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Decarbonizing Steel Overview

Mimi Khawsam-ang, Max de Boer, Grace Frascati & Gernot Wagner

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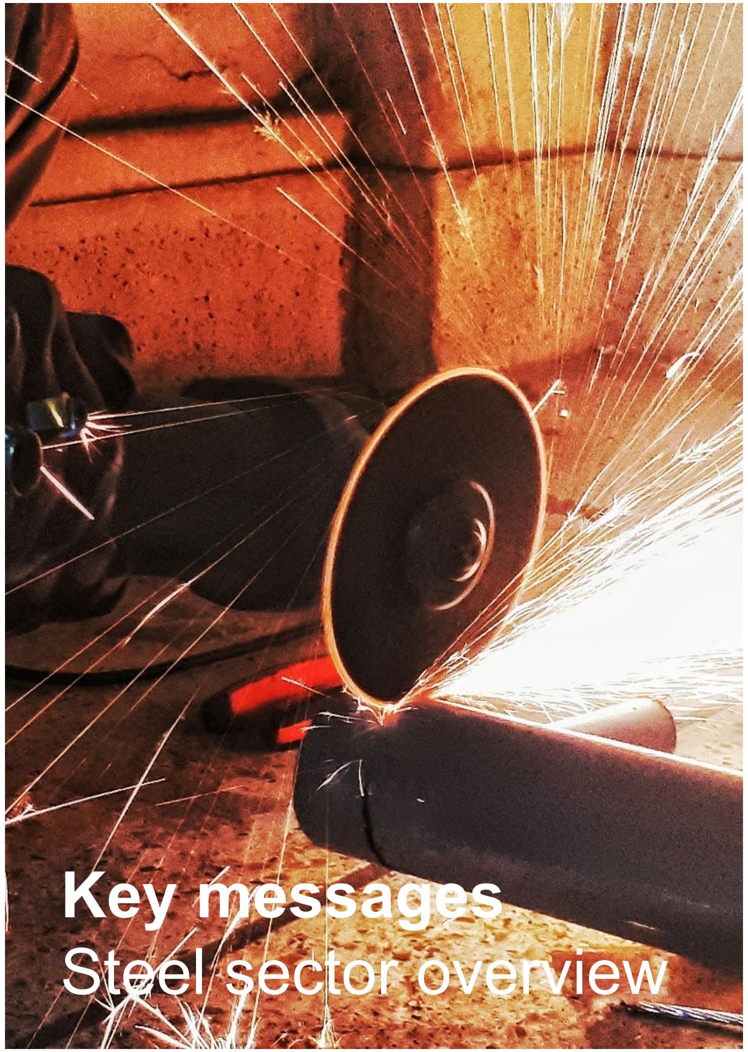
Steel sector overview: The problem



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

- **Global steel emissions** have **more than doubled since 2000** (from 1.2 gigatonnes in 2000 to 2.5 gigatonnes in 2021). However, **emissions** have **started to decouple** from production levels since 2016
- 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 **three main production routes, all of which emit CO_2**:

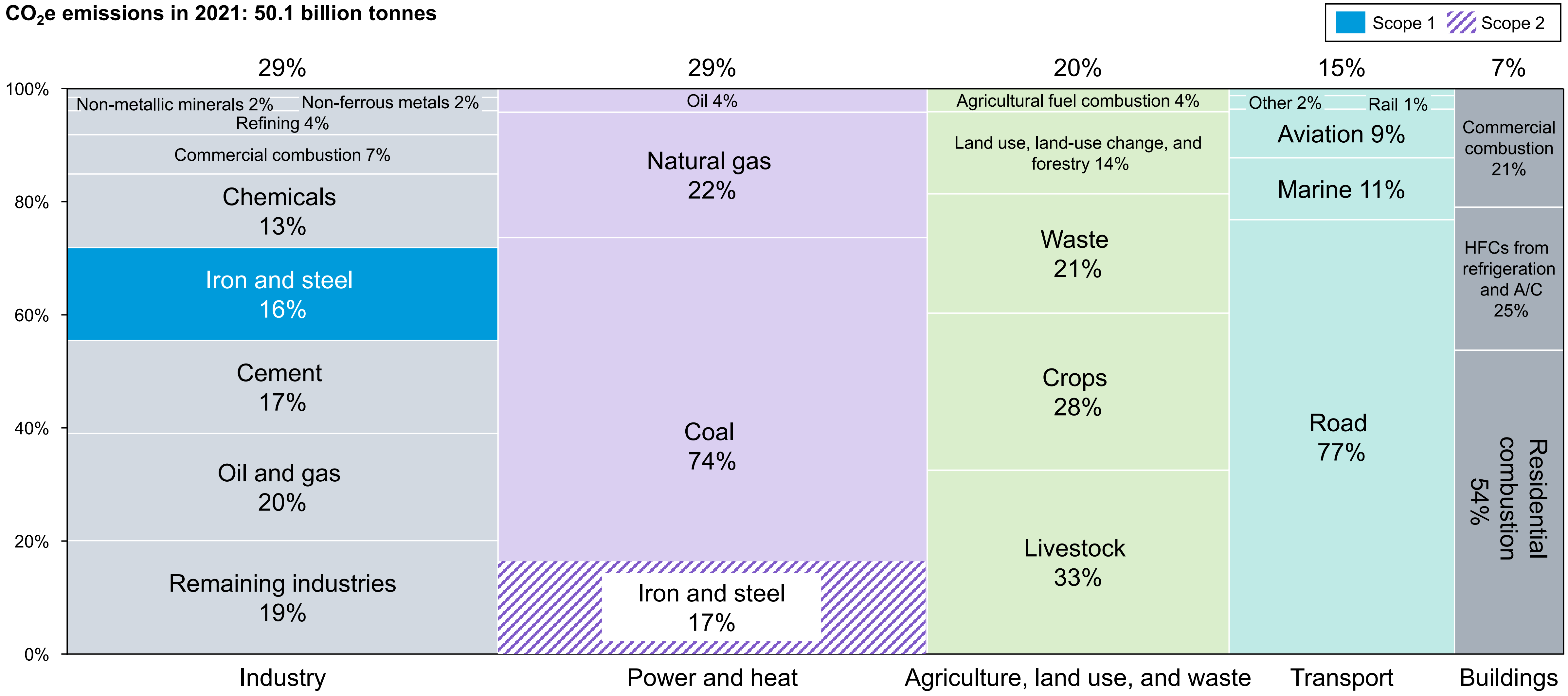
- **Blast furnace-basic oxygen furnace (BF-BOF):** 72% of global steel production. It uses coke and limestone to produce pure iron from iron ore in a blast furnace, which is then turned into steel in an oxygen furnace
- **Scrap electric arc furnace (scrap EAF):** 21% of global steel production. Scrap 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) 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 scope 1 and 2 emissions are ~10% of global emissions



Sources: Scope 1 emissions from Rhodium Group ClimateDeck (September 2023); Scope 2 iron and steel estimate from IEA (2023).
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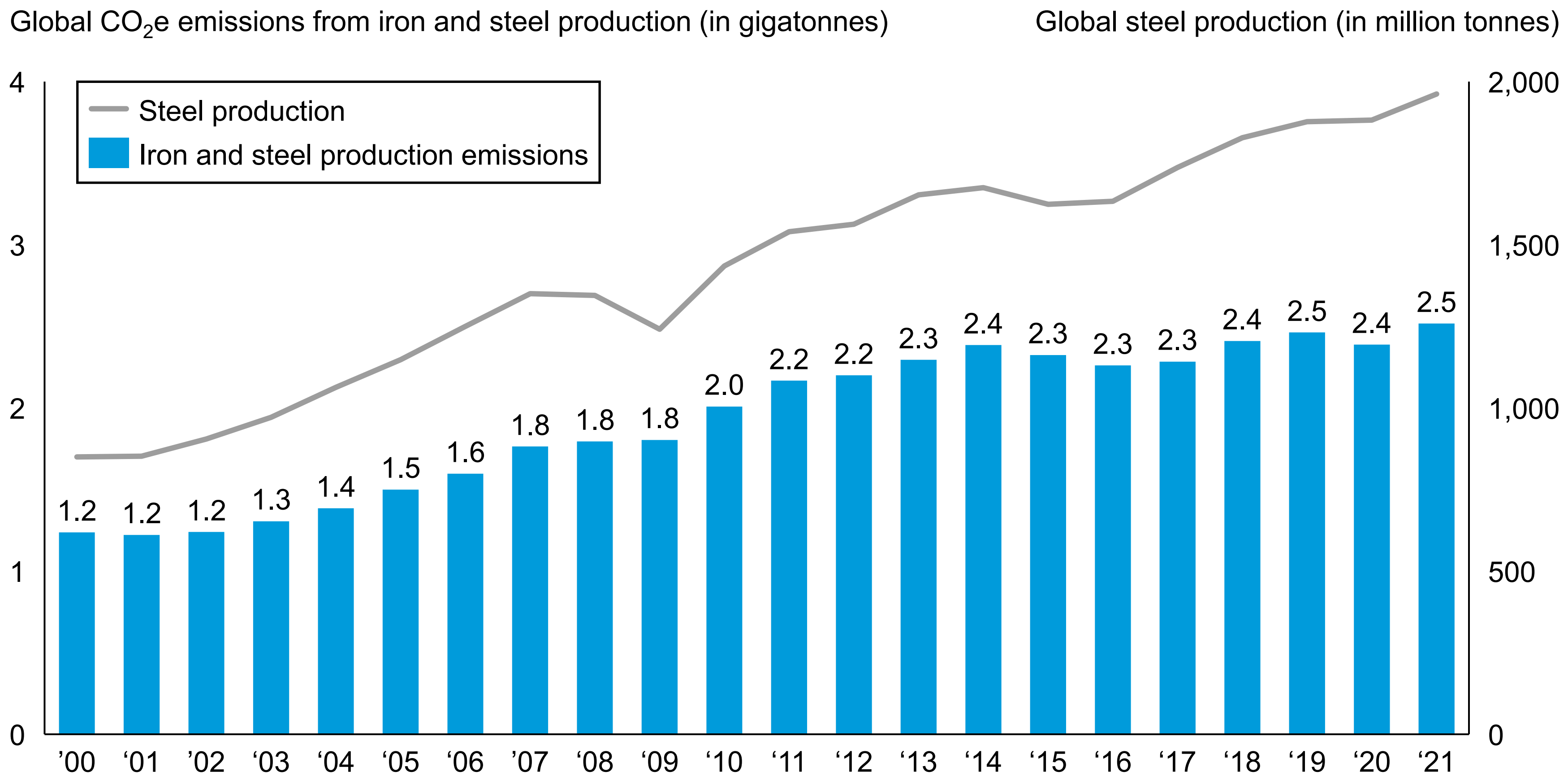
Global steel emissions have more than doubled since 2000, with emission growth decoupled from production growth after 2016

Global CO_2e emissions decoupled from steel production post-2016



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

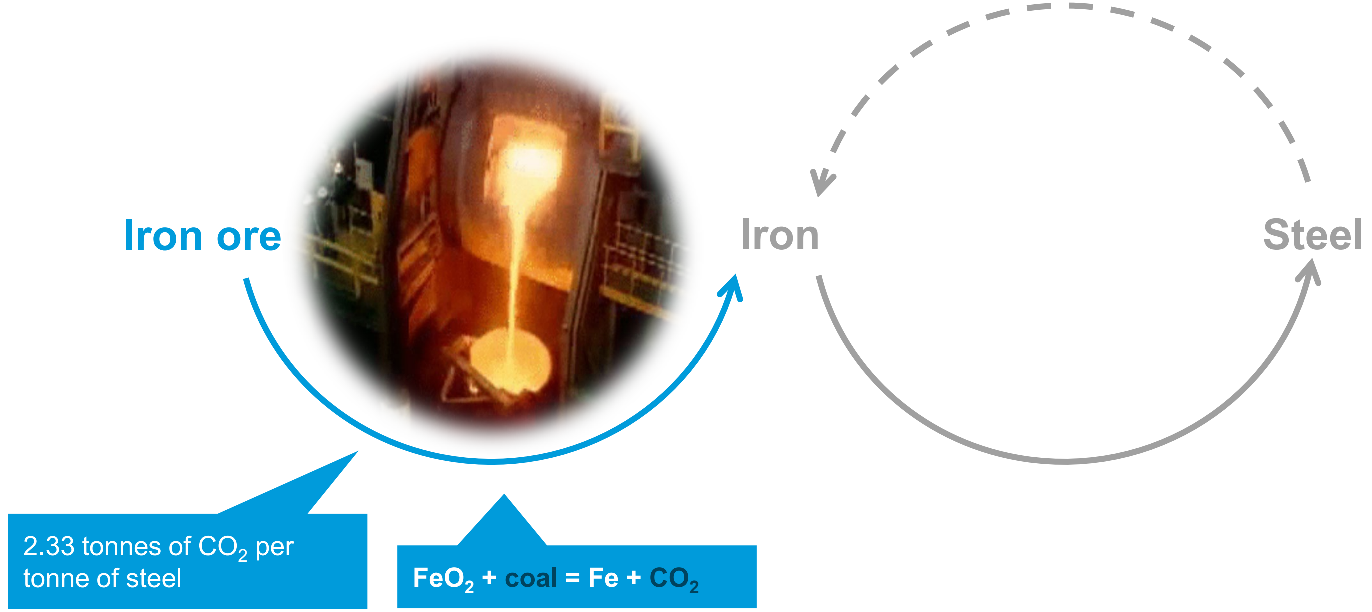
Note: The majority of the world's iron is used to make steel. Sources: Rhodium Group ClimateDeck (September 2023); World Steel Association; McKinsey, Decarbonization Challenge for Steel; IEA, CO_2 Emissions in 2022, Reuters, China 2021 Crude Steel Output. Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (22 February 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

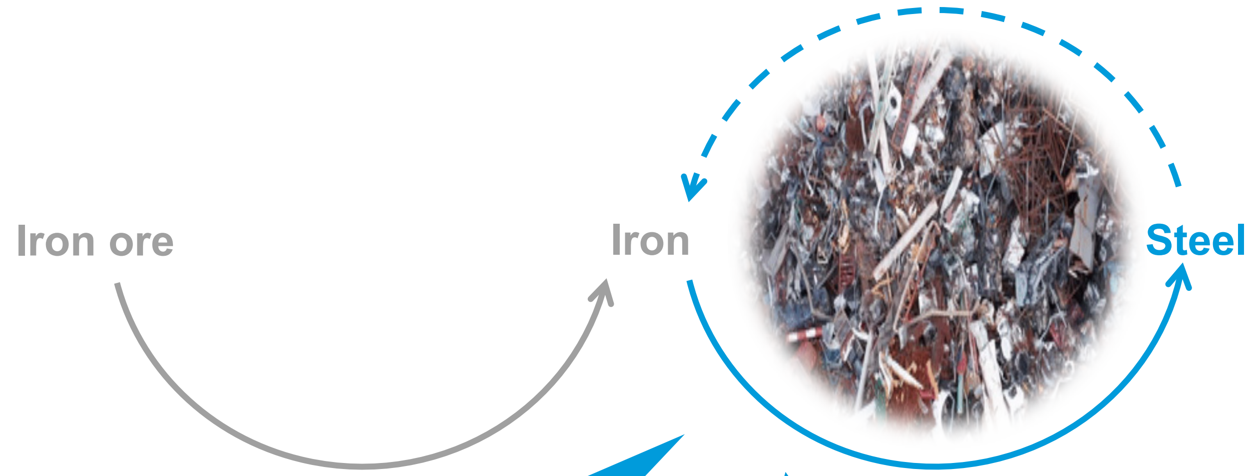


Observations

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

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



Produces 0.66 tonnes of CO_2 per tonne of crude steel, 72% less than BF-BOF

Takes collected scrap steel as input into an EAF

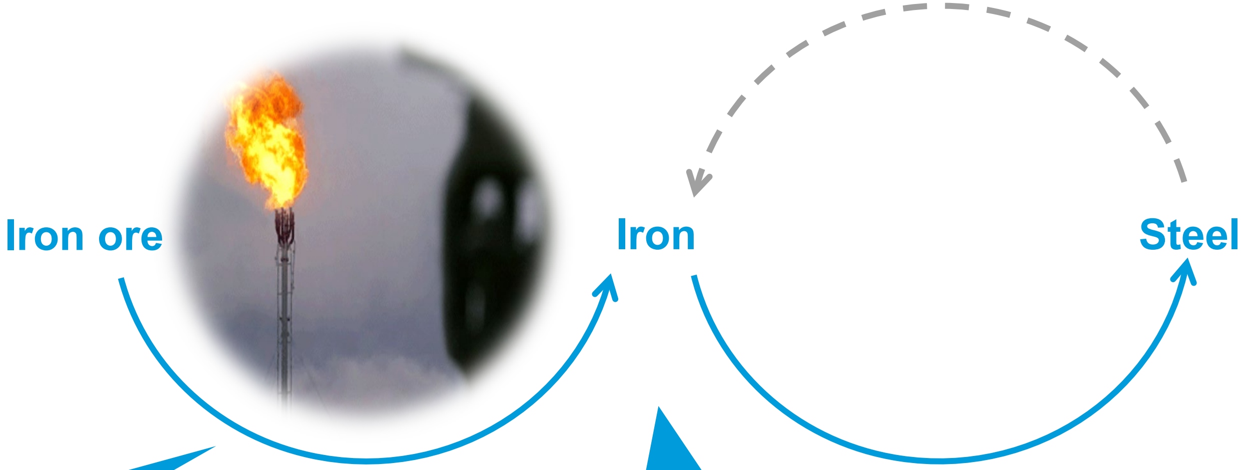
Observations

- **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 (22 February 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

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

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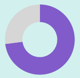
At present, crude steel is produced through three main methods that all emit CO_2: BF-BOF, scrap EAF, and NG DRI-EAF

	1 Blast Furnace-Basic Oxygen Furnace (BF-BOF)	2 Scrap Electric Arc Furnace (Scrap EAF)	3 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 ton 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 (22 February 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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Steel Decarbonization Technologies

Key messages
Steel decarbonization technologies

Several **emerging deep decarbonization steelmaking technologies** now exist:

- **Green hydrogen DRI-EAF:** hydrogen produced using zero-carbon electricity is used as iron ore reductant instead of natural gas. Second step still 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. The current causes the iron ore to split into oxygen and molten iron
  - **Electrowinning-EAF (EF-EAF):** iron from iron ore is dissolved in an acid, which leaves behind impurities. 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 and DRI-EAF can be retrofitted with point capture equipment. Captured carbon is then used or stored

These technologies produce steel with **over 90% less 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 to capture all carbon that's released**. **Electrolysis** may be **cheaper** than conventional processes, but **has not been tested at scale yet**

There are also some **emerging transitional steelmaking technologies** with **lower decarbonization potential**:

- **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)

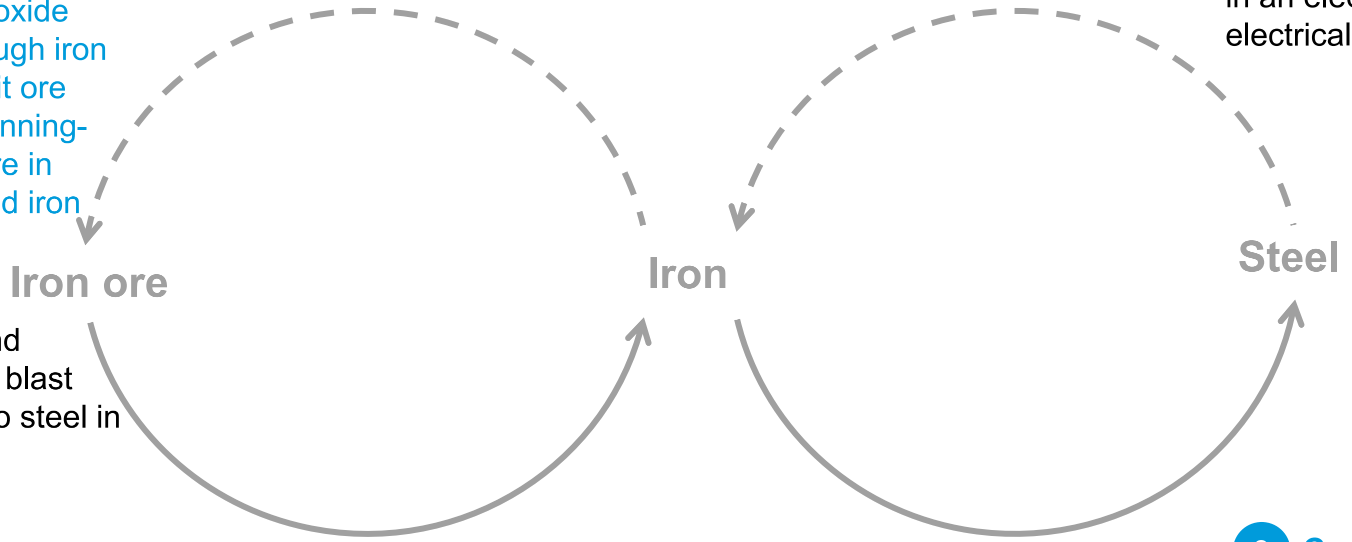
Decarbonization potential of transitional technologies ranges **between 10-50%**, while they still come with a **considerable green premium**

Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, and Gernot Wagner (22 February 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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 (22 February 2024); share/adapt with attribution.

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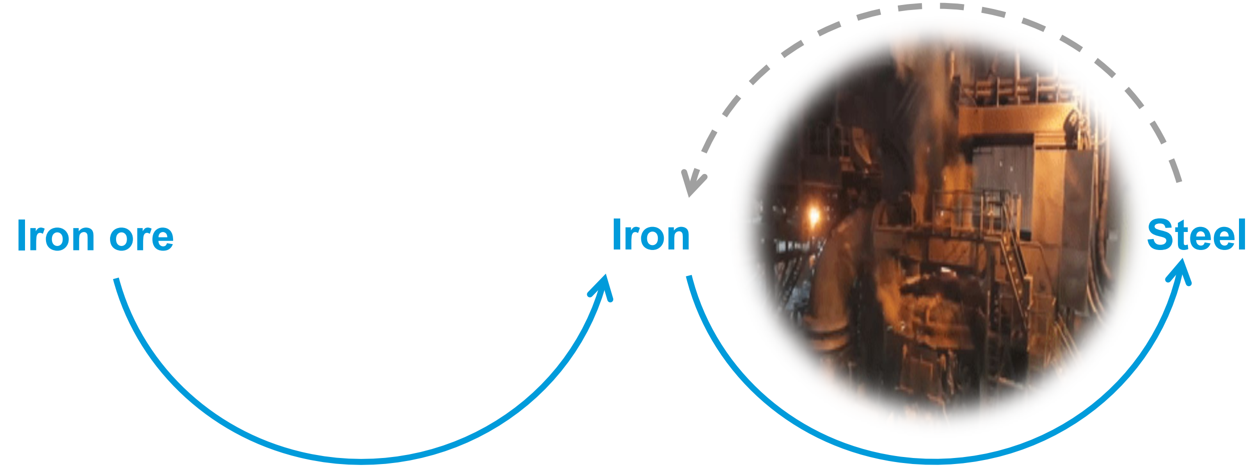
1 Green H_2 DRI-EAF is an emerging technology using green hydrogen instead of natural gas as an iron ore reductant with standard electric arc furnaces

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

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- **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

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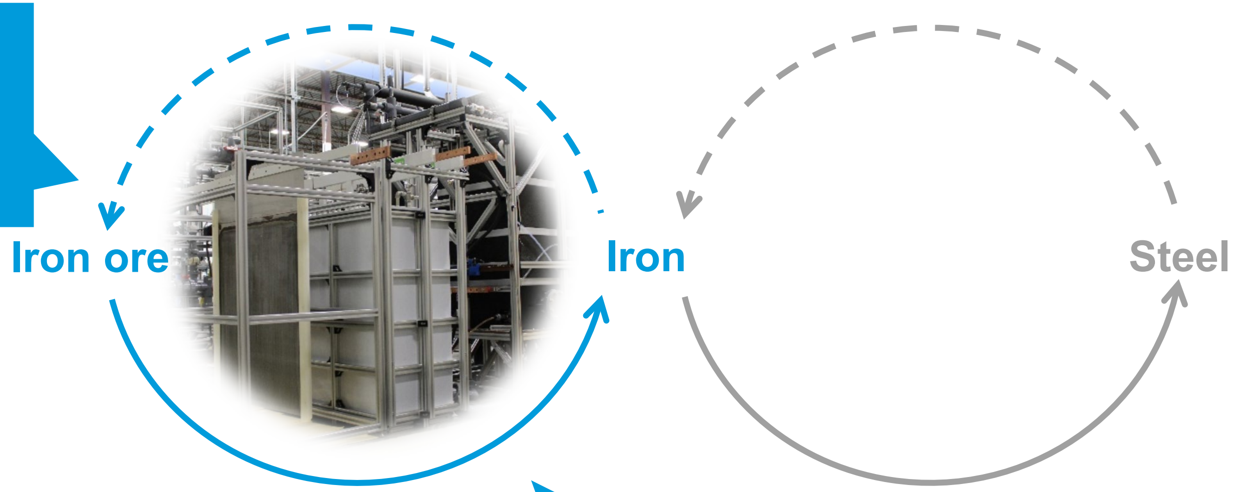
2 Iron ore electrolysis is an emerging technology that uses an electric current to drive a chemical reaction, producing molten iron or pure solid iron

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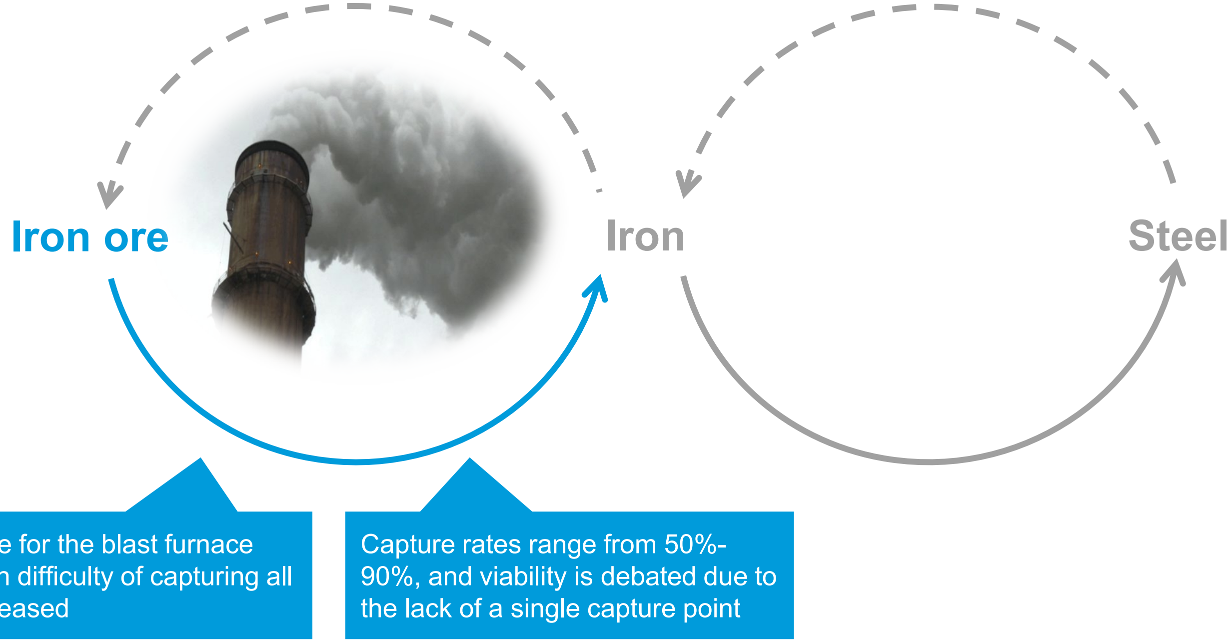
3 Carbon capture, utilization, and storage (CCUS) is an emerging technology that reduces steel's carbon footprint by capturing released CO_2

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



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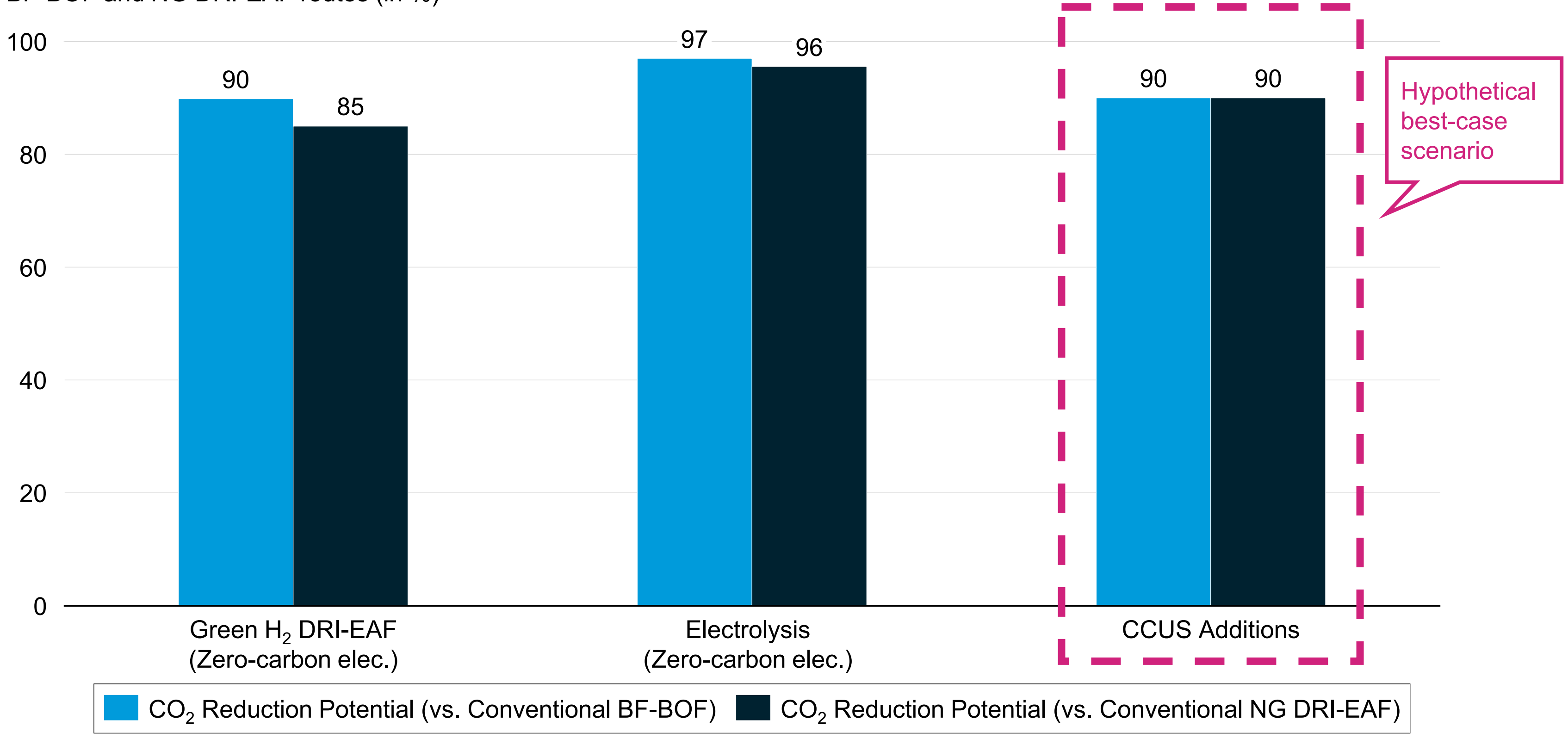
Green H_2, electrolysis, and CCUS could reduce steelmaking CO_2 emissions by over 85% if implemented at scale

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

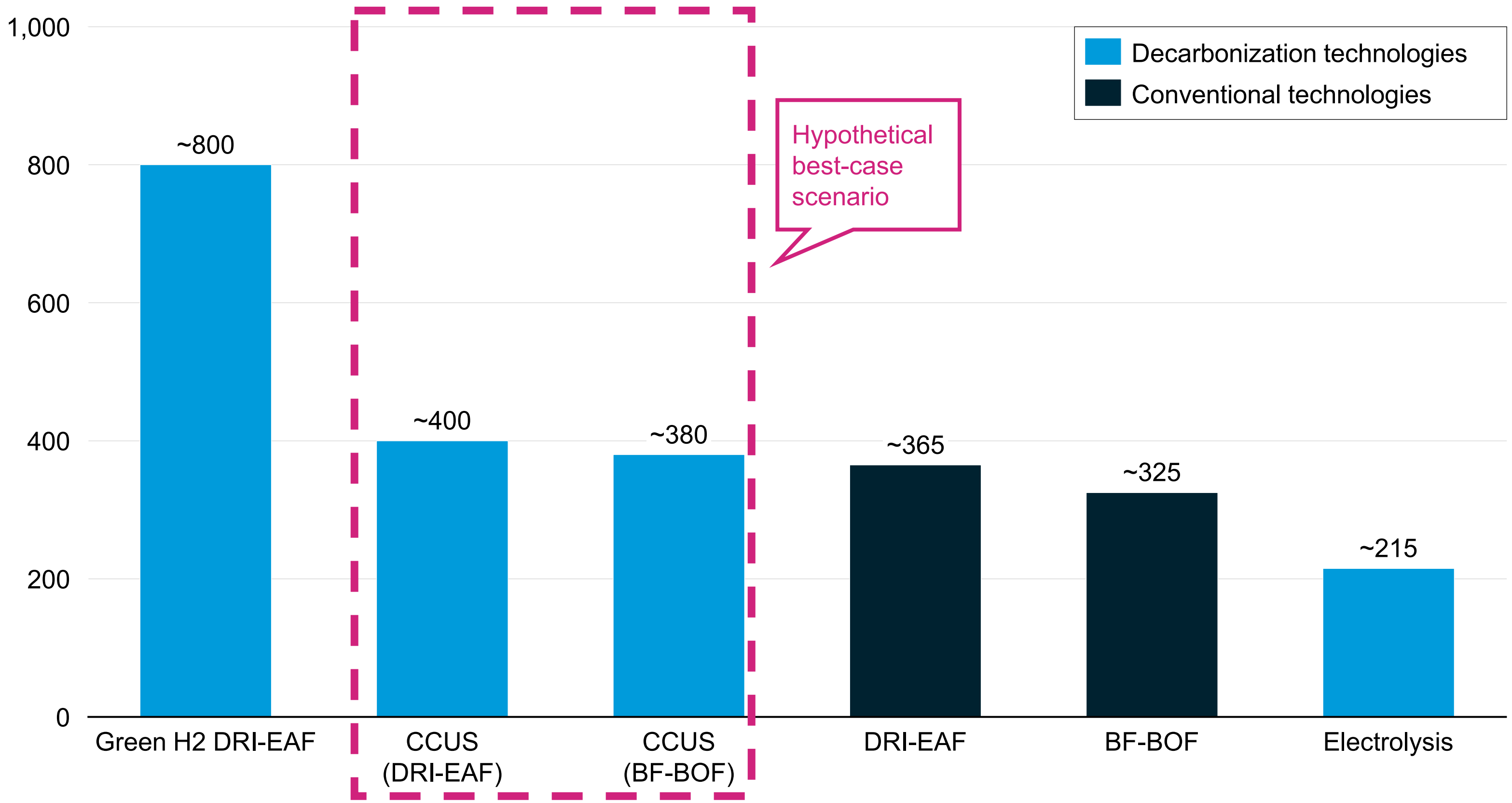
- A key enabler for green steel production is an **abundance of green electricity,** which is required for both **powering electrolysis** and the **production of green hydrogen**
  - Assuming the current global electricity mix does not change, H_2 DRI-EAF would have a **decarbonization potential of only 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 (22 February 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 (22 February 2024); share/adapt with attribution.
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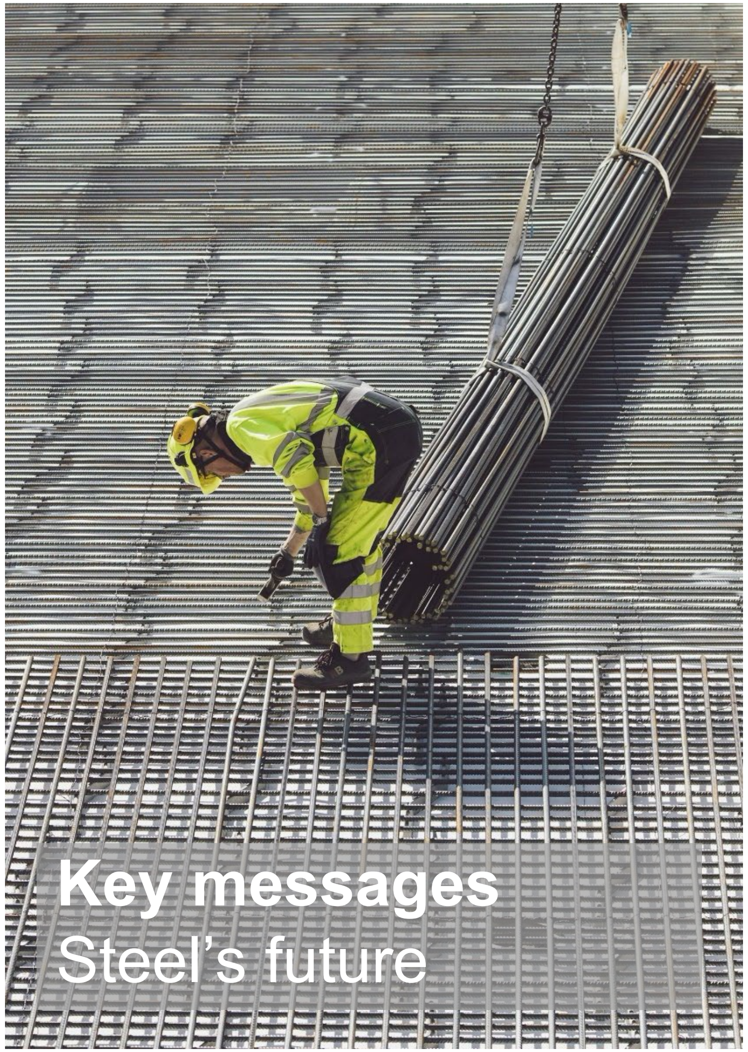
Adoption trends & obstacles



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 H2 Green Steel's and Electra's new generation plants

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

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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**

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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