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Decarbonizing Steel

Max de Boer, Grace Frascati, Mimi Khawsam-ang, Hassan Riaz, Hyae Ryung Kim & Gernot Wagner

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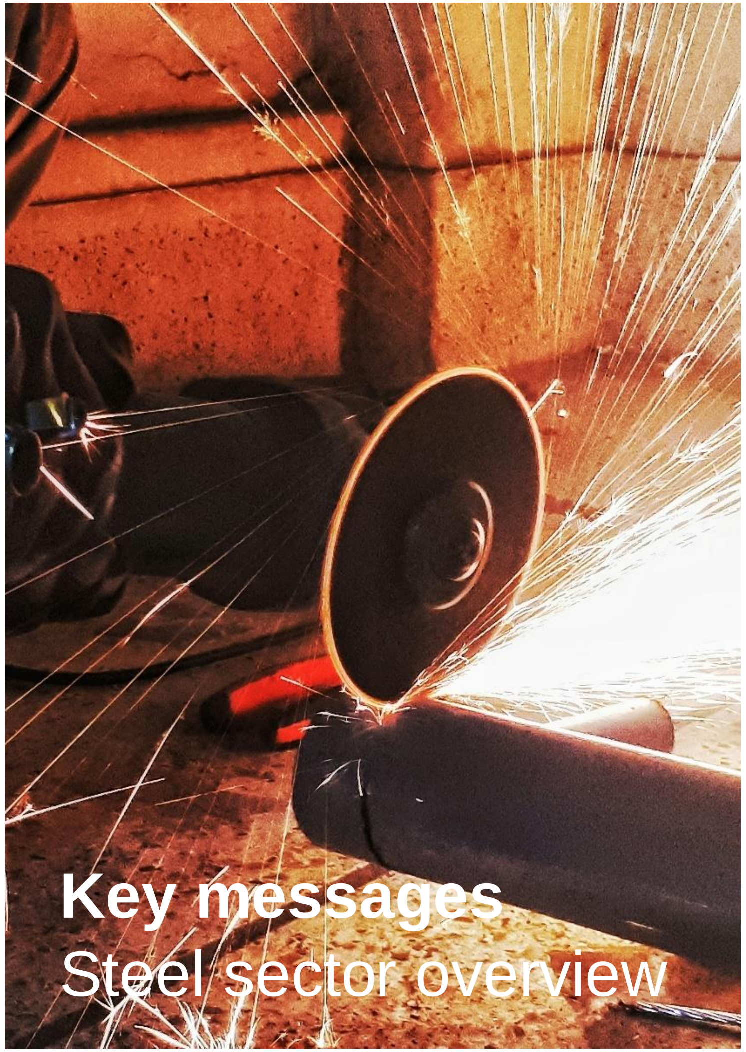
Steel sector overview: The problem



The **global steel sector** is responsible for **~10% of global CO_2e emissions:**

- **Global steel emissions** have **more than doubled since 2000** (from ~1.2 gigatonnes (Gt) in 2000 to ~2.5Gt in 2021). However, **emissions** have **started to decouple** from production levels around 2015.
- Without intervention, **emissions are expected to continue growing** due to rising **demand from emerging economies**. Reaching **net zero by 2050** would require a **25% emission reduction by 2030.**

Steel is currently produced through **3 main production routes, all of which emit CO_2:**

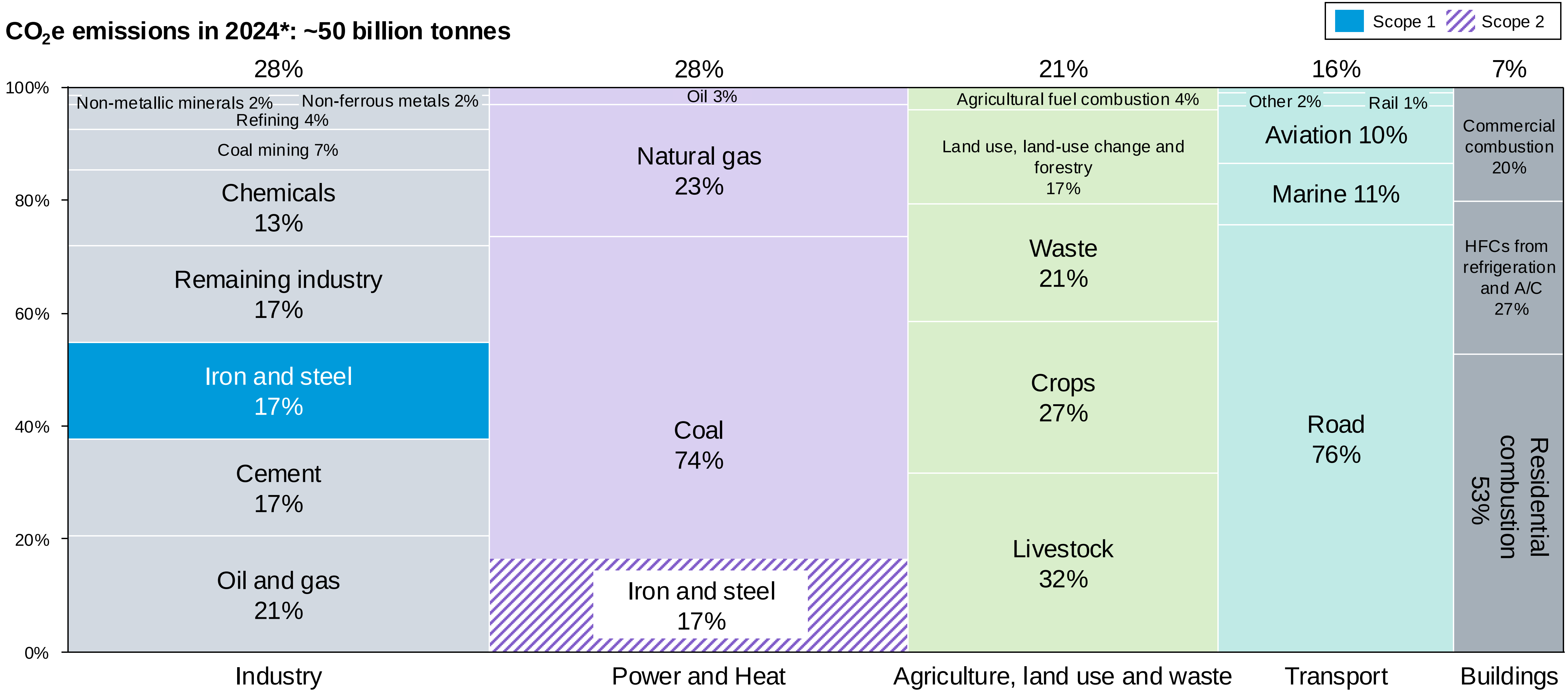
- **Blast furnace-basic oxygen furnace (BF-BOF)** accounts for ~72% of global steel production. It uses coke and limestone to produce pure iron from iron ore in a blast furnace, which is then turned into steel in an oxygen furnace.
- **Scrap electric arc furnace (EAF):** ~21% of global steel production. Scrap metal is melted in an EAF using electrical energy.
- **Natural gas-based direct reduced iron-electric arc furnace (NG DRI-EAF):** ~7% of global steel production. Iron ore is turned into iron using natural gas, which is then melted in an EAF to produce steel.

On average, **BF-BOF is the cheapest production method** (~$390 per tonne vs. ~$415 for scrap EAF and ~$455 for NG DRI-EAF). However, **regional variations in costs** (such as for raw material and fuel) and different quality standards make all **three methods competitive.**

Downstream activities after crude steelmaking (e.g., refining, casting, rolling) represent **less than 20% of the total steel production emissions.**

Because steel is a **100% recyclable material**, increased use of **scrap metal** can help **decarbonize** the steel sector.

Steel sector Scopes 1 and 2 around 10% of global CO_2e emissions



Sources: Scope 1 emissions from Rhodium Group ClimateDeck (September 2024); Scope 2 iron and steel estimate from IEA (2023); * 2024 emissions based on projections.
Credit: Theo Moers, Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (27 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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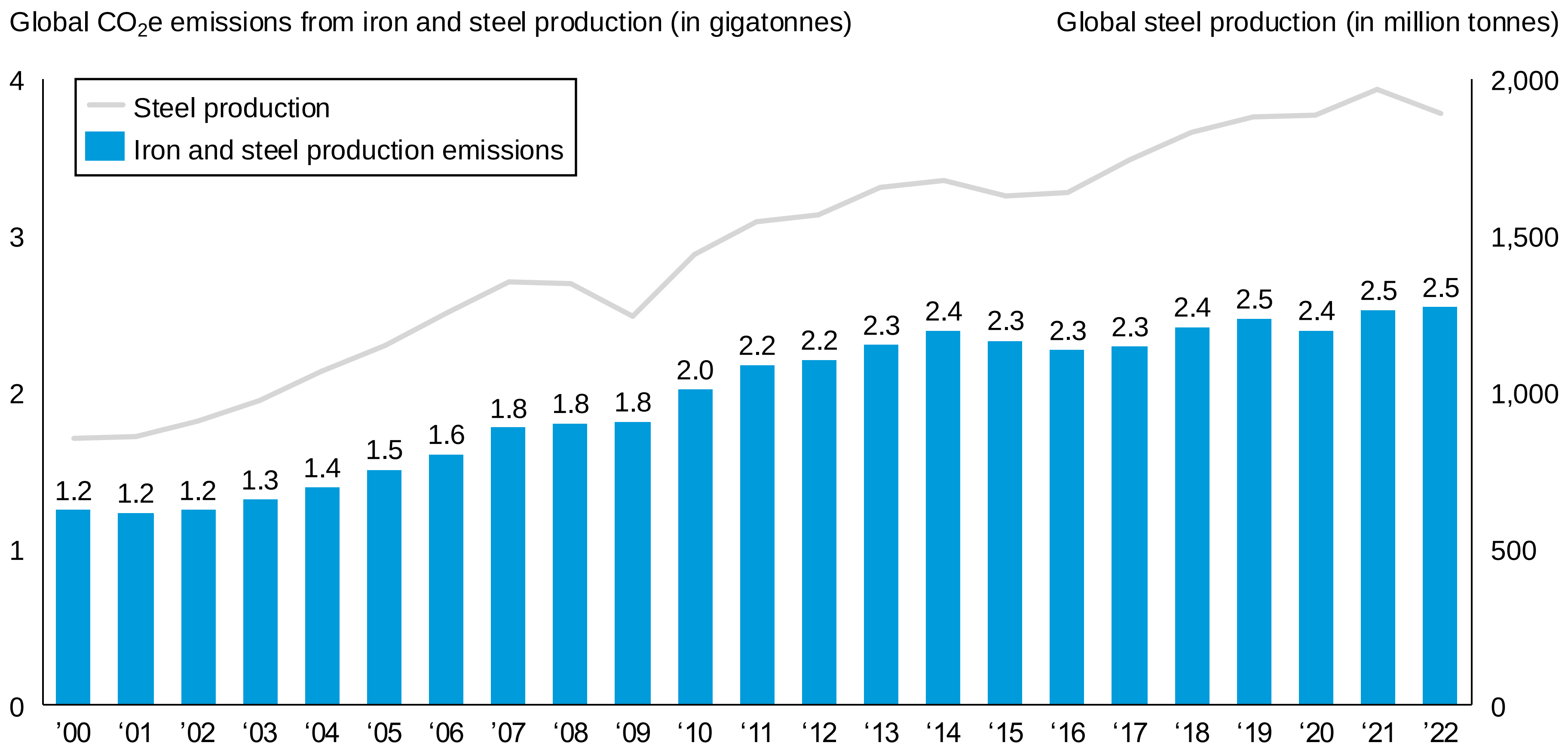
Global steel emissions have more than doubled since 2000, with emission decoupled from production growth after ~2015

Global CO_2e emissions decoupled from steel production after ~2015



Observations

- In recent years, the steel industry has made efforts to **reduce its carbon footprint** with **more energy-efficient processes and technologies**
  - Though not enough by itself, recycling rates **have improved** (sitting around 80%-90% globally)
  - **Better manufacturing yields** have made supply chains more efficient
  - **Enhanced control processes** and **predictive maintenance strategies** have led improvements in **operational efficiency**
- **China**, the largest steel producer in the world, saw a **3% decline in steel output** in 2021 and a similar decline in the years since

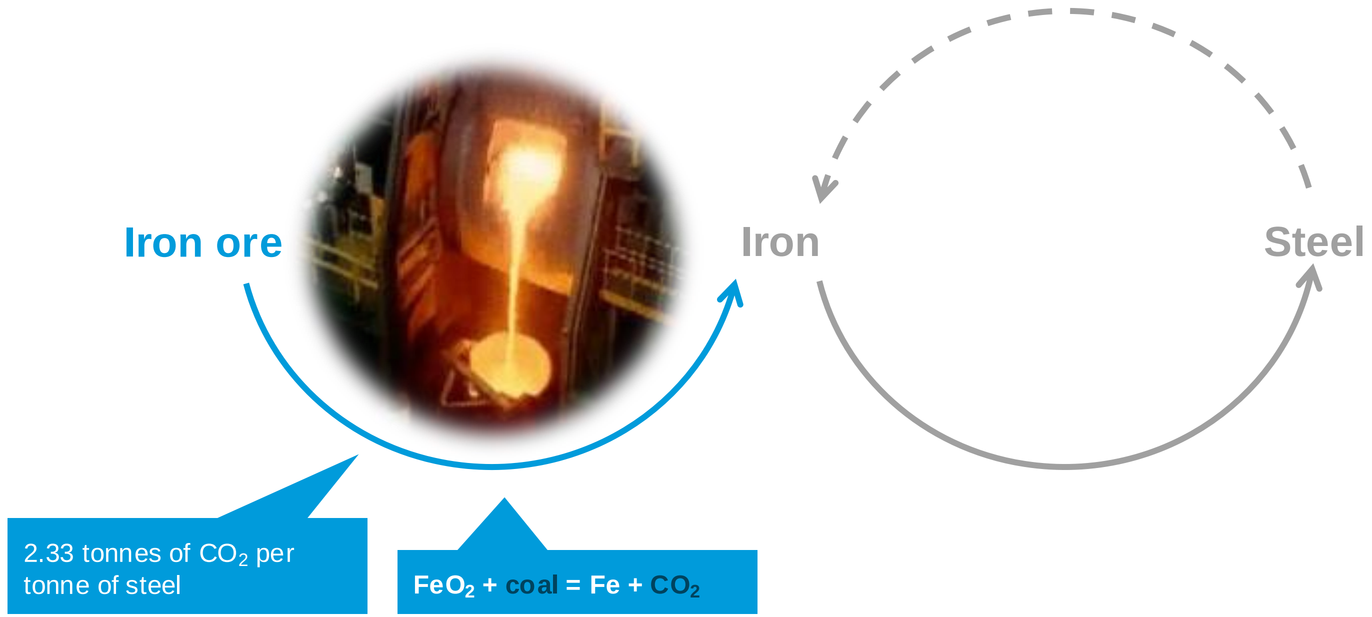
Note: The majority of the world's iron is used to make steel. Sources: Rhodium Group ClimateDeck (September 2023); World Steel Association; McKinsey, Decarbonization Challenge for Steel; IEA, CO_2 Emissions in 2022, Reuters, China 2021 Crude Steel Output. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hassan Riaz, Hyae Ryung Kim and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Crude steel is now produced through three main methods that all emit CO_2:

1. Blast furnace-basic oxygen furnace (BF-BOF), which alone produces ~80% of iron & steel CO_2
2. Scrap electric arc furnace (EAF), limited to recycled scrap
3. Natural gas-based direct reduced iron-electric arc furnace (NG DRI-EAF) most expensive, least used

1 Of three main steelmaking methods, blast furnace-basic oxygen furnace (BF-BOF) is the cheapest, most popular, and most polluting

BF-BOF ~73% of global steel production and ~80% of iron and steel CO_2 emissions



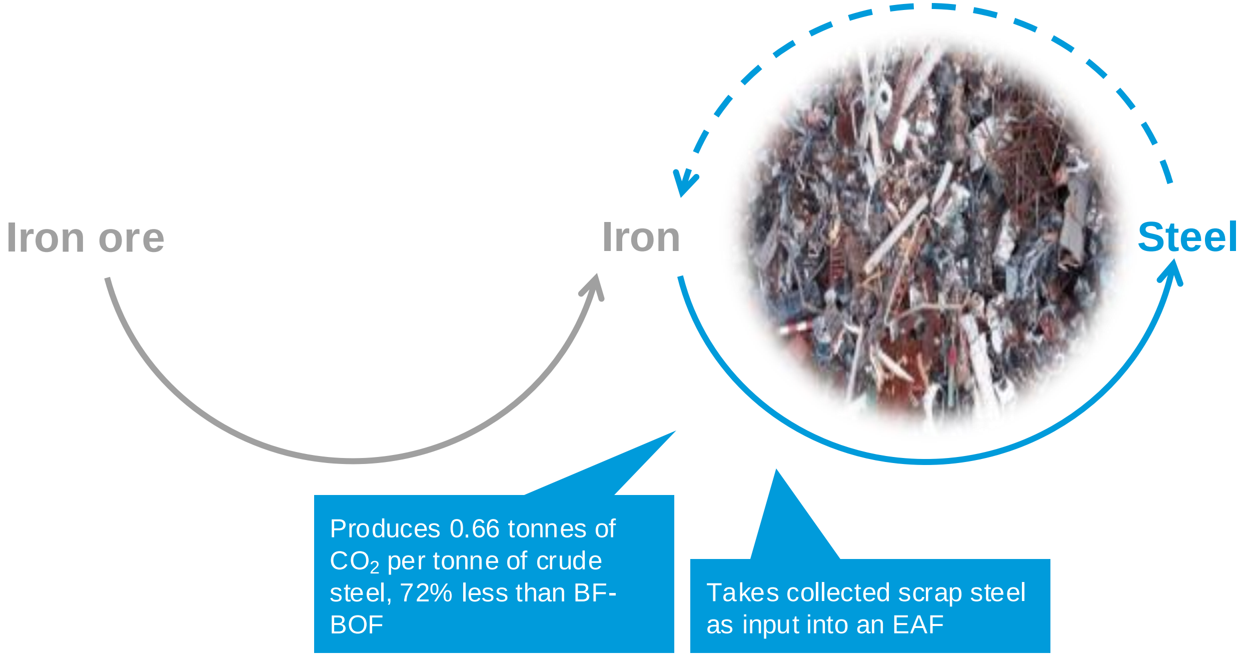
Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

2 Of the three main steelmaking methods, scrap electric arc furnace (EAF) is the cleanest, though limited by the scarcity of scrap material

More than 80% of steel recycled; scrap EAF accounts for ~22% of global steel production



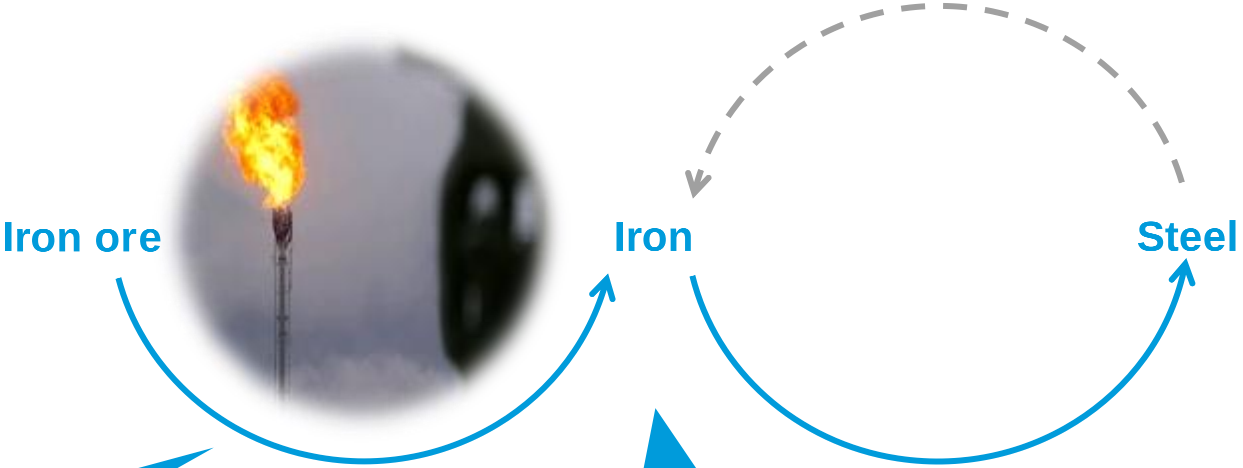
Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an EAF using electrical energy

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

3 Of the three main steelmaking methods, natural gas-based direct reduced iron-electric arc furnace (NG DRI-EAF) is the most expensive and least used

NG DRI-EAF ~7% of global steel production and 4% of iron and steel CO_2 emissions



Produces 1.39 tonnes of CO_2 per tonne of crude steel, 40% less than BF-BOF

Uses natural gas, a cleaner reduction agent than coal

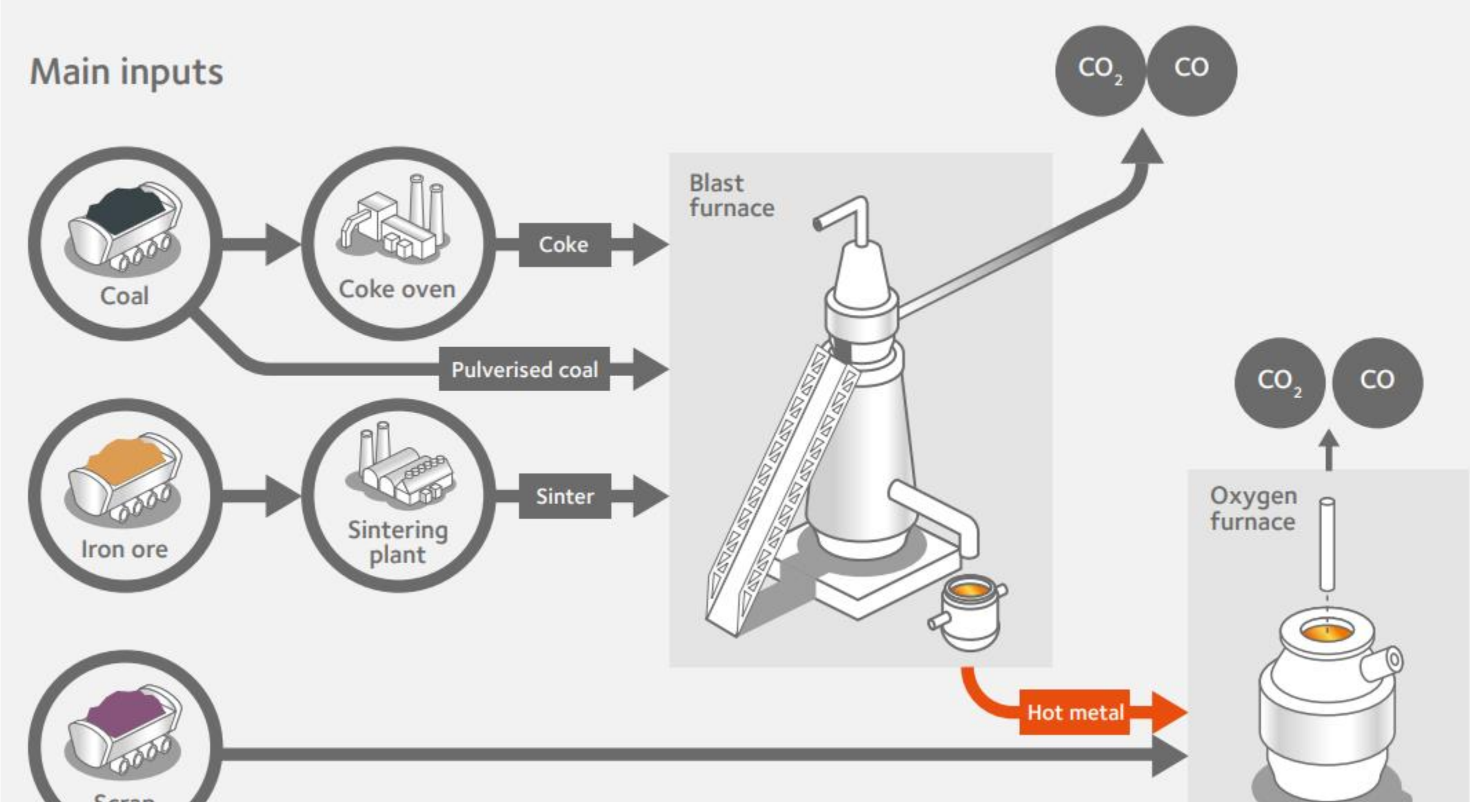
Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an EAF using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hassan Riaz, Hyae Ryung Kim and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

BF-BOF is the cheapest, most popular, and most polluting process which relies heavily on coal

Blast Furnace-Basic Oxygen Furnace (BF-BOF)



Source: ArcelorMittal

Process description

- In the first step, **coking coal and limestone** is **mixed with iron ore** in a Blast Furnace (BF) to perform **iron reduction** and obtain **molten crude iron**
- Crude iron is sent to **Basic Oxygen Furnace (BOF)** to be converted into cast iron
  - At this stage, up to **30% scrap steel** can be added

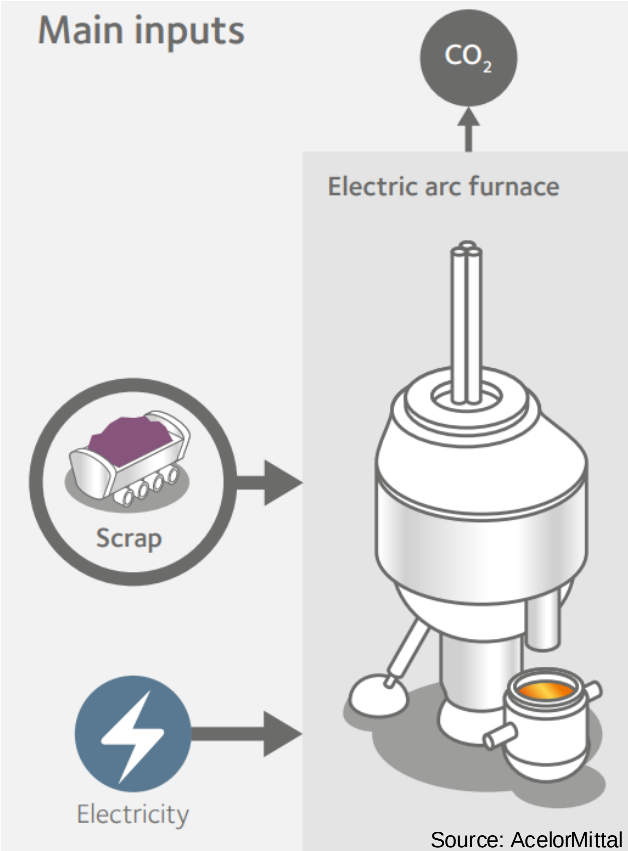
Observations

- **BF-BOF accounts for 72% of global steel** production
  – China, the world's #1 steel producer, accounts for >50% world output and **uses BF-BOF for 90% of steel production**
- Both steps in the BF-BOF process **produce CO2 as a byproduct.** On average, BF-BOF emits **2.3 tonnes of CO2 per ton of crude steel** – the **highest amount** of the three conventional steel routes
- BF-BOF remains **cheapest means of steelmaking**, with **average production cost of $390/tonne**

Source: MIDREX (2021), ArcelorMittal (2021), World Steel Association (2021), IEEFA (2022), IEA *Iron and Steel Technology Roadmap* (2020).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Scrap EAF is a cleaner steel making method that uses an Electric Arc Furnace to recycle scrap steel

Blast Furnace-Basic Oxygen Furnace (BF-BOF)



Source: AcelorMittal

Process description

- Scrap EAF takes **collected scrap steel** as input
- An **Electric Arc Furnace (EAF)** converts **electricity into heat** which is used to melt scrap steel into crude steel

Observations

- **Scrap EAF accounts for 21% of global steel** production, but use of technology is **limited** by the **scarcity of scrap material**
- Cleanest conventional route, emitting **0.7 tons of CO2 per ton of steel** (72% less than BF-BOF)
  - EU and US lead in scrap EAF production, accounting for **~40% of their steel production**
- Scrap EAF **average cost of production of $415/ton** – but cost **fluctuates** based on **scrap and electricity prices**

Source: MIDREX (2021), ArcelorMittal (2021), World Steel Association (2021), IEEFA (2022), IEA *Iron and Steel Technology Roadmap* (2020), Columbia Center on Global Energy Policy (2021).
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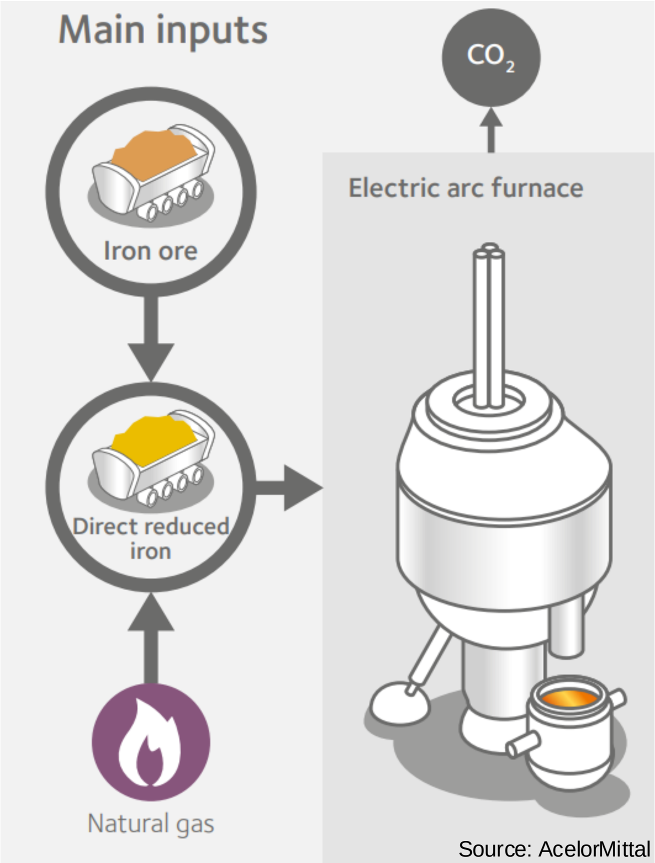
DRI-EAF is less common and uses natural gas to reduce iron ore to pure iron, which then enters into an EAF to make crude steel

Natural Gas-Based Direct Reduced Iron – Electric Arc Furnace (NG DRI-EAF)



Source: AcelorMittal

Process description

- **Iron ore** is **mixed with natural gas** in a **Direct Reduced Iron (DRI) shaft** to perform iron reduction and obtain **pure iron**
- The iron is then fed into an **Electric Arc Furnace (EAF)** where it is **converted into crude steel**

Observations

- DRI-EAF accounts for **remaining 7% of global steel production** and is **most dominant in the Middle East and Africa**, where gas is cheap and abundant
- Natural gas is a **cleaner reduction agent than coal**. DRI-EAF on average emits 1.4 tons of **CO2 per tonne of crude steel**, 40% less than BF-BOF
- DRI-EAF is the **most expensive conventional production route at $455/ton**

Source: MIDREX (2021), ArcelorMittal (2021), World Steel Association (2021), IEEFA (2022), IEA *Iron and Steel Technology Roadmap* (2020).
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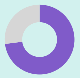
At present, crude steel is produced through three main methods that all emit CO_2: BF-BOF, scrap EAF, and NG DRI-EAF

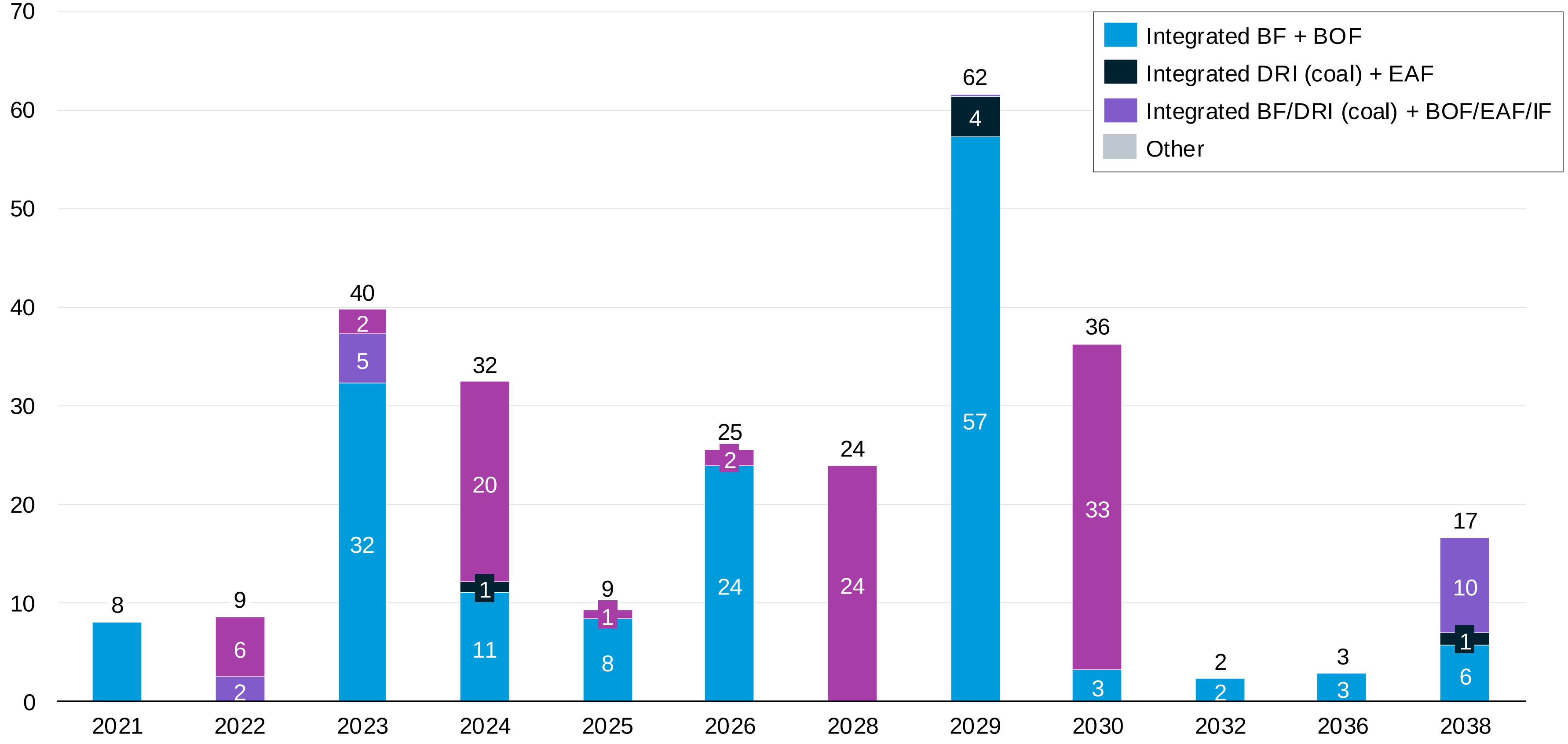
	1	2	3
	Blast Furnace-Basic Oxygen Furnace (BF-BOF)	**Scrap Electric Arc Furnace (Scrap EAF)**	**Natural Gas-Based Direct Reduced Iron – Electric Arc Furnace (NG DRI-EAF)**
Description	**Iron ore, coke, and limestone** produce pure iron in a **blast furnace**, which **is turned into steel in an oxygen furnace**	**Scrap metal** is **melted in an EAF** using **electrical energy**	**Iron ore** is turned **into iron** using **natural gas**, which is then **melted in an EAF** to **produce steel**
Main inputs	**Iron ore, cooking coal**	**Scrap steel, electricity**	**Iron ore, natural gas**
% of global steel production	 72%	 21%	7%
CO2 per tonne of crude steel	**2.3 tonnes**	**0.7 tonnes**	**1.4 tonnes**
Energy intensity per tonne of crude steel	**~24 GJ**	**~10 GJ**	**~22 GJ**
Average cost per tonne of crude steel	**~$390**	**~$415**	**~$455**

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

India is one of the fastest growing steel producers, and set to continue use of blast furnaces to meet rapid demand

India's new crude steel production capacity (2021 – 2038E)

New crude steel production capacity in India 'announced' or 'under construction' (in million tonnes per annum)



Observations

- India is now the **world's second largest producer of crude steel**, and it has **typically been a net exporter** post **FY2016-17**, apart from economic downturns
- Because of continued investment, India's steel making capacity is **expected to hit 300 mm tonnes per annum by 2030-31**
  - To meet demand, India is **set to build at least 200 MTPA of new fossil-fuel based, emission-intensive steel production capacity** over the next 15 years
  - **68% of this capacity** is expected to be **blast furnaces**
  - Remaining **32% expected** to be from **other processes** like integrated BF + BOF

Source: India Steel – The Indian Steel Industry. Climate Policy Initiative – Taking Stock of Steel. Credit: Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution.
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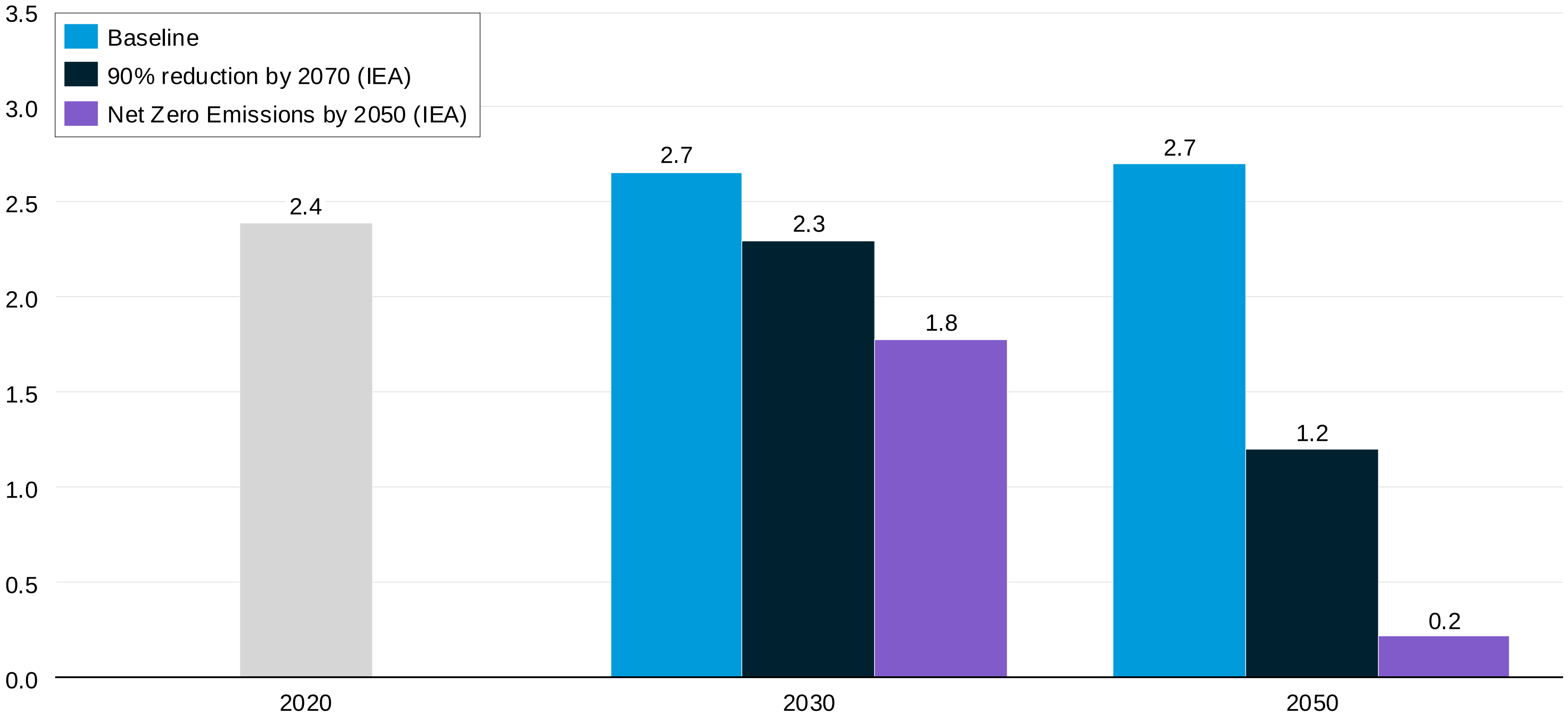
Global iron and steel emissions expected to rise without intervention; future reduction scenarios will require drastic cuts

Only with intervention will CO_2e from iron and steel decline into 2050

Direct CO_2 emissions in the iron and steel sector per IEA scenario (in Gt Co_2 per year)



Observations

- If no action is taken, **global emissions** from the iron and steel sector are **expected to peak at 2.7 gigatonnes per year in 2050**
  - Increase in emissions attributable to **growing steel demand from emerging economies**
  - Over time, gradual shift in demand is expected from **China to India, Southeast Asia and Africa**
- The **International Energy Agency (IEA)** has developed several possible pathways for the steel industry:
  - In the **90% reduction by 2070** pathway, emissions would still need to drop **by 50% by 2050**
  - In the **net-zero emissions by 2050** pathway, emissions would already need to **drop by 25% by 2030**, and **drop to close to zero by 2050**

Notes: Baseline scenario reflects the policies and implementing measures that have been adopted as of September 2022 NZE = Net Zero Emissions. Source: IEA (2020), IEA *Net Zero by 2050* (2021), IEA *Iron and Steel Technology Roadmap* (2020), McKinsey (2023). Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution.
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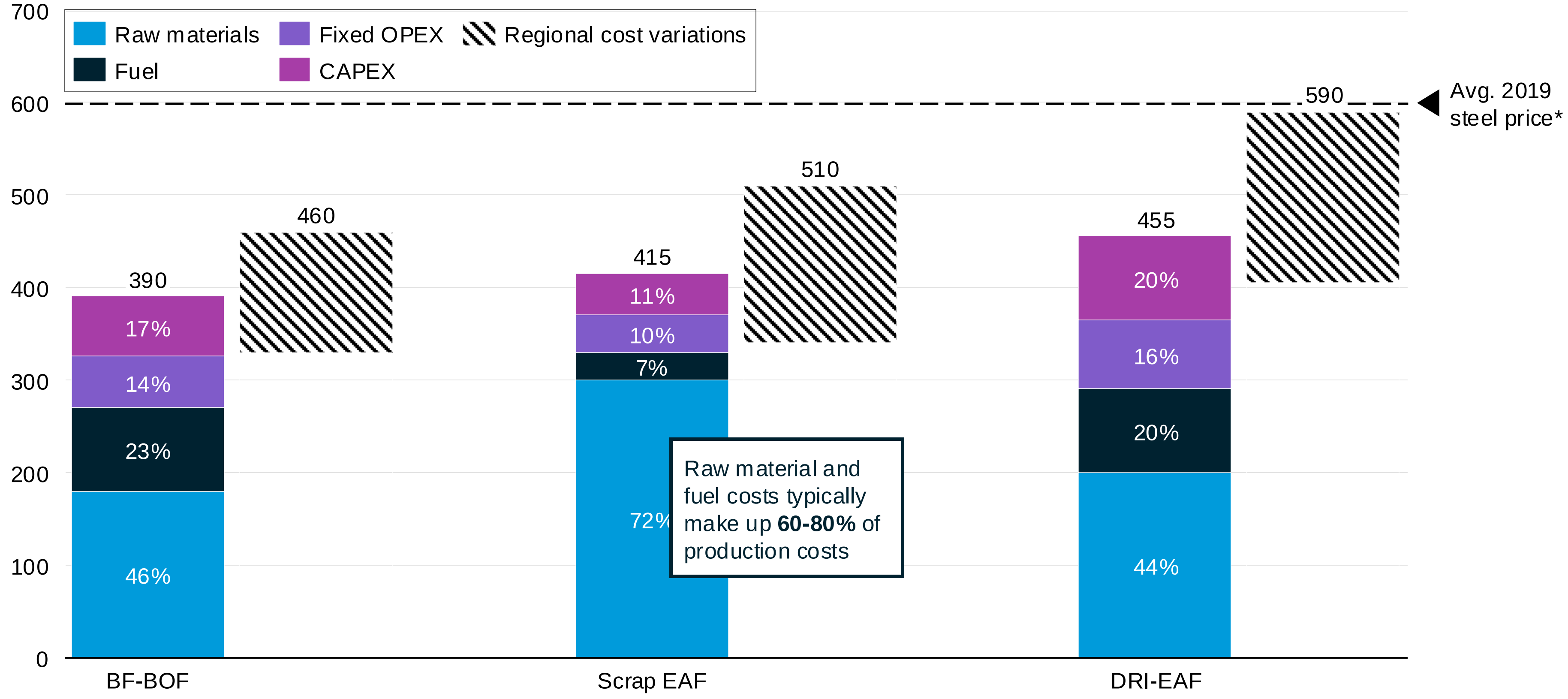
BF-BOF is the cheapest production method, but regional cost differences impact margins across production methods

Regional cost differences cause all steel making methods to be competitive

Simplified levelized cost breakdown of crude steel production via conventional routes (in USD per tonne, 2020)



Observations

- **Profit margins** across the industry are slim – the **average EBITDA** margin of steel producers over the **past 10 years** was **8-10%**
- **Raw material** and **fuel prices** can cause **strong fluctuations in margins**, given that these typically make up between **60-80% of total production costs**
  - While **some of these markets are global** (iron ore), **others are more regional** (e.g. electricity, scrap steel) which can **drive regional cost differences**
- **Labor costs**, feeding into fixed OPEX, are typically **higher in advanced economies than** in **emerging economies**
- **CAPEX** for **production equipment** is usually **consistent across regions**. However, **engineering, procurement and construction costs** can **vary significantly**

(*) Average steel price based on Hot Rolled Coil Steel Futures Continuous Contract (HRN00), average of 2019 monthly prices. Source: MarketWatch (2019) McKinsey,IEA *Iron and Steel Technology Roadmap* (2020), European Commission Joint Research Centre *Science for Policy Report* (2016). Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Downstream activities post-crude steelmaking use process heat and represent <20% of total steel production emissions

Downstream steelmaking process

Molten, Base Crude Steel

↓

Metallurgy & Refining Stage

↓

Refined Steel Grades

Carbon ("Structural") Steel	Alloy Steel	Stainless Steel	Tool Steel
• Low to high carbon steels • Strong, durable, & affordable • Uses: building & construction, manufacturing	• Low to high alloy steels • Easily machinable, heat & corrosion resistant • Uses: oil & gas pipelines, auto panels, kitchenware	• 10%-20% of chromium, nickel, or molybdenum • Corrosion resistant, low maintenance, sanitary • Uses: medical devices, food processing	• Designed specifically for tools & dies • Hard & wear-resistant • Uses: cutting & drilling equipment, auto cylinder heads, aerospace blades

Continuous Casting

Semi-Finished Products: Slabs, Billets, Blooms

↓

Final Rolling

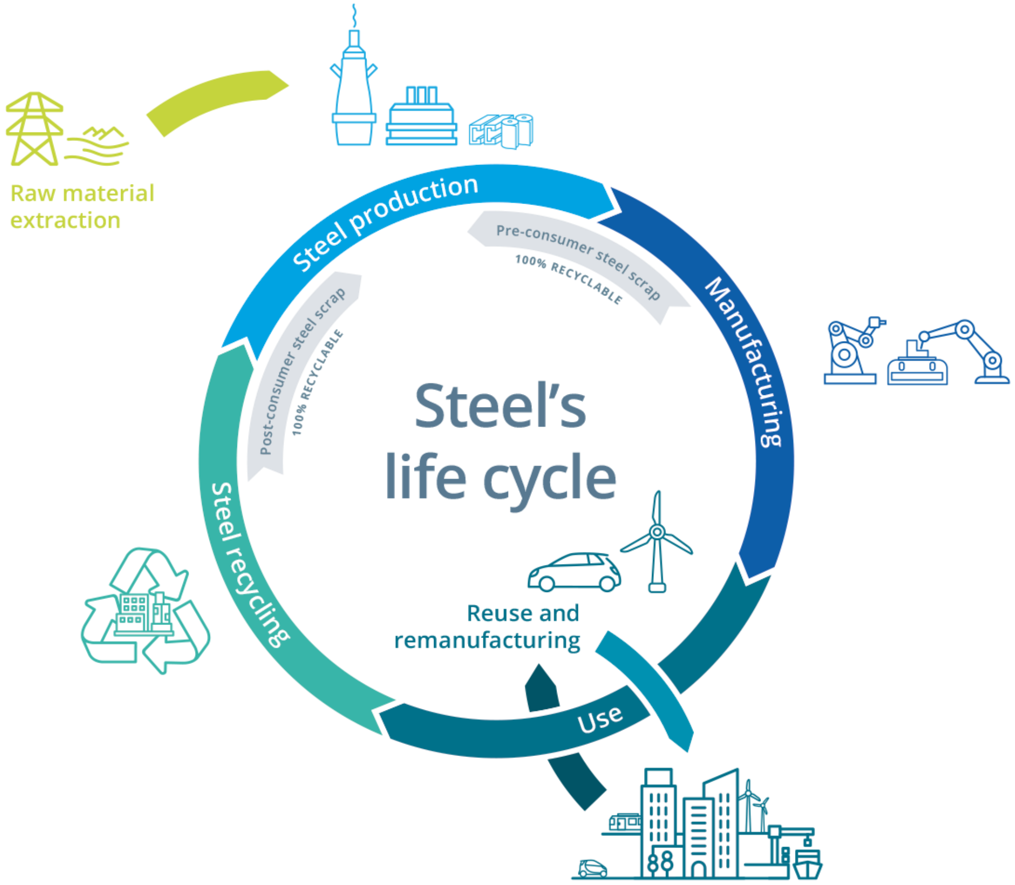
Hot-Rolled Products: Coils, Plates, Sections, Tubes, Rods, Wires, etc.

Observations

- On average, <**20% of steelmaking CO_2 emissions** come from downstream processes
- Metallurgy involves **adding alloys** in hot ladle to **convert base crude steel into different types of refined steel** (carbon, alloy, stainless, or tool)
  - Common alloys: manganese, chromium, cobalt, nickel, tungsten, molybdenum, vanadium
- Refining step traps and **removes impurities** through processes like stirring molten steel with gas like argon
- Continuous casting **molds liquid steel into semi-finished products**, usually slabs, billets, or blooms
- Finally, the steel goes through a number of different **finishing processes** (e.g. hot or cold rolling, galvanizing) depending on the **intended end use of the steel**

Source: World Steel Association, Association for Iron & Steel Technology, Eziil, Industrial Metal Supply, Steel Manufacturer's Association *Steelmaking Emissions Report* (2022).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Steel 100% recyclable material; increased use of scrap in primary and secondary routes expected to help decarbonize sector



Source: World Steel Association

Observations

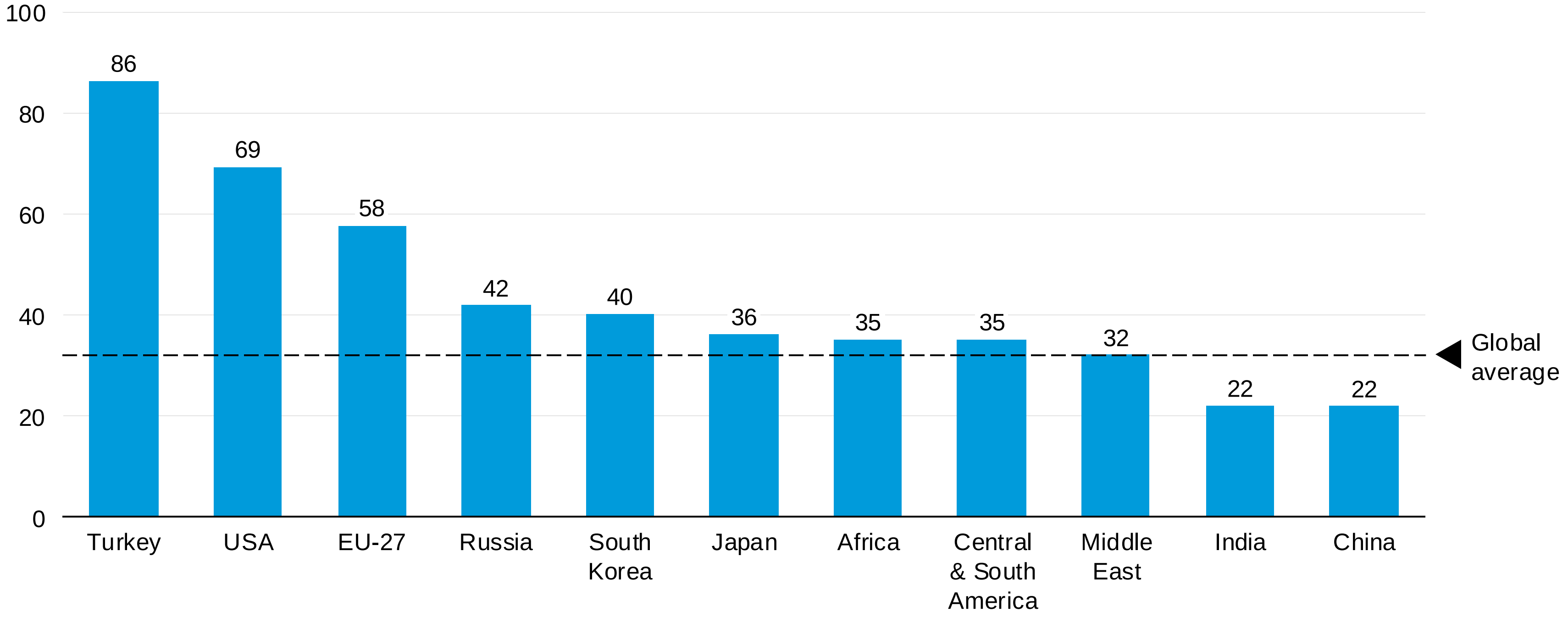
- Steel is **100% recyclable** and can be **infinitely reused** due to **magnetic properties** allowing **easy separation from waste streams**
- Scrap EAF is the **least emitting** and **least energy intensive** conventional route and is also cost competitive
  - **As a share of steelmaking, Scrap EAF expected to grow from 22% today to almost 50% by 2050** in Net Zero scenario
- Scrap separated into **two categories: pre-consumer scrap** (scrap from downstream steel manufacturing) and **post-consumer scrap** (~50/50 split)
  - As a share of steelmaking, Scrap EAF expected to grow from 22% today to almost 50% by 2050 in Net Zero scenario
- **Over 85% of steel is recycled today**, world's most recycled material. Scrap steel supply only grows as steel products become obsolete
- The **scrap steel market** is already **well-functioning**, and expectations are that as **scrap becomes more expensive** there will be **more incentives** to **recover steel from difficult applications** such as foundations

Source: World Steel Association (2020), World Steel Association *Scrap use in the steel industry* (2021), World Steel Association *Fact sheet: Raw materials in the steel industry* (2023), Net Zero Steel (2021), Mission Possible Partnership *Net Zero Steel Sector Transition Strategy* (2021), IEEFA (2021), World Economic Forum (2023).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Among major steel producing countries and regions, Asian economies lag in scrap steel consumption

Scrap steel consumption varies regionally but lags places like India and China

Scrap steel consumption as a share of crude steel production by major producing countries and regions (in %)



Crude steel share of global production	Turkey	USA	EU-27	Russia	South Korea	Japan	Africa	Central & South America	Middle East	India	China
	2%	4%	7%	4%	3%	5%	1%	3%	3%	7%	54%

Observations

- **Average lifespan** of a steel product is ~**40 years**, but with a **wide range.** Steel packaging (such as tin-coated steel cans) lasts **only a few weeks on average**, while steel used for buildings may **last 100 or more years**
- This long life-span means **that scrap steel is still scarce in emerging economies**, as these countries industrialized later
- Usually, **local scrap steel recycling markets** feed the domestic steel industry. But there is some **international trade** taking place:
  - Turkey, the world's 7th largest steel producer, imported over 90% of their scrap steel inputs
  - The EU and the US are both large exporters of scrap steel

Source: Bureau of International Recycling World Steel Recycling in Figures 2017-2021 (2021), IEA Iron and Steel Technology Roadmap (2020), World Steel Association Scrap use in the steel industry (2021), World Steel Association World Steel in Figures 2023 (2023), IEEFA New From Old: The Global Potential for More Scrap Steel Recycling (2021).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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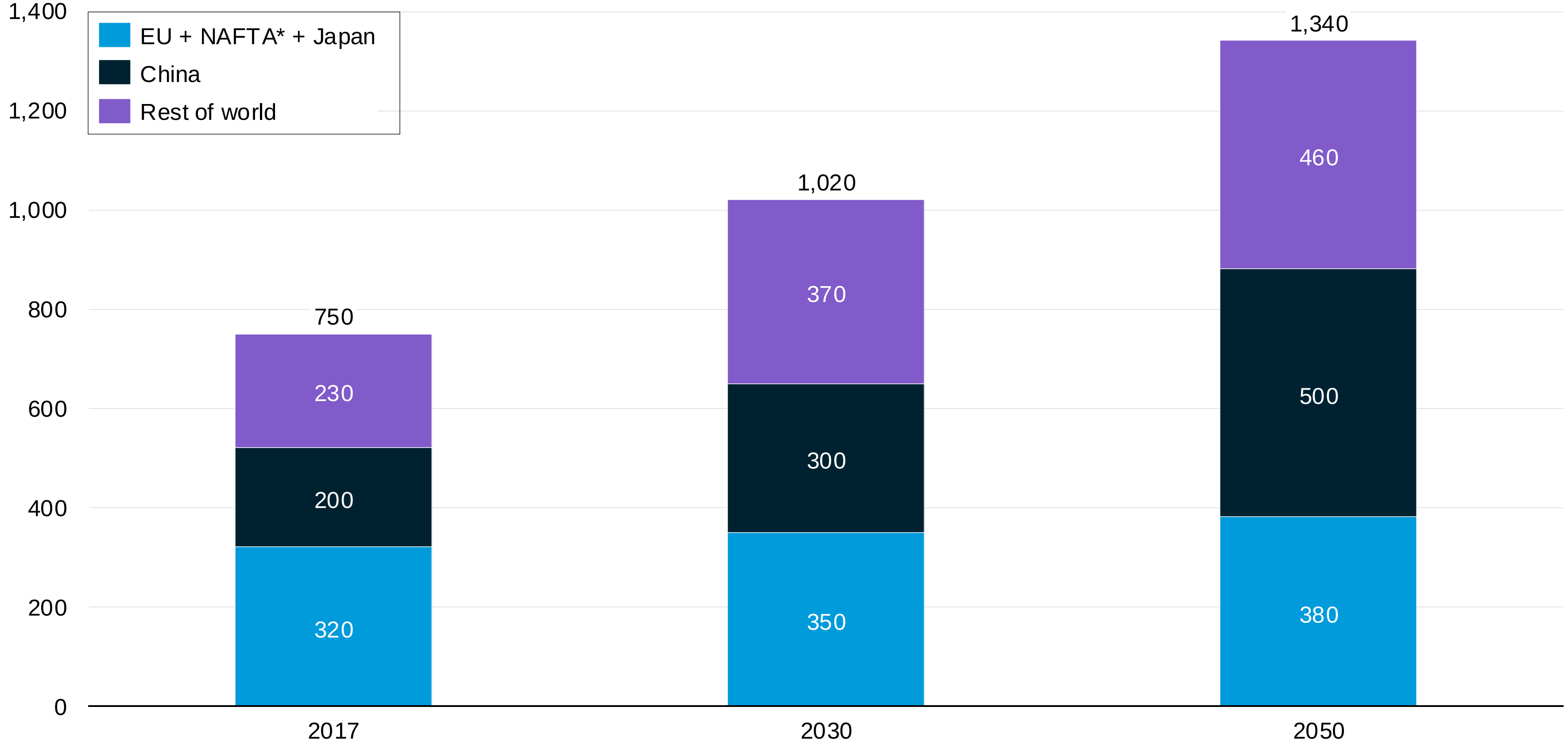
Scrap steel stock is expected to continue growing globally, allowing for more markets to increase scrap steel recycling

Growing amount of scrap steel to alleviate demand in emerging economies like China

Global scrap steel availability by major regions, 2017-2050 (in mm)



(*) Canada, Mexico and USA. Source: World Steel Association (2018), World Steel Association *Scrap use in the steel industry* (2021), IEEFA *New From Old: The Global Potential for More Scrap Steel Recycling* (2021). Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Observations

- **Domestic scrap availability** to **increase significantly** in **emerging economies** over the coming years
  - As **China** matures, it is expected to **fuel much of global scrap steel supply through 2050**
- Today, **steel stock** in **OECD nations** has reached **12-13 tonnes per capita**, while in **India and Africa** this is only **1 tonne per capita** – meaning **less scrap steel** is likely to become available in India and Africa over time
- As **scrap availability improves, adoption of Scrap EAF** and a **growing share of scrap steal in total steel production** become more feasible

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Steel Decarbonization Technologies

Key messages
Steel decarbonization technologies

Three main **deep decarbonization steelmaking technologies:**

- **Green hydrogen DRI-EAF:** Hydrogen produced using zero-carbon electricity is used as iron ore reductant instead of natural gas; second step uses an Electric Arc Furnace (EAF).
- **Iron ore electrolysis:** Use of electricity to split pure iron from iron ore. Two technologies:
  - **Molten Oxide Electrolysis (MOE):** A high current is run through a mixture of iron ore and a liquid electrolyte, which causes the iron ore to split into oxygen and molten iron.
  - **Electrowinning-EAF (EF-EAF):** Iron from iron ore is dissolved in an acid; the iron-rich solution is electrocuted to form pure solid iron, which is melted in an EAF.
- **Carbon Capture, Utilization and Storage (CCUS):** BF-BOF or DRI-EAF retrofitted with point capture equipment. Captured carbon is then used or stored.

These technologies produce steel with **over 90% fewer CO_2 emissions** compared to conventional processes. However, **green hydrogen DRI-EAF** and **CCUS BF-BOF / DRI-EAF** come at a **green price premium. CCUS is also less viable for BF** route, given **difficulty of capturing all released carbon. Electrolysis** may be **cheaper** than conventional processes but **has not been tested at scale.**

There are also some **emerging transitional steelmaking technologies** with **decarbonization potential of ~10-50%:**

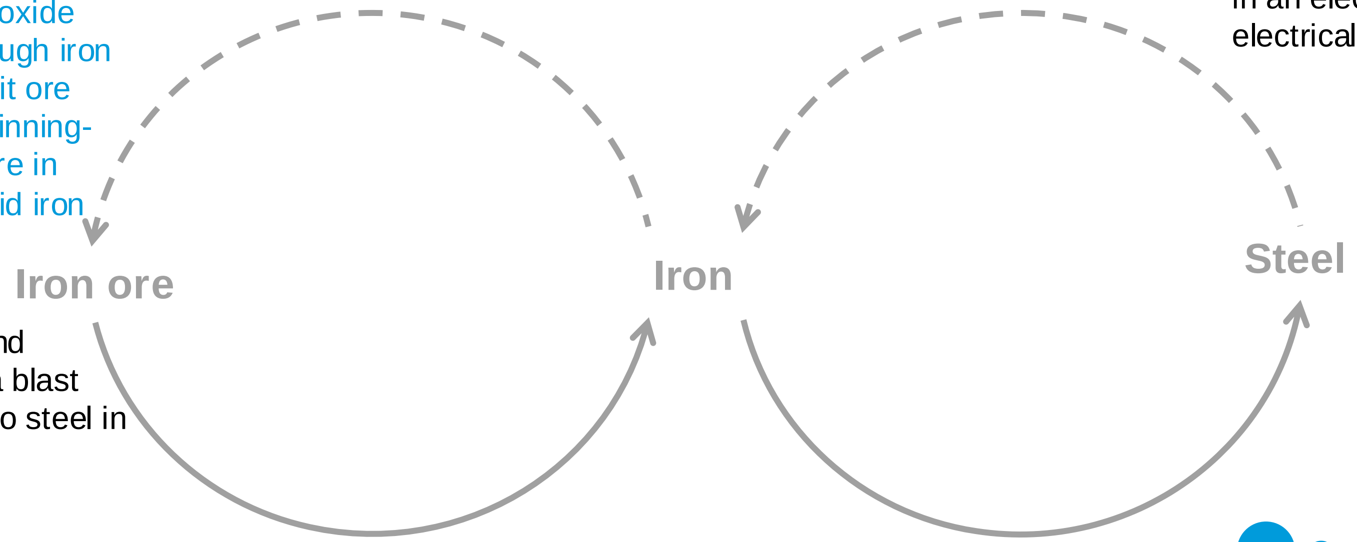
- **Modifications to existing BF-BOF and DRI-EAF:** using biomass as input, switching to zero-carbon electricity, partial green hydrogen injections.
- **Different production process:** Smelting Reduction-BOF (SM-BOF).

Transitional technologies may be appropriate in **specific circumstances,** but despite lower overall decarbonization potential, they often still come with a **considerable green premium.**

Most steel production uses BF-BOF, scrap EAF, and NG DRI-EAF, with Green H_2 DRI-EAF, iron ore electrolysis, and CCUS technologies emerging

2 **Iron ore electrolysis:** Molten oxide electrolysis runs a current through iron ore and liquid electrolyte to split ore into pure molten iron; electrowinning-EAF dissolves iron from iron ore in acid, then electrifies it from solid iron

Scrap EAF: Scrap metal is melted in an electric arc furnace using electrical energy



BF-BOF: Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace

NG DRI-EAF: Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel

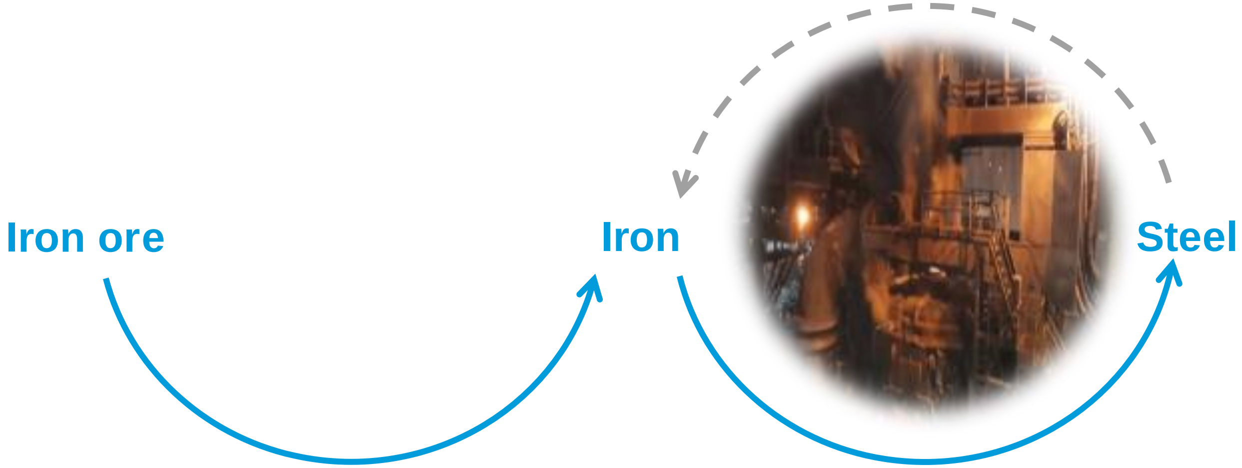
1 **Green H_2 DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; water instead of CO_2 is generated as a byproduct

3 **Carbon capture, utilization, and storage (CCUS):** Equipment is added to existing steel-producing infrastructure to capture emitted CO_2, which is then sequestered or reused

See glossary. Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution.
Contact: gwagner@columbia.edu

1 Green H_2 DRI-EAF is an emerging technology using green hydrogen instead of natural gas as an iron ore reductant with standard electric arc furnaces

Green H_2 direct reduced iron-EAF has an average cited decarbonization potential of ~90%



Renewable electricity is used throughout the production process, including the creation of green hydrogen

Comes at a green price premium

Observations

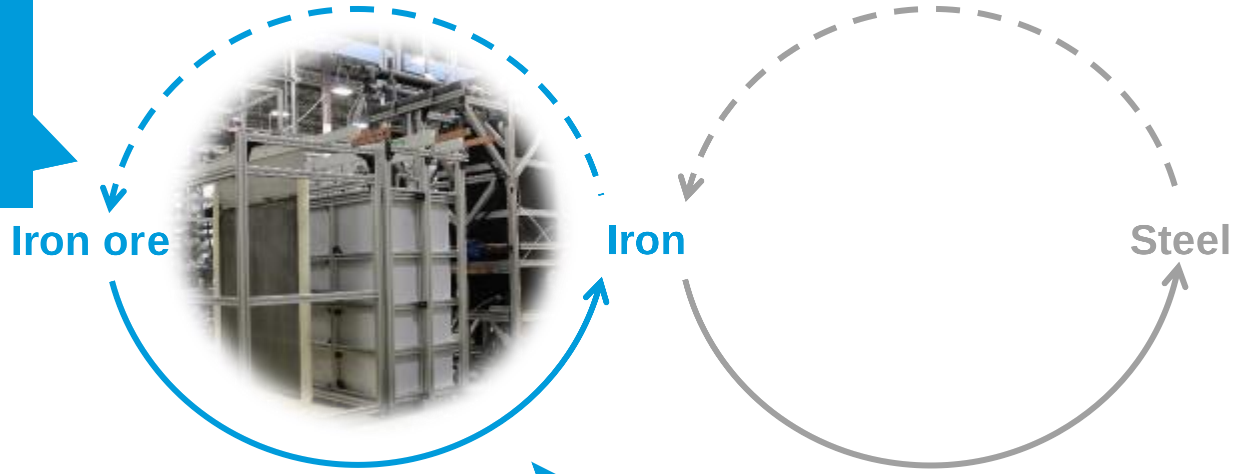
- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an EAF using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel
- **Green H_2 DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO_2

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

2 Iron ore electrolysis is an emerging technology that uses an electric current to drive a chemical reaction, producing molten iron or pure solid iron

Iron ore electrolysis has an average cited decarbonization potential of ~97%

Iron is now akin to solid-state battery, allowing for a reversed process that *produces* electricity



Electrowinning-EAF dissolves iron from iron ore in acid, then electrifies it to form pure solid iron; molten oxide electrolysis runs a current through iron ore and liquid electrolyte to split ore into pure molten iron

May be cheaper than conventional processes but has not yet been proven at scale

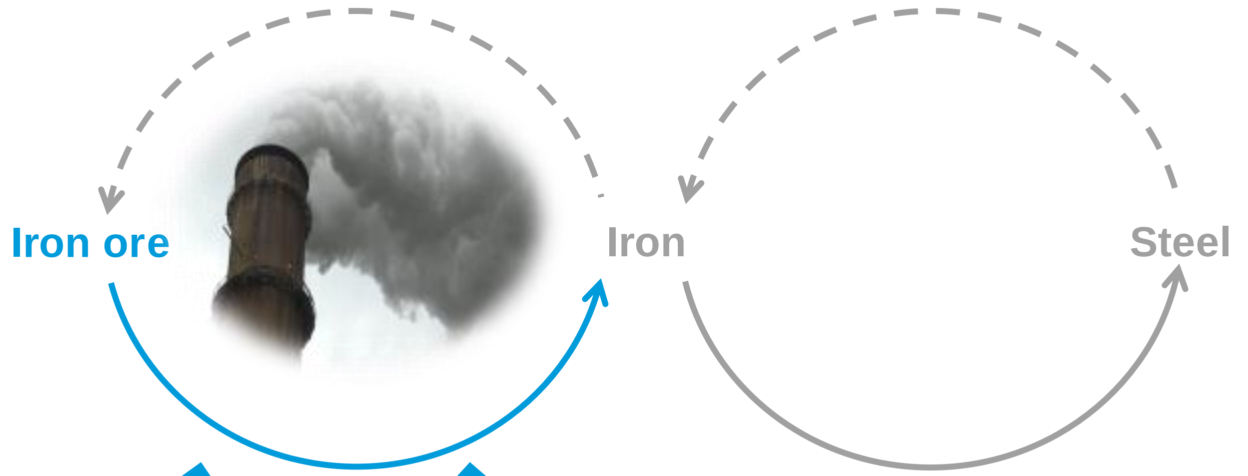
Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an electric arc furnace (EAF) using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel
- **Green H_2 DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO_2
- **Iron ore electrolysis:** Molten oxide electrolysis runs a current through iron ore and liquid electrolyte to split ore into pure molten iron; electrowinning-EAF dissolves iron from iron ore in acid, then electrifies it to form solid iron

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (13 March 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

3 Carbon capture, utilization, and storage (CCUS) is an emerging technology that reduces steel's carbon footprint by capturing released CO_2

Despite a cited ~90% decarbonization potential, CCUS technology is largely unproven



Less viable for the blast furnace route given difficulty of capturing all carbon released

Capture rates range from 50%-90%, and viability is debated due to the lack of a single capture point

Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an electric arc furnace using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel
- **Green H_2 DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO_2
- **Iron ore electrolysis:** Molten oxide electrolysis runs a current through iron ore and liquid electrolytes to split ore into pure molten iron; electrowinning-EAF dissolves iron from iron ore in acid, then electrifies it to form solid iron
- **CCUS:** Equipment is added to existing steel-producing infrastructure to capture emitted CO_2, to then sequester or reuse

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Green H_2, electrolysis, and CCUS could reduce steelmaking CO_2 emissions by over 85% if implemented at scale

	1	2	3
	100% Green Hydrogen (H2) DRI-EAF	**Iron Ore Electrolysis**	**Carbon Capture, Utilization, and Storage (CCUS)**
Description	• **Green hydrogen** replaces **natural gas** as an iron ore reductant in DRI shaft; the rest of the process remains the same • Generates **water as a byproduct** instead of CO_2	• **Two different processes** are **possible:** **Molten oxide electrolysis:** High current runs through mixture of iron ore and liquid electrolyte to split ore into pure molten iron **Electrowinning-EAF:** Iron from iron ore is dissolved in acid. Iron-rich solution is then electrified to form pure solid iron	• **CCUS equipment** can be added to **existing steel-producing infrastructure** to **capture** emitted CO_2 • Captured CO_2 is then **sequestered underground** or **reused**
Real-time sector initiatives	HYBRIT/Stegra 100% fossil fuel-free DRI-EAF production with green H_2 used for DRI	Electra Electrowinning to produce high-purity iron plates ready for EAF input (no DRI or MOE step)	ArcelorMittal Carbalyst® captures carbon from a blast furnace and reuses it as bio-ethanol. However, technology not proven at scale
Applicability to conventional routes	**Applicable to existing DRI-EAF route**, with minor retrofitting	**Full overhaul** of BF-BOF equipment required; **replacement** of DRI shaft in DRI-EAF	**Retrofitting** of capture technology is possible on **conventional BF-BOF and DRI-EAF**
Decarbonization potential (vs. BF-BOF)	**~90%**	**~97%**	**~90%** (Hypothetical best-case scenario)
Estimated production cost (excl. CapEx)	**<$800 per tonne of steel**	**~$215 per tonne of iron + cost of 'stranded' iron ore**	**~$380 – 400 per tonne**

Sources: Columbia Center on Global Energy Policy (2021); IEA, Iron and Steel Technology Roadmap (2020); McKinsey (2020); Mining Technology (2023); Tata Steel; Primetals Technologies; Edie, ArcelorMittal accused of net-zero greenwashing (2023). Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (13 March 2024); share/adapt with attribution.

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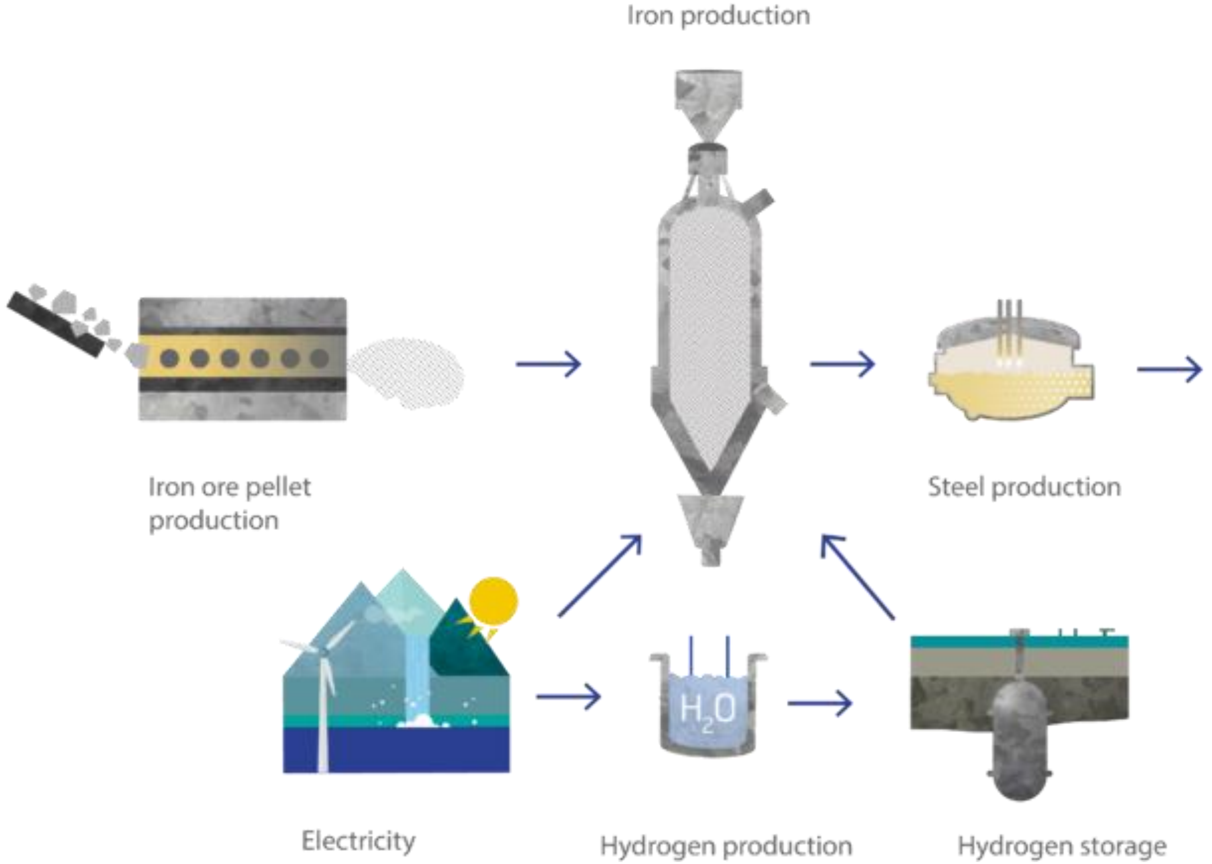
1 In green hydrogen DRI-EAF, hydrogen replaces natural gas as reductant to create pure iron, with water as the main byproduct

100% Green H_2 DRI-EAF production process



Source: HYBRIT

Description

- **Hydrogen** is used as a **reductant instead of natural gas** to **transform iron ore into solid, purified iron.** After this, the iron is moved to an **electric arc furnace** where it is **transformed into crude steel**
- Instead of CO_2, the **main byproduct** of this production process is **water**
- For the process to be CO_2 neutral, two important criteria must be met
  - The **electricity** used to power the **electric arc furnace** should come from a **renewable source**
  - The **hydrogen** used in the production process should be **green hydrogen**

Hydrogen sourcing

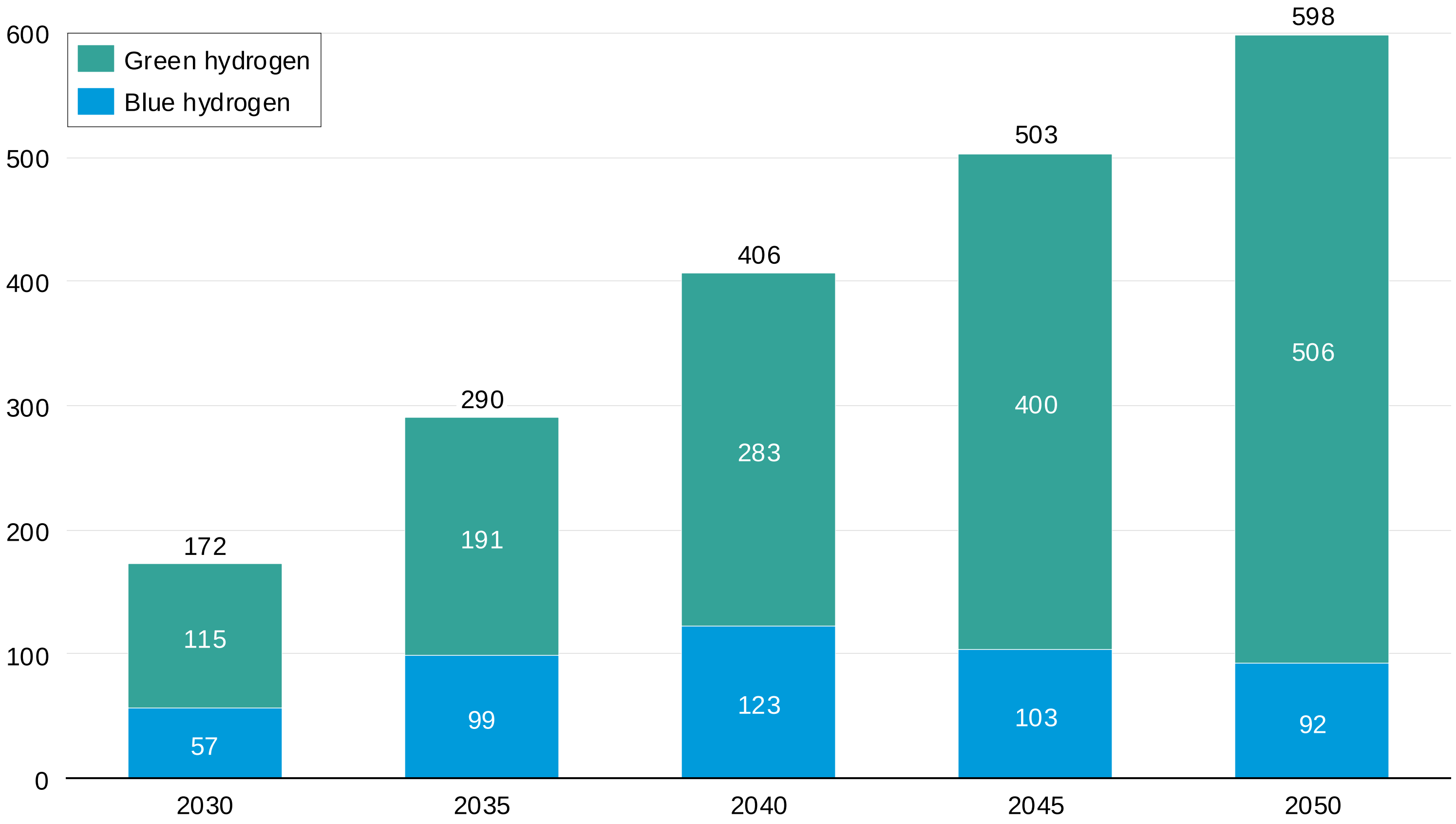
Hydrogen can be produced in several ways, not all of which are CO_2 neutral

- **Green hydrogen**: produced from **water electrolysis using 100% renewable electricity** – zero-carbon option
- **Grey hydrogen**: produced from **natural gas, methane, or other carbon-containing feedstock**
- **Blue hydrogen**: similar to grey hydrogen, but with **carbon capture** (capture rate of 85-95%) – low-carbon, but not zero-carbon, option

1 Global green hydrogen production needs to expand significantly for green hydrogen DRI-EAF to become feasible

Green hydrogen production needs to grow at a rapid rate

Low and zero-carbon hydrogen production for Net Zero scenario by Deloitte, 2030-2050 (in mm tonnes)



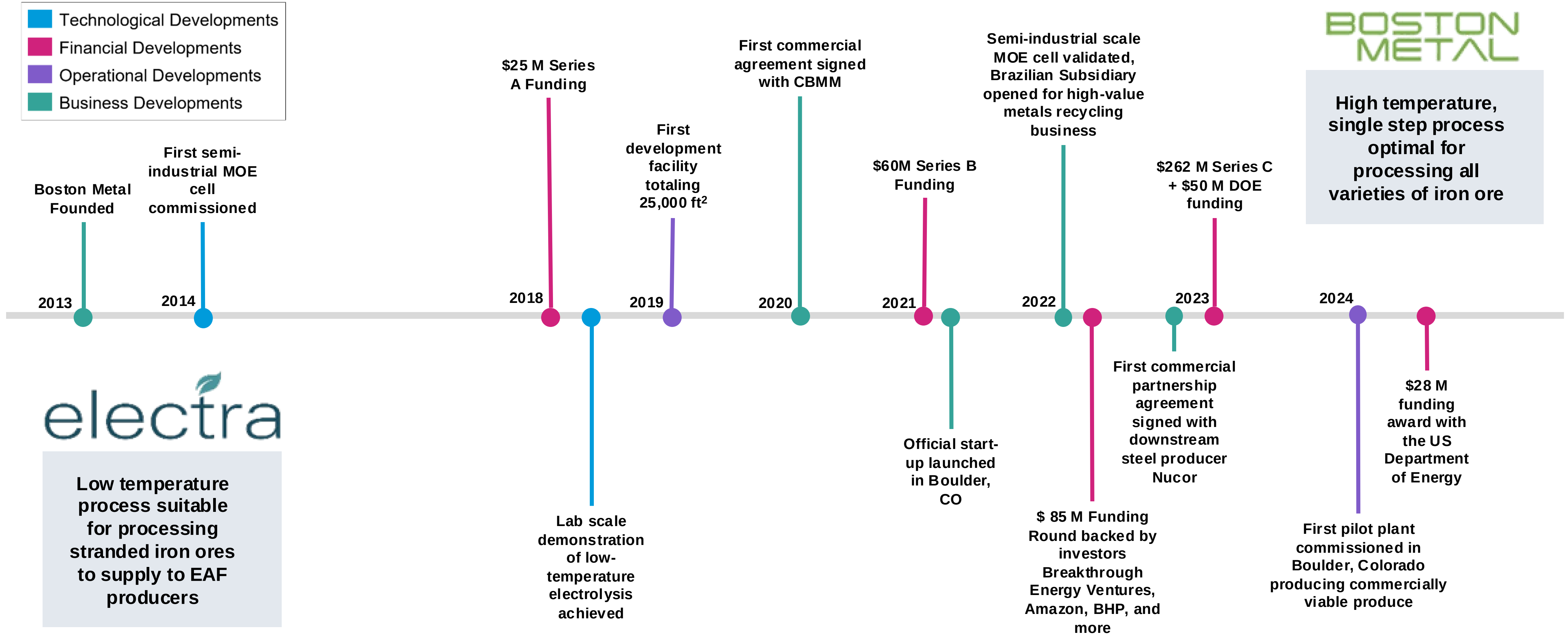
Observations

- Hydrogen already produced commercially today, but currently **only 1% produced using renewable energy**
- **New green hydrogen production** should be built **close to renewable energy suppliers** like solar and wind farms
  - Production can then even be synced to ramp up when solar and/or wind energy is available
- **Strong policy support** for green hydrogen is expected to help scaling efforts. For example, in the US tax code section 45V provides **tax credits for hydrogen production**
- **Blue hydrogen production** projected to grow in **regions with abundant natural gas resources** to **help kickstart the global hydrogen economy.** Peak production expected in **2040**

Source: Deloitte *Green hydrogen: Energizing the path to Net Zero* (2023), Washington Post (2023), IRENA (2021).

Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hassan Riaz, Hyae Ryung Kim & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

2 Between Iron Ore Electrolysis start-ups, Electra and Boston Metal are leading the charge



Source: Boston Metal, Mining Technology (2023), Electra (2024), Mission Possible Partnership *Net Zero Steel Sector Transition Strategy* (2021)
Credit: Hassan Riaz, Hyae Ryung Kim & Gernot Wagner (13 June 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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2 Boston Metal is a leading Iron Ore Electrolysis Start-up with a novel Molten Ore Electrolysis (MOE) technology

BOSTON METAL

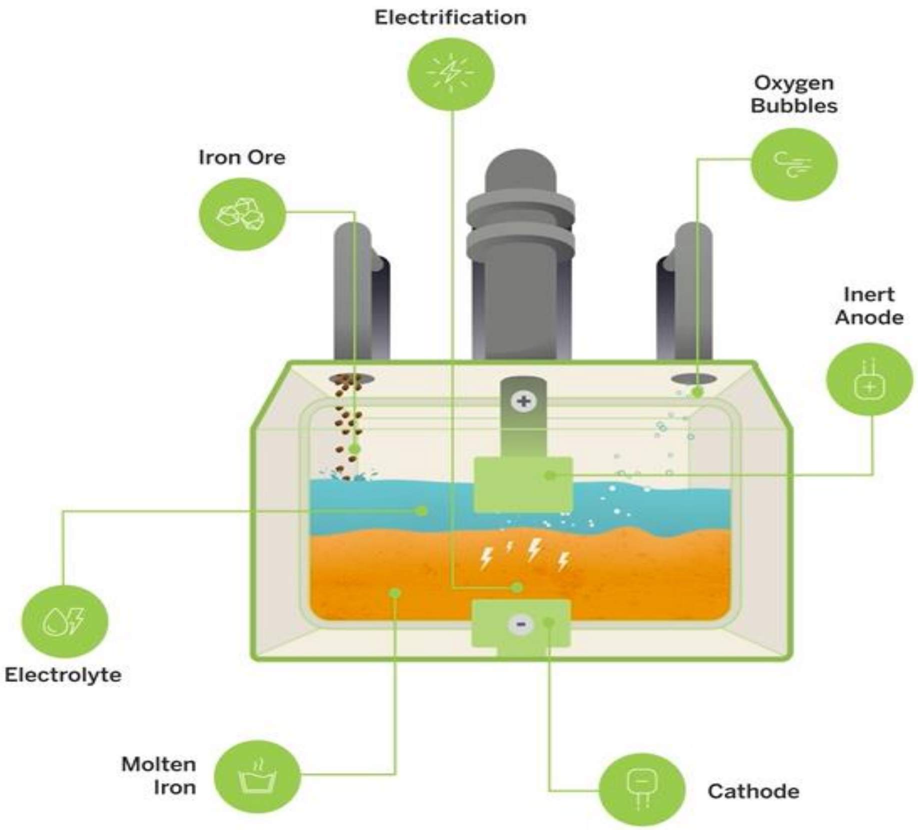
Founded: 2013, MA, USA

Total funding raised to date: $397M

Technology description

- In a **Molten Ore Electrolysis (MOE)** reactor, **iron ore** is combined with an **electrolyte**, and a **strong electrical current** is applied to **initiate the electrolysis process**
- The result of this process is **molten iron**, which is **immediately suitable for transfer to the refining stage.** In this subsequent stage, carbon and other elements are added to **transform the molten iron into refined steel**
- **Boston Metal's** technology is capable **of processing iron ore grades of all varying levels of impurity** due to the **high temperature (1600 ⁰C)** mode of operation allowing **flexibility** to operate in both the **incumbent iron ore** supply streams as well **as mining waste** supply streams
- The **only significant byproduct** from this process is **oxygen (O_2)**, coming from the iron oxide in the iron ore
- **MOE power consumption** per tonne of steel (13 GJ / tonne) is **considerably less** than that of **BF-BOF** (24 GJ / tonne)
- For the process to be **completely carbon neutral**, **electricity** used to power the reactor should come from **renewable sources**

Boston Metal's unique MOE Cell Design allows ample processing flexibility and minimizes manufacturing steps



Source: Boston Metal

Source: Boston Metal, Mining Technology (2023), Mission Possible Partnership *Net Zero Steel Sector Transition Strategy* (2021)
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hassan Riaz, Hyae Ryung Kim & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

2 In electrowinning-EAF, an iron-rich solution is electrified to create pure grade iron ready to be used in an electric arc furnace

electra

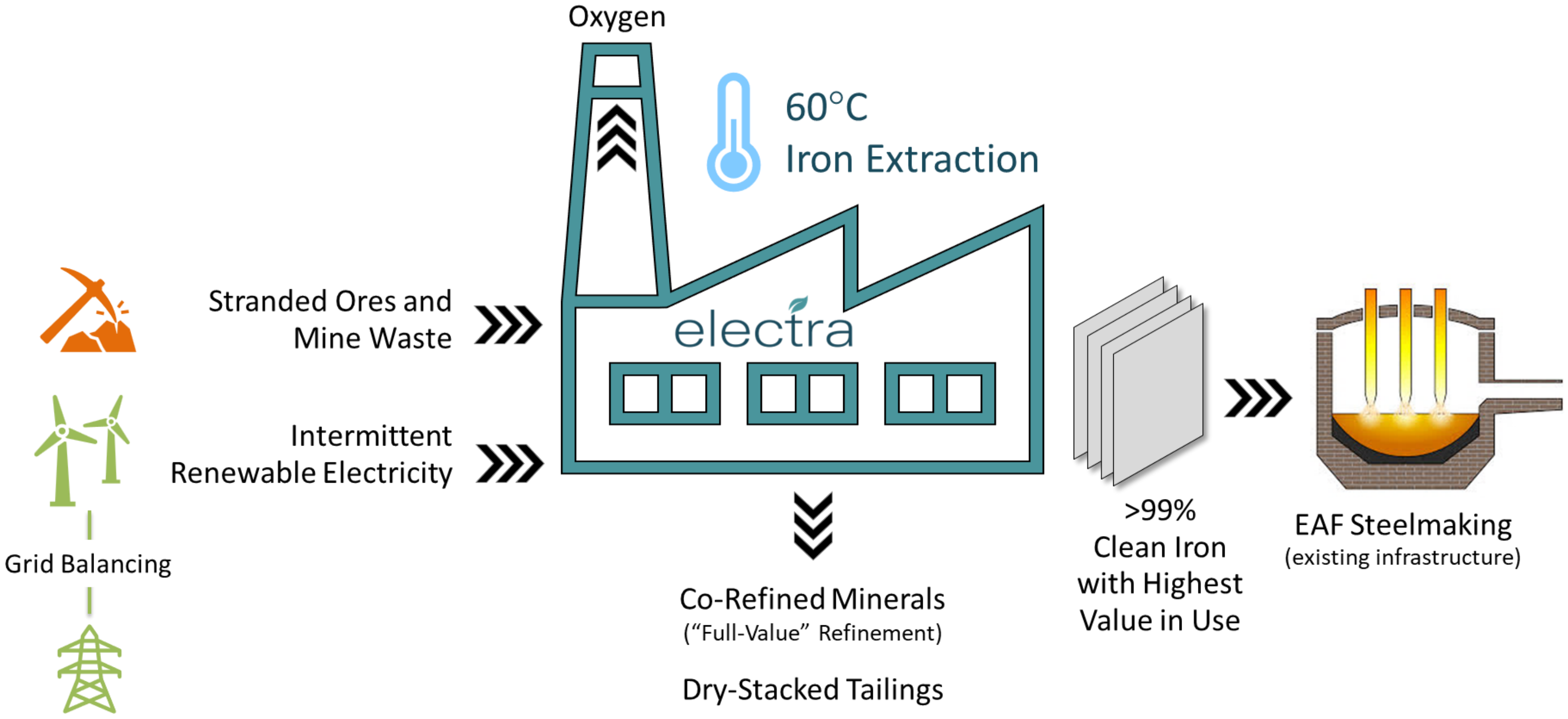
Founded: 2020, CO, USA

Total funding raised to date: ~$100M

Process description

- **Iron ore is dissolved into an acid** to create a **stable iron-rich liquid** while removing ore impurities. An **electric current** is then applied to **extract iron** from this liquid, **releasing oxygen** but **no CO_2**
- **Electrowinning at 60°C** (140F), enables **low-cost intermittent renewables** and energy **demand responsiveness,** lowering OpEx.
- **High-impurity,** otherwise **stranded ores** (> 1 billion tonnes available globally) lower OpEx and CapEx in the ore-to-metal value chain, producing **co-product revenue**
- **Product is 99.9% pure iron metal, allowing for premium steelmaking** with contaminated scrap **in EAFs at lower costs**

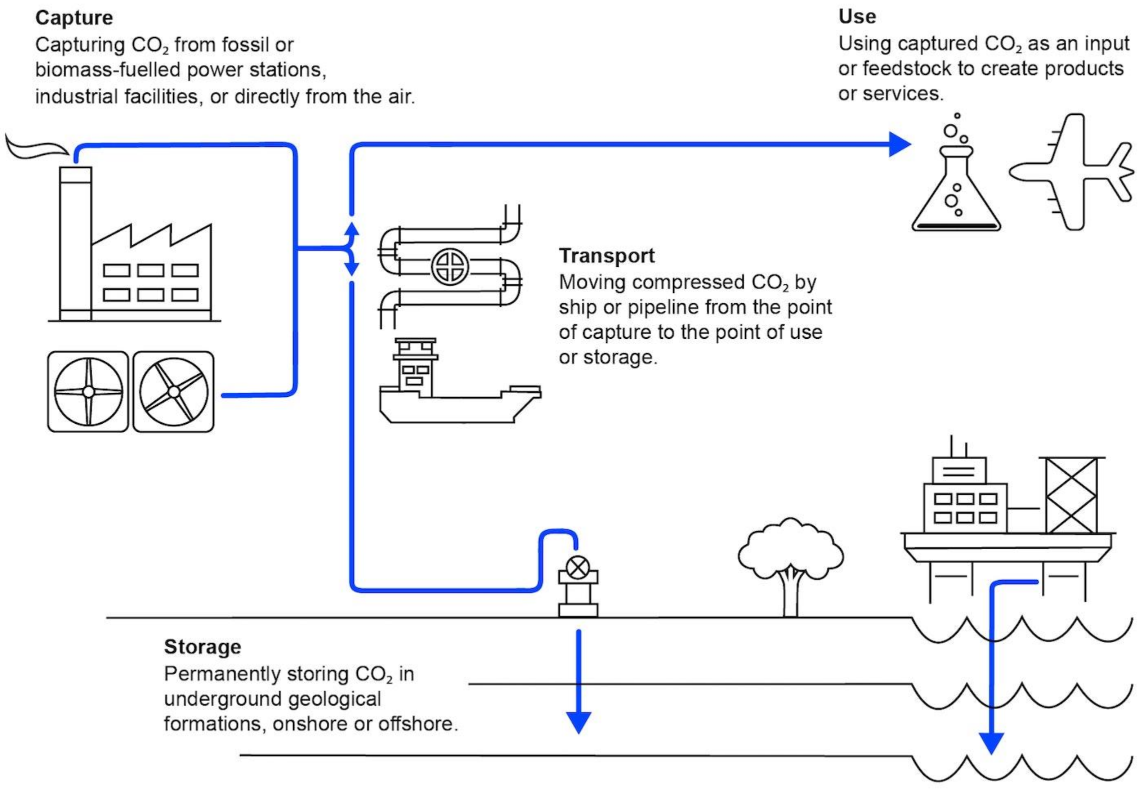
Electrowinning produces pure iron at low temperatures ready for EAFs



Source: Electra

3 Carbon capture and storage technologies available, but CCUS remains unproven for use on blast furnaces

Captured carbon either stored or used as feedstock



Source: IEA

Carbon capture

- In theory, point capture technologies can be **retrofitted** onto **BF-BOF and DRI-EAF**
- CO_2 is primarily captured from the **shafts of both Blast Furnaces and Direct Reduced Iron reactors,** and at the **end of the crude steelmaking process**
- **Capture rates up to 90%**, but **efficacy varies**, with **some systems as low as 50%**

Carbon utilization and storage

- CO_2 is commonly **stored in rock formations deep underground** to ensure long-term sequestration
- While the majority of captured CO_2 is **currently used for enhanced oil recovery**, other **emerging applications** include **feedstock** for synthetic fuels, chemicals, and building materials

CCUS Drawbacks

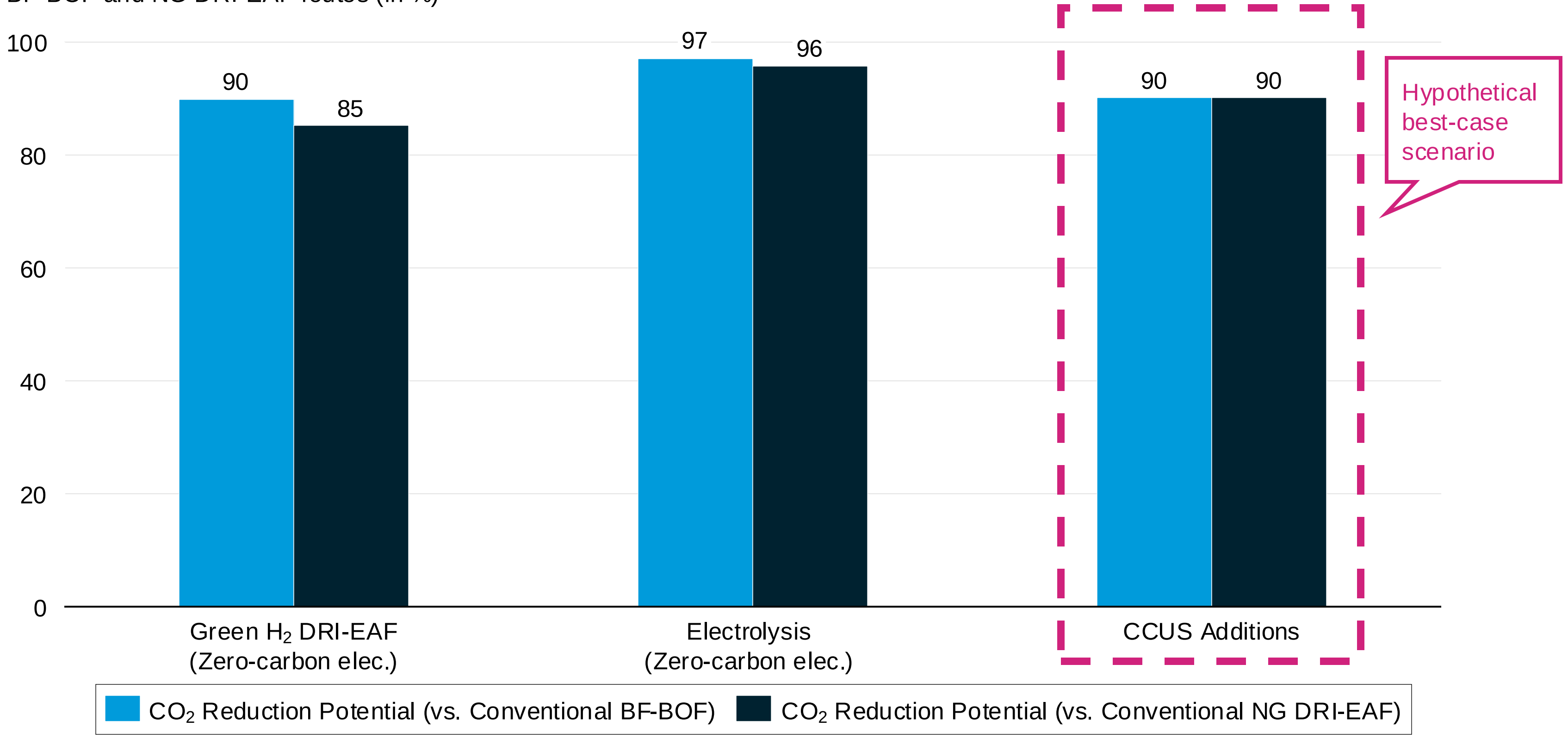
- Despite CCUS innovation, **viability of CCUS for blast furnace is hotly contested** due to **absence of a single, harnessable carbon egress point** on a blast furnace and the scarcity of pure carbon
  - Despite a few small pilot projects, **no full-scale CCUS facilities for blast-furnace steelmaking are operational anywhere**

Sources: IEA *Energy Technology Perspectives* (2020), IEA *Transforming Industry through CCUS* (2017), IEA *Iron and Steel Technology Roadmap* (2020), Global CCS Institute (2017), MIT (2021), International Journal of Greenhouse Gas Control *Volume 61* (2017), IEA *Greenhouse Gas R&D Program* (2017), Primetals Technologies, Edie – ArcelorMittal accused of net-zero greenwashing. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hassan Riaz, Hyae Ryung Kim & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Green H_2, electrolysis, and CCUS could reduce steelmaking CO_2 emissions by over 85% if implemented at scale

All discussed technologies have a CO_2 reduction potential of >85%

Crude steelmaking CO_2 emissions reduction potential of deep decarbonization technologies relative to conventional BF-BOF and NG DRI-EAF routes (in %)



Observations

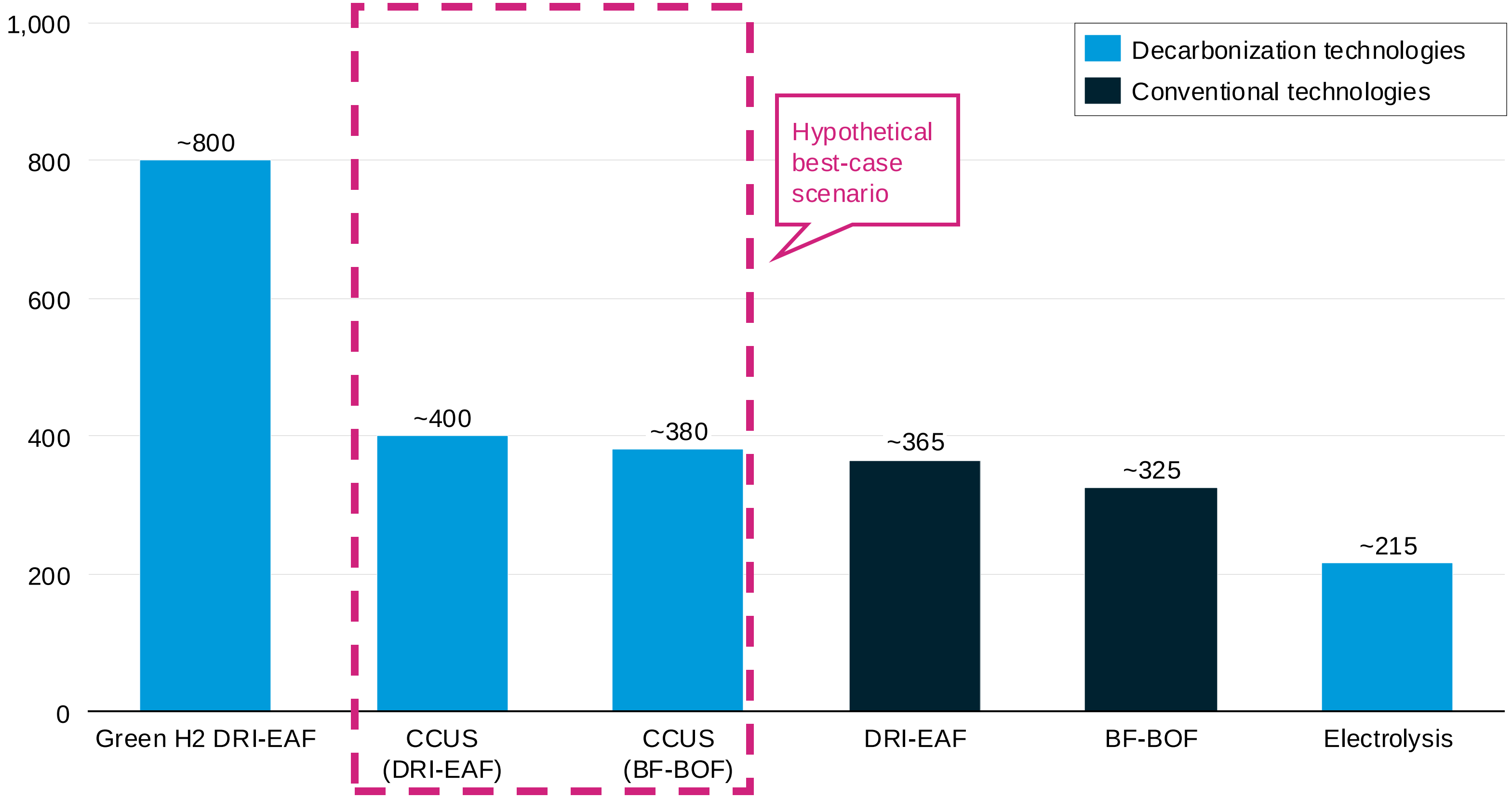
- A key enabler for green steel production is an **abundance of green electricity,** which is required for both **powering electrolysis** and the **production of green hydrogen**
  - Assuming the current global electricity mix does not change, H_2 DRI-EAF would have a **decarbonization potential of only 60%** instead of >85% when 100% green electricity is used
- The 90% CO_2 reduction for CCUS is a **hypothetical best-case scenario,** which at present **has not been proven at scale**

Sources: Columbia Center on Global Energy Policy (2021); American Institute of Chemical Engineers (2023); Electra; Boston Metal; Midrex (2021); International Journal of Greenhouse Gas Control Volume 61 (2017); Mission Possible Partnership Net Zero Steel Sector Transition Strategy (2021). Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Steel decarbonization technologies, however, often come with a green premium and require large amounts of green energy

Green technologies often come at a green premium

Average steel production cost estimates per technology (excluding CapEx) at current price levels (USD per tonne)



Observations

Green H_2 DRI-EAF

- **Green H_2 prices** are expected **to fall >50%,** to **$2.20-$2.90 per kg by 2030**, making H_2 DRI-EAF adoption much more attractive
- Switching from **BF-BOF to green H_2 DRI-EAF** is **costly** without government support. **CapEx** required for a new plant **ranges from $1.1 billion to $1.7 billion** and operating expenses are higher

Electrolysis/Electrowinning

- **Claimed cost savings** compared to conventional steel production methods are still uncertain due to the **nascency of technology**
- At present, there is **not enough green electricity available** on grids to support large-scale electrolysis-based steelmaking

CCUS

- **According to the IEA**, CCUS retrofits are at present the **most advanced and cost-effective low-carbon solutions** for the steel industry
- Adding CCUS technology to existing plants is expected to require **only minor modifications**

Note: Electrolysis costs are assumed to see a 15% reduction relative to BF-BOF. Carbon capture costs as $25/tonne-$CO_2$ with a ~90% capture rate. Green H_2 price at $6.40/kg.
Sources: Columbia Center on Global Energy Policy (2021); Boston Metal; MIT (2018); Journal of Cleaner Production Volume 389 (2023); IEA, Is carbon capture too expensive? (2021); McKinsey (2020); Nature Energy (2022); IEA, Iron and Steel Technology Roadmap (2020). Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (13 March 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Other transitional decarbonization technologies take less time and effort to implement but have lower decarbonization potential

	MODIFICATIONS TO BF-BOF / DRI-EAF PROCESSES			NEW PRODUCTION PROCESS
	Biomass as input	**Switch to zero-carbon electricity**	**Partial green hydrogen injections**	**Smelting Reduction BOF (SR-BOF)**
Process description	**Biomass** used as **substitute for coal** in BF-BOF **Biosyngas** used as **substitute for natural gas** in DRI shaft	Switch from **fossil-fueled electricity** to **100% green electricity** **>60% electricity generation** is **fossil fuel-based** today	**Injection of hydrogen** (~5-10%) to **reduce coal** use in BF **Injection of hydrogen** (~30%) to **reduce natural gas use** in DRI shaft	Production process that **eliminates need for coke making** and **iron ore sintering** Emits **less CO_2 than regular BF-BOF**
Decarbonization potential (vs. BF-BOF)	**~40%**	**~5 – 40%**	**~20%**	**~20%**
Estimated production costs / tonne (excl. CAPEX)	**~$455 – 700**	**~$345 – 435**	**~$375 – 495**	**~$310**
Limits to decarbonization	**Insufficient sustainable biomass** is likely available to enable a global transition to this production method	**Direct process emissions** from BF-BOF and DRI-EAF are **not addressed**	There is a **limit to how much H_2** can be injected **without replacing production equipment**	**Coal**, a primary input, **emits CO_2**, but smelting reduction-BOF provides a concentrated **CO_2 stream, ideal for capture**

Source: IEA *Iron and Steel Technology Roadmap* (2020), World Steel Association (2021), Energy Institute *Statistical Review of World Energy* (2023), Columbia Center on Global Energy Policy (2021) Journal of Cleaner Production *Volume 393* (2023). Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution.

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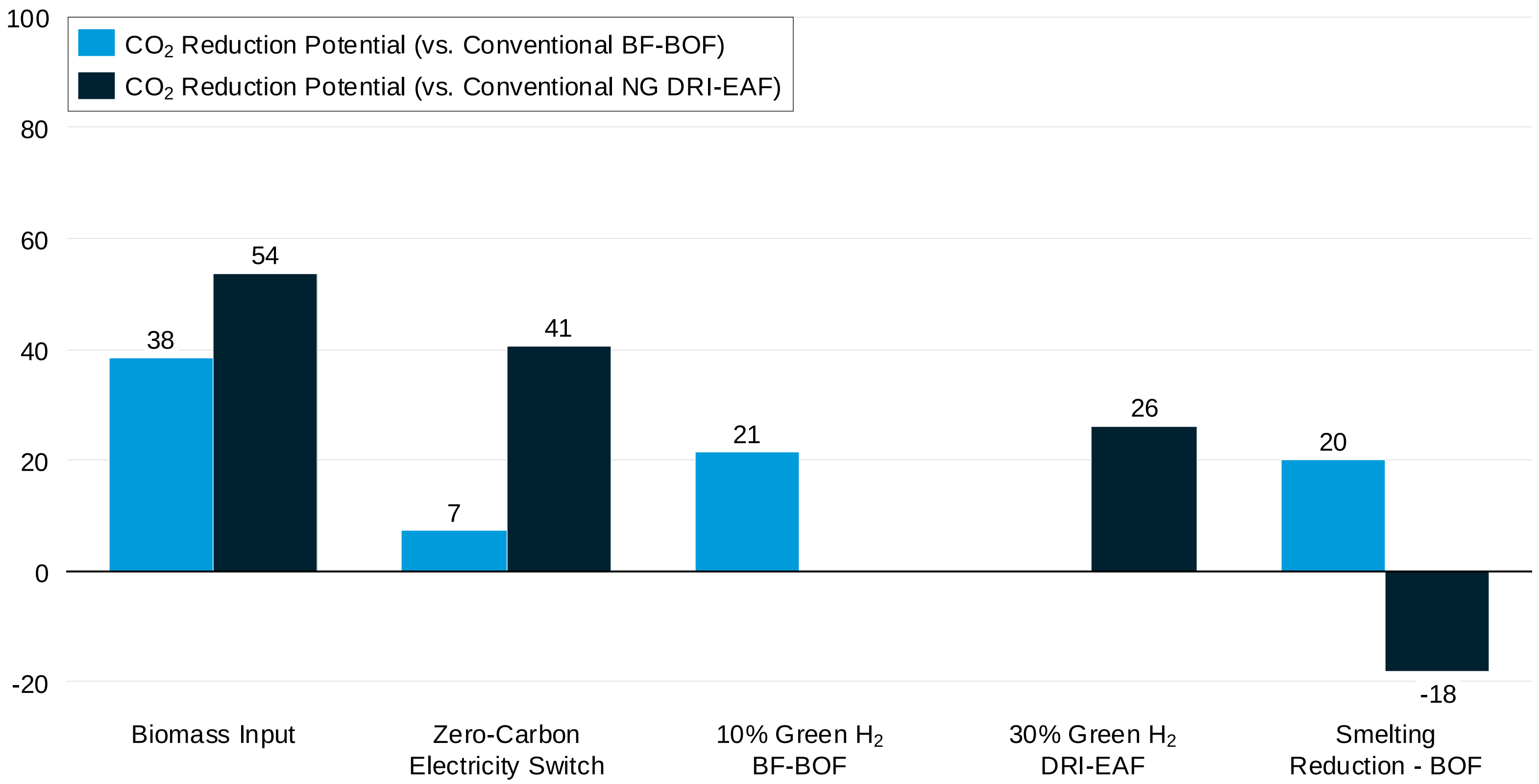
Transitional decarbonization technologies only achieve CO_2 reductions of up to 50%

Transitional technologies have limited decarbonization potential

CO_2 emissions reduction potential relative to conventional BF-BOF and NG DRI-EAF routes (in %)



Observations

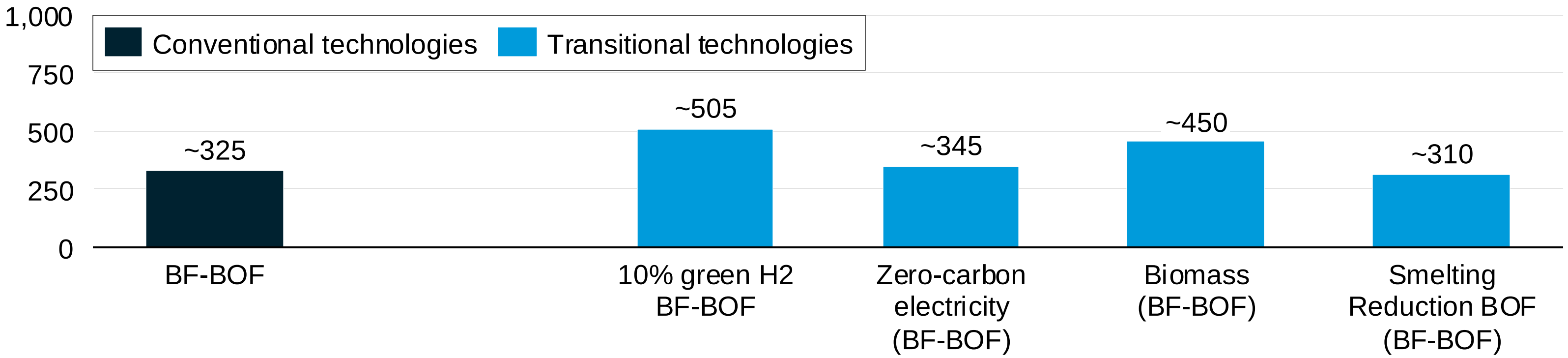
- Switching to **biomass input** assumes the use of **sustainably-sourced biomass**. Using biomass with **large carbon footprint** will **offset achieved reductions**
- **Switching to zero-carbon electricity sources** is necessary to **power deep decarbonization technologies** such as electrolysis, but **switching to zero-carbon electricity alone** will only have **limited effect**
- Replacing a **BF-BOF setup** with a **smelting reduction-BOF route** requires **high CAPEX** and **still emits more CO_2** than DRI-EAF
  - However, **CO_2 stream** from smelting reduction-BOF is **typically highly concentrated**, making it ideal for **carbon capture**

Note: methane leakage not accounted for in gas substitution methods. Source: Columbia Center on Global Energy Policy (2021), MIDREX (2020), Tata Steel Europe (2020).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

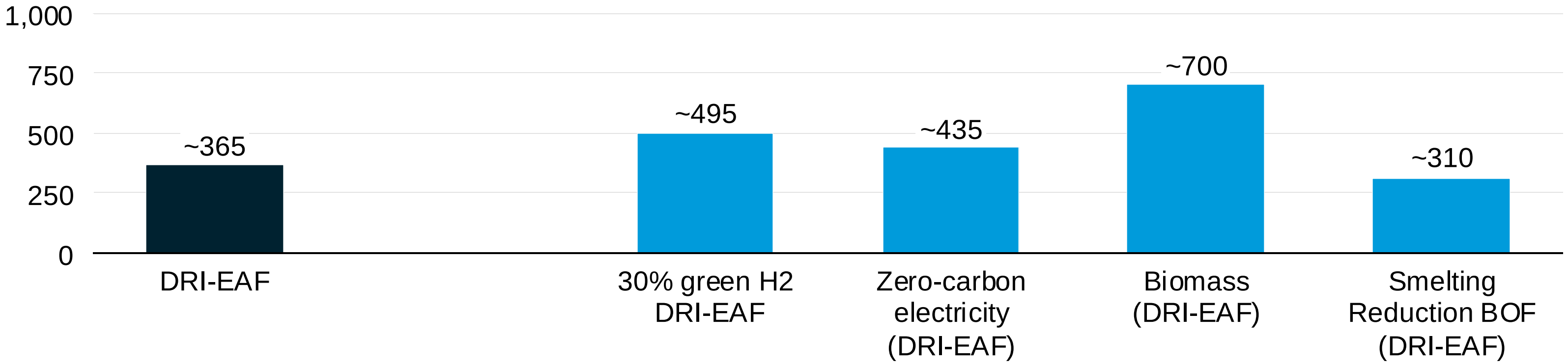
Transitional technologies also come with green premiums, possibly locking in uneconomical pathways

Most transitional technologies also have considerable green premiums

Avg. steel production cost estimates (excl. CAPEX) for transitional technologies applied to BF-BOF (in USD / tonne)



Avg. steel production cost estimates (excl. CAPEX) for transitional technologies applied to DRI-EAF (in USD / tonne)

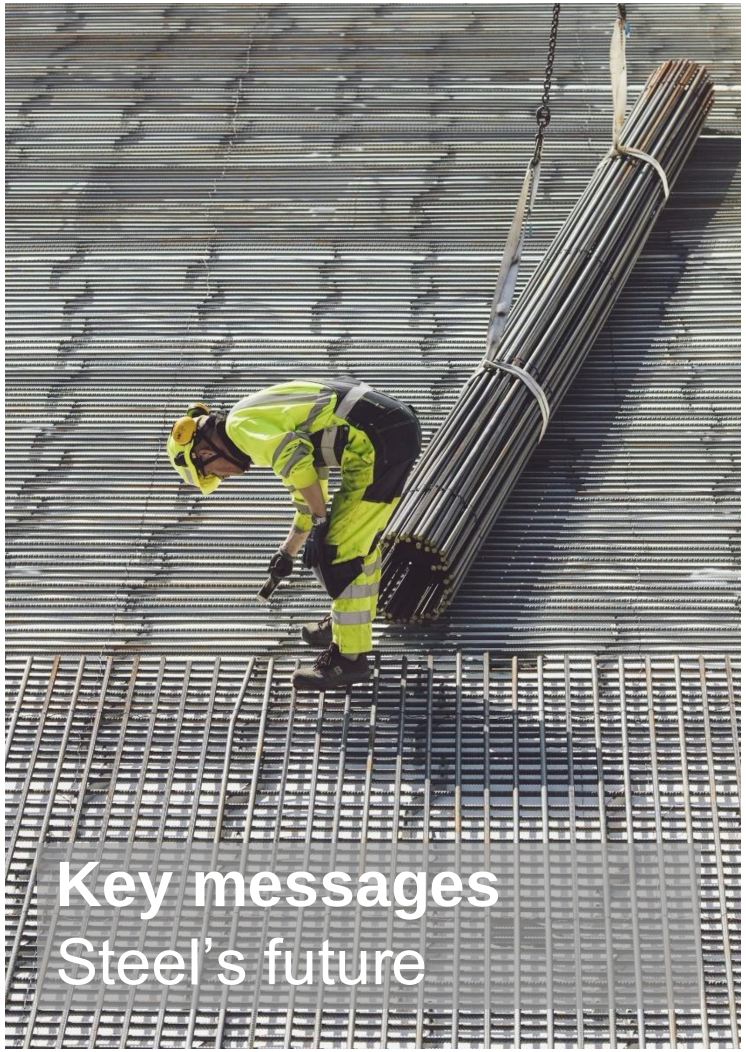


Observations

- **DRI-EAF** sees a **higher jump in costs** when **switching to zero-carbon electricity** than BF-BOF because the **Electric Arc Furnace (EAF)** runs only on **electricity**
- To use **biomass** in the **DRI-EAF process** biomass has to be **gasified** to turn it into **biosyngas**, which **leads to higher estimated costs**
- A number of these transitional technologies result in **higher production costs per tonne of steel** than when **CCUS is installed on BF-BOF or DRI-EAF**
  - It is however important to again note that **CCUS for blast furnaces** has **not yet been proven to work at scale**
  - Furthermore, **these numbers do not include CAPEX**, which is likely to be **considerable** for a CCUS installation

Note: assumes hydrogen price of $6.64 per kg. Source: Columbia Center on Global Energy Policy (2021), MIDREX (2020), IEA *Iron and Steel Technology Roadmap* (2020).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Adoption trends & obstacles



Key messages
Steel's future

Reaching **net zero by 2050** would require a **~25% emissions reduction by 2030.**

Policymakers can and should step in to assist with **green technologies**, such as Stegra's, formerly H2 Green Steel's, and Electra's new generation plants.

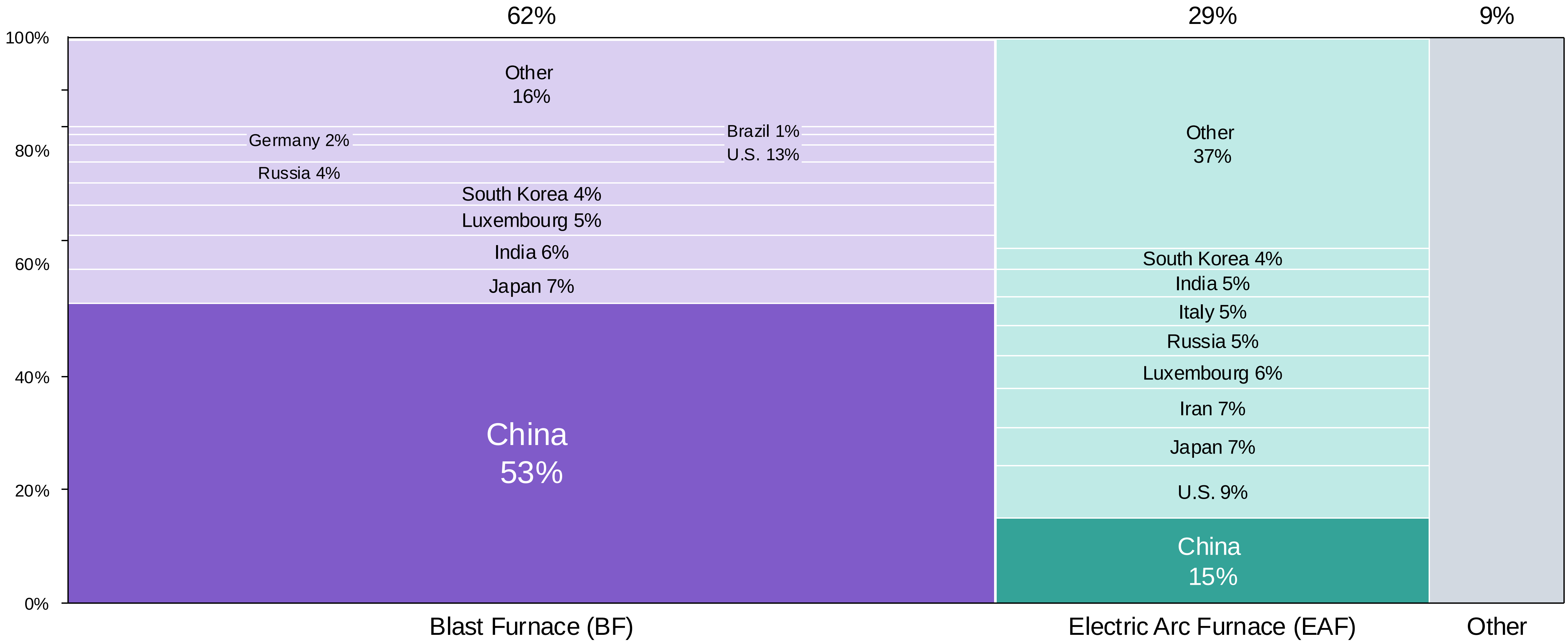
The focus should be on creating **low-cost, low-carbon electricity** and on **driving down capital costs** for new technologies.

A **production tax credit** for **low-emission iron** would support electrolysis as well as green H_2.

Time is of the essence, as **Asia's large fleet of high-carbon legacy blast furnaces** (~75% of global iron production) **are due for costly relining in the next 10 years**. This presents an **opportunity** to instead invest in **newer, greener technologies**.

BF and EAF, bolstered by China, lead global steel capacity, while other technologies – including clean – constitute <10%

Global steel capacity in 2023: 2.27 billion tonnes



Source: Global Energy Monitor – Global Steel Plant Tracker
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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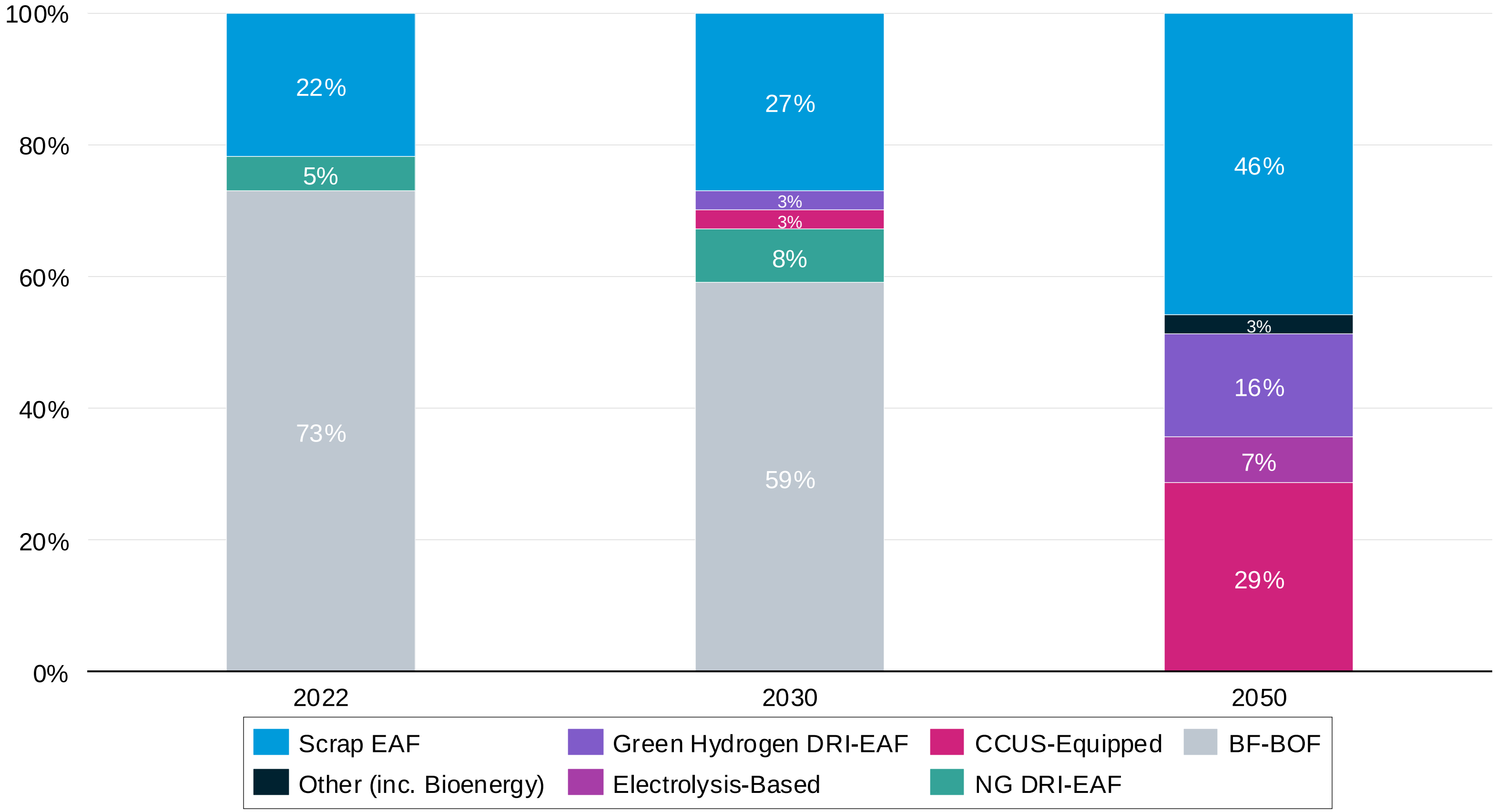
IEA expects technology transition to take off after 2030, and CCUS to play the biggest role in 2050 of all green steel technologies

IEA expects scrap steel recycling to play a significant role by 2050

Production of crude steel by technology in IEA net zero scenario, 2022-2050 (in %)



Observations

- **The International Energy Agency (IEA)** expects **limited decarbonization progress until 2030**, with only a slight increase in scrap EAF production and first production using green hydrogen and electrolysis
- **Scrap steel electric arc furnace (EAF)** is expected to become the **most used production method** for steel **by 2050 – taking 46% market share**
- In the IEA's scenario, the remaining 54% is split between green hydrogen, electrolysis-based production, and CCUS-equipped production
  - It should be noted that **the effectiveness of carbon capture, utilization, and storage** on blast furnaces is still challenged and **debated within the steel industry**

Sources: IEA (2022); IEA, Net Zero by 2050 (2021); IEEFA (2022): Net Zero Steel (2021).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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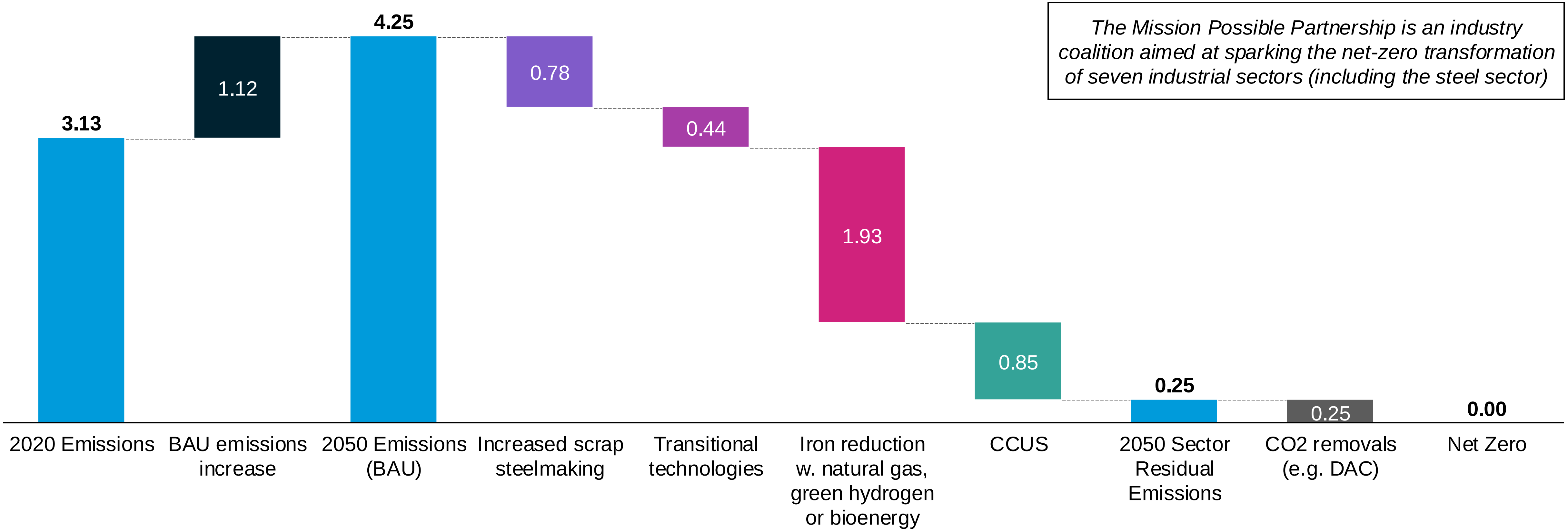
Mission Possible Partnership, on the other hand, expects green hydrogen and bioenergy to drive decarbonization

Iron and steel sector breakdown of Mission Possible Partnership (MPP) decarbonization route from 2020 to 2050

Annual iron and steel sector CO_2 emissions (Scope 1 & 2) reduction by decarbonization route (in Gt CO_2)

The Mission Possible Partnership is an industry coalition aimed at sparking the net-zero transformation of seven industrial sectors (including the steel sector)



Notes: BAU = Business as usual, assuming production route mix as of 2020 maintained; Increased scrap steelmaking refers to increase in both Scrap EAF production and use of scrap in primary production routes; DAC = direct air carbon capture. Sources: Mission Possible Partnership *Making Net Zero Steel Possible* (2022).

Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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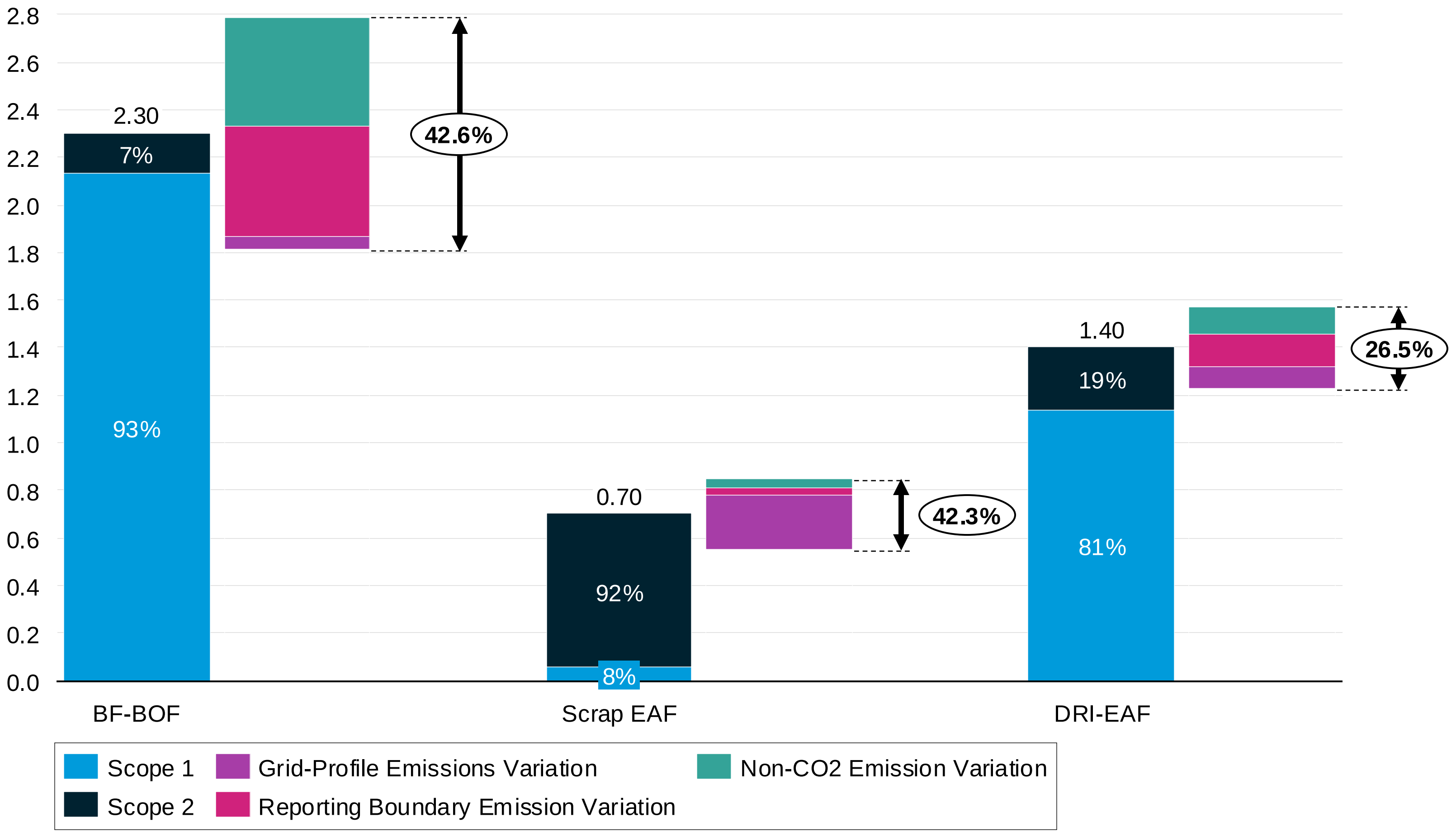
Uniform carbon accounting standards key to guide transition

Variations in Carbon Intensity of different production modes (tonnes of CO_2 per tonne of steel)



Observations:

- **BF-BOF** is a process with **higher Scope 1 emissions**. Thus, it is more sensitive to the **Reporting Boundary** and **Non-CO_2** related emissions
- **Scrap EAF** and **DRI-EAF** are less sensitive to **Carbon Accounting** related emissions variation and instead more sensitive to the **Grid-Profile** due to **higher Scope 2 Emissions**

Recommendations

- Uniform reporting standards based **on fixed boundaries from cradle to gate** relying on primary data whenever possible
  - This is especially important in inclusion of **upstream emissions** from **extraction and mining of ores/feedstocks** in **BF-BOF** processes
- **Accounting for temporal differences in electricity consumption** in differing jurisdictions for calculating scope 2 emissions
- Strongly consider emissions reporting standards **(eg: EU ETS)** which consider other important GHG emissions **(CH_4, N_2O, HFC/PFC/SF_6)**

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, CCSI Do We Really Need Coal to Make Steel, Conflicts Between GHG Accounting Methodologies in the Steel Industry (2022)

Credit: Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner (23 May 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Besides green premiums, there are other barriers preventing the adoption of green steel technologies (1/2)

Stranded asset risk

- Existing conventional plant equipment worldwide has an **average age of only 13-14 years** (<50% of the typical lifetime of 40 years)
- Overhaul of production routes for to transition to Net Zero could result in **$345-$518B of stranded assets**
- Stranded assets **expected to be concentrated in Asia**, particularly **China and India**

Infrastructure and equipment risk

- **Green infrastructure**, especially **zero-carbon electricity generation** and **hydrogen production capacity**, have **to expand significantly** to enable the steel industry to transition
- **Electrolysis technologies** are **nascent – production equipment** still needs to be **proven successful at mass scale**

Transport and storage cost of CO_2

- As it relates to global carbon storage, **demand** is **outpacing storage space development**
- Without increased efforts to accelerate CO_2 storage development, the **availability of CO_2 storage** could **become a bottleneck to CCUS deployment,** alongside aforementioned drawbacks, like unproven technology

Sources: IEA CO2 Transport and Storage, IEA *Iron and Steel Technology Roadmap* (2020), Financial Times (2022), McKinsey (2020), McKinsey *Transition to Net Zero: Steel* (2022), US DoE Oak Ridge National Laboratory; icons via Noun Project. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Besides green premiums, there are other barriers preventing the adoption of green steel technologies (2/2)

A consensus definition for green steel and iron

- **Pressing need for unified definition** of green steel and green iron, as **diverse approaches are currently being pursued**
- Having **shared definitions is crucial**, but of course, **no single definition can accommodate all perspectives**

Dwindling steel workforce

- **Insufficient educational and training** opportunities for the steel industry's workforce
- **Declining interest in younger generations** to pursue careers in this field
  - Those that are interested **typically gravitate toward green steel**, meaning employees in the grey steel space are dwindling

Limited governmental support

- Transitioning to new production technologies expected to cost **$4.4T over ~30 years**
- Production costs per tonne of steel **could rise by 30%** driven by **higher OPEX** and **required CAPEX** of green hydrogen and CCUS technologies
- At present, there is **limited governmental** support to **incentivize producers to adopt greener production routes**

Sources: IEA CO2 Transport and Storage, IEA *Iron and Steel Technology Roadmap* (2020), Financial Times (2022), McKinsey (2020), McKinsey *Transition to Net Zero: Steel* (2022), US DoE Oak Ridge National Laboratory; icons via Noun Project. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner (16 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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Appendix

Glossary

BAU	Business as usual
BF-BOF	Blast Furnace-Basic Oxygen Furnace
CAPEX	Capital expenditure(s)
CCUS	Carbon capture, utilization & storage
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent, using global warming potential as conversion factor
DAC	Direct Air Capture
DRI-EAF	Direct Reduced Iron-Electric Arc Furnace production process
EAF	Electric Arc Furnace
EBITDA	Earnings before interest, taxes, depreciation, and amortization
EW-EAF	Electrowinning-Electric Arc Furnace
Gt	Gigatonne, equal to 1 billion metric tonnes
H_2	Hydrogen
IEA	International Energy Agency
HRC	Hot Rolled Coil (type of finished steel product)
MPP	Mission Possible Partnership – industry decarbonization coalition
MOE	Molten oxide electrolysis
NG	Natural gas
NAFTA	North American Free-Trade Agreement
NG	Natural gas
NG DRI-EAF	DRI-EAF production process using natural gas
NZE	Net Zero Emissions
O_2	Oxygen
OECD	The Organization for Economic Cooperation and Development
OPEX	Operational expenditure(s)
SR-BOF	Smelting Reduction-Basic Oxygen Furnace
Tonne	Metric ton