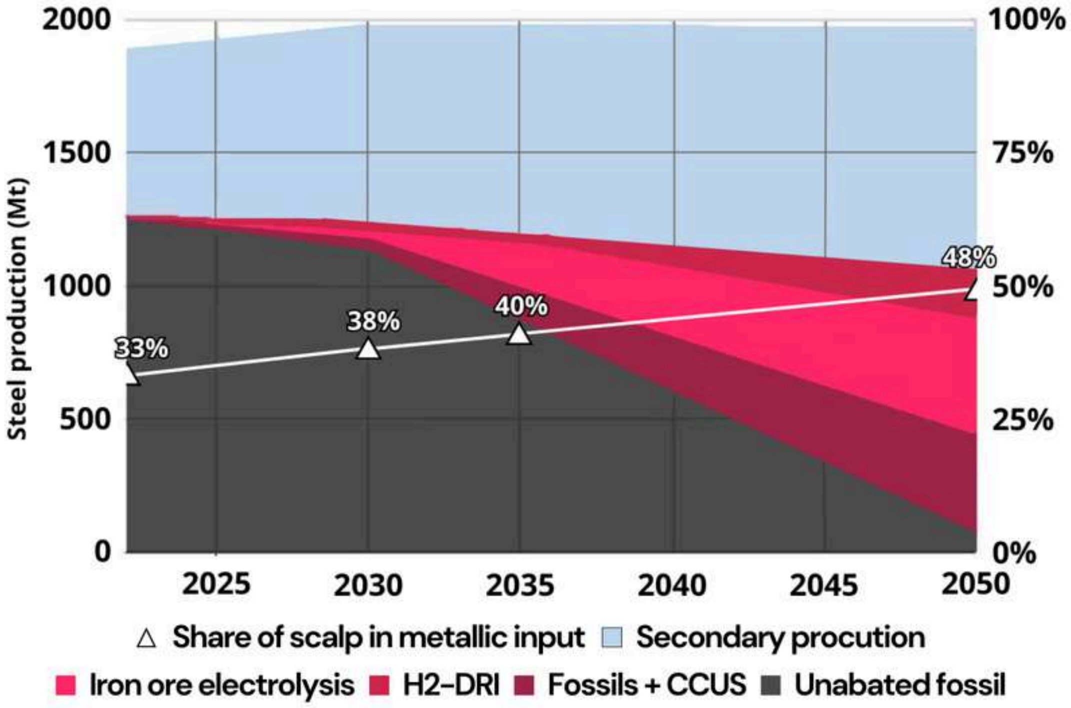
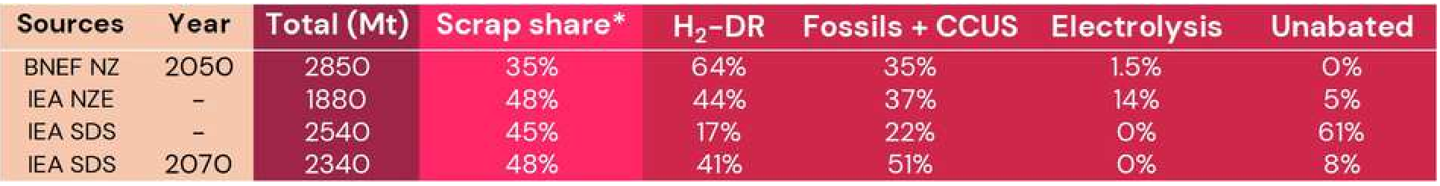


Figure 14: Steel production routes in the IEA NZE by 2050 scenario, and share of scrap (end-of-life + prompt) vs primary iron input (right axis). Source: (IEA, 2023c).

The total demand for steel in 2050 in IEA´s NZE is 1960 Mt, almost stable compared to today, whereas BNEF anticipates a growth to 2850 Mt, and the Energy Transitions Commission (ETC) also pictures demand growing to 2450 Mt in their three scenarios. The share of scrap recycling is 33% today in IEA´s scenario, versus 24% according to BNEF, because BNEF refers to end-of-life scrap only, while the IEA includes prompt scrap produced by steel buying industries. The share of recycling rises to 35% in 2050 in BNEF´s scenario, and to 48% for the IEA (thus increasing by about 45% in both cases).

For primary production, both the IEA and BNEF now see H_2-based DR as the dominant decarbonized technology in 2050, weighing 64% for BNEF and 44% for the IEA. BNEF sees DR being first deployed to about 500 Mt capacity using natural gas in the early 2030´s, then massively retrofitted to hydrogen from the second half of the 2030´s. Such vision of a progressive fuel shift for DR, gas being a "bridging fuel", is also found in IEA and ETC scenarios, and others. Concerning fossil-based production with CCUS, both IEA and BNEF paint a similar share of 35-37% in 2050. BNEF´s scenario attributes 2/3 of that CCUS deployment natural gas-based DR, and only 1/3 to coal-based BF routes. Finally, direct electrolysis of iron ore covers 14% of primary production in 2050 for the IEA, and only 1.5% for BNEF (and up to 33% in (Birat, 2023)).



Sources	Year	Total (Mt)	Scrap share*	H_2-DR	Fossils + CCUS	Electrolysis	Unabated
BNEF NZ	2050	2850	35%	64%	35%	1.5%	0%
IEA NZE	-	1880	48%	44%	37%	14%	5%
IEA SDS	-	2540	45%	17%	22%	0%	61%
IEA SDS	2070	2340	48%	41%	51%	0%	8%

Table 4: Shares of steel production technologies inIEA´s and BNEF-s net zero scenarios and IEA's 2020 SDS scenario. Scrap share if for end-of-life (EoL) only for BNEF, versus EoL + prompt scrap for the IEA. Sources: (BNEF, 2023; IEA, 2023c, 2020)

It is also insightful to compare IEA´s latest SDS and the current NZE. As seen in Table 4, in IEA's 2020 SDS, unabated fossil routes (or little-abated, using, e.g., some biomass) still accounted for 61% of primary steel production in 2050, falling to 8% in 2070 only.

Another major difference is that **until 2020, fossils + CCUS were presented by the IEA as the main route for decarbonization,** weighing 51% of primary production in 2070 versus 41% for H_2-DR, whereas the hierarchy has been reversed in the NZE, due to the erosion of credibility of CCUS-based solutions.

IEA´s scenarios : SDS 2020 versus NZE 2021

It is also insightful to compare IEA´s latest SDS and the current NZE. As seen in Table 4, in IEA's 2020 SDS, unabated fossil routes (or little-abated, using, e.g., some biomass) still accounted for 61% of primary steel production in 2050, falling to 8% in 2070 only. Another major difference is that until 2020, fossils + CCUS were presented by the IEA as the main route for decarbonization, weighing 51% of primary production in 2070 versus 41% for H_2-DR, whereas the hierarchy has been reversed in the NZE, due to the erosion of credibility of CCUS-based solutions.

These numerous differences illustrate that **uncertainties remain very high,** as of course, these scenarios are mere visions, based on highly arbitrary opinions about technologies maturities, potentials, and future costs.

3.3 Decarbonization projects pipeline

Figure 15 shows the pipeline of announced low (or towards low-) carbon steel projects until 2030. The pipeline, reaching almost 200 Mt of capacity by 2030, is strongly dominated by the secondary EAF and the DRI routes, in almost equal shares, with EAF projects currently dominating, and DRI projects starting to surge after 2025. In this survey, CCS projects are strongly lagging behind. BF-BOF with CCS and DR-EAF with CCS have only 1 Mt of capacity announced in 2030 each[16]. As for electrolysis, the two routes of Alkaline Electrolysis (AEL) and Molten Oxide Electrolysis (MOE) have only 100 kt of announced capacity announced to start by 2024 and 2027, respectively.

Within the announced new DRI projects however, only 31% plan to run on pure hydrogen by 2030, while the largest share (46%) would run on natural gas (NG) but being H_2-ready, and 22% would be only based on gas. As noted, e.g., in (Hermwille et al., 2022), the vast majority (>80%) of announced low carbon steel projects are in the EU.

This is even larger than in the survey by (IEEFA, 2024a), where the only coal BF+CCUS project announced by 2030 is Chinese Baotou project, with 0.5 Mt CO_2 capture capacity (as the US Cleveland Cliffs Burns Harbor project, with 2.8 Mt CO_2 announced capacity, has not announced start date).

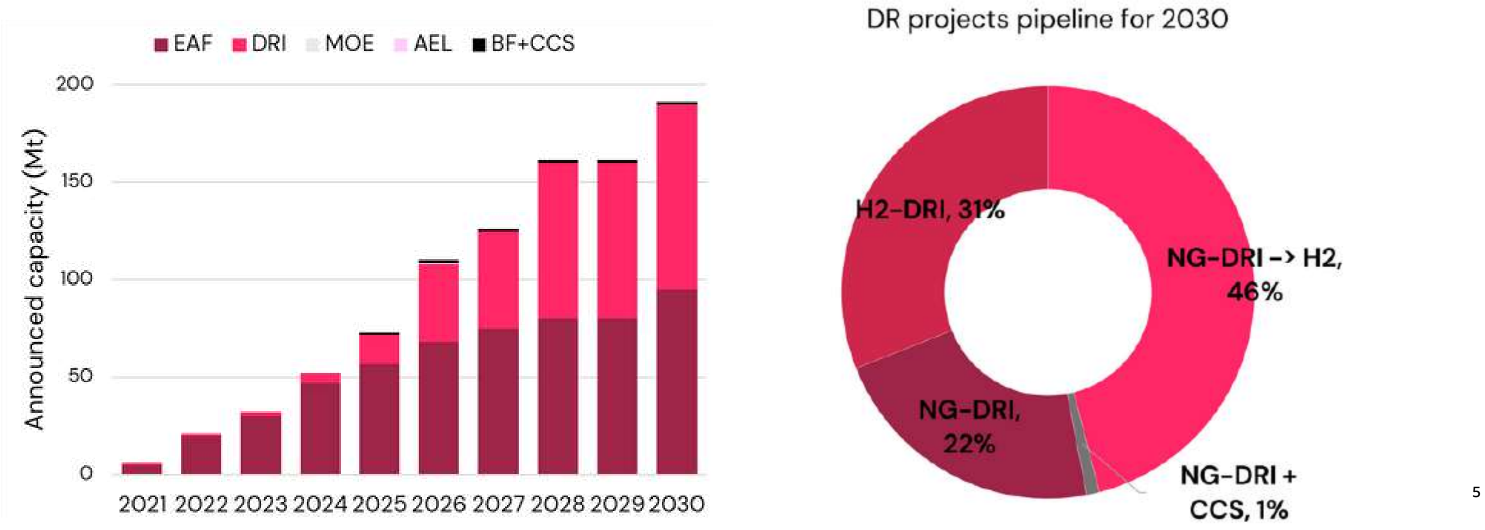


Figure 15: Left: Announced low carbon steel projects, by planned starting year and technology. Right: Announced DRI capacities in 2030, by fuel. Source: (Agora Industry and Wupperthal Institute, 2023)

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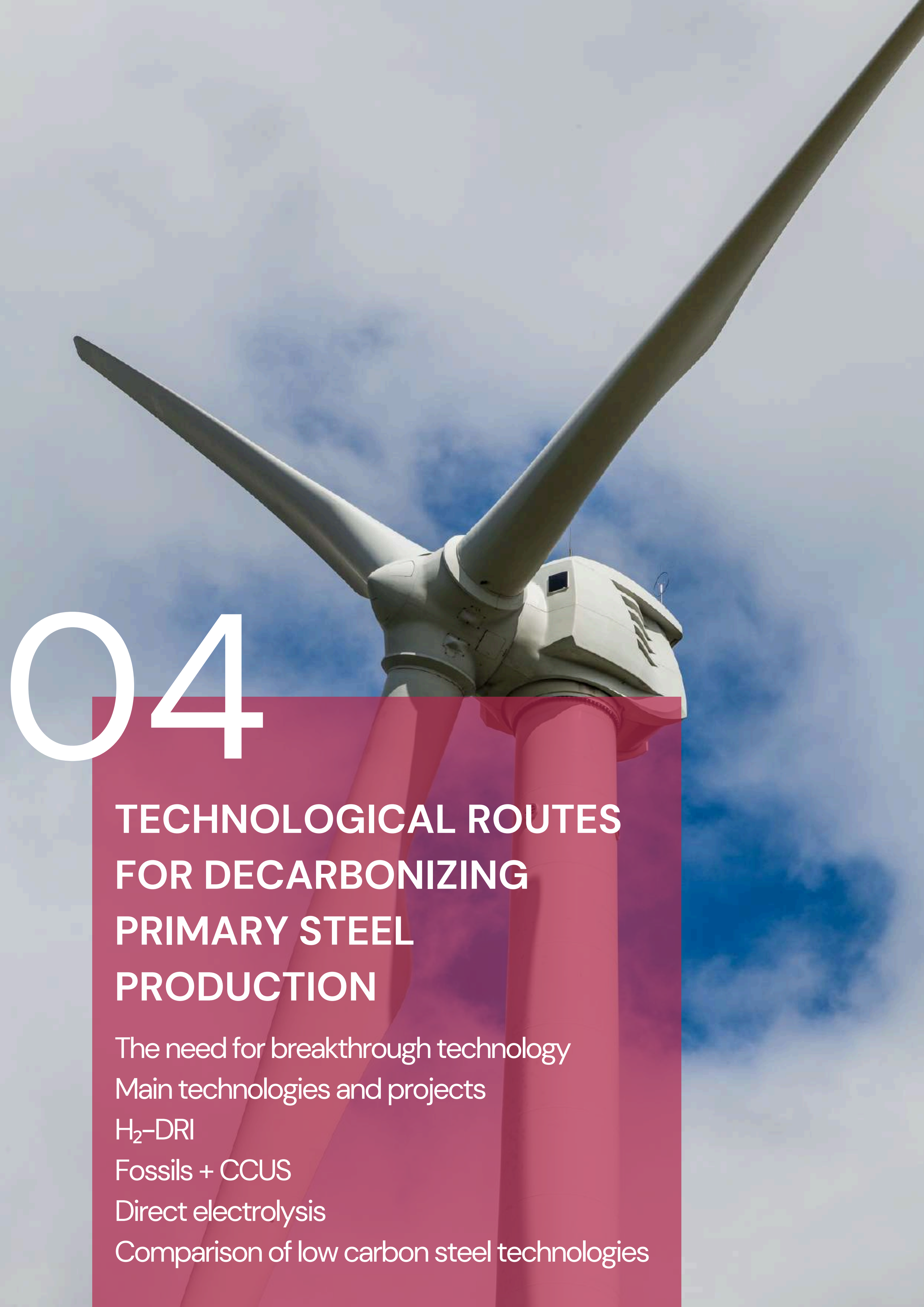
[16] This is even larger than in the survey by (IEEFA, 2024a), where the only coal BF+CCUS project announced by 2030 is Chinese Baotou project, with 0.5 Mt CO_2 capture capacity, while the US Cleveland Cliffs Burns Harbour project, with 2.8 Mt CO_2 announced capacity, has not announced start date.



04

TECHNOLOGICAL ROUTES FOR DECARBONIZING PRIMARY STEEL PRODUCTION

The need for breakthrough technology
Main technologies and projects
H_2–DRI
Fossils + CCUS
Direct electrolysis
Comparison of low carbon steel technologies

4.1 The need for breakthrough technologies

In the **secondary scrap-based EAF (recycling) route,** most of the GHG emissions are indirect, stemming from the power consumption (see Figure 13), and can thus be cut using low carbon electricity form dedicated assets or the grid. This already leads to large differences in the emission intensity of EAF steel by countries, depending on their average power mix (see Figure 21, or (Hasanbeigi, 2022; JRC, 2022)).

Energy efficiency gains in primary production can be achieved at all stages, including off-gases reuse, heat recovery, better preparation of inputs (ore, coke, etc.), and optimizing processes. Since the most ancient forms of steel production, the energy consumption per tCS has probably been reduced by an order of magnitude. Since 1960, it was reduced by 60%, from about 50 GJ/tCS to 20 GJ/tCS today (Worldsteel, 2022). However, blast furnaces are now operating close to the efficiency limit set by the process energy needed to reduce the ore, and best available technologies are now well spread. The global average energy intensity has even increased by 4% from 2007 to 2022, and the CO_2 intensity, by 6% (Worldsteel, 2023).

Limited incremental reductions in CO_2 emissions are also possible via minor adaptations to current primary fossil-based BF-BOF and DR-EAF routes, such as partial fuel switches using biomass, in particular charcoal, as is done in some plants in Brazil, or low carbon hydrogen, as, e.g., tested by ThyssenKrupp in Duisburg[JA1] (see, e.g. (IEA, 2020) for an overview). But potentials are limited, so breakthrough technologies are fundamentally needed.

4.2 Main technologies and projects

Three main pathways are currently proposed to decarbonize primary steel production:

- using low carbon hydrogen for DRI (followed by EAF or SMELT[17]+BOF),
- applying CCUS to adapted fossil-based routes (BF-BOF, DRI-EAF, or the novel HISARNA process, explained below)
- direct electrolysis of the iron ore (at high or low temperature).

Examples of most advanced projects for these pathways are detailed in Table 5.

Techno	Location	Project	Company	Capacity (Mt/y)	Fuel / tech	Start year
			H_2-DRI			
H_2-DRI+EAF	China, Hebei	HBZX	Hebei Iron & Steel Group, Tenova	1.2	> 60% H2 + coke oven gas	2022
-	Sweden, Lulea	HYBRIT pilot	LKAB- SSAB-Vatenfall	0.01	RE H2	2021
-	Sweden, Gällivare	HYBRIT demo	-	1.3	RE H2 (500 MW electrol.), Energiron DR	>2027
-	Sweden, Boden	Stegra Boden	(ex-H2 Green Steel)	2.5	RE H2 (740 MW electrol.), Midrex	2026
-	Spain, Gijon	Sestao	Arcelor Mittal	2.3	NG > H2	2025
H_2-DRI-Smelt+BOF	Germany, Duisburg	tkH_2Steel	Thyssenkrupp	2.5	100% NG > H2	2026
			Direct electrolysis			
MOE	USA, Massachussets	Woburn pilot	Boston Metal	0.025	1600°C	2024
AEL+EAF	France	Volteron	ArcelorMittal, John Cockerill	0.04 - 0.08	110°C	2027
MSE+EAF	USA, Boulder, Colorado	Electra Pilot	Electra	0.05	60°C	2028
			Fossils + CCUS			
NG-DRI+EAF+CCUS	UAE, Abu Dhabi	Al Reyadah	ADNOC, Emirates Steel Arkan	3.5	0.8 MtCO2/y for EOR	2016
-	USA, Louisiana	Convent	Nucor, ExxonMobil	2.5	0.8 MtCO2/y for CCS	2026
BF-BOF+CCUS	France, Dunkirk	3D/DMX pilot	Arcelor-Mittal	0.4 ktCO2	CCS export (North Sea)	2025
-	China, Inner Mongolia	Baotou CCUS	Baotou Steel	0.5	Sequestration in steel slags / EOR	2024-25
HISARNA+BOF+CCS	Netherlands, Ijmuiden		Tata steel	0.06	CCS try cancelled	2018

Table 5: Examples of prominent low (or lower) carbon steel projects. Start year refer to announcements. RE H_2: renewables based H_2. EOR: Enhanced Oil Recovery. Sources: (Agora Industry, 2024; IEEFA, 2024a)

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[17] SMELT refers to a melting stage following the DRI, and before sending to BOF

4.3 H_2-DRI

4.3.1 H_2-DRI + EAF

The process of DRI is flexible and some DR shaft technologies can be run flexibly with natural gas, pure hydrogen, or a mixture at any ratio[18]. Plants can thus be built and start running on natural gas, then progressively switch to low carbon hydrogen when it becomes available (Midrex, 2023). As shown in Figure 15, of the 98 Mt of DRI capacity planned by 2030, only 31% is planned to run on pure H_2, while 69% would at least start on natural gas. The DRI or HBI produced by H_2-DRI can then be fed in an EAF, just like gas-based DRI.

DRI using 100% H_2 (but based on natural gas reforming, without CCS) has already been implemented at industrial demonstration scale with the Circored process, in Trinidad, from 1999, with a plant of capacity 500 ktpy of hot briquetted iron (HBI)[19]. It ceased operating after a few months, having produced 300 kt of high-grade HBI. By the mid-2020s, the first commercial-scale DRI plants running exclusively on 100% renewable hydrogen have been announced to begin operations in Sestao (Spain), Boden and Gallivare (Sweden), Salzgitter (Germany) and Inkoo (Finland)[20].

The technology for using 100% H_2 is similar to NG-based DR, but several differences exist, so **H_2-DRI cannot be considered fully mature industrially** (Birat, 2023). Detailed modeling of the reduction process shows that H_2 acts about 3 times faster as reductant than the CO/H_2 mixture used in NG-based DR (in about 3.4 m versus 10 m), so that the optimal shaft height could be reduced, from a total of 30 m to perhaps 20 m (Patisson et al., 2021), saving CAPEX. Another difference is that, contrary to NG-based reduction, H_2-reduction is endothermic, thus requiring additional heating, which could be electric, or burning some H_2 for example. Overall, some uncertainty still concerns the hydrogen use intensity, for which reported numbers vary between 51 - 98 kgH_2/tCS[21].

The HYBRIT pilot project in Lulea, Sweden, with 10 kt capacity, has been since 2021 the first facility to produce steel with 100% low carbon H_2, based on electrolysis (and the very favorable Swedish low carbon power based on hydro, nuclear and wind). A subsequent demo project is planned in Gällivare, with 1.3 Mt capacity, using approximately 500 MW electrolysers (see Table 5), but issues concerning the contracts for the power supply and permitting, have delayed the commissioning to beyond 2027. In the HYBRIT pilot, EAF was valdated with DRI pellets or HBI briquettes. More recently, Stegra (ex H_2GreenSteel) announced a 2.5 Mt H_2-DRI plant to start in 2026 in Boden, also in Sweden.

4.3.2 H_2-DRI + SMELT + BOF

When the ore purity is low (<65% iron content), the resulting DRI cannot be processed in an EAF, as excess floating gangue would prevent the EAF to work. It is thus preferable to first smelt the DRI, and then use a BOF. Smelters can be submerged arc furnaces (SAF) or open slag bath furnaces (OSBF), that use electricity. The SMELT-BOF route allows to remove gangue impurities in both the smelter and the BOF via slag formation. The main advantage of this route is thus that lower-grade iron ore pellets, with an iron content >62%, can be used, which corresponds to 50% of the current seaborne iron ore supply, versus only 3% for the DR-grade needed for EAF steelmaking (see Figure 18).

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[18] A full demonstration of 0-100% H_2 or NG is for example, is claimed to be demonstrated by Salzgitter, in their 1ktpy mDRAL test facility

[19] Although CIRCORED used a fluidized-bed type of reactor, different from the shafts usually considered for H_2-DRI

[20] Several other announcements for H_2-DRI plants have been made, e.g. Arcelor-Mittal had announced an H_2-ready DRI plant to be commissioned in Dunkirk in 2025, a demonstration of 100 kt of DRI in Hamburg in 2025, and DRI plants in Ghent, Belgium and Bremen, Germany to start in 2026, but most of these projects have not received FID.

[21] In the academic side, for example, (Vogl et al., 2018) mention 51 kgH_2/tCS, without considering any losses, while Baowu has mentioned 78 kgH_2/tCS and POSCO, 98 kgH_2/tCS, while (Agora Industry, 2024) uses 69 kgH_2/tCS and BNEF assumes 93.5 kgH_2/tCS (BNEF, 2024).

Also, as the DRI fed into the smelter still carries some non-reduced iron oxide, it undergoes further reduction during smelting by the prevailing reducing atmosphere, due to the addition of carbon (coal or charcoal), hence higher metallization rates are obtained compared to the EAF route, making the process more efficient. Another advantage of the DRI-SMELT-BOF route is that the slag generated in the smelter should have similar properties to that produced in the blast furnace and could therefore also continue to supply the cement industry, as a key clinker substitute, which is not the case in the H_2-DRI-EAF route.

However, the SMELT-BOF route has two major drawbacks. First, the addition of another step increases energy use and raises costs. Second, for the BOF to work efficiently, **the DRI needs to be "carburised"**, i.e., made similar to the pig iron obtained from BF, with about 4.5% C content, and the main share of this carbon becomes CO_2 in the BOF or the smelter. Then, unless CCS is applied, emissions of around 0.2 tCO_2/tCS occur in the off-gases of the smelter and the BOF, which represents 11% of the 1.87 tCO_2/tCS of direct emissions in the BF-BOF route. To actually reduce emissions to near-zero, both the DRI-EAF and the DRI-SMELT-BOF routes would require the use of biogenic carbon.

To date, the only project of H_2-DRI-SMELT+BOF is Thyssenkrupp planning to start operation of a 2.3 Mt commercial-scale plant in Duisburg, by 2026.

4.4 Fossils + CCUS

Carbon capture and use or storage (CCUS) can be implemented on adapted coal-based BF-BOF or gas-based DR-EAF assets, the CO_2 capture being followed by geologic underground storage, or CO_2 use, for production of chemicals, fuels, enhanced oil recovery, etc. Until recently, CCUS was often presented as the major solution for steel decarbonization (see above), and several concepts have been explored. However, for coal-based BF routes, no CCUS project as yet been implemented at more than pilot scale (< 5 $ktCO_2$ captured per year)[22]. Concerning the "use" cases, when CO_2 is turned into fuels, it is later emitted to the atmosphere so the emissions reduction is low, and such schemes are (for example) excluded from the EU regulations on renewable fuels. For gas-based DRI, the only working project has a low capture rate of about 29% of onsite emissions.

The pipeline of steel CCUS projects is in fact quite depleted overall (IEEFA, 2024a), and expectations for CCUS in steelmaking are being revised down. As pointed, e.g., in (Agora Industry, 2024; IEEFA, 2024a), the major obstacles to CCS in steel are the limited capture rates due to multiple sources of CO_2: the additional upstream emissions during fossil fuels extraction, and the immaturity of yet inexistant infrastructures for CO_2 transport and sequestration, including uncertainties related to the long-term stability of CO_2 in geological sites having often different characteristics, making risk reduction by learning effects more difficult. Putting aside the two latter, which are general CCS-related issues, recent studies have proposed a **"CCS ladder"** approach, classifying possible applications of CCS by relevance according to criteria of feasibility, CO_2 mitigation potential, absence of alternative mitigation technologies, and absence of CO_2 lock-in effects (E3G and Bellona, 2023; Pisciotta et al., 2024). With these criteria, those two rankings found placed steel on the lowest levels of the ladder, especially for BF-BOF.

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[22] For example, Tata Steel started in 2021 a pilot capturing 5 tCO_2 per day (<2 kt CO_2 per year) at its Jamshedpur plant in India (which has 10 Mt steel capacity), the CO_2 being re-used onsite. Since April 2023 Arcelor-Mittal has started running its pilot project 3D in Dunkirk ("Dunkirk DMX Demonstrator") in test phase, at 0.5 tCO_2/h capacity (4 kt per year), aiming for a 1 $MtCO_2$ per year demo "around 2025", to be later exported for offshore underground storage in the North Sea. Some CCU projects are also being developed, e.g. in Ghent, Belgium, Arcelor-Mittal started in june 2023 its "Steelanol" pilot that captures 0.3 tCO_2/day (0.1 kt per year), for conversion into ethanol fuel, a technology developed in New Zealand by Lanzatech since 2008.

4.4.1 BF-BOF + CCS

Conventional BF can be retrofitted with a CO_2 capture unit, using amine-based chemical absorption, or more efficient pressure swing absorption (PSA), requiring more deeply modified concepts, as was for example demonstrated in the EU-funded ULCOS program (2004-2010), with top gas recirculation and pure oxygen feed in the BF, allowing high CO_2 concentration in the top gas and efficient capture using PSA (Meijer et al., 2009). However, **industrial demonstration within ULCOS II was not pursued after Florange was closed in 2013**, despite a well-advanced plan including an identified sequestration site in northern France, and a CO_2 pipeline from Florange to that site.

The major hurdle for CCS on coal-based BF-BOF, is the multiplicity of substantial CO_2 sources besides the BF. The three typical on-site sources of CO_2 at highest concentration are the blast furnace, the coking plants, and the power plant running on the steel plant's flue gases. According to (Agora Industry, 2024), extending the capture to remaining flue streams with lower CO_2 concentrations (the sinter plant, emitting about 0.28 tCO_2/tCS at about 4-5% concentration, but also the lime kiln, venting flares and oxygen heaters for the BOF) would be technically and economically difficult. Assuming a 90% capture rate on the three above major sources, **the capture rate on the BF-BOF+CCS route would be limited to about 70–75% of on-site CO_2 emissions**, leaving 0.51 tCO_2/tCS direct emissions uncaptured. Thus, even without considering scope 3 emissions, CCS on the BF-BOF route would most likely not be compatible with net-zero targets, in particular, it would largely exceed the proposed IEA threshold for "near-zero steel" of 0.34 tCO_2/tCS, for BF-BOF with the typical scrap share (see Figure 22).

Upstream methane emissions in the coking coal extraction are another issue, common to any CCS project. According to (Ember, 2023), upstream methane emissions add 10% of global emission from the steel sector (on a 100-year equivalent effect). The mining of coking coal emitted 10 Mt of methane in 2022, equivalent to 320 $MtCO_2eq$ based on a 100-year climate impact. Considering that regulations are increasingly taking into account emissions in life cycle analysis (LCA), upstream methane emissions thus present an economic risk and future regulatory constraint.

The infrastructure and logistics needed for transport and storage of CO_2, are another hurdle. According to (Danish Energy Agency, 2024), considering exploration, feasibility studies, site preparation, infrastructure construction, etc., the lead time to start injecting CO_2 is 6-7 years, and 10 years to reach nominal capacity.

4.4.2 NG-DRI + CCS

Installing CCS on natural gas-based DRI units is also possible, and largely deemed more favorable than on BF-BOF sites. The DRI shaft is the largest source of CO_2, and a 90% capture rate could theoretically be achieved. In practice, CO_2 capture in the top gas of the DRI shaft has been ongoing in the Al Reyadah plant in Abu Dhabi, UAE and the CO_2 is used for enhanced oil recovery, and only one other NG-DR project, but with CO_2 destined to CCS, is planned for 2026 in Louisiana, USA (IEEFA, 2024a), as hown in Table 5.

But, as noted in (IEEFA, 2024b), the CO_2 capture rate has been rather low in the Al Reyadah plant, the only commercial project of DRI+CCS, which uses the Energiron technology developed by Tenova and Danielli. CO_2 capture is implemented on the top gas exiting the DR shaft, but not on the flue gases of the integrated reformer unit which prepares the reducing gas (mostly CO and H_2) from the incoming natural gas. Thus, **only 60% of CO_2 emissions of the plant are available for capture,** not even considering the emissions from the pelletizing process. The project has a capture capacity of only 0.8 Mt CO_2, and has reported 2.8 Mt CO_2 per year in 2020-2022 of scope 1 emissions, i.e., the capture rate was only 29% (only 0.25 $tCO_2/tDRI$), not even accounting for scope 2 and 3 emissions. Despite having been running for 8 years, the Al Reyadah project triggered no local follow-ups, and Emirates Steel Arkan is currently rather investing in green H_2-based DRI.

4.4.3 HISARNA + BOF + CCS

HIsarna is an innovative ironmaking process developed by Tata Steel and partners, within the EU ULCOS project, that replaces the BF with a simplified oxygen-rich carbon-based smelting reduction process, where **all inputs can be used in powder form**, including coal, eliminating the iron ore agglomeration steps (from sinter or pelletizing plants) and the need for coke (Tata Steel, 2017). Compared to BF-BOF, lower iron ore and coal qualities can be used and the energy demand and CO_2 emissions are reduced.

The process designed to be **more suitable for combination with CCS because of the high CO_2 concentrations in the off-gases and fewer CO_2 point sources.** However, the development prospects of the HIsarna technology are highly uncertain. The demonstration phase with CCS of the experimental project in Europe (at Ijmuiden, in the Netherlands, with a small capacity of 0.06 Mt) has been cancelled. Tata Steel also seems to have halted its larger scale 0.5 Mt project in Jamshedpur, India, and now no company is working on the technology's commercialization.

4.5 Direct electrolysis

Several technologies are being developed to use electricity directly to reduce the iron ore (see, e.g., (Humbert et al., 2024)). This report describes the two most mature, illustrated in Figure 16: Molten Oxide Electrolysis (MOE) at high temperature, which directly produces liquid steel, and Alkaline Electrolysis (AEL), at low temperature, which requires subsequent melting. The less mature Molten Salt Electrolysis (MSE) technology can also work at low temperature. All are at low TRL 3-4, but offer promising advantages in terms of efficiency, operational flexibility regarding power consumption, and costs (Humbert et al., 2024).

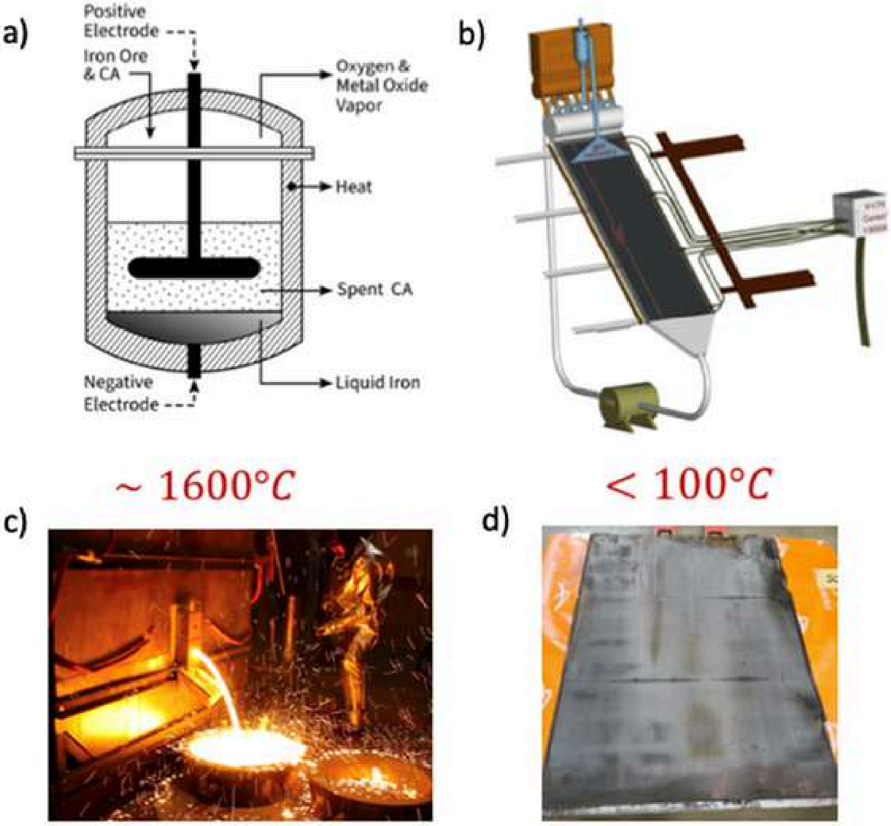


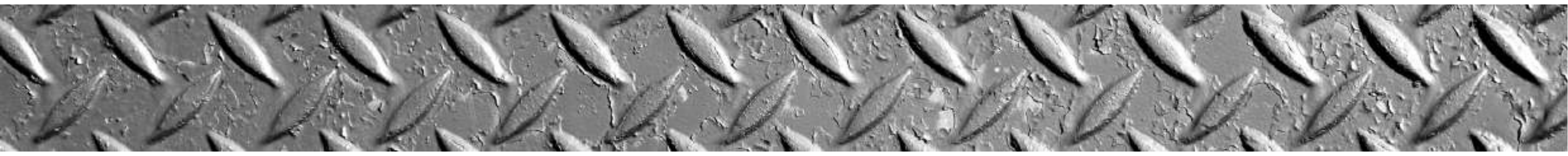
Figure 16: The MOE (left) and AEL (right) direct electrolysis technologies. Top: schematics of the processes. Bottom: pictures of the outputs. Sources: (Boston Metal, 2023; Humbert et al., 2024; Siderwin, 2023)

4.5.1 Molten oxide electrolysis (MOE)

Boston Metal, a spin-off from the MIT, develops a process where the iron ore is dissolved in an electrolyte solution of silicon oxide or calcium oxide at about 1600°C with an immersed inert anode. Electricity is passed through the solution to reduce the iron oxides, producing pure liquid metal, and releasing gaseous O_2 only. The anode, made of a chromium-iron alloy, needs to be especially resistant due to the high temperature and the strongly oxidizing conditions. MOE started using graphite electrodes, as is done in aluminum smelting, which are consumed during the process, causing substantial CO_2 emissions. A yet unsolved fundamental challenge facing MOE is to demonstrate the use **of inert anodes at industrial scale**, and a reasonable lifetime. More challenges, typical to high temperature metallurgy, are related to the wearing of the refractories around the hot chamber.

The process does not require prior treatment of the iron ore feedstock and produces high quality steel in one single process (Boston Metal, 2023). Alloying elements (including carbon) are subsequently added to the iron to achieve the desired steel properties. One advantage of the MOE technology is that it can process without difficulty any type of ore, with any level of impurities, since the forming gangue will be part of the molten electrolyte (Humbert et al., 2024).

Boston Metal has already raised 370 MUSD, has planned to generate first revenues in 2024 applying its MOE technology to the recovery of other higher value metals from low concentration ores (in its Brazil plant), and start commercial deployment of MOE steel in 2026.



4.5.2 Alkaline electrolysis (AEL + EAF)

This technology has been developed within the ULCOWIN project (2004-2017), then within the Siderwin project (2017-2023), with 6.8 MEur of EU funding, led by ArcelorMittal, with 11 European partners. Electrolysis is here performed in solid suspension state, at low temperature (70-110°C). The ore must first be ground to about 10 mm, and leached to remove impurities of silica and alumina. It is then mixed with a water-based electrolyte of sodium hydroxide (NaOH), and warmed up before power is applied. The Siderwin geometry is planar (1.25 m2), and tilted to allow forming oxygen gas to leave the cell by buoyancy, while the iron ions migrate to the bottom graphite cathode, forming a metallic iron plate of thickness 1-2 mm, and total weight 15 kg, with metallization rate 96-99%, within about one hour (Siderwin, 2023). The anode was found to be better interdigitated, to ensure the stability of gas evacuation. Siderwin demonstrated a power consumption of 2.7 MWh/t iron, representing 75% of the total energy consumption of the route.

One advantage of AEL is that it may be able to process various ferrous materials, including waste materials such as “red mud”, the bauxite residue from aluminum production with approximately 50% iron content. On the side of challenges, the recirculation of the electrolyte, as well as the preparation of the ore, by grinding and leaching (which consume 11% of the total process power (Siderwin, 2023) may require some care and technical refinements (Humbert et al., 2024).

Within Siderwin the technology was brought to TRL 4. Now Arcelor-Mittal is planning the construction of the Volteron plant, which in a first phase will produce between 40 - 80 kt/y of iron plates, targeted to start in 2027. Another start-up, Electra, has commissioned a pilot in Boulder, Colorado, in march 2024, for a variant technology that works at 60°C, using an acid electrolyte. It aims at having a pilot producing 50 kt/y in 2028, and 1 Mt/y by 2030.

4.6 Comparison of low carbon steel technologies

Main technical parameters of the different low carbon steel production routes, as modelled in (Agora Industry, 2024), are summarized in Table 6, and energy intensities plotted in Figure 17[23]. For comparison, the proposed IEA threshold for near-zero steel (IEA, 2022) with a typical share of 17% of scrap input in BF-BOF, is 0.34 tCO_2e/tCS (see Figure 22), not attained by the BF-BOF+CCS, and hardly attainable by NG DRI+CCS.

(all quantities per tCS)	H_2-DRI +EAF	H_2-DRI-smelt+BOF	MOE	AEL+EAF	BF-BOF +CCS	NG-DRI +CCS	HISARNA-BOF+CCS	Scrap+EAF
TRL	8-9	8-9	3-4	3-4	3-4	8-9	5-6	10
Ore type	DR-grade pellets	BF-grade pellets	Ore	Fines	Fines + pell./ore	DR-grade pellets (+ lumps)	Fines	Scrap (+ DRI)
Ore (t)	1.39	1.45	1.46	1.51	0.82/0.45	1.37	1.42	0
Scrap (t)	0.19	0.19	0	0	0.19	0.19	0.19	1.1
Elec. ore prep. (GJ)	0	0	0	1.44	0	0	0	0
Elec. iron (GJ)	0.29	0.26	**13.6**	**9.9**	0	0.25	1.52	0
Coal steel (GJ)	0.53	1.43	0	0.37	0	0.07	0	0.37
Coking coal (GJ)	0	0	0	0	**14.79**	0	0	0
H_2 /NG /coal iron (GJ)	**8.25**	**7.55**	0	0	**4.69**	**10.5**	**12.7**	0
Elec. steel (GJ)	1.77	1.7	0	02.03	0	1.24	0	**2.46**
Elec. CCS (GJ)	0	0	0	0	2.77	0.23	0.8	0
Prim. ener. tot (GJ)	**16.3**	**16.0**	**13.6**	**13.7**	**22.3**	**12.3**	**15.0**	**2.82**
CO_2 capture rate	-	-	-	-	73%	90%	89%	-
CO_2 direct (tCO2)	0.01	0.04	0	0.01	0.51	0.2	0.13	0.01
CO2e incl. fossil upstream (tCO2e)	**0.01**	**0.04**	**0**	**0.01**	**0.64**	**0.31**	**0.2**	**0.01**

Table 6: Summary of energy and CO_2e intensities for low carbon steel production technologies. All quantities are per tCS. "Iron" and "steel" denote ironmaking or steelmaking stages. Assumptions: power used is zero carbon, power to hydrogen efficiency is 60%. Upstream emissions from fossil fuels are IEA estimates for 2050, including important reductions from today. Source: (Agora Industry, 2024).

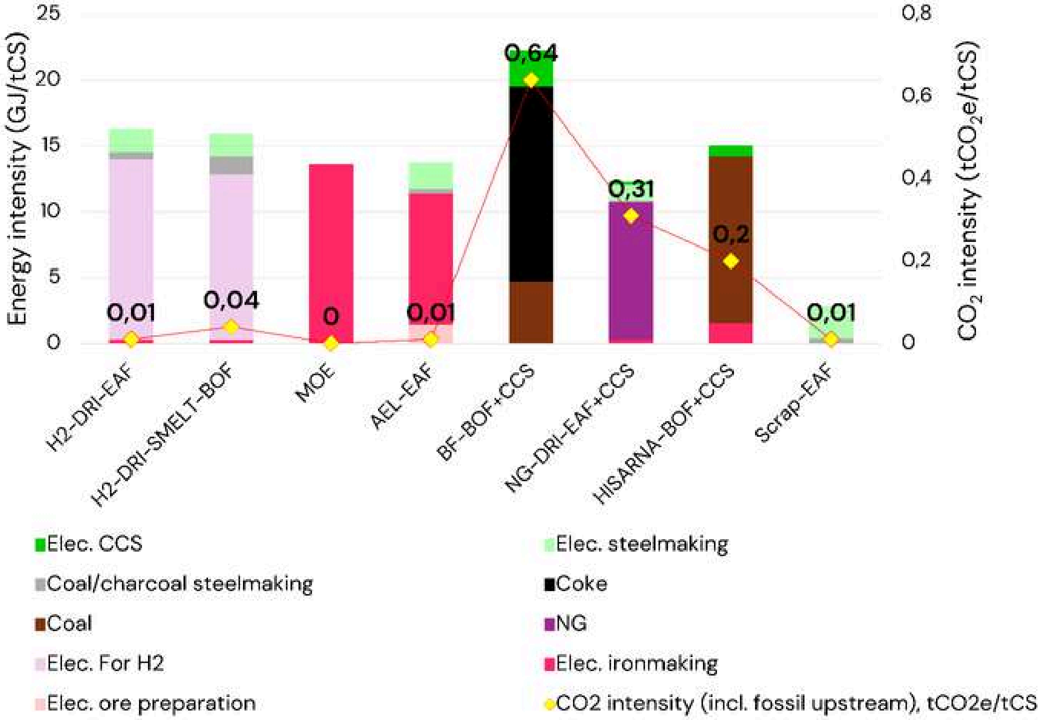


Figure 17: Energy intensities of low carbon steel routes. The efficiency from power to hydrogen is assumed to be 60%. Source: (Agora Industry, 2024).

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[23] Detailed balances of the various routes are also found, e.g. in (Birat et al., 2009).

05

CHALLENGES OF H_2-DRI DEPLOYMENT

DR-grade ore: a possible supply bottleneck
Possible solutions
Costs of a continuous supply of low carbon H_2
Possible solutions: trading green iron, natural hydrogen

So far, the HYBRIT pilot project appears as a successful implementation of H_2-DRI based on low carbon electricity, having produced 5 kt of DRI, with strongly reduced CO_2 emissions as low as 42 kg CO_2/tCS, mostly from biogenic origin (HYBRIT, 2024b). The technology however still awaits to be demonstrated at industrial scale, with full costs understood. Moreover, HYBRIT benefits from exceptionally favorable conditions in terms of availability of high-grade ore from Swedish miner LKAB, and abundant, firm, very low carbon and unexpensive electricity from the Swedish mix. Two major challenges still remain on the way for H_2-DRI to reach deployment at large scale globally.

5.1 DR-grade ore: a possible supply bottleneck

Today's commercial gas-based DRI production needs highest quality (DR-grade) iron ore, with Fe content > 67%, and alumina ($Al2O_3$) and silica (SiO_2) preferably < 2%. Indeed, ore impurities (gangue) such as silica, alumina, phosphorus and sulphur, affect the EAF process, increasing its power consumption, lowering the yield and increasing costs (Birat, 2023). Thus, Fe content often needs to be increased via beneficiation for reaching DR-grade quality. As DR-grade lump ores are becoming increasingly rare, pelletized ore is the primary feedstock for DRI processes globally (IEEFA, 2022a).

The issue, pictured in Figure 18, is that **DR-grade iron ore currently represents only about 3% of globally traded iron ore supply**, and 2/3 of global DR-grade ore production is consumed domestically. The two major DR-grade pellets users, Iran and India (see Figure 10), are also the top two producers, accounting for 64% of DR steel production globally. According to (BNEF, 2024), current plans for DRI new capacities would cause the demand for seaborne DR-grade ore to be multiplied by 5 from 2022 to 2040, causing a whopping 133 Mt per year deficit of seaborne DR-grade ore, which would make such plans impossible to realize, long before 2040. By 2030 already, BNEF sees a maximal DRI output limit at 145 Mt, versus 188 Mt of demand from announced projects (BNEF, 2024)[24].

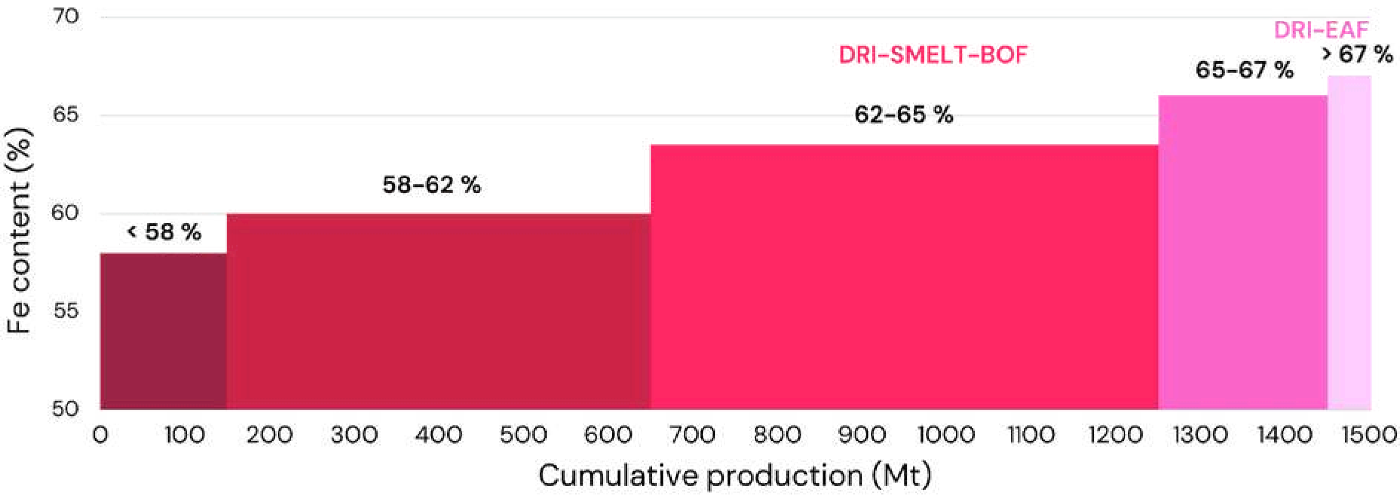

Figure 18: Supply volumes of seaborne iron ore by Fe grade. Shaded areas show the fractions useable by the DRI-EAF and DRI-SMELT-BOF routes. Source: (Agora Industry, 2024)

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[24] RMI estimates similarly that the supply of DR-grade pellets by 2030 (40 Mt) could fall short of the demand in the IEA´s NZE scenario by 117 Mt (Rocky Mountain Institute, 2024).

5.2 Possible solutions

Adding a melting stage after DRI (the DRI-SMELT+BOF route, see above) would release the constraint on the ore quality to be used in DR shafts. The DRI, after being smelted, and the excess gangue removed, can be charged in a BOF (instead of an EAF) to produce high-quality steel. Besides ThyssenKrupp (see Table 5), ArcelorMittal, BlueScope, Tenova, and mining companies such as BHP and Fortescue are investigating similar technologies, at pilot scale (IEEFA, 2022a)[25]. Adding the melting stage after DRI however increases capital expenditure, adds power consumption, and another low maturity technological step, requiring scale-up, development and derisking.

New mines or more beneficiation. A significant switch in iron ore mining focus from hematite towards magnetite could alleviate the issue. Magnetite ores tend to have a much lower Fe content but are often suitable for significant beneficiation (increase of Fe concentration), in part because magnetite is more magnetic, which enables easier separation (IEEFA, 2022b). However, DR-grade ore is scarce. Generalizing beneficiation could significantly raise the costs of ore production, but, due to long lead times in mining projects, it would seem wise that these strategies are unertaken with no delay (BNEF, 2024; Rocky Mountain Institute, 2024).

5.3 Costs and hurdles of large-scale clean H_2 supply

Hydrogen availability. The currently most dramatic challenge, expressed by many stakeholders (e.g., Arcelor-Mittal), concerns the unavailability yet of affordable low carbon hydrogen a scale. This is why most emerging DRI projects are planning to use first natural gas (see Figure 15), unfortunately, such bridging strategy has become much more difficult to consider since 2022 in the EU due to severely constrained gas supply. For example, the tKH_2 project in Duisburg would first run fully on gas until 2028, then gradually switch to 100% low carbon H_2. ThyssenKrupp recently opened a tender to supply up to 140 kt H_2 per year (needed for 2 Mt steel capacity), but the outcome is yet unclear - putting also at risk the deployment of hydrogen transport (pipelines) infrastructures. In terms of volumes, **deploying 50 Mt of H_2-DRI in the EU-27 would require 3.5 Mt of clean H_2, i.e., 200 TWh of upstream clean power**, which are humbling numbers.

Hydrogen storage. Due to their high temperatures and optimized complex operation, DR shafts are designed to work quite continuously, with very little operational flexibility, so the H_2 supply needs to be close to continuous. Hydrogen storage at large scale thus has to be implemented on site, to buffer any fluctuations in supply, particularly relevant if intermittent hydrogen from renewable power like solar PV, and wind power is used (Armijo and Philibert 2020; IEA, 2020). In the HYBRIT pilot, a 100 m3 storage line rock cavern has been built, 30 m below ground level, operating up to 250 bar (Norberg, 2022), but its cost is undisclosed. At a later stage, a full-scale hydrogen storage cavern of about 100,000 m3 would be required, storing 100 GWh of power converted to hydrogen gas, which is sufficient to supply a full-sized DRI plant for 3-4 days. As noted in (Humbert et al., 2024), the cost of H_2 storage is most often omitted in cost models, as, e.g, in (Vogl et al., 2018) for the HYBRIT project.

Hydrogen cost. Considering as in (Agora Industry, 2024), a consumption of 69 kg H_2/tCS (perhaps optimistic, see above), at a delivered cost of 5 USD/kg (also optimistic today), the contribution of hydrogen alone in the cost of steel would be 345 USD/tCS, while crude steel market prices are in the range of 450-600 USD/tCS globally (BNEF and CTC, 2024). For most analysts, e.g., (Vogl et al., 2018), **delivered H_2 would need to cost under 2 USD/kg for H_2-DRI steel to be competitive** (even taking into account carbon taxes of order 50-100 USD/tCO_2), which seems hardly in sight. According to (IEA, 2023d), in 2022 global production costs of hydrogen from renewable electricity were 4-12 USD/kg, and would drop to 2-8 USD/kg in 2030 in a case of fast deployment (NZE scenario). These costs however only represent gross production, excluding any transport or storage, which are both notoriously costly for hydrogen.

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[25] For example, in March 2023, BHP announced that it started designing an Electric Smelter Furnace (ESF) pilot

5.4 Possible solutions: trading green iron, natural hydrogen

Locating green iron production where hydrogen can be produced affordably, i.e., near abundant and cheap renewables resources, and then develop green iron trade, is a proposition that is gaining traction (Gielen et al., 2020; Rocky Mountain Institute, 2024; Trollip et al., 2024; Verpoort et al., 2024). Indeed, DRI is a solid product that can be stored and shipped easily in the form of hot briquettes (HBI)[26], for steelmaking in the EAF or SMELT-BOF steps. HBI could thus be produced in iron ore exporting countries with cheap and abundant renewables, such as Australia, Brazil, Chile, South Africa, the USA, Canada or Mauritania (see Figure 19), or other countries that would import iron ore, reduce it, and then export HBI. As described in (Rocky Mountain Institute, 2024), **several "green iron corridors" are starting to be discussed**, with the EU, Japan and Korea as main importer countries, having set H_2 import targets that could be expanded in scope to the concept of import H_2 embedded in green iron.

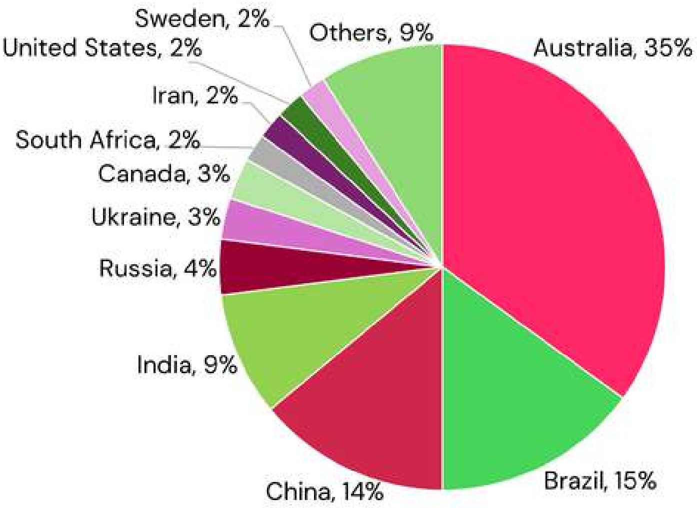

Figure 19: Production of iron ore by countries in 2021 (total 1.6 Mt of pure iron). Source: (USGS, 2022)

Natural hydrogen extraction could offer another solution to supply affordable H_2 at scale for the steel industry, but uncertainty is still huge.

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[26] The transport cost of iron ore from Western Australia to China (largest trade route) is currently about 10 USD/t, and the cost should be similar for HBI (Gielen et al., 2020)

06

POLICIES AND MARKETS FOR STEEL DECARBONIZATION

The need for policy drive
Financial mechanisms
Non-financial mechanisms
Corporate strategies and green procurement

6.1 The need for policy drive

As stated widely (see, e.g.. (Energy Transitions Commission, 2022; IIGCC, 2021)), as the steel sector is so systemic, decarbonizing it requires a wide mobilization of many actors, substantially beyond the steel-producers, including the upstream mining sector, port infrastructures, power utilities, downstream industries, but also governments and demand-side companies.

According to (IEA, 2023e), the iron and steel sector is not on track for decarbonization. It is considered "hard to abate" mostly because of the very large investment needs, the lack of mature technologies, and large abatement costs, in a competitive landscape. The transition towards clean production technologies is thus not expected to come on its own, driven by market forces only. On the contrary, it will need substantial policy drive (BNEF and CTC, 2024; IEA, 2022) to create economic and regulatory conditions, and favor the necessary coordination between all involved stakeholders.

Policy tools can be categorized in "push" and "pull" types, or carrots and sticks (BNEF, 2023; IEA, 2022), where push factors include:

- indicative targets for the industry
- carbon pricing and CBAM mechanisms
- green steel quota for steel buying activities

while pull factors include:

- developing low carbon steel technologies
- supporting technology deployment (hydrogen, CCUS, etc.)
- green public procurement
- supporting measures to access clean energy.

So far, policies have focused more on helping the supply side, however, in the face of a green premium, the procurement of clean products may also need stimulation (BNEF and CTC, 2024).

6.2 Financial mechanisms

Direct public subsidies have been announced in very large amounts in EU, Japan and Korea (BNEF, 2023), both for investments and operational expenses. In the EU, as of November 2024, 14.6 Bn Eur of public subsidies have been granted by governments for steel plants decarbonization in EU countries (Tarasenko, 2024), as shown in Figure 20. For example, Tata Steel´s Ijmuiden site has been granted 3 Bn Eur, and the tkH_2Steel project, almost 2 Bn Eur: 550 M Eur to construct the new facilities, and 1.45 bn Eur to subsidize the procurement of low carbon hydrogen, although the future origin of the needed clean hydrogen is not known. Another example is Arcelor-Mittal´s 1.7 Bn Eur investment plan for France announced in Feb 2022, for which 850 M Eur of subsidies were granted, but have not yet been used, as the project remains pending.

Indirect subsidies can also be deployed, for example to cover production costs of hydrogen, power grid expansions, the required new infrastructure for H_2 or CO_2 pipelines, etc.

Carbon taxes or markets (in particular, the EU-ETS system) are often viewed as the tool of choice, able to level the playing field between high and low carbon technologies (BNEF and CTC, 2024). To be operational however, without subsidies, they might need to be comparable to the abatement costs, typically estimated to 100-300 Eur/tCO_2 (Energy Transitions Commission, 2022; Gérardin, 2024) and sometimes up to 500 Eur/tCO_2.

Carbon Border Adjustment Mechanisms (CBAM). As steel is traded internationally in very competitive markets, a strong risk exists of "carbon leakage", i.e., industrial relocations to escape climate regulations in one jurisdiction. Carbon border adjustment measures (CBAM) are intended to level the playing field for companies preventing unfair competition from producers not subject to similar regulations. Concerning the EU CBAM mechanism, which is set to start in 2026, and cover 6 product families (iron and steel, aluminum, cement, fertilizers, electricity and hydrogen), steel represented 55% of its market from 2019-21, in monetary terms.

The **"scrap loophole"** is one non-trivial concern raised recently about the first version of the CBAM. As scrap in the current setting is attributed no CO_2 footprint, but steel products from BOF or EAF routes can contain variable levels of scrap, and be of equivalent quality, a risk of "resource shuffling" exists, i.e., a country exporting steel to Europe is incentivized to selectively allocate more of its scrap-intense production for export to the EU, to minimize the taxation when entering the EU market, thereby causing unfair competition and an inactivation of the desired effect.

A modeling exercise developed in (Sandbag, 2024) found that for China exporting to the EU-27, resource shuffling could save up to 189 MUSD compared to a BAU scenario, or 269 MUSD compared to a case where country-wide default CO_2 values are used. One of the recommendations in (Gérardin and Ferrière, 2025) is thus to apply a tax (at a wise level) to recycled steel.

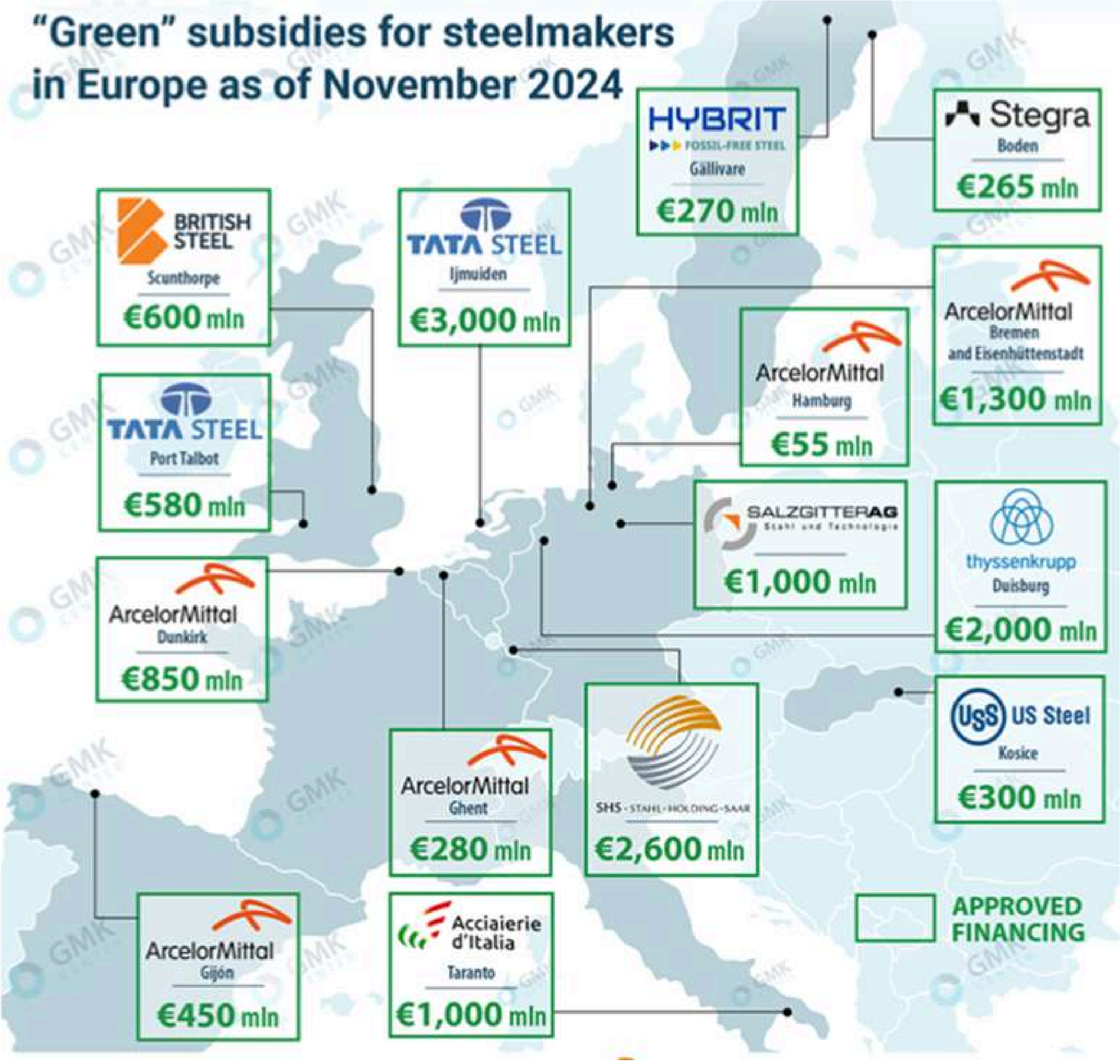

Figure 20: Approved direct public subsidies for steel decarbonization granted by EU governments, as of November 2024. Source: (Tarasenko, 2024)

For illustration, Figure 21 shows average CO_2 intensities per country, for BOF and EAF steel. The CO_2 footprints for EAF steel are much more different among countries than for BOF steel, as explained above (see Figure 13), this is because for EAF, emissions are about proportional to the carbon footprint of each country´s electricity. For example, China´s EAF steel has about 3 times higher CO_2 intensity than EU's.

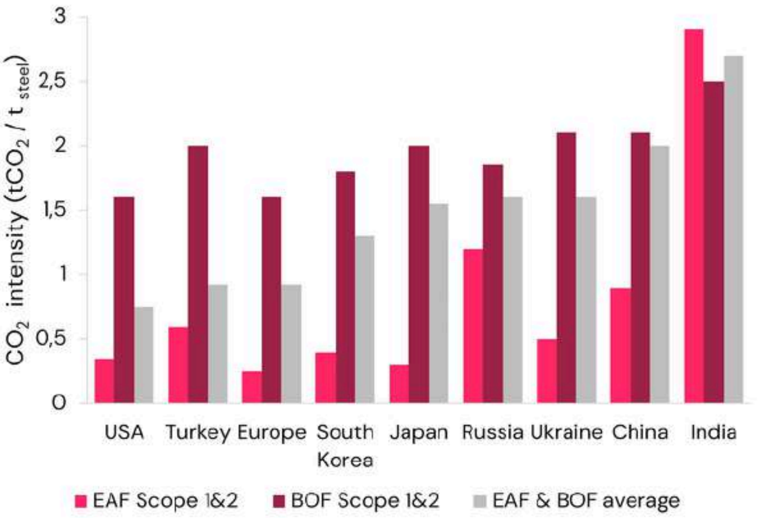

Figure 21: Average emission intensities of steel production for the BF-BOF and EAF routes, by countries. Source: (JRC, 2022)

6.3 Non-financial mechanisms

Promoting material efficiency and sufficiency to bring about demand reductions, are a fundamental lever to directly ease the burden of decarbonizing with limited resources. Possible measures listed, e.g., in (EEB, 2024; Energy Transitions Commission, 2022; IEA, 2020), include for example:

- shift to bio-based materials in construction
- vehicles light weighting and fleet sufficiency
- behavior change towards more shared use of buildings.

Public procurement of low or near zero carbon steel is also a major tool to create demand. Programs like the International Deep Decarbonization Initiative (IDDI), a coalition of public and private institutions, coordinated by the United Nations Industrial Development Organization (UNIDO) seek to expand the use of green procurement programs.

Demand creation by quotas and regulations is another major tool under discussions, that aims at securing future offtake, to make low carbon projects bankable. For example, (Transport & Environment, 2024) recommends that governments mandate carmakers to use at least 40% of green steel in new cars sold in the EU by 2030, increasing to 75% by 2035.

Certifications and standards for lower carbon production pathways, with clear definitions and mutual recognition, are also crucially needed to frame all discussions and allow the emergence of markets for green materials. To provide a common benchmark, The IEA has proposed to define "near-zero steel" with a sliding threshold of 400 $kgCO_2e/tCS$ when no scrap is used to 50 $kgCO_2e/tCS$ when 100% scrap is used, and for intermediate cases, the interpolation value (IEA, 2022), shown in Figure 22. These values are approximately 6 times lower than average current intensities.

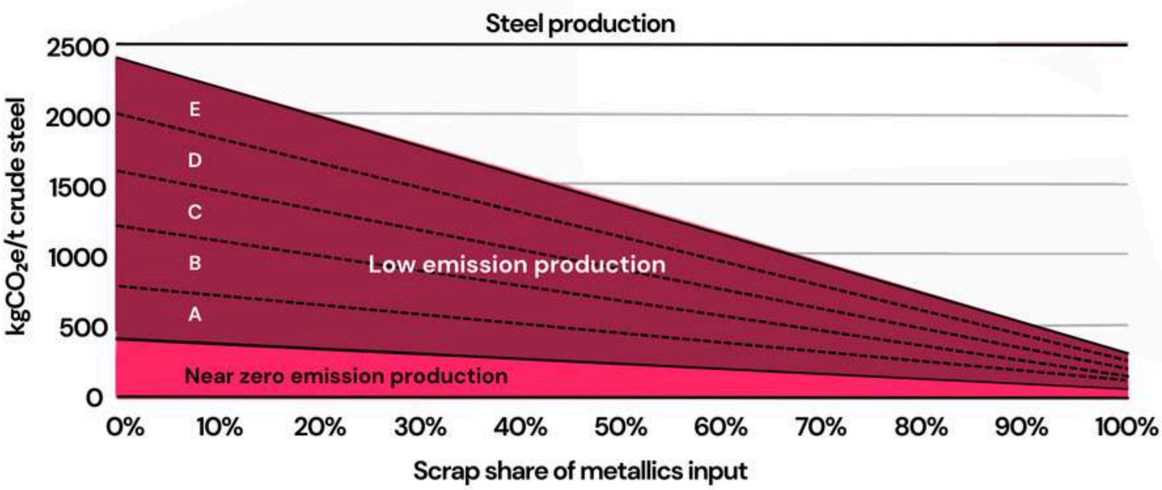

Figure 22: IEA´s proposed sliding scale to define near zero and low emissions steel production routes, products or plants, as function of the scrap share in inputs. Source: (IEA, 2022)

6.4 Corporate strategies and green procurement

Most large steel companies globally have published decarbonization strategies. According to (BNEF, 2023a), Net Zero commitments are most frequent in the EU, reaching 82% of capacities tracked by 2023, while the global average was only 33%. Some players rely on the Science-Based Targets initiative to certify their targets (SBTi, 2023)[27] . However, such pledges are still far from having concrete implementation plans, due to the large uncertainties on technological pathways, costs, and policies that could make such plans economically viable.

Market-driven demand for greener products can also play a substantial role in enabling the deployment of cleaner technologies, especially when offtake for lower carbon products is secured in signed long-term contracts. As of October 2023, BNEF tracked a total of 73 supply agreements for low-carbon and clean steel products. The automotive market-driven demand for greener products can also play a substantial role in enabling the deployment of cleaner technologies, especially when offtake for lower carbon products is secured in signed contracts. As of October 2023, BNEF tracked a total of 73 supply agreements for low-carbon and clean steel products. The automotive (road transport) sector is a particularly strong driver of demand for low carbon steel, accounting for 42% of all agreements (BNEF and CTC, 2024). The case of H_2 Green Steel is emblematic, the startup has raised billions of dollars in large part because it secured early contracts for advance purchases from big companies such as Mercedes-Benz and Ingka Group, preselling a large part of its expected upcoming production of 1.5 Mtpy.

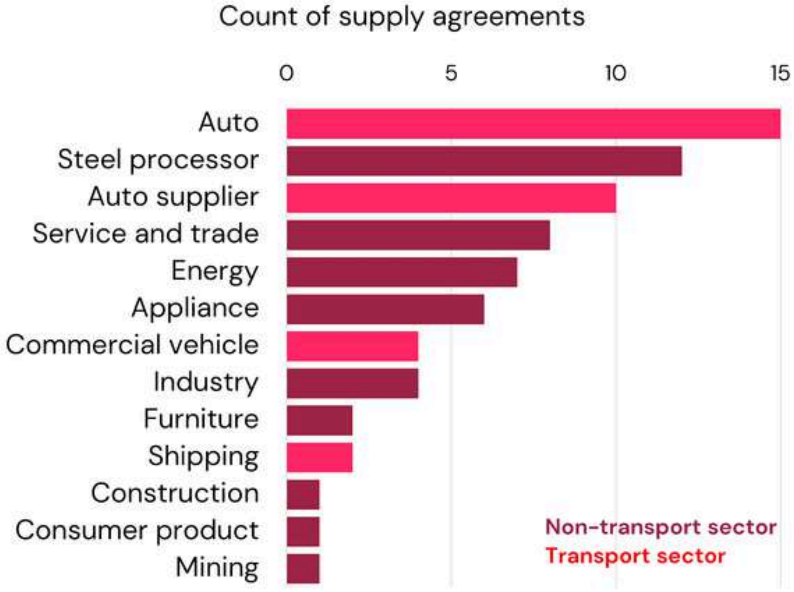

Figure 23: Agreements for low carbon steel procurement, as of oct. 2023.
Source: (BNEF and CTC, 2024)

Multipartite collaboration platforms are flourishing. Industry-led initiatives, like the First Mover Coalition (companies putting together their purchasing power), international collaboration agreements, like the Glasgow Breakthrough Agenda, or international public-private cooperation forums, like the Climate Club, can also play a useful role.

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[27] For example, as of sept. 2023, BNEF reports two steel producers having net Zero targets certified by the SBTI: ThyssenKrupp and SSAB (the two smaller producers among the 8 studied, having respectively 12 and 8 Mt production in 2021) (BNEF, 2023a).

References

Agora Industry, 2024. Low-carbon technologies for the global steel transformation.

Agora Industry, 2021. Global Steel at a Crossroads - Why the global steel sector needs to invest in climate-neutral technologies in the 2020s.

Agora Industry, Wupperthal Institute, 2023. 15 insights on the global steel transformation.

Armijo, J., Philibert, C., 2020. Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina. International Journal of Hydrogen Energy 45, 1541–1558. https://doi.org/10.1016/j.ijhydene.2019.11.028

Birat, J.-P., 2023. Net-Zero transition in the steel sector: beyond the simple emphasis on hydrogen, did we miss anything? Matériaux & Techniques 111, 201. https://doi.org/10.1051/mattech/2023003

Birat, J.-P., Lorrain, J.-P., de Lassat, Y., 2009. The “CO_2 Tool”: CO_2 emissions & energy consumption of existing & breakthrough steelmaking routes. Metallurgical Research & Technology 106, 325–336.

BNEF, 2024. Direct reduction-grade iron ore: a green steel bottleneck.

BNEF, 2023. Steel decarbonization. The scale of the challenge. BNEF.

BNEF, 2021. Decarbonizing aluminum. Technologies and costs.

BNEF, 2019. Hydrogen: making fossil-free steel.

BNEF, CTC, 2024. Scaling Up Hydrogen: The Case For Low-Carbon Steel.

Boston Metal, 2023. Green Steel Solution. Boston Metal. URL https://www.bostonmetal.com/green-steel-solution/ (accessed 6.27.24).

Bureau of International Recycling, 2023. WORLD STEEL RECYCLING IN FIGURES 2018 – 2022.

Cullen, J.M., Allwood, J.M., Bambach, M.D., 2012. Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. Environ. Sci. Technol. 46, 13048–13055. https://doi.org/10.1021/es302433p

Danish Energy Agency, 2024. Technology Data for Carbon Capture, Transport and Storage.

E3G and Bellona, 2023. Carbon capture and storage ladder.

EEB, 2024. Manifesto: A resilient and resource-wise Europe: Sufficency at the heart of the EU’s future.

Ember, 2023. Why the steel industry needs to tackle coal mine methane.

Energy Transitions Commission, 2022. Making Net-Zero Steel Possible.

Eurofer, 2024. European Steel in Figures 2024.

Gérardin, M., Ferrière, S., 2025. Décarbonation de l’acier et des métaux de base : envoyons les bons signaux. France Stratégie.

Gérardin, S.F., Maxime, 2024. Les coûts d’abattement - Partie 7 - Acier.

Gielen, D., Saygin, D., Taibi, E., Birat, J.-P., 2020. Renewables-based decarbonization and relocation of iron and steel making: A case study. Journal of Industrial Ecology 24, 1113–1125.

Global Energy Monitor, 2024. Global Steel Plant Tracker (v1).

GMK Center, 2022. The material of the future: why ferrous scrap has already become a strategic raw material. GMK. URL https://gmk.center/en/posts/the-material-of-the-future-why-scrap-metal-has-already-become-a-strategic-raw-material/

Hamadeh, H., Mirgaux, O., Patisson, F., 2018. Detailed Modeling of the Direct Reduction of Iron Ore in a Shaft Furnace. Materials (Basel) 11. https://doi.org/10.3390/ma11101865

Hasanbeigi, A., 2022. Steel Climate Impact - An International Benchmarking of Energy and CO_2 Intensities. Global Efficiency Intelligence.

Hermwille, L., Lechtenböhmer, S., Åhman, M., van Asselt, H., Bataille, C., Kronshage, S., Tönjes, A., Fischedick, M., Oberthür, S., Garg, A., Hall, C., Jochem, P., Schneider, C., Cui, R., Obergassel, W., Fragkos, P., Sudharmma Vishwanathan, S., Trollip, H., 2022. A climate club to decarbonize the global steel industry. Nat. Clim. Chang. 12, 494–496. https://doi.org/10.1038/s41558-022-01383-9

Humbert, M.S., Brooks, G.A., Duffy, A.R., Hargrave, C., Rhamdhani, M.A., 2024. Economics of Electrowinning Iron from Ore for Green Steel Production. J. Sustain. Metall. 1–23. https://doi.org/10.1007/s40831-024-00878-3

Hybrit, 2024a. Hybrit Fossil-free steel [WWW Document]. Hybrit. URL https://www.hybritdevelopment.se/en/ (accessed 6.20.24).

Hybrit, 2024b. Fossil-free steel production ready for industrialisation.

IEA, 2023a. Iron and Steel. Tracking clean energy progress [WWW Document]. URL https://www.iea.org/tcep/industry/steel/

IEA, 2023b. World Energy Outlook 2023. OECD, Paris.

IEA, 2023c. Steel and aluminium – Analysis [WWW Document]. IEA. URL https://www.iea.org/reports/steel-and-aluminium (accessed 7.5.24).

IEA, 2023d. Global Hydrogen Review 2023. IEA.

IEA, 2023e. Tracking Clean Energy Progress 2023 – Analysis. IEA. URL https://www.iea.org/reports/tracking-clean-energy-progress-2023 (accessed 9.3.24).

IEA, 2022. Achieving Net Zero Heavy Industry Sectors in G7 Members.

IEA, 2021. Net Zero by 2050. OECD, Paris.

IEA, 2020. Iron and Steel Technology Roadmap.

IEEFA, 2024a. Steel CCUS update: Carbon capture technology looks ever less convincing.

IEEFA, 2024b. Carbon capture for steel?

IEEFA, 2022a. Solving iron ore quality issues for low-carbon steel.

IEEFA, 2022b. Iron ore quality a potential headwind to green steelmaking – Technology and mining options are available to hit net-zero steel targets.

IIGCC, 2021. Global Sector Strategies: Investor interventions to accelerate net zero steel.

JRC, 2022. Technologies to decarbonise the EU steel industry.

Meijer, K., Denys, M., Lasar, J., Birat, J.-P., Still, G., Overmaat, B., 2009. ULCOS: ultra-low CO_2 steelmaking. Ironmaking & Steelmaking 36, 249–251. https://doi.org/10.1179/174328109X439298

Midrex, 2024. 2023 World Direct Reduction statistics.

Midrex, 2023. Ironmaking technology for a sustainable steel industry.

Norberg, O., 2022. HYBRIT: Milestone reached – pilot facility for hydrogen storage up and running. Hybrit. URL https://www.hybritdevelopment.se/en/hybrit-milestone-reached-pilot-facility-for-hydrogen-storage-up-and-running/ (accessed 6.20.24).

Our World in Data, 2024. Minerals Data explorer [WWW Document]. URL https://ourworldindata.org/metals-minerals

Patisson, F., Mirgaux, O., Birat, J.-P., 2021. Hydrogen steelmaking. Part 1: Physical chemistry and process metallurgy. Matériaux & Techniques 109, 303. https://doi.org/10.1051/mattech/2021025

Pisciotta, M., Swett, S., Pilorgé, H., Patel, S., Wilcox, J., 2024. U.S. CCS Ladder for Industrial Decarbonization. Kleinman Center for Energy Policy. URL https://kleinmanenergy.upenn.edu/commentary/blog/u-s-ccs-ladder-for-industrial-decarbonization/

Ricardo, 2024. The use of Green Steel in the Automotive Industry.

Roberts, I., Saunders, T., Spence, G., Cassidy, N., 2016. China’s evolving demand for commodities, in: Structural Change in China: Implications for Australia and the World, Proceedings of a Conference, Reserve Bank of Australia, Sydney. pp. 107–158.

Rocky Mountain Institute, 2024. Green Iron Corridors: Transforming the Steel Supply Chains for a Sustainable Future.

Sandbag, 2024. A Scrap Game: Impacts of the EU Carbon Border Adjustment Mechanism.

Siderwin, 2023. D5.7 Public Final test report.

Tarasenko, A., 2024. European countries granted €14.6 bln for decarbonization of the steel sector. GMK. URL https://gmk.center/en/infographic/european-countries-granted-e14-6-bln-for-decarbonization-of-the-steel-sector/ (accessed 12.11.24).

Tata Steel, 2017. HIsarna: Game Changer in the Steel Industry.

Transport & Environment, 2024. Cleaning up steel in cars: why and how?

Trollip, H., Berghmans, N., Khandekar, G., 2024. EU green iron imports for a more competitive steel industry and accelerated decarbonization | IDDRI. IDDRI.

Verpoort, P.C., Gast, L., Hofmann, A., Ueckerdt, F., 2024. Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains. Nature Energy 9, 491–503. https://doi.org/10.1038/s41560-024-01492-z

Vogl, V., Åhman, M., Nilsson, L.J., 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279

Vogl, V., Olsson, O., Nykvist, B., 2021. Phasing out the blast furnace to meet global climate targets. Joule 5, 2646–2662. https://doi.org/10.1016/j.joule.2021.09.007

World Economic Forum, 2023. Closing the Loop on Automotive Steel: A Policy Agenda.

Worldsteel, 2024. World Steel in Figures 2024.

Worldsteel, 2023. Sustainability Indicators 2023 report.

Worldsteel, 2022. Steel Facts.

Worldsteel, 2021. Fact sheet - Scrap use in the steel industry.

Worldsteel, 2020. Steel industry co-products - Public Policy paper.

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Acknowledgements

The author gratefully acknowledges the review and useful suggestions from:

Jean-Pierre Birat, IF Steelman, former coordinator of EU ULCOS program

Joseph Cordonnier, OECD

Rutger Gyllenram, Kobolde & Partners AB