Pedal to the Metal 2021

NO TIME TO DELAY DECARBONIZING THE GLOBAL STEEL SECTOR

Caitlin Swalec and Christine Shearer

Global Energy Monitor

ABOUT GLOBAL ENERGY MONITOR

Global Energy Monitor (GEM) develops and shares information on energy projects in support of the worldwide movement for clean energy. Current projects include the Global Steel Plant Tracker, Global Coal Mine Tracker, Global Coal Plant Tracker, Global Fossil Infrastructure Tracker, Europe Gas Tracker, CoalWire newsletter, Global Gas Plant Tracker, Global Registry of Fossil Fuels, Latin America Energy Portal, and GEM.wiki. For more information, visit www.globalenergymonitor.org.

ABOUT THE GLOBAL STEEL PLANT TRACKER

The Global Steel Plant Tracker (GSPT) provides information on global crude steel production plants, and includes every plant currently operating at a capacity of one million tonnes per year (mtpa) or more of crude steel. The GSPT is being expanded to include all plants meeting the one mtpa threshold that have been proposed since 2017 or retired or mothballed since 2020.

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ABOUT THE COVER

The cover photo shows the POSCO Gwangyang steel plant. Image by Overview, source imagery © Maxar, 2021.

EDITING AND PRODUCTION

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FURTHER RESOURCES

For additional data on proposed and existing steel plants, see Summary Data of the Global Steel Plant Tracker (GSPT). For links to reports based on GSPT data, see Reports & Briefings. To obtain primary data from the GSPT, use the Data Request Form.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The global iron and steel sector faces a reckoning with climate change. The industry is currently responsible for 11% of carbon dioxide emissions and 7% of greenhouse gas emissions globally, and demand for global steel is projected to increase by a third by 2050. To meet the Paris climate agreement, these emissions need to reach net zero by 2050 to 2070. Yet current operating capacity and projected growth in the industry show no clear signals that the global steel sector will significantly reduce emissions under present development plans.

This report introduces Global Energy Monitor's Global Steel Plant Tracker (GSPT), the first comprehensive survey of all steel plants on the globe with capacity of at least one million tonnes per annum (mtpa), and explains what the data reveal about how the iron and steel sector must adapt to meet current and mid-century global climate and energy targets.

Key Findings

- **Inefficient Plants:** Over 60% of global steelmaking capacity in the GSPT uses the blast furnace-basic oxygen furnace (BF-BOF) pathway, the most carbon-intensive conventional method of producing steel with limited, difficult, and high-cost decarbonization options.

- **Doubling Down On Old Technology:** Over 75% of steel capacity currently under construction in the GSPT will also be carbon-intensive BF-BOF which could lock in carbon emissions for the lifetime of each plant (40 or more years) without intervention in investment cycles.

- **China, Japan, and India Lead In Production:** Steel plants in China account for 51% (1,023 mtpa) of the steelmaking capacity in the GSPT, followed by Japan (117 mtpa) and India (90 mtpa).
- **Excess capacity:** Current global steelmaking capacity is about 25% higher than global steelmaking production, meaning many older and polluting steel plants can be closed without disrupting global supply. Countries with the most overcapacity as a percentage of total production in 2020 were EU27+UK with 26.6%, Japan 23.7%, US 20.0%, and China with between 13.5% and 20.0%.
- **Stranded asset risk:** If innovative low-emissions technologies reach commercial scale at the projected pace, the steel industry faces 47–70 billion USD in stranded asset risk for carbon-intensive steel plants currently under development.
- **Potential of carbon commitments:** More than three-quarters of global steel capacity now falls under net-zero and low-emissions carbon commitments from steelmaking companies and countries.
- **The Green Steel Opportunity:** Over the next one to two decades, new low-emissions steelmaking technologies are projected to reach commercial scale, if pilot and demonstration projects prove successful. At the same time, the majority of steel plants will face reinvestment cycles, creating difficult decisions about whether coal-based furnaces should be prolonged, retrofitted, or replaced with lower-emissions technology. These decisions must be carefully managed depending on how innovative technologies have advanced to avoid locking in emissions that exceed international climate goals.

THE GLOBAL STEEL PLANT TRACKER

Tracking iron and steel plant status, capacity, and production over the next decade will be vital to understanding the role that the sector is playing in climate change and global decarbonization efforts. In a new publicly available dataset, GEM has identified, mapped, and recorded plant level details including plant ownership, iron and steelmaking capacity, production process/technology, and geolocation for all crude steel plants with capacity of 1 mtpa or greater. GEM's dataset, which builds on historic global datasets and regionally specific datasets, provides a robust view of the current and developing global steel plant fleet, and the opportunity to examine the status of the iron and steel sector compared to global decarbonization roadmaps.

The majority of operating steelmaking capacity relies on conventional, coal-based steelmaking processes. In order to align with mid-century net-zero emissions goals, steelmaking capacity must transition to lower-emissions steelmaking technology.

However, recent announcements from key steel producers, major economies, and technology development projects present promising opportunities for the steel industry to shift onto the path to decarbonization—if immediate action is taken.

To align with pathways for mid-century global energy net-zero carbon emissions, three main targets need to be met in the global steel plant fleet:

1. Steelmaking capacity needs to be aggressively shifted from the dominant blast furnace-basic oxygen furnace (BF-BOF) steelmaking route to electric arc furnace (EAF) steelmaking;

2. All remaining BF-BOFs need to be outfitted with best available technology (BAT) or retired; and

3. Novel low-emissions and net-zero steelmaking technologies, including hydrogen-DRI production, need rapid development, scaling up, and deployment.

ACRONYMS

BAT	best available technology
BF	blast furnace
BOF	basic oxygen furnace
DRI	direct reduced iron
EAF	electric arc furnace
Mt	million metric tonnes
$MtCO_2e$	metric tonnes carbon dioxide equivalent
MTPA	million tonnes per annum
NZE	IEA's Net-zero by 2050 scenario (1.5°C by 2050)
OHF	open hearth furnace
SDS	IEA's Sustainable Development Scenario (1.5°C by 2070)
TTPA	thousand tonnes per annum

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BACKGROUND

The global iron and steel industry is currently responsible for 11% of global carbon dioxide emissions and 7% of global greenhouse gas emissions. Steel is an essential material for engineering, construction, medical, technology, energy, and transportation applications. As economies develop and build up infrastructure, global demand for steel is expected to continue increasing. Although steel demand declined 0.2% in 2020 as a result of the global Coronavirus pandemic, steel demand is forecasted to grow by 5.8% in 2021 and an additional 2.7% in 2022, according to the World Steel Association. In order to meet global climate and energy goals, the current dominance of carbon-intensive steelmaking processes in operating and development status must be challenged, and emissions reduced through a combination of strategies including material efficiency to lessen demand, increased recycling, and production decarbonization through retrofits and advanced technology.

CURRENT STATUS OF GLOBAL STEEL PLANT FLEET

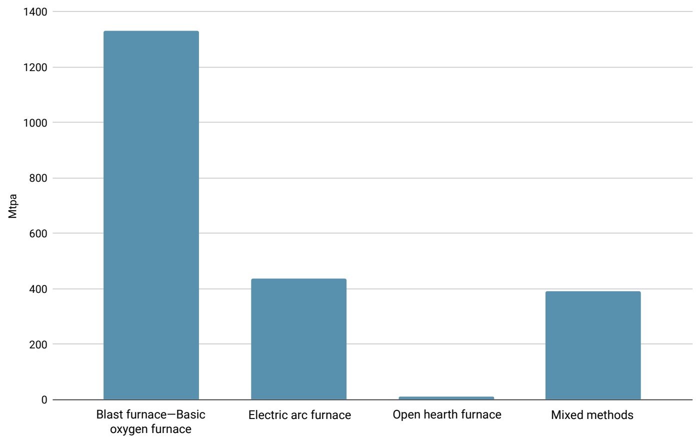
The Global Steel Plant Tracker (GSPT) is the first systematic attempt to document all steel plants on the globe with crude steelmaking capacity of at least one million tonnes per annum (1 mtpa). The GSPT serves to provide current and accurate data on the status of the global steel plant fleet. Providing such data supports efforts to track and analyze steel sector decarbonization, which is essential in order to meet the Paris Agreement 1.5°C pathway.

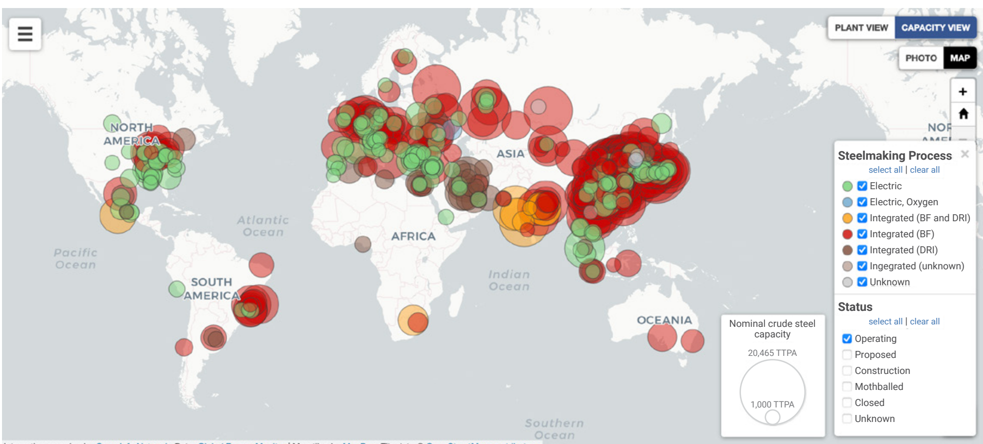
According to the GSPT, approximately 61.3% (1,329 mtpa) of global crude steel capacity currently uses the blast furnace-basic oxygen furnace (BF-BOF) route, 20.2% (438 mtpa) uses electric arc furnace (EAF) steelmaking, and 0.6% (12 mtpa) uses open hearth furnace (OHF) steelmaking. The remaining 18.6% (390 mtpa) of capacity uses mixed methods of BF-BOF, EAF, and OHF.[1,2] Steel plants in China account for 51% (1,023 mtpa) of the steelmaking capacity in the GSPT, followed by Japan (117 mtpa) and India (90 mtpa) (see Appendix 2 for full list of operating steelmaking capacity by type and country). (Figure 1, on the next page.)

The average age of the existing global fleet of BF and direct reduced iron (DRI) furnaces is 13 years and 14 years, respectively. Over half the world's global steel fleet is in China, where the average age for BFs is 12 years and DRIs is 8 years. BF and DRI furnaces are typically operated for around 40 years with investment cycles of 15–20 years for BFs and 20 or more years for DRI plants,[3] though refurbishments may extend their overall lifetime by several decades. By 2050, around half of the global ironmaking capacity could be considered for end-of-life decommissioning and most will reach the beginning of their investment cycle by 2030. This means that over the next decade, plant owners may need to decide whether to spend hundreds of millions of dollars refurbishing them or shutting them down. (Figure 2, on the next page.)

1. GEM Global Steel Plant Tracker, February 2021. The OECD reports a total global steelmaking capacity of approximately 2,453 mtpa.
2. Open hearth furnace steelmaking combusts fuel to convert steel scrap and/or pig iron to crude steel. OHF steelmaking has been almost completely replaced by BOF and EAF steelmaking.
3. DRI investment cycles are estimated at 20 to 25 years, though some estimates are longer due to the relatively low operating temperatures of some DRI plants. Blast furnace investment cycles are estimated around 15 to 20 years, though lengths vary significantly depending on the unit configuration, intensity of production, and level of maintenance performed on the unit. Some sources estimate investment cycles as low as 10 to 15 years or approaching 30 years, though most sources cite approximately 15 to 20 years under typical operation and maintenance. The IEA estimates a combined average investment cycle for BF and DRI at 25 years.

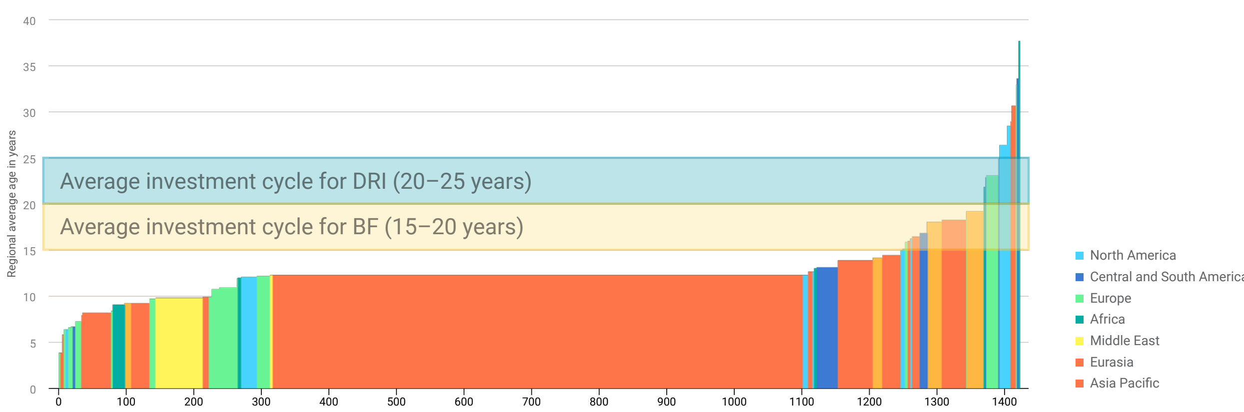
Figure 1: Global operating steelmaking capacity by type





Source: Global Steel Plant Tracker, Global Energy Monitor, February 2021.
Note: includes only steel plants with capacity of at least 1 mtpa.

Figure 2: Age profile of global production capacity for the steel sector (blast furnaces and DRI furnaces)



Source: IEA, Age profile of global production capacity for the steel sector (blast furnaces and DRI furnaces), IEA, Paris as modified by Global Energy Monitor.

Over 130 mtpa steelmaking capacity is currently under development of which 38% (50 mtpa) uses the BF-BOF route and 21% (27 mtpa) uses EAF steelmaking, according to the GSPT. The share of BF-BOF, EAF, and OHF steelmaking for the remaining 41% (54 mtpa) of capacity is unknown. Of the steelmaking capacity underdevelopment with known steelmaking processes, 65% uses the BF-BOF route and only 35% uses EAF steelmaking. Together, India and China account for over 61% of steelmaking capacity under development with approximately 39% (51 mtpa) in China and 22% (29 mtpa) in India. (Figure 3.)

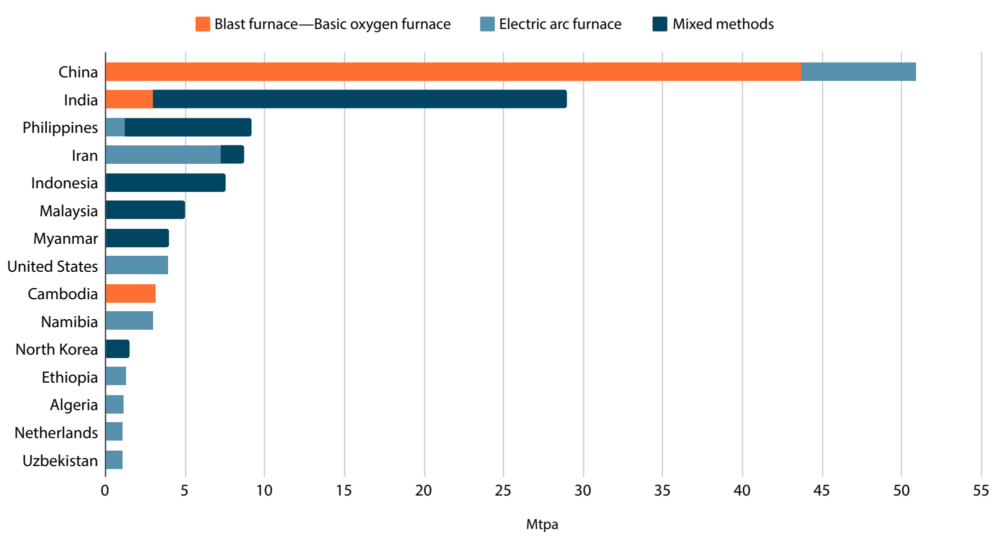
The BF-BOF pathway is the most carbon-intensive method of producing steel with limited, difficult, and high-cost decarbonization options. Yet it dominates both operating steelmaking capacity (61%) and capacity under development (65%) in the GSPT (where technology is known). Decisions about the refurbishment, retrofit, and retirement of existing steel plants and proposals and investments in new steel plants, particularly BF-BOF, will determine whether the global steel sector aligns with a 1.5°C pathway, or not.

An opportunity in overcapacity

In March 2021, the OECD reported that overcapacity in the steel industry grew to 625 Mt in 2020, representing the gap between all global steelmaking capacity (2,543 Mt) and crude steel production (1918 Mt in 2020)—an excess of about 25% of capacity. The overcapacity is mainly due to decreased demand for finished steel during the Covid-19 pandemic, coupled with global capacity growth. The OECD projects that finished steel demand will stay below pre-pandemic levels in 2021, which indicates that overcapacity will remain an issue unless expansion plans are cancelled or scaled back.

Steel overcapacity causes a host of problems in the steel industry and global markets. Overcapacity serves as a longtime source of tension in trade between various countries, leading to international "trade wars" and disputes. Overcapacity also constrains the profitability of steelmakers, creating challenging and volatile market conditions.

Figure 3: Steelmaking capacity under development by country and type

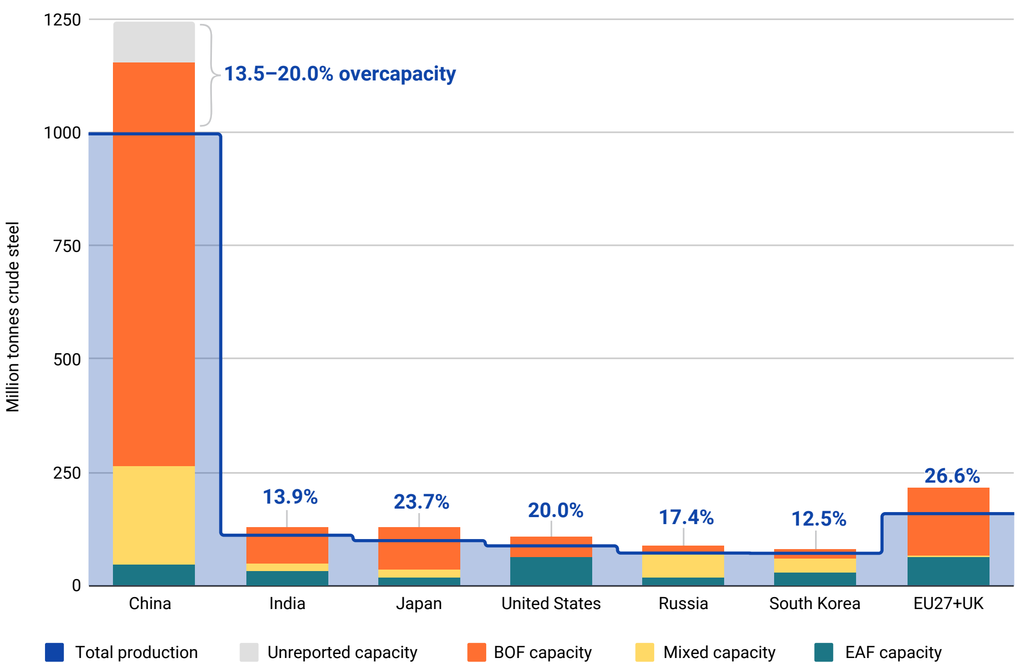


Source: Global Steel Plant Tracker, Global Energy Monitor, February 2021.
Note: includes only proposed steel plants with capacity of at least 1 mtpa.

Addressing overcapacity requires reducing capacity to meet demand. Given that demand could drop 20% by 2050 under the effects of material efficiency gains, significant capacity reductions are in order. Overcapacity presents an opportunity to shift the status of the global steel plant fleet by creating strategic reductions in capacity by retiring or permanently downscaling plants with higher emissions intensities, primarily blast furnace-basic oxygen furnace (BF-BOF) capacity, and ensuring that new projects use only the cleanest steelmaking technologies.

Strategies to create this shift in the global steel plant fleet include incentives for early retirement or underutilization of plants with higher emissions. For example, setting national Best Available Technology (BAT) standards for low carbon steel making technologies or adopting carbon markets or tax schemes that favor green steel production would raise the operating costs for carbon-intensive BF-BOF capacity and incentivize closures (see section *Best Available Technologies (BAT)*). Closing older and dirtier BF-BOF capacity, in turn, will help lower the average energy and emissions intensity of global steelmaking. (Figure 4.)

Figure 4: 2019 steelmaking capacity vs production in top producing countries



Source: Global Steel Plant Tracker, Global Energy Monitor, February 2021. OECD Steelmaking Capacity Database, 2000–2019, OECD, December 2019. World Steel in Figures 2020, World Steel Association, April 2020.

Note: OECD capacity estimates for 2019 used aggregate values from official sources, which underreport plant operations. Estimate of unreported capacity is based on a total estimated steel capacity for China of 1245 mtpa in 2019.

Overcapacity represents a particular challenge in China, which is estimated to have around 350 mtpa of operating capacity in excess of the capacity control target in 2020, meaning that if Chinese capacity control targets were actualized, global overcapacity would be cut in half (52% reduction). These operations are often used by provinces for large-scale construction projects to grow their economies, enabled by lax enforcement of central government agencies. Starting in June, China's central government has ordered steelmakers to start scaling back production in order to address overcapacity issues and meet emissions reductions targets. At the same time, China has experienced a building boom since May 2020 as a result of government stimulus in response to the Covid-19 pandemic, boosting demand for steel (see *China central to global steelmaking decarbonization*). In addition, countries such as the U.S., Japan, South Korea, and Germany have steelmaking capacity that has long exceeded production, including a significant percentage of older BF-BOF plants.

The risk of stranded assets

Several countries and regions with major steel industries have pledged to reach carbon neutrality or achieve partial carbon reductions (see section *Steel and global decarbonization goals*), but at the same time plan to build numerous large BF-BOF steel plants. Unless BF-BOF retrofits for low carbon steelmaking are developed and brought to market in a fraction of the time predicted in various steel decarbonization roadmaps, these commitments are at odds with each other since BF-BOF steel plants offer limited options for decarbonization (see section *Steel sector decarbonization pathways*).

If these plants are built, but become obsolete, the steel industry faces the risk of 47–70 billion USD in stranded assets (see Table 1).[4] Steel plants could become unnecessary or inoperable in a number of situations. For example, if the cost of carbon is realized through carbon pricing (i.e. taxes) or emission standards, a conventional steel plant may be unable to price competitively with low carbon steelmaking plants. Conventional steel plants could also become stranded assets due to changes in the steel market including decreases in steel demand from material efficiency (see section *Material efficiency*) or overcapacity (see section *An opportunity in overcapacity*), or shifts in steel demand as a result of product differentiation (green steel vs. conventional steel).

Table 1: Stranded asset risk in the global steel industry

Country	Carbon commitment	Proposed or under construction BF-BOF steel capacity (ttpa)	Stranded asset risk (billion USD)
India	33–35% reduction from 2005 by 2030	3,000[5]	3.0–4.5
China	Carbon neutrality by 2060	43,675	43.7–65.5

4. The capital cost of a new integrated BF-BOF steelmaking facility is approximately 1–1.5 billion USD.

5. An additional 26,000 ttpa steelmaking capacity of mixed steelmaking methods (BOF, EAF, or OHF) has been proposed in India, meaning that the proposed BF-BOF steelmaking capacity in India could be as high as 29,000 ttpa.

The steel industry faces major challenges in the timing of technology development and plant retirements. New low-emissions steelmaking technologies are expected to reach commercial scale over the next decades. At the same time, most global ironmaking capacity will face major investment decisions by 2030 and around half could be considered for end-of-life decommissioning by 2050. Ideally, low-emissions steel technologies will reach the market before decisions are made about the operation status of plants facing retirement, enabling older plants to be replaced with the newest, most efficient technology. However, in the case that these new low-emissions technologies are still under development, steel plants will need to use other solutions to decarbonize their operations and avoid becoming stranded assets.

The IEA's Iron and Steel Technology Roadmap explicitly states that all new plants must be built "retrofit-ready"—meaning ready to transition to low-emissions steelmaking as these technologies reach the market—in order to avoid the risk of stranded assets in the steel industry.[6] Proposals for new steel plants and retrofits for existing assets must be strategically managed to ensure the application of low-emission steelmaking technologies and to avoid locking-in investments with high emissions steelmaking. For example, in some cases it may be preferable to continue operating existing steel assets for a few extra years until new low-emissions technologies reach market, rather than locking in investments with a new, conventional steel plant.

Governments and financial institutions will play a key role in guiding investment decisions to avoid creating stranded assets. Examples of policy and finance levers that may be used to manage investments in new plants and retrofits of existing assets include:

- Carbon pricing
- Emissions schemes
- Technology sunsetting (i.e. phasing out BF-BOF steelmaking)
- Efficiency policies
- Climate-related financial risk assessment frameworks
- Credit ratings that account for the cost of carbon emissions
- Green steel demand decreation through public procurement policies

6. See Iron and Steel Technology Roadmap (pp 163–164). "With regard to near-term investment, an important step is for any new plants to be built retrofit-ready—that is, with adequate space and technical characteristics to allow the smooth transition to very low-emission pathways, such as those involving CCS, hydrogen or biomass."

STEELMAKING PROCESSES

Steelmaking currently uses two main production routes: (1) integrated blast furnace-basic oxygen furnace (BF-BOF) and (2) electric arc furnace (EAF) steelmaking, which typically uses a feedmix of direct reduced iron (DRI) and/or steel scrap. Open hearth furnaces (OHF) are less commonly used, accounting for <1% of global steel capacity. Figure 5 displays the main steelmaking pathways.

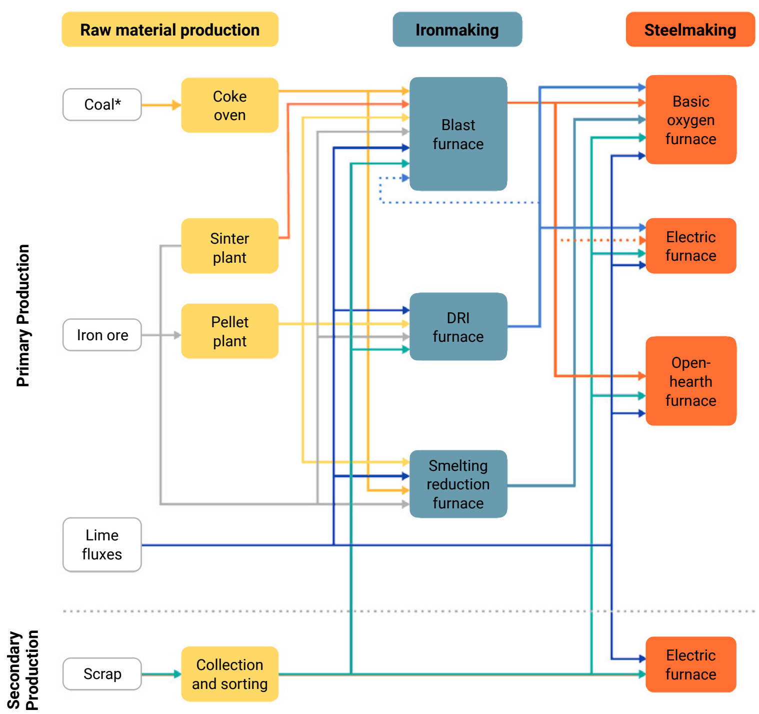
STEELMAKING AND DECARBONIZATION

Blast furnace-basic oxygen furnace (BF-BOF) steelmaking uses coal as the main fuel source, which not only provides heat but also chemical properties that make it hard to substitute coal with alternatives, and relegates the main decarbonization option to capturing carbon emissions and storing them underground, known as carbon capture utilization and storage (CCUS).

Direct reduced iron (DRI) is a form of ironmaking that uses gas. The gas can be natural gas or sometimes coal, which can also be used with CCUS. Alternatively, the gas can be hydrogen created by renewable energy, making DRI more easily retrofit for a wider array of decarbonization options than BF ironmaking.

Electric arc furnace (EAF) is a form of steelmaking that uses electricity. The emissions depend on the make-up of the electricity system and raw materials used, meaning emissions from EAF steelmaking can be more easily reduced than from BOF steelmaking.

Figure 5: Main steel production pathways



Source: Iron and Steel Technology Roadmap, IEA, October 2020 as modified by Global Energy Monitor.

*Coal is a key material input to coke ovens for conversion into coke; while not represented here, it is also an energy input into other process units, alongside other energy inputs like natural gas and electricity.

Notes: Iron ore includes concentrate, lump and fines. Electric furnace includes both EAFs and induction furnaces. DRI input into blast furnace and blast furnace input into EAFs are less common (dashed lines).

BF-BOF steelmaking

In BF-BOF steelmaking, iron ore and metallurgical coal are converted to pig iron (aka hot metal, crude iron) in the blast furnace. Crude steel is produced in the basic oxygen furnace, which uses pig iron and steel scrap as its primary feedstocks, though small amounts of direct reduced iron (DRI) may be used as a supplemental input. The BF-BOF steelmaking process often includes pelletization and sintering of iron ore, and coking of metallurgical coal as preliminary processes for iron and steelmaking. Producing one tonne of steel through the BF-BOF steelmaking route emits around 2.2 tonnes of CO_2 and requires roughly 20.8 GJ of energy, assuming global average electricity carbon intensity (see Table 2). Options for decarbonizing the BF-BOF steelmaking route are difficult and limited because of the use of metallurgical coal as a reductant in the ironmaking process: as coal is heated to melt the iron ore, carbon monoxide is produced that reduces oxygen in the iron ore but releases CO_2 as a byproduct, called process emissions. Given that process emissions are a fundamental step of BF-BOF steelmaking, the abatement potential is limited, with the use of zero carbon electricity in the BF-BOF steelmaking process reducing emissions by just 7.4%. Hydrogen can be used to partially substitute metallurgical coal as a reductant in the BF-BOF steelmaking process, with a maximum carbon emissions reduction of 21.4% per tonne of steel. Together, zero carbon electricity and hydrogen injection can abate a maximum of 28.8% of CO_2 emissions in BF-BOF steelmaking, based on current estimates.

EAF steelmaking

EAF steelmaking uses steel scrap, DRI (aka sponge iron), or a combination of these materials as the primary feedstock. DRI production turns iron ore into iron using a reducing gas such as carbon monoxide (produced from natural gas or coal) or hydrogen (produced from natural gas, coal, or using an electrolyzer that relies on electricity to split water into hydrogen and oxygen). Scrap-based EAF production results in approximately 0.3 t CO_2 / t crude steel, while natural gas-based DRI-EAF production results in approximately 1.4 t CO_2 / t crude steel. Coal can also be used in DRI-EAF production, with average emissions ranging from 1.3–1.8 t CO_2 / t crude steel for the COREX/FINEX process and 3.2 t CO_2 / t crude steel for the rotary kiln process. Hydrogen-based DRI-EAF production results in an average 0.71 t CO_2 / t crude steel, though actual emissions vary widely depending on the production route of the hydrogen (see section *Hydrogen in steelmaking*). Producing one tonne of steel through the EAF steelmaking process requires 9.0 GJ of energy on average globally.[7]

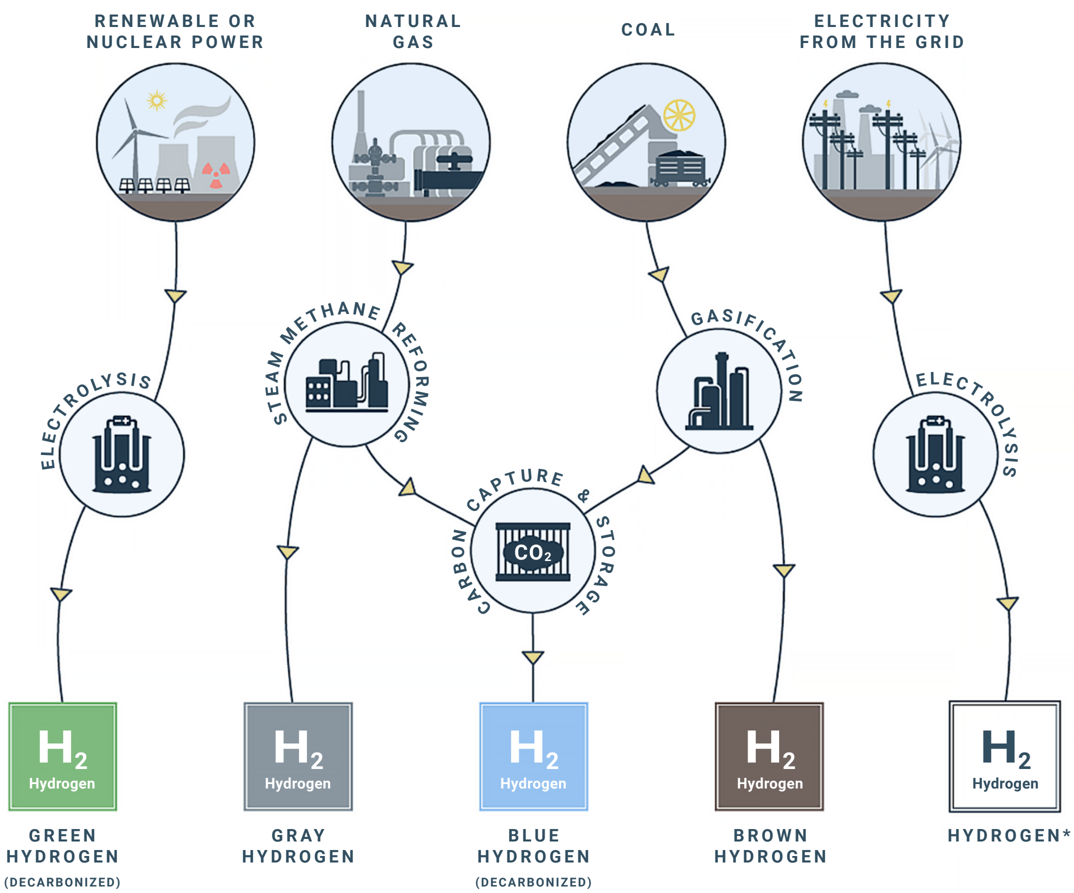
It is important to note that the emissions intensities of EAF steelmaking processes vary based on electricity sources and feed materials, particularly the choice of reductant in the DRI process. For the purpose of comparing the emissions intensities of major steelmaking processes, Table 2 assumes the IEA's global average emissions intensity for electricity imported from the grid. In both BF-BOF and EAF steelmaking, the iron production portion is responsible for the majority share of emissions in the steelmaking process.

7. The average energy intensity for EAF steelmaking drops to 6.2 GJ/t crude steel if China and India are excluded from estimates. EAF energy intensity for these countries is high due to the high use of DRI and pig iron as feed materials.

Hydrogen in steelmaking

Currently, the most advanced net-zero option for steelmaking that does not involve carbon capture and storage (CCUS) is electrolytic hydrogen-based DRI-EAF production where the electricity for hydrogen electrolysis and EAF operations are sourced from renewable sources. Electrolytic hydrogen produced via electrolysis using renewables is called green hydrogen and achieves approximately zero emissions. Hydrogen produced from natural gas with carbon capture and storage or reuse (CCUS) is called blue hydrogen. CCUS plants are designed to capture a portion of their carbon emissions and either utilize them (e.g. as a gas to retrieve oil from depleting oil fields) or directly store them underground. Depending on the usage and capture rate, blue hydrogen can result in significantly lower emissions than grey hydrogen (hydrogen produced from natural gas without CCUS) or brown hydrogen (hydrogen produced from coal) (see section *CCUS in steelmaking*). Emissions for hydrogen produced via electrolysis using grid electricity depend on the grid mix and can therefore vary significantly (see Table 2).

Figure 6: Common hydrogen production pathways (Credit: Resources for the Future)



Source: Decarbonized Hydrogen in the US Power and Industrial Sectors, Resources for the Future, December 2020.

*Emissions depend on the mix of electricity sources on the grid.

CCUS in steelmaking

In cases where it is not possible to avoid the generation of off-gasses altogether, another technology under development for lowering net carbon emissions from steelmaking is carbon capture, use, and storage (CCUS). CCUS can be built with new plants or retrofitted to units like blast furnaces and natural gas-based DRI to significantly lower net emissions, though the full scope of reductions depend on the emissions being stored without leakage or used to fully displace other carbon emissions sources. Additionally, the credit for carbon emissions reductions may be shared with other industries (i.e. chemical industry for CCUS projects where carbon is captured for chemical production), leading to the possibility of overestimating emissions reductions. Thus, building infrastructure and ensuring demand and proper utilization and storage of captured carbon emissions is essential to the success of CCUS technologies.

Equipping blast furnaces with CCUS can theoretically reduce crude steel production emissions up to 63% per tonne of steel in blast furnaces with suitable configurations. The application of CCUS in natural gas-based DRI can lower the average emissions intensity of steel production by 59% (see Table 2). At present, CCUS has yet to be adequately demonstrated at industrial levels and proven economically.

Table 2: Average emissions and energy intensities of main steelmaking pathways

Steelmaking Route[8]	Average Emissions Intensity (tonnes CO_2 per tonne of steel; indirect + direct)	Average Energy Intensity (GJ per tonne of steel)	Source
BF-BOF	2.2	20.8[9]	IEA Iron and Steel Technology Roadmap (2020); Hasanbeigi, A. and Springer, C. (2019)
EAF (average)		9.0[10]	Hasanbeigi, A. and Springer, C. (2019)
EAF (scrap-based)	0.3[11]	2.1	IEA Iron and Steel Technology Roadmap (2020)
EAF (natural gas-based DRI)	1.4	17.1	IEA Iron and Steel Technology Roadmap (2020)
EAF (natural gas-based DRI with CCUS)	0.57		IEA Iron and Steel Technology Roadmap (2020)
EAF (coal-based DRI; rotary kiln)[12]	3.2		Sohn, H.Y. (2019)
EAF (coal-based DRI; COREX/FINEX)[13]	1.3–1.8		Sohn, H.Y. (2019)
EAF (hydrogen-based DRI)	0.71[14]		IEA Iron and Steel Technology Roadmap (2020)

8. Open hearth furnace (OHF) steelmaking emissions intensity is not included because it accounts for <1% global steelmaking capacity.

9. Weighted average final energy intensity from top 15 steel producing countries in 2016.

10. Ibid.

11. Embodied emissions of scrap not included in estimate. Fan, Z. and Friedmann, J. 2021 offers an estimate of 0.8 t CO_2 / t crude steel when considering embodied emissions of scrap steel.

12. Emissions from coal-based DRI range widely based on the production process used. Rotary kilns, which provide continuous DRI production from a cylindrical rotating vessel, result in 3.2 t CO_2 / t crude steel while the COREX/FINEX process, which produces DRI in batches from a series of fluidized bed reactors, results in 1.3–1.8 t CO_2 / t crude steel. The majority of coal-based DRI occurs in India where both rotary kiln and COREX/FINEX processes are used, giving India a blended national carbon intensity of 2.1 t CO_2 / t crude steel for coal-based DRI steel production. Fan, Z. and Friedmann, J. 2021 also offers an estimate of 2.0 t CO_2 / t crude steel.

13. Ibid.

14. The CO_2 intensity for hydrogen-based DRI-EAF steelmaking varies widely based on electricity source. This estimate uses an electricity CO_2 intensity of 144 g CO_2 / kWh, which is the global average CO_2 intensity assumed under the IEA's Sustainable Development Scenario in 2035. This average is roughly 60% below the 2020 CO_2 intensity of the US power sector (366 g CO_2 / kWh). Using variable renewable energy (VRE) could potentially eliminate CO_2 emissions in steelmaking.

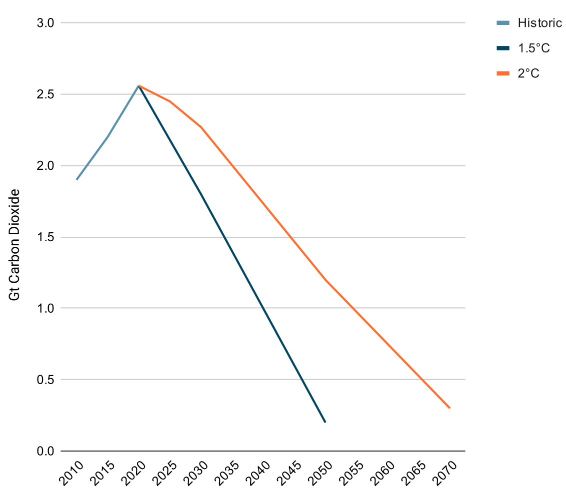
STEEL SECTOR DECARBONIZATION PATHWAYS

Decarbonizing the steel sector is a challenging task for two main reasons: (1) steel has unique properties with few to no substitutes in essential applications like technology and construction; and (2) net zero emissions and low carbon steelmaking processes are still in development. Still, a number of research and strategy organizations have recently published steel sector decarbonization roadmaps for part or all of the steel industry, showing that significantly reducing the emissions of the steel industry is not only possible in the future, but possible in the current moment.[15]

One of the most comprehensive and detailed steel decarbonization roadmaps published in recent months is the IEA's Iron and Steel Technology Roadmap (October 2020). This report, in conjunction with the IEA's Energy Technology Perspectives 2020 report, laid out a pathway for reducing iron and steel sector emissions by 90% relative to a baseline projection by 2070 in order to reach net zero CO_2 emissions for the whole energy system by 2070. The pathway is in line with the IEA's Sustainable Development Scenario (SDS) to keep global warming well below 2°C, the upper limit of the Paris climate agreement. The IEA's roadmap did not provide a full pathway, but a broad overview of adjustments that would be needed to reach net-zero by 2050 (the Faster Innovation Case). In May 2021, the IEA provided a pathway for the global energy sector to reach Net Zero by 2050 (NZE), in line with limiting global warming to 1.5°C, which included additional details on the adjustments needed for the iron and steel sector to reduce emissions 92% by 2050 (see Table 3).[16]

Figure 7 shows the emissions reductions needed to meet the IEA's NZE pathway (1.5°C) and SDS pathway (well below 2°C), while Table 3 lays out the strategies and timelines within the various IEA steel decarbonization roadmaps to achieve these emission reductions.

Figure 7: Paris-compliant pathways for CO_2 emissions from the iron and steel sector



Source: 1.5°C pathway (IEA Net Zero by 2050), Historic emissions and 2°C pathway (IEA Iron and Steel Technology Roadmap, Sustainable Development Scenario).

15. Recently published steel sector decarbonization roadmaps include the IEA's Iron and Steel Technology Roadmap and Net-Zero by 2050 report; McKinsey & Company's Decarbonization challenge for steel, The future of the European steel industry, and Tackling the challenge of decarbonizing steelmaking reports; OECD's Low and Zero emissions in the steel and cement industries issue paper; and various scientific journal articles. A net zero roadmap from the Mission Possible Partnership is also forthcoming in 2021.

16. The IEA reports that total direct emissions from the iron and steel sector were approximately 3.7 Gt CO_2 in 2019 (2.6 Gt CO_2 direct emissions and 1.1 Gt CO_2 indirect emissions). According to the IEA's NZE report, direct emissions in 2020 were 2.4 Gt CO_2. The NZE projected heavy industry (including steel, chemicals, and cement) emissions reductions of 20% by 2030 and 93% by 2050 relative to a 2020 emissions baseline. Emissions reductions for the NZE were recalculated relative to a 2019 baseline for comparison with the SDS and Faster Innovation Case.

Table 3: Comparison of IEA decarbonization roadmaps[17]

	Sustainable Development Scenario (SDS)	Faster Innovation Case	Net-zero by 2050 Scenario (NZE)
Report source	Iron and Steel Technology Roadmap	Iron and Steel Technology Roadmap	Net-zero by 2050
Energy system goal	2°C / net-zero 2070	1.5°C / net-zero 2050	1.5°C / net-zero 2050
Steel sector goal relative to 2019 CO_2 emissions	2.3 Gt CO_2 emitted in 2030 1.2 Gt CO_2 emitted in 2050 0.3 Gt CO_2 emitted in 2070 54% reduction in direct, process emissions by 2050	0.3 Gt CO_2 emitted in 2050 88.5% reduction in direct, process emissions by 2050[18]	1.8 Gt CO_2 emitted in 2030 0.2 Gt CO_2 emitted in 2050 92% reduction in direct, process emissions by 2050
Share of steel production using EAF	29% in 2019; 57% by 2050	Assumed same as SDS	24% in 2020; 37% by 2030; 53% by 2050
Scrap as share of input	32% in 2019; 45% by 2050	Assumed same as SDS	32% in 2020; 38% by 2030; 46% by 2050
Material efficiency	Responsible for 40% of cumulative emissions reductions relative to 2019 baseline by 2050	Reduces steel demand by 19% relative to 2019 by 2050	Reduces steel demand by 20% relative to 2020 by 2050
Technology performance improvements (BAT and best practices)	21% of cumulative emissions reductions by 2050		While the NZE cites the importance of installing BAT and optimizing operational efficiency of equipment, they do not provide estimated emissions savings from technology performance improvements.
Technologies still in development/prototype phase	Responsible for 30% of cumulative emissions reductions by 2050 Responsible for approximately 40% annual emissions savings in 2050	Introduced to market by 2026 Responsible for approximately 75% annual emissions savings in 2050	Responsible for 54% of cumulative emissions reductions by 2050[19]
Hydrogen-based DRI	Responsible for 8% of cumulative emissions reductions by 2050 15% of steelmaking capacity equipped by 2050 Introduced to market by 2030 One electrolytic hydrogen-based DRI plant built per month after market introduction	Introduced to market by 2026 Two 100% renewable hydrogen-based DRI plants built per month after market introduction	29% steelmaking capacity equipped by 2050
CCUS (including blue hydrogen-DRI)	Responsible for 16% of cumulative emissions reductions by 2050 Introduced to market by 2030 One 1 Mt CO_2 captured per year CCUS project installed every 2–3 weeks after market introduction Reaches 400 Mt CO_2 captured per year by 2050	Introduced to market by 2025 Two 1 Mt CO_2 captured per year CCUS projects built every month after market introduction	53% steelmaking capacity equipped by 2050 Reaches capture total of 670 Mt CO_2 by 2050
Iron ore electrolysis	Not deployed	5% of steelmaking capacity equipped by 2050 Introduced to market by 2030 One plant built every two months from 2030 to 2050	13% of steelmaking capacity equipped by 2050

17. Ibid.
18. IEA states that direct global emissions from the iron and steel sector "fall to reach a level in 2050 that is 75% lower than in the Sustainable Development Scenario."
19. Recalculated for 2019 baseline. Responsible for 60% of cumulative emissions reductions by 2050 relative to 2020 baseline.

Three key strategies to align with decarbonization pathways

In the IEA's SDS pathway, over 85% of cumulative emissions reductions relative to a baseline projection between 2020 and 2050 in the iron and steel sector will be achieved through material efficiency (40%),[20] hydrogen and carbon capture utilization and storage (CCUS) (24%), and technology performance improvements (21%), which include the installation of best available technologies (BAT) and best practices for efficient operations. Other processes such as HIsarna that achieve emissions reductions through the use of alternative coal products make up the remaining 15%.

The Net-Zero by 2050 and Faster Innovation Case each rely on the ability to accelerate innovation and adoption of clean energy, including iron and steel decarbonization technologies, at an unprecedented rate. Both scenarios require deploying current decarbonization technologies at a faster rate and scale than the SDS scenario, while technologies currently in lab and prototype stages must reach scale more quickly and with broader deployment. In the SDS, 30% of cumulative emissions reductions by 2050 are delivered by novel, low-emissions technologies that have yet to reach commercial scale, while the NZE attributes 54% of these cumulative emissions reductions to these technologies currently under development.[21]

The following sections discuss the progress of the global steel industry towards these three key strategies (development of technology, material efficiency, and technology performance improvements) for aligning with decarbonization pathways.

Development of novel, low-emissions steelmaking processes

Though readily available technologies provide the opportunity to reduce carbon emissions in the steel industry, deep decarbonization of the sector will require new steelmaking processes. In order to meet the goal of net-zero emissions by 2070, the IEA attributes nearly one-quarter (24%) of the cumulative emissions reductions from by the iron and steel sector by 2050 to two new technologies: (1) hydrogen-based DRI and (2) carbon capture and storage (CCUS), primarily new or retrofitted DRI plants capturing gas emissions from reducing iron.[22] To reach net-zero emissions by 2050, hydrogen and CCUS need to reach commercial application sooner and grow even more quickly, with 29% of steelmaking capacity being equipped with hydrogen and 53% with CCUS.

In addition to hydrogen and CCUS, there are several new technologies in early development stages that could accelerate the opportunities for steel decarbonization. This report focuses on the development of hydrogen and CCUS given their comparatively advanced stages of development, which still require significant levels of innovation and investment before reaching commercial scale.

Hydrogen: Reaching net-zero steelmaking

In order to align with the IEA's pathway to net-zero by 2070, electrolytic[23] hydrogen-based DRI-EAF production must account for at least 15% of primary steel production (12 Mt H_2 / year) globally by 2050. This target requires the equivalent of building one hydrogen-based DRI plant per month following market introduction of the technology, projected for 2030. To reach net-zero by 2050, green hydrogen-based DRI technology should be introduced to the market by

20. Material efficiency refers to reduced demand for crude steel through efficient product design, steel recycling, process efficiency, etc.

21. Recalculated for 2019 baseline. Responsible for 60% of cumulative emissions reductions by 2050 relative to 2020 baseline.

22. Of these cumulative emissions reductions, electrolytic hydrogen accounts for 8% and CCUS, which includes blue hydrogen (via natural gas-based DRI with CCUS), accounts for 16%.

23. The IEA's model is based on the assumption that the global electricity supply will include a substantially larger share of renewables by 2050, with the global average electricity CO_2 intensity falling 95% from current levels to 18 g CO_2 / kWh. In H1 2021, the IEA revised their wind and solar growth forecasts "upwards by over 25% from last year," meaning that electrolytic hydrogen-based DRI-EAF production may be able to achieve greater reductions in CO_2 emissions than previously predicted.

2026 and two 100% renewable hydrogen-based DRI plants should be built per month, a rate twice as fast as electrolytic hydrogen-based DRI-EAF plants under the net-zero 2070 pathway. By 2050, 29% of steel-making capacity should be equipped with hydrogen processes.

According to the Green Steel Tracker and IEA roadmap, no electrolytic hydrogen-based DRI plants are currently operating at the commercial scale, though one pilot project known as HYBRIT began operations in Sweden in August 2020, with the goal of operating a 1 Mt H_2 / year plant by 2025. Operated by Swedish steelmaker SSAB and European energy company Vattenfall, HYBRIT will use green hydrogen (100% renewables-based) to achieve its goal of becoming the first net zero steel plant in the world. SSAB plans to convert SSAB Oxelösund from BF-BOF operations to green hydrogen-DRI-EAF operations by 2025, and aims to convert SSAB Raahe and SSAB Luleå BF-BOF plants to fossil-free steelmaking between 2030–2040, potentially replacing a total of 6,400 ttpa crude steel capacity with green steel.

Several additional projects including pilot plants using electrolytic hydrogen and natural gas-based DRI plants transitioning to electrolytic hydrogen-based DRI are under development. On a scale of 1–9, electrolytic hydrogen-based DRI production currently ranks at a Technology Readiness Level of 5 according to the IEA and 5–7 according to the OECD, meaning that the process must advance from its current "large prototype"

Figure 8: Low-carbon investments in the steel industry

Source: Green Steel Tracker, Vogl, V, Sanchez, F, Gerres, T, Lettow, F, Bhaskar, A, Swalec, C, Mete, G, Åhman, M, Lehne, J, Schenk, S, Witecka, W, Olsson, O, Rootzén, J, Version 06/2021.

Note: Bubble sizes are relative to the size of disclosed investments. Investments announced range in size from $6–36,000 million USD. When investment size was undisclosed, standard bubble size equivalent to $1 million USD was used.

stage through pilot project, demonstration, and scaling up stages before reaching commercial viability.

Continued innovation and investment to achieve commercial operation of 100% renewable, green hydrogen-based DRI is essential to decarbonizing the steel industry, as such investment is essential to reaching market readiness and reducing production costs. However, there is no need to wait for green hydrogen production to reach full scale to make significant progress towards decarbonizing steelmaking. The steel industry can still commit now to reducing BF-BOF steelmaking capacity, with a focus on building steel plants that will reach net-zero production.

METALLURGICAL COAL AND STEEL DECARBONIZATION

A recent report from Global Energy Monitor found that there are currently 78 proposed metallurgical coal mines for steelmaking and heavy industry use, accounting for 20% (455 mtpa coal) of global proposed coal mine capacity. GEM calculated that these proposed metallurgical coal mines risk a potential methane leakage of approximately 3.5 mtpa. These emissions are not accounted for in steelmaking emissions calculations, meaning that the emissions savings potential of switching to green steel technologies from coal-based DRI and BF steelmaking is even greater than currently reported. According to the IEA Net-zero by 2050 Scenario (NZE), there should be no new coal mines or mine expansions after 2021 to hold global warming to 1.5°C.

CCUS: Lowering emissions in steelmaking

While the IEA has ranked configurations for natural gas-based DRI with CCUS at a technology readiness level of 9, meaning that the technology is currently available, there is currently only one steel plant in the world operating at a commercial scale with this technology. The Emirates Steel plant in Abu Dhabi in the United Arab Emirates began a CCUS project in 2016 with the ability to capture up to 800 ttpa CO_2 emissions. These carbon emissions are captured and injected into nearby oil fields run by the Abu Dhabi National Oil Company (ADNOC) in place of natural gas, a process called enhanced oil recovery (EOR). Though actual carbon capture rates have not been reported since the CCUS facility began operations, ADNOC plans to expand the CCUS program fivefold by 2030 to reach a capture capacity of 5 mtpa CO_2 emissions.

For applications of CCUS with blast furnaces, the IEA applies a technology readiness levels (TRL) of 5–8 (prototype and demonstration projects), with expected market readiness between 2025–2030 for commercial scale.[24]

According to the IEA's pathway for net-zero emissions by 2070, one large CCUS project, equivalent to 1 Mt CO_2 captured per year, should be installed every 2–3 weeks from 2030. By 2050, the global capacity of CCUS at steel plants must reach 400 Mt CO_2 captured per year. To reach net-zero by 2050, CCUS should reach market readiness by 2025 and two CCUS projects should be built every month through to 2050. Over half (53%) of global steelmaking capacity should be equipped with CCUS by 2050, having captured a total of 670 Mt CO_2. CCUS may play an important role in regions with younger furnace fleets like China where the average age of BFs is 12 years and DRIs is 8 years. Thus, investment and continued innovation in CCUS technologies will be essential for scaling up the technology to reach the levels of deployment in the IEA pathways.

As plants face reinvestment cycles at the same time that green hydrogen-based DRI and CCUS remain underdevelopment, the IEA finds that natural gas-based DRI can play an important role as a transitional technology. Natural gas-based DRI-EAF without CCUS emits about 20% lower direct CO2 emissions compared to conventional BF-BOF production. By transitioning

24. Though the OECD, IEA, and Agora Energiewende have each assigned slightly different TRLs to various CCUS retrofits and new builds, all predict market readiness between 2025–2030.

BF-BOF steel plants to natural gas-based DRI-EAF production, partial CO_2 emissions reductions may be achieved immediately, while also readying the plants for transitioning to green hydrogen-based DRI-EAF or natural gas-based DRI-EAF production with CCUS. Natural gas-based DRI technology with CCUS is expected to reach market readiness before 2025 and retrofittable and new build technology for green hydrogen-based DRI could reach market readiness by 2030.

At present, CCUS has yet to be adequately demonstrated at industrial levels and proven economically. In addition, green hydrogen is projected to be lower in cost than blue hydrogen by 2030, raising questions over whether steel technology should simply leapfrog to green hydrogen rather than equip plants with expensive CCUS capability.

MATERIAL EFFICIENCY

Material efficiency reduces overall demand for virgin crude steel through a number of strategies including efficient product design, steel recycling, process efficiency, and maintenance to elongate product lifetime. Under both the IEA's net-zero by 2050 and net-zero by 2070 pathways, material efficiency reduces demand for steel by around 20% by 2050. Examples of material efficiency include:

- Reducing scrap generation during semi-manufacturing processes (conversion of crude steel to products like sheets, rebar, coils, etc) and product manufacturing (conversion of semi-manufactured steel products to end-use goods like cars, appliances, medical devices, etc);
- Designing lighter vehicles (aka vehicle lightweighting), which can reduce steel demand by 75% in a single vehicle;
- Extending building lifetimes through refurbishment or repurposing to avoid early demolition;
- Improving building designs and construction practices to reduce overall material requirement; and
- Increasing scrap recycling rates by designing products to make steel recovery easier.[25]

In addition to reducing scrap generation during steel production and increasing scrap availability through improved product design, another important aspect of material efficiency is direct reuse of steel. Direct reuse refers to the "recycling" of steel products without re-melting, such as recovering steel beams or pipelines to be reused for new or different purposes.

Though many material efficiency strategies occur at the product design, consumer, and end-of-life stages of steel products, steel plants will play a key role by implementing best practices to improve process efficiency and reduce waste during steel production.

TECHNOLOGY PERFORMANCE IMPROVEMENTS

Technology performance improvements, as defined by the IEA, refer to strategies and technologies that create incremental reductions in energy intensity in steelmaking processes (as opposed to sharp changes in efficiency due to major technology or process changes). Technology performance improvements include changes made by implementing state-of-the-art, high efficiency technology (aka best available technologies) upgrades, as well as process optimization strategies (aka best operating practices).

In order to stay aligned with the IEA's roadmap for meeting net-zero for the entire energy system by 2070, technology performance improvements are assumed to contribute 21% of emissions reductions between 2020 and 2050, meaning the IEA regards technology performance improvements as essential to aligning the steel industry with the Paris climate agreement.

25. The global average for scrap recycling rates is approximately 85%, though recycling rates vary widely across different end use products. For example, steel recycling rates from packaging and rebar average 50–60% globally. Thus, increased recovery and collection of these steel products provides the opportunity to reduce crude steel demand and emissions.

BEST AVAILABLE TECHNOLOGIES

Best Available Technologies (BAT) mainly refers to proven technologies and processes available at commercial scale that transform waste heat to useful energy, thus lowering the energy intensity of the steelmaking process. Examples of BAT for integrated BF-BOF plants include:

- Waste heat recovery systems, which collect excess heat for use within the steelmaking process or for export outside the steel plant;
- Coke dry quenching systems, which recover heat from coke ovens to generate electricity and/or lower coke oven fuel consumption; and
- Top-pressure recovery turbines, which generate electricity from blast furnace gas heat.

Operating BF-BOF plants can be retrofitted with the current BAT to immediately lower steelmaking footprints. In fact, to align with the IEA's Iron and Steel Technology Roadmap, nearly all operating integrated steel plants must be equipped with coke dry quenching systems and top-pressure recovery turbines by 2050, in addition to implementing best operating practices. In the NZE, BF capacity is reduced and by 2050 nearly all remaining blast furnaces (primarily those in regions with young fleets today) are equipped with CCUS.

A 2019 report led by the OECD found that BAT standards must reach net-zero by the mid 2030s in order for the iron and steel industry to align with the Paris climate agreement, meaning that BF plants will need to be equipped with CCUS or other low carbon technologies, or transitioned to an alternative innovative steelmaking route such as green hydrogen-DRI. This will require commercialization and increased affordability of new steel making technologies (see section *Development of novel, low-emissions steelmaking processes*).

BEST OPERATING PRACTICES: THE UNTAPPED POTENTIAL OF DIGITALIZATION

One major opportunity to improve steel plant performance is through the enhanced digitalization of process controls, which means using sensors and machine learning algorithms to provide real-time and predictive feedback on process operations. Enhanced digitalization can improve steel plant performance in a variety of ways including reduced process down time (minimizing thermal losses with less frequent unit shutdowns/startups), optimized feed mix ratios, and "smart" maintenance schedules. At integrated BF-BOF steel plants, digitalization is particularly effective at lowering energy intensities through the optimization of process gases by using computer-controlled calorific value control systems to reduce off-gas flaring and emissions.

Digitalization solutions that reduce steelmaking energy intensities are readily available and relatively inexpensive, and provide significant co-benefits like improved customer service and inventory management, while also saving on operating costs.

Both government and industry leaders recognize digitalization as an important tool for improving plant efficiency. However, a recent study of major steel companies found that while 78% have launched a digital program, 68% of the companies with digital programs launched less than 3 years ago and 75% have not successfully scaled up from pilot programs, illustrating the untapped potential of digitalization in the steel industry.

The main barriers to implementing enhanced digitalization in the steel sector appear to be organizational rather than technical or financial. Recent studies of the European steel industry found that stakeholders are most worried about how digitalization will affect job security, personnel training, and internal management, with technology performance and financial returns being of less concern to stakeholders.

Thus, the key to implementing best operating practices and lowering energy intensities at steel plants may be cultural and behavioral shifts achieved through workforce education and training programs.

STEEL AND GLOBAL DECARBONIZATION GOALS

There is 2,010 mtpa of steelmaking capacity on the globe for plants with capacity of at least 1 mtpa, according to the GSPT. Of this capacity, 75% (1,503 mtpa) is located in countries that have pledged to be carbon neutral by 2050, with China and Kazakhstan by 2060 (see Appendix 2 for full list). In addition, at least 16 companies comprising 24% of global steelmaking capacity in the GSPT (491.6 mtpa) have pledged to be carbon neutral by 2050. While most of these companies are located in countries with carbon neutrality pledges, they also include JSW Steel and Tata Steel of India, BlueScope Steel of Australia, and Metalloinvest of Russia.

The combined country and company pledges means that over three-quarters of the world's steelmaking capacity should be on course to hit net zero carbon emissions by 2050 to 2060. These pledges cover over 85% of the world's BF-BOF steelmaking capacity (Appendices 1 and 2), the most difficult to decarbonize steelmaking process.

Below we assess country-level progress toward decarbonizing their steel sectors, and evaluate what actions can be taken through 2030 to put the countries on the road to net zero steel, in line with the IEA roadmap.

INTERNATIONAL EFFORTS TO DECARBONIZE STEEL

On June 2, 2021, the Clean Energy Ministerial announced the launch of the Industrial Deep Decarbonization Initiative (IDDI), which aims to develop a global strategy for steel decarbonization by 2050. One of IDDI's primary strategies is to create market demand for low-carbon industrial materials like steel through green public procurement commitments. IDDI estimates that public construction accounts for around 25% of global steel use, meaning that widespread implementation of green public procurement policies could apply low-carbon steel production standards for a significant share of global steel capacity.

IDDI has set the goal of securing public procurement commitments for low-carbon steel from at least ten governments within three years, with the first set of government green public procurement commitments at the 2021 United Nations Climate Change Conference (COP26) in November. While IDDI members currently include the UK, India, Germany, Canada, and the UAE, each of the countries explored in this report (China, India, Japan, the US, South Korea, and the European Commission) are members of the Clean Energy Ministerial.

Other international efforts to decarbonize the steel industry include initiatives from industry and civil service organizations such as SteelZero, a net zero steel procurement pledge organization, and ResponsibleSteel, a steel standard and certification initiative.

China central to global steelmaking decarbonization

China is home to over half of the world's steel-making capacity, and over 60% of global carbon emissions from steel plants. According to the Global Steel Plant Tracker (GSPT), steel plants in China account for 51% of the world's steelmaking capacity (1,023 mtpa of 2,010 mtpa), though additional unreported operating capacity may make China's share of global capacity as high as 58%.[26] Hebei province, for example, reported 250 Mt of steel production in 2020 but only 200 mtpa of steelmaking capacity (the GSPT has identified 253 mtpa of operating steelmaking capacity for Hebei, above the province's official number but likely still below actual operating capacity, given the 250 Mt production level).

About 77% (790 mtpa) of China's operating steel capacity is BF-BOF steelmaking, a significantly more carbon-intensive and difficult to decarbonize steelmaking process than EAF steelmaking. Over 80% of BF-BOF steelmaking capacity in China was built after the year 2000, giving blast furnaces in the country an average age of just 12 years, compared to an average lifetime of 40 years and investment cycle of 15–20 years. In China, blast furnaces are not just part of integrated BF-BOF steelmaking, but also provide an estimated 45% of the feedstock for the country's EAF facilities, rather than lower emission DRI or scrap metal.

Despite the relatively young age of China's steelmaking fleet and its reliance on carbon-intensive blast furnaces, President Xi Jinping pledged in September 2020 that China will aim to reach net-zero emissions before 2060, and peak CO_2 emissions "before 2030." These pledges set the groundwork for decarbonization of the country's energy system, including steelmaking, which currently comprises 15% of the country's CO_2 emissions (1.5 of 10 Gt).

Before Xi's carbon neutrality pledge, the central government had introduced some measures to lower emissions from steelmaking, including identifying and shutting down the most highly-polluting and often illegal steel mill operations. In 2019 the Ministry of Ecology and Environment also vowed that 60% of China's steel capacity would complete facility upgrades to be more efficient and less polluting by the end of 2020, reaching 80% by 2025. Yet by November 2018, only 30% of targeted operating capacity had reportedly been upgraded. Additionally, operating steelmaking capacity still exceeds the national 1,000 mtpa limit that the Chinese government had set for 2020; in fact, even China's national steel production exceeded the capacity limit, reaching 1,053 Mt in 2020.

Much like the country's large coal plant build-out, provinces have often relied on steel plants to hit economic targets and create jobs, bolstered by central government lending to grow the national economy, particularly for steel-heavy infrastructure. As a result, steel production in China has been on the rise since 2015. In December 2020, the Minister of Industry and Information Technology said that China will reverse this trend and ensure crude steel output falls in 2021. Yet this statement is at odds with the China Metallurgical Industry Planning and Research Institute, which said it is expecting another increase in steel production in 2021, to 1,070 Mt.

The diverging views over China's future steel production shows the fundamental tension between Beijing's goals to lower its carbon emissions, and the fact that carbon-intensive heavy industry—particularly steel—has played a central role in China's economic growth, including domestic stimulus spending. However, the pressure for domestic stimulus may only grow as the China steel industry faces the prospect of reduced

26. In 2020, China's total operating steelmaking capacity was estimated to be as high as 1,350 mtpa (1,000 mtpa legally operating capacity and an additional 350 mtpa operating capacity in excess of the government's capacity control targets), based on government reports of total output and utilization. Our estimate is lower given (1) we exclude operations below 1 mtpa, and (2) many steel mills are still believed to be operating illegally in China, making them difficult to track.

steel exports from measures such as the EU carbon border adjustment mechanism, which would apply carbon taxes to imports from countries that do not have equivalent carbon pricing or emissions targets, including steel.

In December 2020, the Ministry of Industry and Information Technology released the “guiding opinions” for the upcoming five-year plan that called for steel sector CO_2 emissions to peak ahead of the targeted national peak, or “before 2030.” The draft five-year plan is currently being prepared and reportedly includes targets for steelmaking CO_2 emissions to peak before 2025 and achieve a 30% reduction from the peak by 2030, reducing CO_2 emissions from the steel industry by an estimated 420 Mt.

To meet the 2030 reduction in emissions, the Ministry has called for increasing EAF steelmaking from scrap metal, requiring a transition away from the country’s predominant BF-BOF steelmaking. Yet according to the GSPT, BF-BOF makes up 93% (39 mtpa) of steelmaking capacity under construction in China, compared to 7% (3 mtpa) for EAF steelmaking (among plants with capacity of 1 mtpa or greater). Over half of the BF-BOF capacity under construction is in just two provinces: Hebei (31%) and Shandong (23%). The dominance of proposals in these provinces is notable given that Hebei has pledged to scale back its steelmaking capacity by 14 Mt, and Shandong by 22 Mt. Jiangsu and Fujian account for an additional 15% and 13%, respectively, of the remaining BF-BOF capacity. The EAF capacity under production is shared between Guangdong and Sichuan, which each have one EAF plant of around 1.5 mtpa under construction (see Table 4).

In 2021, China’s top steelmakers by capacity, HBIS Group and Baowu Group, each pledged to reduce its emissions 30–35% by 2035 and be carbon-neutral by 2050. Despite their pledge, both countries continue to propose and build new BF-BOF steelmaking capacity. Yet HBIS Group is also planning to open this year a 0.6 mtpa DRI plant using Energiron technology, which allows for a mixture of 70% hydrogen and 30% coke oven gas to be used as the reducing agent.

To meet the more immediate goals of the IEA roadmap for industrial decarbonization, China will need to radically ramp up its identification and closure of excess steelmaking capacity, specifically higher polluting BF-BOF plants; accelerate its retrofitting of remaining BF-BOF capacity with best available technologies; and ensure future steelmaking capacity is scrap and DRI-based EAF, which presents greater options for electrification and decarbonization.

Table 4: Steel plants under construction in China

Province	Capacity	Number of plants	Steelmaking technology
Fujian	4,945	2	BF-BOF
Guangdong	1,200	1	EAF
Hebei	12,000	4	BF-BOF
Henan	1,750	1	BF-BOF
Inner Mongolia	2,700	1	BF-BOF
Jiangsu	5,850	1	BF-BOF
Shandong	8,850	2	BF-BOF
Sichuan	1,500	1	EAF
Yunnan	2,980	1	BF-BOF

India's renewables-based path to decarbonization

According to the Global Steel Plant Tracker (GSPT), India has 90.1 mtpa of operating steelmaking capacity, behind only China (1,023.7 mtpa) and Japan (117.1 mtpa). The make-up of India's operating capacity is 63% BF-BOF (56.7 mtpa), 24% EAF (21.8 mtpa), and 3% OHF (2.5 mtpa), with the remaining 10% (9.1 mtpa) a combination of the three. The country's BF-BOF capacity is a mix between older plants, such as the IISCO steel plant first built in 1918, and newer plants, like the Kalinganagar steel plant built in 2016. In 2020, the steel sector in India emitted 242 Mt CO_2, a 35% share of India's industrial CO_2 emissions and a 33% increase from 2010 (183 Mt CO_2).

From 2015 to 2019 steel production in India was on a continual rise from 89 to 111 Mt, before falling to 100 Mt in 2020 due to a slowdown from the Covid-19 pandemic—a slump that is not expected to last. In fact, steel production in the rapidly industrializing country is projected to quadruple by 2050. Given the anticipated rise, and as the country with the second highest steel production on the globe behind China, India's efforts are vital to decarbonization of the global steel industry.

India is unique in that it has a large amount of DRI capacity (52 mtpa) that is primarily powered by coal rather than natural gas. DRI is an iron production process that strips oxygen from iron ore through reducing gases (usually natural gas or coal-based syngas), with additional processing (typically EAF) needed to transform the iron into steel. While natural gas-based DRI has an average CO_2 intensity below BF-BOF production, the average CO_2 intensity for coal-based DRI-EAF in India is higher, giving India one of the largest average carbon intensities per tonne of steel produced on the globe (see Table 2). Due to the high ash content of India's domestic coal, the vast majority (90%) of its coking coal for steel production is imported, making the country captive to external swings in fuel prices. However, unlike the BF-BOF production method, emissions from DRI can be more easily eliminated by swapping out fossil fuels with renewables-based hydrogen as the reducing gas, meaning India is arguably better situated than many countries for decarbonization of its steel sector.

Although India has not committed to reaching net zero emissions, nor specified individual commitments for the steel sector in its Paris climate pledge, its government has implemented a plan to reduce energy use in the steel sector through the Perform Achieve and Trade (PAT) scheme, which currently covers a total of 158 iron and steel assets. The first cycle of the PAT scheme achieved 2.1 million tonnes oil equivalent (mtoe) energy savings from India's steel industry which consumes 25.3 mtoe annually. One of the primary strategies for the PAT scheme is the application of best available technologies (BAT), such as waste heat recovery and flue gas recycling, to older and inefficient steel plants. Recent estimates by India-based The Energy and Resources Institute (TERI) found that the average steel plant in India could lower its energy consumption between 24 to 38% through adopting BAT.

India's government has also laid out an ambitious renewable energy source (RES) target of 175 GW by 2022 and 450 GW by 2030. While not directly aimed at steel, the RES target does pave the way for decarbonization of the country's steel industry. In the short term, a power sector with a greater share of renewables can lower the CO_2 intensity of the country's electricity-powered EAF facilities, which make up 24% of its operating steelmaking capacity in the GSPT. Over the longer term, a greater share of renewable power can pave the way for replacement of India's coal-based DRI with renewables-based hydrogen DRI, which has near-zero emissions.

In short, the Indian government could help align its steel sector with the Paris climate agreement by achieving its RES targets and immediately strengthening energy efficiency and conservation measures in the steel sector. Commissioning large amounts of renewable power capacity, in turn, could lower the carbon intensity of its EAF facilities and pave the way for replacing the country's coal-based DRI with hydrogen. In addition, reducing the steel sector's demand for materials and energy, and lessening its reliance on financially volatile coal prices, could help reduce industry costs. Already, India's largest private steel companies are moving toward decarbonization: JSW Steel and Tata Steel Europe have committed to be carbon-neutral by 2050, with JSW Steel aiming to cut its carbon dioxide emissions more than 40% by 2030 (below 2005 levels).

Can the EU policy engineer its way to green steel?

The European Union 27 has 157.6 mtpa of operating steelmaking capacity, according to the Global Steel Plant Tracker (GSPT). Of this, 69% (108.2 mtpa) is BF-BOF and 30% (46.8 mtpa) is EAF. The EU also has hundreds of mini steel mills with capacity under 1 mtpa that are not included in the GSPT, meaning total operating capacity is larger and the share of EAF capacity is likely higher. About 55% of operating capacity in the GSPT is located in just three countries: Germany (44.6 mtpa), Italy (26.9 mtpa) and Spain (15.7 mtpa). EU steel production was 159 Mt in 2019, 8.5% of the global total.

In December 2019, all EU member states except Poland formally endorsed the goal of domestic climate neutrality by 2050. In December 2020, the European Council also voted to decrease the EU's economy-wide GHG emissions 55 per cent by 2030 (relative to 1990 emissions of 5,720 $MtCO_2e$). For the industrial sector, the European Commission estimates that industrial emissions should be reduced by 168 and 188 $MtCO_2e$, about 12 to 14% below the EU's 1,359 $MtCO_2e$ of industrial emissions in 1990.

The lower percent target for industry reflects the fact that most immediate emission reductions are planned for the power sector, given the widespread availability in that sector of low-carbon, cost-competitive alternatives like solar and wind power, whose prices continue to decrease. Industry, in turn, is expected to lower the bulk of its emissions with novel technologies and widespread electrification powered by a low-carbon grid. To meet the emission reductions for industry through 2030, the European Commission suggests using best available technologies.

In contrast, the German clean energy think tank Agora Energiewende argues that retrofitting BF-BOF plants with BAT may simply prolong their use far beyond 2050, when the EU plans to be net zero. That is because unlike more newly industrializing countries such as China, the EU has an older iron and steel fleet, with half of capacity due for replacement by 2030 based on average lifetimes. Rather than retrofit, Agora Energiewende recommends that BF units be replaced with DRI and BOF with EAF, as DRI and EAF are more easily transitioned to cleaner production methods. The EU, in turn, is advised to strengthen its climate policies to ensure low-carbon steel technologies are ready and available when old BF-BOF plants are due to be replaced.

EU climate policies include its Emissions Trading System (ETS), which governs about 40% of total EU greenhouse gas emissions. The ETS sets a cap on GHG emissions that is strengthened over time, with anything above the cap requiring the use of emission certificates. The price of emission certificates within the ETS depends on the overall number of certificates put up for auction. In May 2021, the price of certificates reached €56 per ton, a record high and almost double the beginning of the year. The surging price has been attributed to both a post-pandemic recovery and the December 2020 European Council vote to decrease 2030 emissions by 55%, expected to result in stricter annual carbon emission limits with reduced carbon allowances.

ETS revenues are then handed out to EU member states, under the condition that half of the revenues are spent on climate action. About 1–2% of ETS revenues are also allocated to the EU's €30 billion innovation fund for industrial decarbonization projects. The EU Innovation Fund supports the scale-up of novel technologies to demonstration stage, including for iron and steel production. According to the recently launched Green Steel Tracker (June 2021), 31 of the 47 pilot and demonstration projects on the globe are in the EU, suggesting the fund is successfully encouraging innovation above the global average. In May 2021, the EU's largest steelmaker Germany said it planned to spend an additional €5 billion to lower its emissions from steel production, as the country aims to reach carbon neutrality by 2045.

To scale up these demonstration projects, recent estimates have found that a carbon emission price near €70 per tonne of CO_2 could make novel production methods like green hydrogen the most economical option for steel producers. While the current price of €56 a tonne is still too low to incentivize widespread carbon reduction measures, the rate of increase for carbon allowances suggests new green steel technologies could be cost-competitive within this decade, if not the next few years. However, while the ETS includes a cap on emissions from iron and steel production, steel producers have been receiving free allocations of emission certificates, potentially lowering the impetus to shift away from fossil fuels.

The free allocations have been provided under the argument that increasing emission costs will lead producers or buyers to source production from countries with lower emissions standards, resulting in little to no carbon reductions at the global level—an effect known as "carbon leakage". To address the issue of carbon leakage, the European Commission is planning for a carbon border adjustment mechanism (CBAM) to begin phasing in from 2023, which will put a carbon price on imports covered by the EU ETS from countries that do not have equivalent carbon pricing or emissions targets.

Although in principle the CBAM was designed to tax all global steelmakers for their carbon emissions, to date the program appears more interested in protecting domestic steel industry interests than climate change concerns. EU steel producers have lobbied to keep their free emission allowances after the CBAM is in place. In 2021, the European Commission announced that the CBAM will replace the free allowances, yet leaked documents of the CBAM proposal revealed that free allowances will be maintained under a "transitional provision" that has no set time frame for replacing the free allowances. The Commission also introduced provisional restrictions on steel product imports through June 2021, which twelve EU member states have petitioned to extend.

The combined effect of rising carbon prices and decreasing costs for renewable energy and green hydrogen could make hydrogen-based steel production competitive this decade. This would allow for replacement of the EU's aging BF-BOF capacity with cleaner DRI and EAF capacity, and put the region at the forefront of having a clean steel sector. Many of the EU's largest steel producers have pledged to be carbon neutral by 2050, including ArcelorMittal, ThyssenKrupp, SSAB, and Outokumpu, with SSAB planning to offer fossil-free steel as early as 2026.

Japan's excess capacity as green steel opportunity

Japan has 117 mtpa of operating steelmaking capacity (of at least 1 mtpa), according to the GSPT; including plants with capacity below 1 mtpa puts the country's total operating steelmaking capacity at 130 mtpa. Japan is second only to China for operating steelmaking capacity, according to the GSPT, of which about three-fourths (85 mtpa) is BF-BOF. The steel industry is the largest emitter among the country's manufacturing industries, making up 16% of the country's 2019 CO_2 emissions (172 of 1,030 Mt).

The country's dominant BF-BOF capacity is a legacy from its meteoric industrial growth. In the early 1950s, the Japanese government launched a strategy to develop a modern steel sector to act as a core industry for its economic development, supported by measures like tax breaks and export subsidies. Japanese crude steel output increased ten-fold in just 17 years, from 10 Mt in 1956 to 100 Mt in 1973. By the 1970s the country's steelmaking capacity levels were similar to today, and dominated by large BF-BOF facilities fueled by iron ore imports. In 1980, Japanese crude steel production surpassed that of the U.S.

Most of the country's steel production was consumed domestically for construction, as well as to create high-end consumer products such as automobiles and electrical machinery. To supply these consumer products, Japanese demand for crude steel increased from 5 Mt in 1950 to 87 Mt in 1973 to over 100 Mt in 1990.

Yet 1990 turned out to be the peak for demand. Following the Asia financial crisis of the 1990s, Japanese consumption of crude steel decreased from 100 Mt in 1990 to 74 Mt in 2000. In addition, Japanese steelmakers were increasingly competing with steel exports from South Korea and later China.

To improve the competitiveness of large Japanese steelmakers, Nippon Steel and JFE Steel each merged with smaller companies and consolidated in the early 2000s. Today, Nippon Steel is Japan's largest producer accounting for nearly half (56 mtpa) of the country's crude steel capacity, with JFE Steel (38 mtpa) second and making up one-third of national capacity.

Despite the mergers, Japanese demand for steel never rebounded to its pre-crisis levels. The tepid demand has been attributed to stagnant economic growth and a declining population, causing an increased reliance by the industry on steel exports. The economic slowdown from the Covid-19 pandemic only aggravated matters, with Japan's crude steel production falling from 99 Mt in 2019 to 83 Mt in 2020, the lowest level since 1968. Most of the decline was from BF-BOF capacity, with operations temporarily halted at one-third of the country's 25 blast furnaces in 2020.

In 2020, Japanese Prime Minister Yoshihide Suga announced that the country will aim to achieve carbon neutrality by 2050, and for renewables to make up 36–38% of the power mix by 2030. Nippon Steel also pledged to be carbon-neutral by 2050, and JFE Steel "as soon as possible after 2050". In May 2021, Japan's third largest steelmaker by capacity, Kobe Steel, pledged to cut its CO_2 emissions from its steelmaking production process 30–40% by 2030, and be carbon neutral by 2050, through the use of hydrogen reduction ironmaking and greater use of EAFs in its steelmaking.

To address the issue of declining production and excess capacity, Nippon Steel has decided to shut down one of two blast furnaces at its Wakayama Works steel plant in 2021 and one of two at its Kashima Works steel plant in 2024, reducing its production capacity by 20%. The four blast furnaces at these sites range in age from 45 to 60 years old, with one rebuild completed two years ago and the remaining three completed between 12 to 17 years ago. With average investment cycles of around 15–20 years, the decision to close these two blast furnaces shows the company would prefer to shut them down rather than reinvest in them.

Nippon Steel's BF closures are part of its recently announced package of "major structural reforms" that also include the integration of green technologies, such as much larger electric arc furnaces. Japan's Mitsubishi Heavy Industries will soon complete in Austria the world's largest hydrogen-based DRI plant, with a capacity of 250,000 tonnes of steel product a year. And four Japanese steelmakers have partnered on COURSE50, designed to mitigate CO_2 emissions by 30% compared to conventional steelmaking methods, primarily through CCS of blast furnace gas (66% of emission reductions) and hydrogen injection in BF (33% of emission reductions). To date, the pilot project has achieved a 10% reduction in CO_2 emissions through hydrogen injection.

To increase demand for domestic green steel from its large producers, Japan could reposition itself as a supplier of green steel consumer goods like automobiles and appliances. The Japanese government could also require green steel in its infrastructure projects. Since steel makes up a small portion of the total costs of most products, the International Energy Agency estimates that using green steel increases the cost of a mid-sized home by just 0.2% and a mid-sized car by only 0.1%, resulting in negligible increased costs for consumers and taxpayers. Demand for green steel, in turn, will increase the incentives for the country's large steelmakers to shut down polluting BF-BOF capacity in favor of lower-emission iron and steel technologies, as well as cut down on the industry's need for costly iron ore imports.

Japan's steel production has been falling and looks unlikely to rebound. While resulting in short-term losses, the declining production combined with the country's centralized steel ownership and large consumer goods industry gives Japan the unique opportunity to close down excess BF-BOF capacity and situate itself as a green steel supplier.

The U.S.'s policy window for green steel

The U.S. has 84.2 mtpa of operating steelmaking capacity (of at least 1 mtpa), according to the GSPT. Of this, 58% (48.8 mtpa) is EAF and 42% (35.3 mtpa) is BF-BOF. Steel production in the country has been in steady decline, from 102 Mt in 2000 to 88 Mt of steel in 2019, with the bulk of the declines in higher-emission BF-BOF production. This trend is expected to continue as declining prices for steel have hampered the ability of integrated steelmakers to compete with lower cost EAF production, forcing ArcelorMittal and U.S. Steel to idle 4.3 mtpa of U.S. BF-BOF production in 2019.

EAFs began to spread throughout the U.S. in the late 1980s, when plentiful scrap metal supply and new design innovations enabled them to produce steel types that had long dominated by BOFs, such as flat-rolled steel for the power, oil and gas, and automotive sectors. Due to the predominant use of EAF capacity, the U.S. has one of the lowest energy intensities and carbon intensities per tonne of steel produced on the globe. Yet the energy intensity of U.S. BF-BOF steel production is higher than China, due to the older age of the U.S. fleet: the youngest operating BF plant is at the Burns Harbor steel plant in Indiana, which began operating in 1964.

Remaining BF-BOF capacity in the U.S. consists of nine plants owned by three companies, primarily located on the East Coast near old coal and iron ore mines. Of the three companies, only U.S. Steel Corporation has pledged to be carbon neutral by 2050. U.S. Steel built its first EAF facility in 2020, the Fairfield steel plant in Alabama, and in 2019 became partial owner of the Big River EAF plant in Arizona, with plans for full ownership by 2023. The company has also indicated that it will not make further investments in its aging Great Lakes and Granite City integrated steel mills, which have a combined steelmaking capacity of nearly 6 mtpa.

In 2021 newly elected President Joe Biden pledged to reduce the country's greenhouse gas (GHG) emissions 50–52% by 2030, compared to 2005 levels (6,635 $MtCO_2e$). The pledge represents the country's new climate commitment, known as its nationally determined contribution (NDC), as part of officially rejoining the Paris Climate Agreement. While the bulk of emission reductions in the U.S. NDC are planned for the power sector, which is expected to fully decarbonize by 2035, emission declines will also need to take place in the industrial sector, which makes up nearly a quarter of all U.S. GHG emissions. To decrease industrial emissions, the U.S. NDC proposes increased investment in technology demonstration projects, including CCUS and hydrogen. To date, the U.S. is behind other advanced economies in financing these projects, and is the site of just one of 47 projects listed in the Green Steel Tracker (June 2021), compared to 31 projects in the EU. To spur additional projects, more action like the recently announced investment partnership of six U.S. banks led by the Rocky Mountain Institute is needed.

Additional policies to incentivize industrial decarbonization in the country include proposals for government procurement standards for green steel, as federal, state, and city governments are the source for an estimated 50% of U.S. steel product purchases, either directly or indirectly. Such requirements could be built into Biden's proposed $2 trillion infrastructure plan. For U.S. construction projects, federal, state, and city governments accounted for nearly 40% ($692 million) of the $1.8 billion spent in the year 2012 on procurement of steel for private and government led construction projects, according to estimations based on the most recent U.S. Bureau of Economic Affairs data. Steel procurement represents a small share of overall construction project costs—less than 1% of the $75.4 billion that the U.S. Federal Government spent on construction in 2012—meaning that the increased cost of procuring 100% green steel, even with conservative estimates of steel costs 50–80% above conventional steelmaking, would have minor impacts on the overall cost of construction.[27]

Corporations could also require low carbon production and supply chains for what they purchase. Similar to the impact of using green steel in construction, the increased costs for taxpayers and consumers of using green steel in products are estimated to be less than 1% the cost of a typical project, since steel accounts for a small portion of the total cost. For example, the average vehicle uses about 1 U.S. ton of steel. Assuming the pre-pandemic 2019 average hot-rolled coil steel prices of $604 per U.S. ton, and an estimated steel cost increase of 20–80% over conventional steelmaking, using 100% green steel in a typical car would cost the consumer as little as $121 to a maximum of $483, representing just 0.3% to 1.2% of the average cost of a brand new vehicle in the U.S.[28]

According to an analysis by Columbia University, transitioning the country's remaining BF-BOF steelmaking to electrified steelmaking (EAF and scrap metal) will result in cost savings due to the decreased energy demand from EAF compared to other process routes. The study also estimated that steel from green hydrogen and electrolysis would be economically competitive with BF-BOF steelmaking if the price per unit of electricity decreased by 50%—a not too distant prospect if the U.S. decarbonizes its power sector by 2035 with large amounts of wind and solar power, which have much lower marginal costs of production than fossil fuel plants.

The U.S. has reentered the Paris climate agreement and pledged to decarbonize its power sector by 2035. Decarbonization of the power sector, if realized, will increase the cost savings from electrified steelmaking compared to BF-BOF, and help make emerging technologies like green hydrogen and electrolysis cost-competitive. In addition, the increased use of green steel procurement standards, including by the federal government for large infrastructure projects, would further disincentivize the use of the country's remaining BF-BOF capacity in favor of lower emission EAF steelmaking and new, cleaner technologies.

27. Compared to conventional steelmaking, green steel is estimated to cost approximately 20–30% more by 2050, though conservative estimates predict as much as 50–80% additional cost by 2050.

28. Over the past year, the price of hot-rolled coil steel ranged from $460 to $1,500 per U.S. ton, though the upper range of these prices is a record high price nearly triple the 20-year average. Even so, using this range and the estimated cost increase of 20–80% for using 100% green steel, the cost increase in a typical car would be $92 to $1,200, representing 0.2% to 2.9% of the price of a brand new vehicle.

South Korea's green new deal

South Korea has 70.3 mtpa of steelmaking capacity over 1 mtpa, the sixth highest of steelmaking countries, according to the GSPT. Capacity comprises 25.9 mtpa EAF, 17.4 mtpa BOF, and 27.0 mtpa mixed. The country's use of aging BF-BOF capacity gives South Korea one of the highest energy intensities for steel production on the planet, behind only China. South Korean steelmakers POSCO and Hyundai Steel were the country's largest CO_2 emitters in 2019, at 88 Mt and 21 Mt, respectively.

South Korea began developing its first integrated steel mill in the 1960s under the leadership of General Park Chung-hee, who initially came to power under a military dictatorship. Park regarded steelmaking as key to building a modern industrial society. To achieve this, the Pohang Iron and Steel Company was established in 1968, later known as POSCO. The company's first integrated steel plant, POSCO Pohang, began operating in 1973. The plant was built largely with financing and technical assistance from Japan, in part as war reparations and normalization of relations following Japan's occupation of Korea.

By the 1980s Korea's steel exports were competitive with Japan, and South Korea opened another integrated steel plant in 1987, known as POSCO Gwangyang. POSCO Gwangyang went on to become the largest steel plant in the world, with four operating blast furnaces and 23 mtpa of steelmaking capacity.

Funds from growing steel exports allowed the country to finance and build more large, new integrated steel plants, as well as develop high-end products including electronics, cars, and shipbuilding. Domestic steel demand was further boosted by the movement of the population from predominantly rural to urban areas, which increased construction demand. By the mid-1990s, South Korea was the world's sixth largest steel producing country.

Yet while crude steel production grew at an average annual growth rate of 18% from 1970 to 1997, it slowed to 2% from 1997 to 2019. South Korea's steel demand also slowed, particularly following the 2008 global financial crisis, and as of 2021 demand has yet to recover to pre-2008 levels. Three new blast furnaces opened at Hyundai's Dangjin steel plant from 2010 to 2013 only increased the gap between the country's steel production and demand, leading to overcapacity.

In April 2020, the incumbent Democratic Party was reelected, allowing President Moon Jae-in to push ahead with his party's pro-environmental agenda including a 2050 net-zero target. Current government proposals include a carbon tax, 40% renewable power by 2034, and "green new deal" projects such as government funding for renewables and clean hydrogen production.

In December 2020, POSCO pledged to be carbon neutral by 2050, requiring the eventual phase out of its nine blast furnaces. In February 2021, South Korea launched a green steel committee of its major steelmakers with the goal of creating a plan to get the country's steel industry to net zero by 2050. Yet to date most of the country's green steel proposals rely on distant emission reductions through new technology innovation. According to the Green Steel Tracker (June 2021), the country is involved in three green steel pilot projects, all through POSCO, none of which are planned for operation until 2030 or later.

Much like Japan, the South Korean government created a rapidly modernized and urbanized society in part through the aggressive pursuit of steel. Yet the cycle of growth had exhausted itself by the late 1990s, with steelmaking capacity now exceeding demand. Although led by a pro-climate government, South Korean steelmakers appear hesitant to make the immediate changes and investments needed to green the steel sector in line with the Paris climate agreement. Implementation of Green New Deal projects to increase renewable energy deployment and hydrogen production, as well as implementation of a national carbon tax, could help the country phase out its aging BF-BOF capacity in favor of green new steel technologies.

APPENDIX 1

Companies that have committed to be carbon-neutral by 2050

Company	HQ	Total capacity (ttpa)	BOF capacity (ttpa)	Percent BOF capacity
ArcelorMittal	Luxembourg	113,699	72,599	64%
Nippon Steel	Japan	56,488	46,985	83%
HBIS Group	China	53,905	38,112	71%
Baosteel Group Corporation	China	53,520	31,977	60%
JSW Group	India	45,000	10,793	24%
POSCO	South Korea	35,440	19,500	55%
Tata Steel Europe	England	31,400	23,800	76%
United States Steel Corporation	USA	23,747	20,500	86%
Kobe Steel Group	Japan	20,400	20,400	100%
Baotou Steel Group[29]	China	16,500	16,500	100%
ThyssenKrupp	Germany	15,800	14,800	94%
Metalloinvest	Russia	9,100	0	0%
SSAB	Sweden/Norway/USA	8,804	6,400	73%
BlueScope Steel Ltd	Australia	4,505	2,600	58%
Outokumpu	Finland	2,200	0	0%
Liberty Steel	UK	1,092	0	0%
Total capacity		**491,600**	**324,966**	
Global capacity		**2,010,250**	**1,266,118**	
Percentage of global capacity		**24%**	**26%**	

29. Over 93% of the plant is controlled by state enterprises, including the Inner Mongolia Autonomous Region People's Government (controls nearly 77% of plant shares).

APPENDIX 2

Operating steelmaking capacity by country, and the amount and percentage covered by carbon-neutral pledges. Data includes plants of at least 1 mtpa steel capacity.

Country	Total capacity (ttpa)	BOF capacity (ttpa)	Percent BOF capacity	Carbon neutral pledge
China	1,023,671	790,415	77%	Yes
Japan	117,083	85,455	73%	Yes
India	90,125	56,718	63%	
Russia	85,927	16,032	19%	
United States	84,151	35,346	42%	Yes
Korea, Republic of	70,260	17,400	25%	Yes
Turkey	47,970	13,300	28%	
Germany	44,600	35,600	80%	Yes
Ukraine	42,872	27,252	64%	
Brazil	42,200	30,100	71%	
Iran	34,000	5,300	16%	
Italy	26,950	10,000	37%	Yes
Mexico	23,006	2,400	10%	
Vietnam	20,500	17,000	83%	
Taiwan	18,180	15,900	87%	Yes
Spain	15,687	5,000	32%	Yes
Canada	14,000	5,300	38%	Yes
Indonesia	13,700	10,300	75%	
Egypt	13,650	0	0%	
Korea, North	13,500	0	0%	
France	12,000	12,000	100%	Yes
Saudi Arabia	11,700	0	0%	
Malaysia	10,550	0	0%	
United Kingdom	9,500	6,100	64%	Yes
Algeria	7,550	0	0%	
Austria	7,500	7,500	100%	Yes
Belgium	7,500	5,500	73%	Yes
Netherlands	7,500	7,500	100%	Yes
Poland	7,200	6,000	83%	
Australia	6,700	5,200	78%	

Continues on next page

Operating steelmaking capacity by country, and the amount and percentage covered by carbon-neutral pledges. *—continued*

Country	Total capacity (ttpa)	BOF capacity (ttpa)	Percent BOF capacity	Carbon neutral pledge
South Africa	6,400	6,400	100%	Yes
Czech Republic	6,200	3,600	58%	Yes
Argentina	6,200	3,200	52%	Yes
Sweden	4,810	3,800	79%	Yes
Slovakia	4,500	4,500	100%	Yes
Kazakhstan	4,000	4,000	100%	Yes
Finland	3,800	2,600	68%	Yes
Luxembourg	3,400	0	0%	Yes
Thailand	3,300	0	0%	
United Arab Emirates	3,100	0	0%	
Romania	3,000	3,000	100%	
Belarus	3,000	0	0%	
Oman	2,600	0	0%	
Qatar	2,558	0	0%	
Pakistan	2,380	1,100	46%	
Serbia	2,200	2,200	100%	
Singapore	2,000	0	0%	
Libya	1,750	0	0%	
Hungary	1,600	1,600	100%	Yes
Georgia	1,570	0	0%	
Chile	1,500	1,500	100%	Yes
Bulgaria	1,400	0	0%	Yes
Nigeria	1,300	0	0%	
Iraq	1,250	0	0%	
Jordan	1,250	0	0%	
Peru	1,250	0	0%	Yes
Kuwait	1,200	0	0%	
Bosnia and Herzegovina	1,000	0	0%	
Moldova	1,000	0	0%	
Morocco	1,000	0	0%	
Total	**2,010,250**	**1,266,118**		**67**
Total under pledge	**1,503,642**	**1,070,216**		**26**
Percent under pledge	**75%**	**85%**		**39%**