NET-ZERO STEEL
SECTOR TRANSITION STRATEGY

NET-ZERO STEEL INITIATIVE / OCTOBER 2021

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PREFACE

Concrete, steel, aluminium, and chemicals—as well as the trucks, ships, and planes that move them—are the building blocks of the global economy. However, these seven sectors are jointly responsible for 30% of greenhouse gas emissions and, without action, this share is expected to grow.

The mission is clear. Humanity needs to cut emissions by 50% in this decade and reach net-zero emissions by 2050 at the latest to limit the rise in global temperatures to 1.5°C. By 2030, we must see entire value chains committing to and transitioning towards net-zero emissions, and we must have systems in place to reliably track those commitments. The next wave of low-carbon technologies must be brought to market and deployed on a scale that will unlock cost reductions. Simultaneously, industries need to stop investing in and begin retiring carbon-intensive assets.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonise these high-emitting industries. Led by the Energy Transitions Commission, RMI, the We Mean Business Coalition, and the World Economic Forum, our objective is to propel a committed community of CEOs from carbon-intensive industries, together with their financiers, customers, and suppliers, to agree—and more importantly, to act—on the essential decisions required for decarbonising industry and transport. MPP will orchestrate high-ambition disruption through net-zero industry platforms for steel, cement and concrete, trucking, chemicals, shipping, aviation, and aluminium.

The MPP industry platform for steel, the Net-Zero Steel Initiative (NZSI), aims to put the global steel sector on a path to net-zero emissions by midcentury. It brings together high-ambition steel producers—alongside energy and feedstock suppliers, equipment suppliers, and buyers, and in close collaboration with financial institutions and policymakers—to pursue a unique end-to-end supply chain approach to decarbonisation. The Initiative provides a platform for these stakeholders to align on a net-zero transition pathway for the industry and intends to shape a favourable environment to invest in decarbonisation solutions, underpinned by supportive policy frameworks, rising demand for low-emissions steel, and financial flows towards the steel transition.

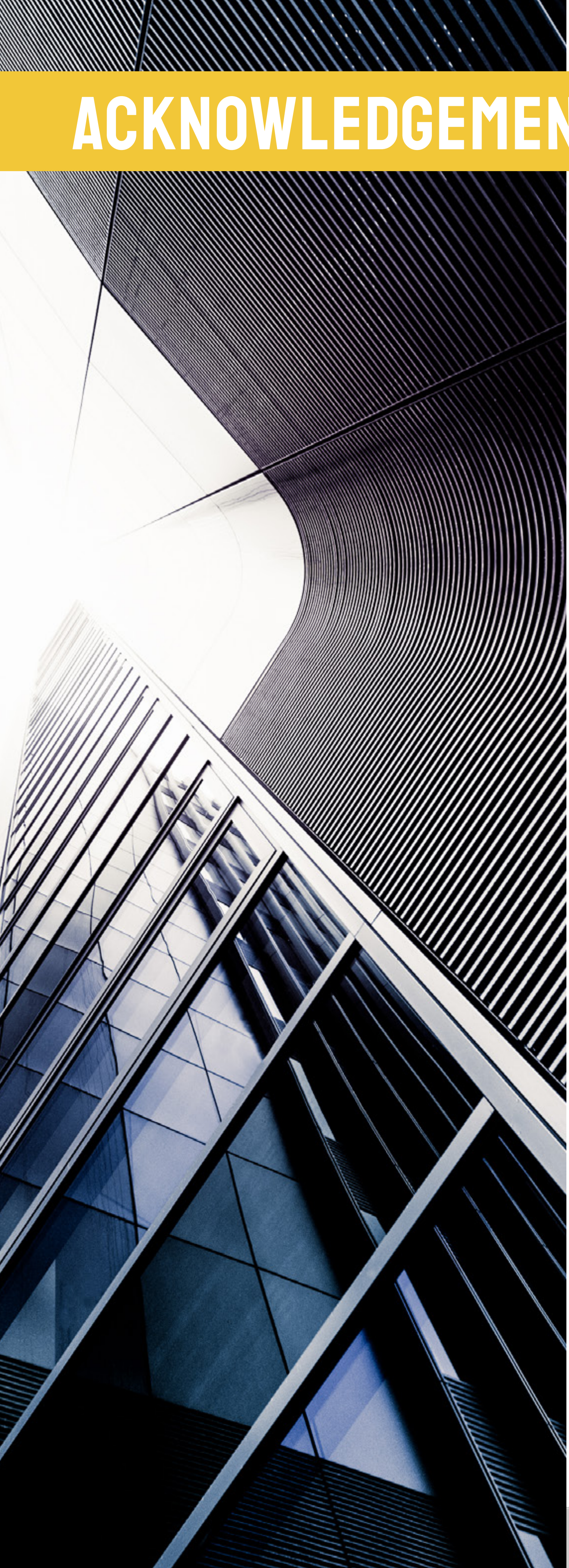
This report sets out an industry-backed and science-based net-zero transition strategy for the steel sector and identifies what needs to happen to enable this future between now and 2050. It is underpinned by the Steel Sector Transition Strategy Model (ST-STSM), which has been developed in close collaboration with steel industry representatives and experts through the NZSI. The transition strategy has three main aims:

- ✓ To provide a detailed reference point for the changes that will be needed over the next 30 years to underpin corporate target setting, Science Based Targets, and financial-sector alignment methodologies
- ✓ To inform priority actions, trade-offs, and decisions in the 2020s by stakeholders who will shape the steel markets, including industry leaders, governments, buyers of carbon-intensive materials, and financial institutions
- ✓ To underpin a coherent set of commitments to actions from stakeholders across the value chain, which together will unlock investment in zero-carbon solutions

The model materials and analytics are open-access to promote transparency and collaboration, such that the inputs and assumptions are available for enquiry, and future iterations may build off this effort. This open-access approach lends itself to regular refinement as data and insights evolve. Critically, it also ensures that the industry can align behind a strategy it considers technically and economically feasible, subject to appropriate value-chain collaboration, finance, and policy support. An accompanying Archetype Explorer provides a tool for stakeholders to start to consider different transition pathways based on individual plant-level circumstances and costs.

Through this work, we hope to inspire and inform an accelerated transition to net zero for the steel sector, including actions—innovation, investments, policy, and procurement decisions—by the broader industry value chain that are essential to support the transition.

ACKNOWLEDGEMENTS



This report constitutes a collective view of the Net-Zero Steel Initiative. Members of the Initiative have validated the model inputs and architecture and endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. These companies agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by midcentury and share a broad vision of how the transition can be achieved. The fact that this agreement is possible between these industry leaders should give decision makers across the world confidence that it is possible to simultaneously meet global steel demand and reduce emissions from the sector to net zero by 2050. It should also provide confidence that the critical actions required in the 2020s to set the sector on the right path are clear and can be pursued without delay, and that the industry is ready to collaborate with its value chain to achieve those goals.

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Led by the ETC, RMI, the We Mean Business Coalition, and the World Economic Forum, the Mission Possible Partnership (MPP) is an alliance of climate leaders focused on supercharging the decarbonisation of seven global industries representing 30 percent of emissions – aluminium, concrete, chemicals, steel, aviation, shipping, and trucking. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030. MPP brings together the world's most influential leaders across finance, policy, industry and business. MPP is focused on activating the entire ecosystem of stakeholders across the entire value chain required to move global industries to net-zero. **www.missionpossiblepartnership.org**

ETC is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C. Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. **www.energy-transitions.org**

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing. **www.rmi.org**

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SUMMARY

Seven Critical Insights on the Path to a Net-Zero Steel Sector

1. More efficient use of steel could materially lower future demand, but large volumes of low-CO_2 primary steel will still be needed out to 2050 and beyond

Steel scrap will play an increasingly important role in decarbonising the sector, both as an input to secondary steelmaking (which is an electrified process and will therefore decarbonise as the power sector decarbonises) and as an input to primary steelmaking that can help lower the GHG intensity of production.[i] Growth in the supply of steel scrap, particularly in China, will see its share of total steel charge composition increase from 30% today to over 40% by 2050, replacing iron ore.

Future demand for primary (ore-based) steel can be further reduced through measures that improve scrap recirculation, productivity of steel use, and material efficiency across steel production and use. If deployed maximally, such measures could reduce crude steel demand by up to 40% relative to business as usual by 2050, avoiding 18 Gt of steel production over the next three decades. However, even with these measures, not all steel demand can be met by recycling scrap. To achieve deep decarbonisation in the steel sector, primary steel production must also decarbonise.

2. This is the critical decade, and both steelmaking technologies and enabling infrastructure will need to be ready in the 2020s

Long investment cycles mean that investments in new or existing steel plants from 2030 onwards should be compatible with a net-zero 2050 objective to avoid stranding these assets. For this to be feasible, several commercial-scale plants using (near-) zero-emissions technologies need to be built this decade to prove them at scale. Delays to the development of critical technologies or to the build-out of zero-carbon hydrogen, electricity, and CO_2 infrastructure would throttle the pace of the sector's transition. Unlocking final investment decisions for first-of-a-kind plants will require policy and value-chain collaboration to make these plants competitive, given they will have operating costs up to 55% higher than conventional steelmaking in the 2020s.[ii]

3. Early progress on steel decarbonisation could unlock 1.3 Gt of CO_2 emissions reductions in 2030, helping to keep the target of limiting global warming to 1.5°C alive[iii]

Incremental improvements in existing steelmaking technology could deliver 15% emissions reductions in 2030 compared to 2020 at little additional cost. But incentivising early switches to technologies with greater abatement potential could achieve much sharper reductions this decade and radically lower cumulative emissions. Up to 1.3 Gt of CO_2 emissions could be eliminated in 2030 (a 37% reduction compared to 2020) if carbon pricing reaching around $70 in 2030, or equivalent mechanisms, were implemented.[iv] Following this faster trajectory would avoid an additional 14 Gt of cumulative emissions by 2050—roughly 3% of the remaining global carbon budget—compared to a second modelled scenario in which action is delayed to 2030.[v] This level of decarbonisation would require a major ramp-up in low-CO_2 steelmaking investments in the 2020s, approaching 280 Mt of annual primary steel production by 2030, equivalent to about 70 (near-) zero-emissions steel plants.

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[i] Primary steel uses iron ore as the main ferrous input, whereas secondary steel is made with mostly steel scrap (i.e., recycled steel).

[ii] Operating costs here include annual capital charges.

[iii] See Keeping 1.5°C Alive: Closing the Gap in the 2020s, Energy Transitions Commission, 2021, https://www.energy-transitions.org/publications/keeping-1-5-alive/.

[iv] All costs throughout this report are in US dollars based on an exchange rate of 0.877 EUR per USD.

[v] Carbon budgets are based on an IPCC estimate of 490 Gt CO_2e from 2020 with a 50% chance of limiting global average temperature rise to 1.5°C (IPCC, 2018).

4. There is no silver bullet for decarbonising steelmaking, but several key trends are likely

A portfolio of solutions is needed to decarbonise steelmaking, as different technologies will be cost-competitive in different locations. Most of today's primary steelmaking is located in places that have historically offered access to coal mines, iron ore deposits, and water and rail transport infrastructure. The transition to net zero will add new location contexts. Access to low-cost zero-carbon electricity, access to carbon capture and storage (CCS) infrastructure and sequestration sites, access to competitively priced natural gas, and proximity to an industrial cluster will shape the technology transition. The exact mix of steelmaking technologies in 2050 will depend on the price dynamics of key commodities, maturity timelines of different technologies, and the evolution of government policy, among other factors. Still, several key trends can be predicted with some confidence:

> **Hydrogen will play a key role in decarbonising the sector.**

Our analysis suggests production technologies using 100% green hydrogen could be responsible for 40%–55% of primary steel production in 2050, utilising 35–55 Mtpa of zero-emissions hydrogen. Hydrogen steelmaking could become competitive with carbon capture, utilisation, and storage (CCUS) technologies when prices for zero-carbon hydrogen hit \$2.20–\$2.90/kg, which we anticipate happening in the 2020s. To compete with unabated steelmaking processes, hydrogen prices would need to reach \$0.65/kg in the absence of carbon pricing or other support, which is not expected to happen by 2050. Supporting the growth of hydrogen-based steelmaking could help drive down the cost of zero-carbon hydrogen production, unlocking its use in a wide range of other industrial applications where direct electrification is challenging. A single steel plant with an annual capacity of 5 Mt could utilise at least 300,000 tonnes of hydrogen, absorbing the output of 5 GW of electrolysers.

> **Steel can decarbonise without large volumes of bioresources, though policies may be required to prioritise their use in sectors with few alternative decarbonisation options.**

Given the limited supply of genuinely sustainable bioresources, their use may need to be prioritised for sectors with few alternative abatement options. Our analysis demonstrates that steel decarbonisation is possible while peaking annual bioresource use at less than 2% of the total sustainable supply globally.[1] The use of bioresources to charge blast furnaces or to replace natural gas in direct reduced iron (DRI) production can help to bring down steel emissions in the 2020s but, barring new technological breakthroughs in steelmaking applications, use is expected to peak in the 2030s as technologies with greater abatement potential become competitive. Bioresource use could increase if biofeedstock is combined with carbon capture and storage (BECCS) to generate negative carbon emissions in locations where excess bioresources are available.

> **Today's dominant technology, the blast furnace, is likely to undergo significant disruption, even if carbon capture technology is retrofitted.**

Retrofitting existing blast furnace-basic oxygen furnace (BF-BOF) technology with CCUS may not be a competitive long-term strategy. As the cost of zero-carbon electricity, and with it hydrogen, declines over the coming decades, DRI-based steelmaking routes using 100% zero-carbon hydrogen will be increasingly cost-competitive compared to fitting a blast furnace with CCUS. Even in locations with favourable access to CO_2 sequestration sites and industrial clusters for CO_2 utilisation, hydrogen-based steelmaking may still be the more competitive option if zero-carbon hydrogen can be delivered below \$1.10–\$2.20/kg, depending on the emissivity of the initial furnace. In locations where zero-carbon hydrogen remains expensive, other carbon capture-based technology routes may offer more favourable economics than retrofitting blast furnaces. These alternatives include smelting reduction with CCS and natural gas-based DRI-EAF (direct reduced iron with electric arc furnace) with CCS.

New roles for the blast furnace may yet emerge in a net-zero economy. Should a bio-based replacement for coke be developed or closed-loop "circular" carbon value chains be established, the blast furnace may prove to be a cost-efficient source of zero-emissions feedstock for the chemicals industry and/or a valuable source of negative carbon emissions. Significant uncertainty remains over the viability of these technologies, the size of the addressable market for captured CO_2, and the availability of sufficient supplies of sustainable bioresources for the steel sector.

> **Direct reduced iron-based steelmaking's share of primary production could grow from 5% today to more than 50% by 2050, with implications for iron ore markets and emissions.**

The direct reduced iron (DRI) steelmaking process using natural gas provides an immediate emissions savings of about 1 tonne of CO_2 per tonne of crude steel (tCO_2/tCS). Switching to DRI from a BF-BOF can help companies reach 2030 emissions reductions targets.[i] These facilities can be set up to utilise a growing share

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[i] Procurement of certified low-methane emissions natural gas will be important, given the potent warming effects of methane emissions, to ensure the reduction in direct emissions is not counteracted by greater supply chain emissions.

of zero-carbon hydrogen as supplies become available or be fitted with CCS technology, either of which can deliver (near-) zero-emissions steelmaking.

Much of the iron ore available today is not of a suitable grade to use in DRI-based steelmaking. If DRI becomes the dominant ironmaking process, as this report suggests, demand would either need to be met through the development of new ore deposits, greater pre-processing of lower-grade ores to achieve sufficient purity, or the development of new melter technologies that enable lower-grade ores to be utilised in DRI-based steelmaking.

> **Demand for metallurgical coal will decline significantly by midcentury.**

The replacement of blast furnaces with DRI-based steelmaking, smelting reduction, and direct electrolysis technologies, which do not require metallurgical coal to reduce iron ore into molten iron, will precipitate a major decline in demand for metallurgical coal. Our analysis suggests demand could be 80%–90% lower in 2050 than today. Use of thermal coal is likely to follow a similar trajectory, though its continued role in smelting reduction technology may see it decline less sharply.

5. All technologies will have residual emissions, which will need to be addressed to achieve net zero by 2050

Even if global power grids fully decarbonise, there will be ~0.3 Gt of residual CO_2 emissions from the steel sector (equivalent to ~10% of the steel sector's emissions today) remaining in 2050, primarily due to expected leakage from carbon capture technology (90% effective capture rate) and electrode degradation in electric arc furnaces (EAFs). These will need to be managed by the industry and may add a significant cost ($70 billion annually from 2050 based on a $200/tCO$_2$ price for direct air carbon capture). Pricing these emissions into decision-making, and developing further technology solutions to lower residuals, will be key to minimising the cost of achieving net zero by 2050.

6. Commercialisation and deployment of (near-) zero-emissions technologies will require major investment both inside and outside of the steel industry

Even without major transformation, the steel sector is projected to need more than $30 billion in investment annually to meet growing steel demand over the next 30 years and maintain existing sites. Transitioning the global steel asset base to net-zero compliant technologies will require an additional $6 billion investment annually. Evaluated in terms of an investment in CO_2 emissions reductions, the 35 Gt of avoided emissions come at a plant-level capital expenditure cost of only $6/tCO$_2$. Initiatives to focus greater flows of capital towards those companies that align with a net-zero pathway will help to accelerate these shifts.

The scale of investment needed in accompanying infrastructure will ultimately dwarf the needs of steel plants themselves. Hydrogen use in the steel sector will grow to 1,200–1,800 TWh/year by 2050, eventually all coming from zero-carbon energy sources. Electricity demands, both to generate sufficient volumes of green hydrogen and to meet the needs of an increasingly electrified asset base, will increase by 11–13 times beyond current levels. This suggests investment of close to $2 trillion (3% of total expected investment in electricity generation, transmission, and distribution in a net-zero economy).[2] In areas where competitively priced zero-carbon electricity is not available, carbon capture facilities will need to scale rapidly, as storage for 440–620 Mt CO_2 per year will be needed before 2050.

7. Net-zero steelmaking will not cost significantly more in the long term, but value-chain and policy coordination will be needed to address competitive distortions in the preceding decades

The average cost of steelmaking in a deeply decarbonised world could be 15% higher than today's high-carbon steelmaking as learning curve effects and expected declines in the cost of renewable electricity and hydrogen take hold. However, a significant "green premium"—the cost difference between high-emissions and low-emissions steelmaking—will need to be bridged in the 2020s and 2030s.

Measures to address this in the short term could include carbon contracts for difference, public procurement, and bilateral premium off-take agreements with major steel buyers. In the medium term, these initial measures may need to be strengthened with both market-based and non-market-based measures, including carbon taxes, emissions trading systems, and emissions performance standards for products. Such measures would be more effective if coordinated across steel producing regions, but the steel sector lacks a global regulator through which discussions on the international challenges of decarbonising the industry can take place. Creating such a forum will be an important first step.

PART 1

Developing A Steel Sector Transition Strategy

KEY HIGHLIGHTS

- ✓ Steel is critical to a low-carbon economy but producing it is emissions-intensive, accounting for 7% of global GHG emissions. Optimising recycled volumes and production processes can deliver substantial emissions reductions. Still, limits to the quantity and quality of available scrap mean that over 50% of steel in 2050 will likely need to come from primary (ore-based) production in the absence of major materials and circularity breakthroughs. Therefore, cost-competitive breakthrough technologies will be critical to either replace coal as a fuel and reductant with a fossil-free alternative, or capture and store the emissions from it.

- ✓ Progress this decade is essential, and steelmakers are stepping forward. Companies representing 20% of global steel production have set net-zero compatible targets. Major steel-producing and -consuming regions, including the EU, United States, South Korea, Japan, and China, are also committed to net-zero targets, leaving little choice but to invest in a low-carbon future for steelmaking. But the necessary investment in low-CO_2 steel production will require a strong business case and policies that take global competition fully into account.

- ✓ Steel can also unlock decarbonisation in other critical sectors. Steel has been referred to as a “hard-to-abate” sector, but these challenges are not insurmountable. Collectively overcoming them would help kick-start numerous other critical transitions in the wider economy, including hydrogen and carbon capture, utilisation, and storage (CCUS) development and major upstream and downstream investment.

- ✓ The transition to net zero will add new variables to location-specific decision-making. Access to low-cost and abundant zero-carbon electricity, access to carbon capture and storage (CCS) infrastructure and sequestration capacity, access to competitively priced natural gas as a transition fuel, and proximity to an industrial cluster will shape the technology transition.

1.1 INTRODUCTION

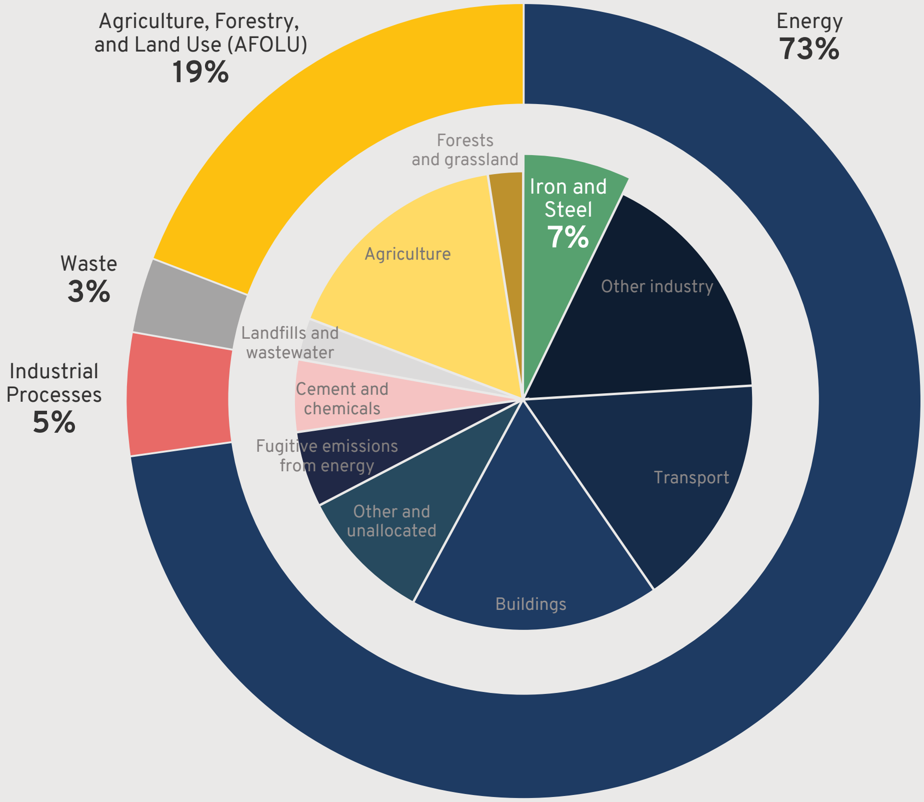
Greening the Steel Sector Is Critical to a Low-Carbon Future

Steel is core to the fabric of modern society. Steel will also be an integral ingredient for the energy transition, serving as a critical material for many technologies that will deliver decarbonisation, such as wind turbines, electric vehicles, and advanced manufacturing processes.

This presents a major challenge for efforts to limit climate change. The steel sector ranks as the greatest carbon emitter of all the heavy industries that provide the basic materials for modern life.[i] Production of both primary and secondary steel emitted approximately 2.6 Gt CO_2 in 2020,[ii, 3] equivalent to about 7% of global emissions (Exhibit 1). As the power sector decarbonises, steelmaking is expected to become the single largest source of industrial emissions.

Global crude steel production capacity has more than doubled over the past two decades. The baseline projection in this report, and those of industry and other experts, sees steel production increasing by a third by 2050 from 1,950 Mt today, driven by growing urbanisation in developing countries in particular. Even with incremental technology performance and material efficiency improvements, such growth will see cumulative CO_2 emissions of 90 Gt by 2050 in the absence of targeted measures and technology breakthroughs. Those emissions are equal to almost 20% of the remaining global CO2 budget for a 50% chance to limit temperature rise to less than 1.5°C.[4]

Exhibit 1. Steel within the context of global greenhouse gas (CO_2e) emissions[5]



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[i] The vast majority of the steel sector's direct emissions are CO_2, as opposed to other greenhouse gases, so decarbonisation in the context of this strategy refers to CO_2 mitigation in the steel sector boundary unless otherwise stated.

[ii] This excludes emissions associated with electricity generation, which account for a further ~1.1 Gt CO_2. The IEA accounts for electricity consumption in final energy terms and emissions from electricity generation as indirect emissions, whereas Worldsteel accounts for it in primary energy terms and attributes these emissions directly to the iron and steel sector. ST-STSM follows the Worldsteel approach to attributing emissions. For a full description of model scope, see the Technical Appendix.

Producing a tonne of crude steel results in 1.4 tonnes of direct CO_2 emissions (scope 1) and 0.6 tonnes of indirect CO_2 emissions (scope 2) on a sectoral average basis.[6] Today, nearly all of the world's steel is made through one of three main production routes:

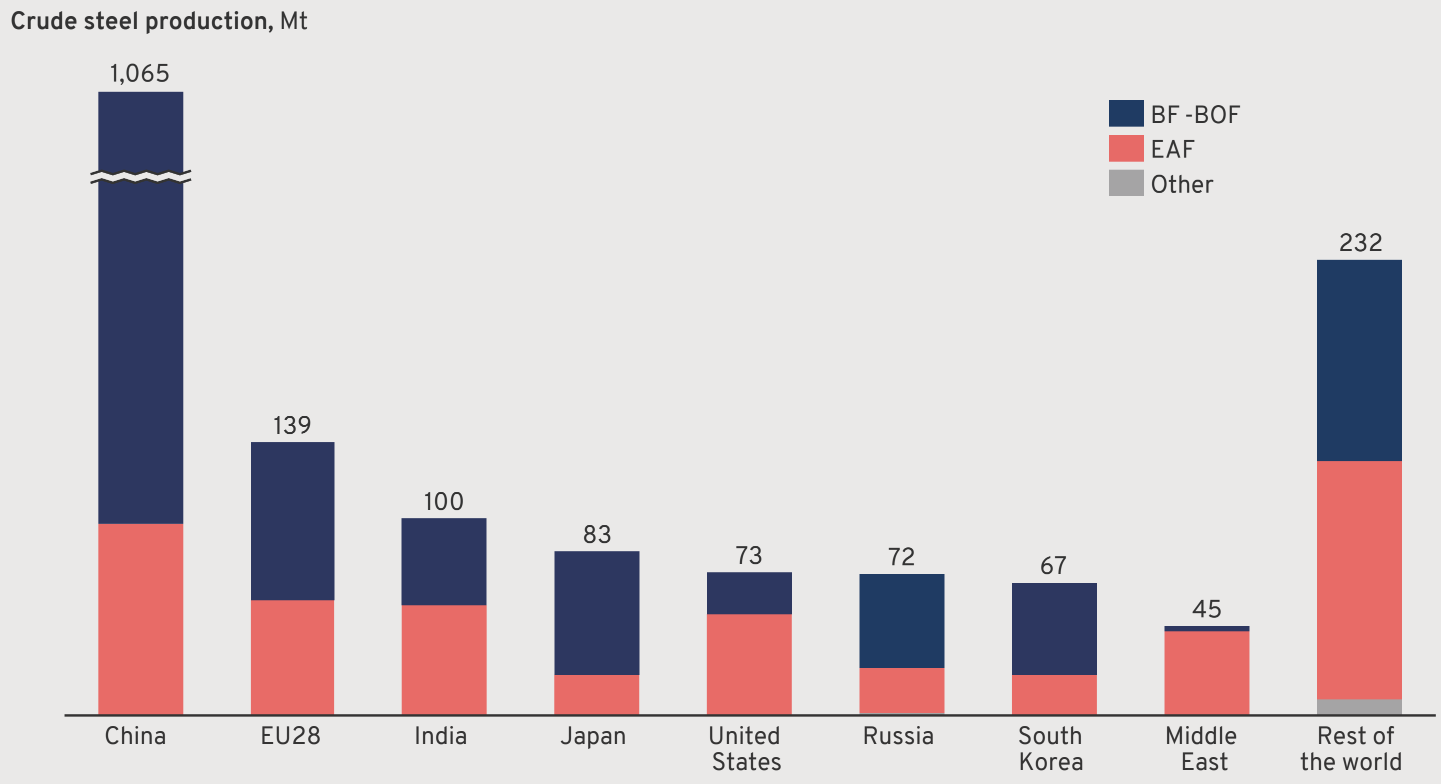
- ✓ **Blast Furnace-Blast Oxygen Furnace (BF-BOF):** Iron ore is reduced in the blast furnace to molten iron, which is subsequently refined to crude steel (CS) in the basic oxygen furnace. The reduction reactions and refining process require temperatures in the range of 1,100°C to 1,600°C, currently achieved with fossil fuel. About 70% of the world's steel is produced via this process, which emits an average of 2.3 tonnes of CO_2 per tonne of crude steel (2.3 tCO_2/tCS).

- ✓ **Electric Arc Furnace (EAF):** The EAF route, accounting for 25% of global production, uses electricity to melt scrap steel. Depending on scrap availability and plant configuration, other sources of metallic iron such as direct reduced iron (DRI) or hot metal can also be used. Emissions are highly dependent on the carbon intensity of the electricity supply but are on average 0.6 tCO_2/tCS.

- ✓ **Direct Reduced Iron-Electric Arc Furnace (DRI-EAF):** Direct reduction is the process of reducing iron ore without melting it, using a reducing gas (typically a blend of hydrogen and carbon monoxide derived from natural gas). The solid product, DRI, is mainly used as feedstock in an EAF. About 5% of the world's steel is produced via this process, which emits 1.4 tCO_2/tCS on average when using natural gas.

The mix of these technologies varies significantly by region (Exhibit 2). The decarbonisation pathway for steel players in North America, where high volumes of scrap have driven growth in EAF capacity, will look different from the pathway in markets such as Europe and China, where primary steel production through the BF-BOF route represents a larger share of production. In locations with abundant and low-cost natural gas, such as the Middle East, DRI-EAF technology typically plays a larger role.

Exhibit 2. Crude steel production by process in 2020[7,i]



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[i] DRI-produced iron is used in both blast furnace and EAF routes and was equal to 106 Mt in 2020.

Steelmakers Are Stepping Forward

Steel producers representing 20% of global primary production capacity, including half of the world's 10 largest producers, have set ambitious climate targets. These targets reflect each company's asset base, technology portfolio strategy, technology commercialisation timings, and location-specific resource circumstances. Major steel-producing and -consuming regions, including the EU, United States, South Korea, Japan, and China, are also committed to net-zero targets, leaving little choice but to invest in low-carbon steelmaking.

This ambition has translated into a growing number of announcements about pilots and demonstration projects for breakthrough low-CO_2 steelmaking technologies. As of June 2021, the Green Steel Tracker has identified at least 25 publicly announced projects developing various breakthrough iron and steelmaking technologies, with the majority concentrated in Europe. However, steelmakers cannot decarbonise the sector on their own.

Exhibit 3. Select global steelmaker climate targets

Steelmaker	Percentage of 2020 global primary steel production	Interim goal	Long-term net-zero goal
China Baowu Group	6.14%*	30% absolute emissions reduction by 2025 (from 2023 peak)	Carbon-neutral by 2050
ArcelorMittal	4.18%	Global: 25% absolute reduction by 2030; Europe: 35% absolute reduction by 2030 (2018 baseline)	Global: carbon-neutral by 2050
HBIS Group	2.33%	30% absolute emissions reduction by 2030 (from 2022 peak)	Carbon-neutral by 2050
Nippon Steel Corporation	2.21%	30% absolute emissions reductions by 2030	Climate-neutral by 2050
POSCO	2.16%	15% reduction in absolute emissions and 30% in emissions intensity by 2030	Climate-neutral by 2050
U.S. Steel Corporation	0.62%	20% emissions intensity reduction by 2030 (2018 baseline)	Carbon-neutral by 2050
Thyssenkrupp Steel Europe	0.57%	30% absolute emissions reduction by 2030 (2018 baseline)	Carbon-neutral by 2050
Tata Steel Europe	0.54%	30% to 40% absolute emissions reduction by 2030 (2018 levels)	Carbon-neutral by 2050
Voestalpine	0.38%	n/a	80% to 95% absolute emissions reduction by 2050
Liberty Steel Group	0.37%	n/a	Carbon-neutral by 2030
SSAB	0.23%	Sweden: 25% absolute emissions reduction by 2025	Global: Fossil-free by 2045
Salzgitter	0.21%	n/a	95% absolute emissions reduction by 2050 without offsets
BlueScope	0.15%	12% reduction in GHG emissions intensity by 2030 (2018 baseline)	Net-zero GHG emissions by 2050

*excludes ongoing Shandong Steel acquisition

Source: Company reports and disclosures

It Takes a Full Value Chain to Decarbonise

Moving from technology validation to commercial-scale deployment of new technologies requires a strong business case for investment, which calls for collaboration across the steel value chain, as well as supportive finance and policy environments. Four challenges, in particular, must be addressed:

1. **Develop (near-) zero-emissions steelmaking processes.** Most steelmaking today is dependent on fossil fuel as a feedstock and energy source. In BF-BOF and DRI-EAF steelmaking, fossil fuels are used as reducing agents (to convert iron ore into iron) and for heat, emitting CO_2 in the process. These fossil fuel inputs also make up the majority of the sector's ~0.7 Gt of scope 3 (supply chain) emissions.[i] The challenge for steelmakers is to find an economic and carbon-free replacement for fossil fuels or to capture and store the greenhouse gases that are generated.

2. **Initiate switching to (near-) zero-carbon steelmaking early to avoid stranded assets.** Large capital financing requirements and long reinvestment cycles narrow the window of opportunity for switching to lower-emissions technologies to achieve net-zero steel by 2050. A blast furnace typically needs relining every 20 years at a cost of hundreds of millions of dollars. There are only one or two investment cycles remaining to align on technologies compatible with net-zero trajectories and avoid stranded assets.[ii] On top of the changes required at steel mills, a major scale-up in zero-carbon energy, hydrogen, and CO_2 infrastructure is required to meet these timelines.

3. **Cover the "green premium" on low-CO_2 steel.** Building and operating low-carbon primary steel production plants will cost more than today's steelmaking in the short to medium term due to higher capital and operating expenditures.[8] Ultimately, the cost increase will need to be borne by end-use markets in the form of higher steel prices.

4. **Level the global playing field.** As steel is a globally traded commodity, investments in emissions reductions must take place while retaining the ability to compete in global wholesale markets, where the majority of steel is traded. Interventions that increase the cost of steelmaking in one geography unilaterally could lead to "carbon leakage," where market share and investment shift to places with lower compliance costs.

This Sector Transition Strategy helps to address these challenges by aligning the steel value chain, financial institutions, and policymakers behind a shared understanding of the critical technologies, milestones, infrastructure, financing, and policies that will be required to reach net zero by 2050.

Steel Can Unlock Decarbonisation in Other Critical Sectors

Steel could provide concentrated demand and certainty of off-take for zero-carbon hydrogen. A single steel plant using hydrogen rather than fossil fuel to reduce iron ore would utilise about 300,000 tonnes of hydrogen annually, absorbing the output of 5 GW of electrolysers.[iii] The growth of hydrogen-based steelmaking could help drive down the cost of zero-carbon hydrogen production, supporting its use in a wide range of industrial applications where direct electrification is challenging.

Carbon capture technology applied to blast furnaces also has the potential to support decarbonisation in other industrial sectors. Blast furnace slag is already utilised as a lower-emissions alternative to clinker in concrete production. Captured CO_2 from the blast furnace could provide a valuable source of carbon for the chemicals industry, replacing virgin fossil carbon. However, for these circular use cases to be compatible with a net-zero economy, it is critical that carbon is only used in products where it will be sequestered long-term, such as in construction aggregates, concrete, and in long-lived or recyclable plastics. Should bioresources be used alongside carbon capture technology, steel could become a source of negative emissions, assuming sufficient supplies of sustainable bioresources were available.

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[i] Scope 3 emissions from steelmaking include upstream emissions from iron ore and energy production, as well as downstream emissions from the transport, manufacturing, and end-of-life treatment of steel. Especially when factoring in methane emissions from the natural gas and coal value chains, upstream energy and commodities production and distribution is the largest piece of scope 3 emissions for the steel sector today.

[ii] An asset is considered "stranded" in this context if it is shut down prior to the end of its useful life due to a lack of economic competitiveness.

[iii] Assuming annual production of 5 Mt of crude steel based on the DRI-EAF technology archetype using 100% zero-carbon hydrogen. Electrolysers are assumed to operate at 33% load factor.

1.2 LEVERS TO DECARBONISE THE STEEL SECTOR

The steel sector can decarbonise by reducing demand for (primary) steel and by changing the way steel is made. Reducing steel consumption and increasing steel circularity is important to remain within planetary boundaries. A High Circularity scenario analyses how far demand could be reduced by those levers. However, reducing demand alone will not eliminate all emissions from the steel sector. The majority of this document will hence focus on reducing emissions by changing the steel production process. Only with those levers can emissions from the steel sector reach net zero.

Reduce Demand and Increase Scrap Recycling

A fundamental shift is ultimately needed towards an economy where prosperity is no longer based on the depletion of finite natural resources.[9] It is therefore essential to assess how total demand for steel could be reduced and whether a greater proportion of demand could be met through secondary (scrap-based) production, which is less carbon-intensive than primary production. With this in mind, two scenarios for future steel demand are modelled: a Business as Usual (BAU) scenario and a High Circularity scenario.

Under BAU, where steel consumption patterns and product life cycles stay relatively consistent, crude steel demand will likely be 30% higher in 2050 than it is today.[i] Much of this growth will be in low-income and emerging economies - India's demand is expected to reach 440Mt by 2050 from 120Mt today - more than offsetting declining demand in China, Europe, Japan, and the South Korea. In the absence of scaled strategies to drive more efficient production, use, and recycling of steel, the sector is on track to use similar volumes of iron ore in 2050 as it does today. Increasing scrap availability, even under BAU, means that the contribution of scrap in the total steel charge will likely grow to 40% in 2050 from 30% today.

Material efficiency strategies could lead to greater emissions savings by reducing demand in the first place. It is less emissions-intensive to avoid producing a tonne of steel altogether than to produce it and later have it available as scrap for secondary production. Some of this change can be driven by the steelmakers themselves, such as through improved metallurgy, but many of the strategies to reduce demand require collaboration with downstream industries or significant behavioural change in society. The demand-side modelling within ST-STSM considers three categories of levers for material efficiency:

Material recirculation strategies increase the collection of end-of-life steel and improve recycling to increase steel reuse and scrap recovery. They include:

- Design for end of life and reuse
- Better systems for collecting and separating end-of-life steel (through logistics and metallurgy)
- Better differentiating of scrap streams by composition—and especially copper content—to reduce contamination and downgrading of steel

Productivity of use strategies increase the utilisation and lifetime of steel in use. They include:

- A shared, service-oriented, and increasingly electric mobility system
- Shared buildings—especially as virtual work and commerce models persist post-COVID-19
- More durable product design to extend product lifetimes

Material efficiency strategies decrease the amount of crude steel needed per product by decreasing steel losses in fabrication and using less steel in each end use. They include:

- Vehicle lightweighting;
- Substitution of steel for other materials and increased efficiency in building construction
- 3D printing and powder metallurgy
- Designing products and processes to minimise fabrication scrap

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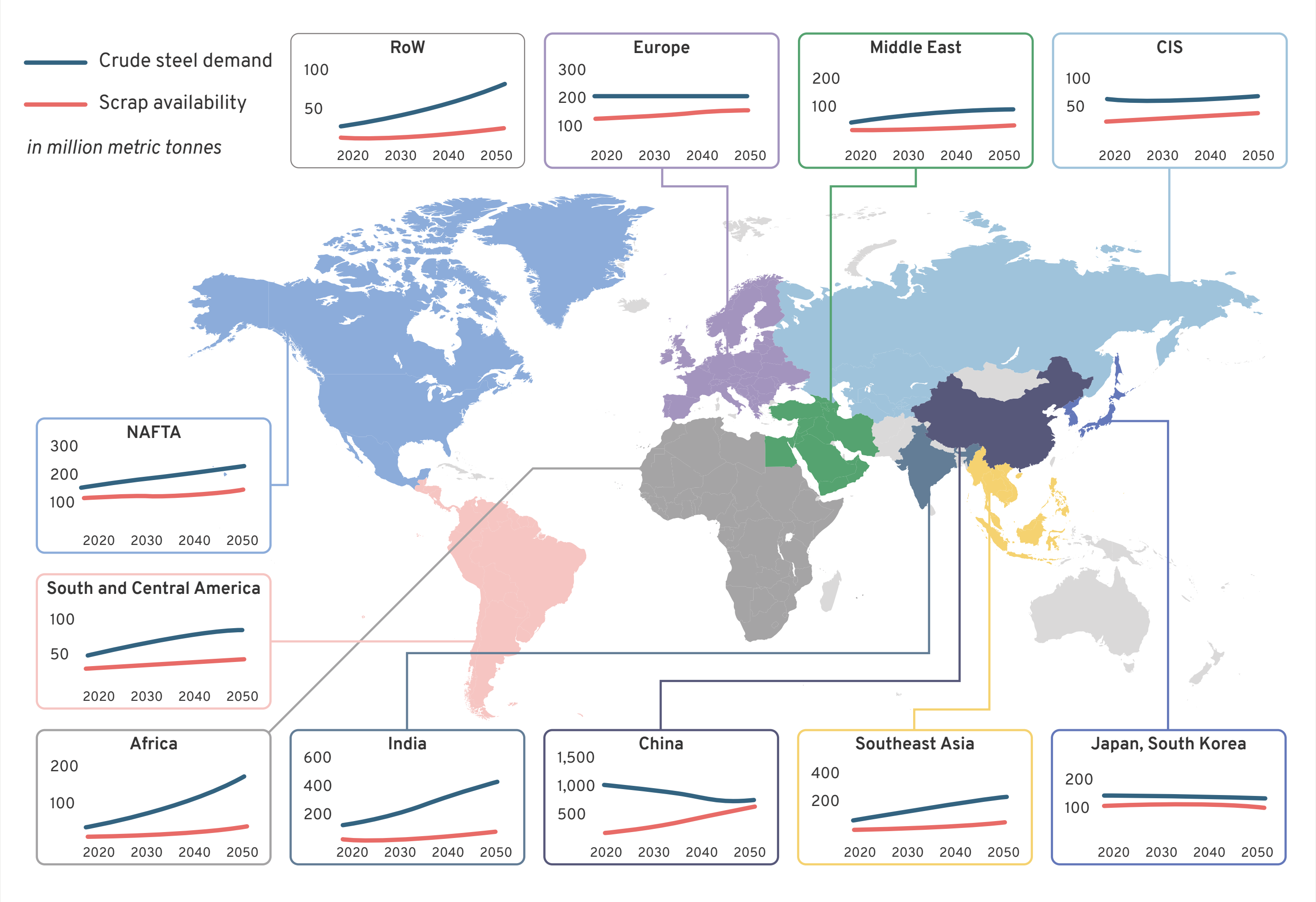
[i] The BAU scenario closely mirrors demand outlooks from other prominent sources, including the IEA STEPS scenario, and was intentionally modelled to represent a near-consensus view.

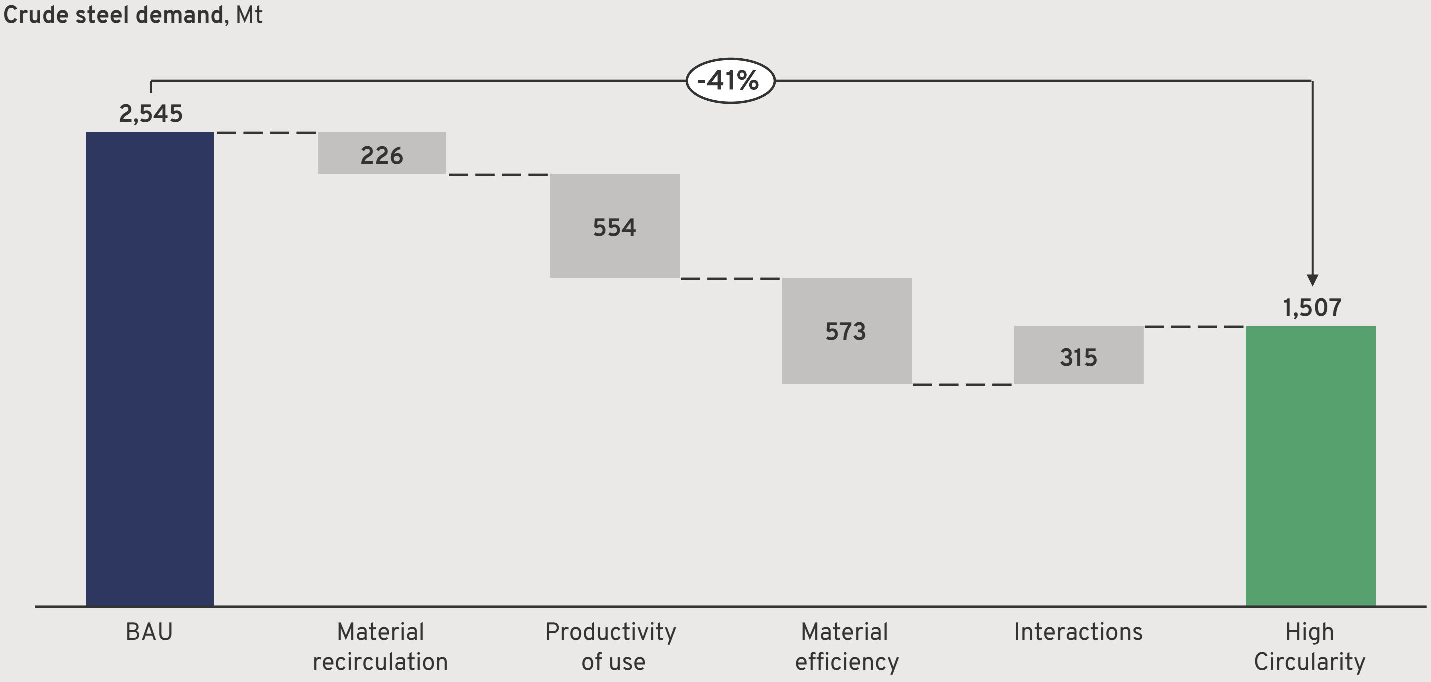
Exhibit 4. BAU demand for crude steel and scrap availability by region



In the High Circularity scenario, these strategies are employed maximally to reduce global steel demand by up to 40% in 2050 against BAU, avoiding 18 Gt of steel production over the next three decades. Scrap's share of total steel charge in 2050 increases from 40% under BAU up to 70%, as lower steel demand and greater scrap recirculation combine to reduce iron ore consumption by 75%. This would avoid 28 Gt of cumulative scope 1 and 2 CO_2 emissions by 2050 at little or no cost to end-consumers. Scope 3 emissions associated with iron ore and coal mining would also decline by about one-third, with further associated environmental benefits to air quality and resource use.

Even in a maximal scenario such as High Circularity, where secondary steel meets up to 70% of projected global steel demand in 2050, limits to the quantity and quality of available scrap mean that decarbonising primary (ore-based) production remains critical to a net-zero future. In India, crude steel demand reaches 300Mt in 2050 under High Circularity. Domestic scrap supply provides only a fifth of that volume, pointing to the need for significant new primary steelmaking capacity. Scrap volumes do, however, have the potential to exceed steel demand in some regions, notably in China, Japan, South Korea, and possibly in Europe. This dynamic has implications for the decarbonisation pathways for steel players in these regions, as scrap-based EAF may have a competitive advantage over ore-based technologies.

Exhibit 5. Circular economy impacts on 2050 crude steel demand in the High Circularity scenario[i,ii]



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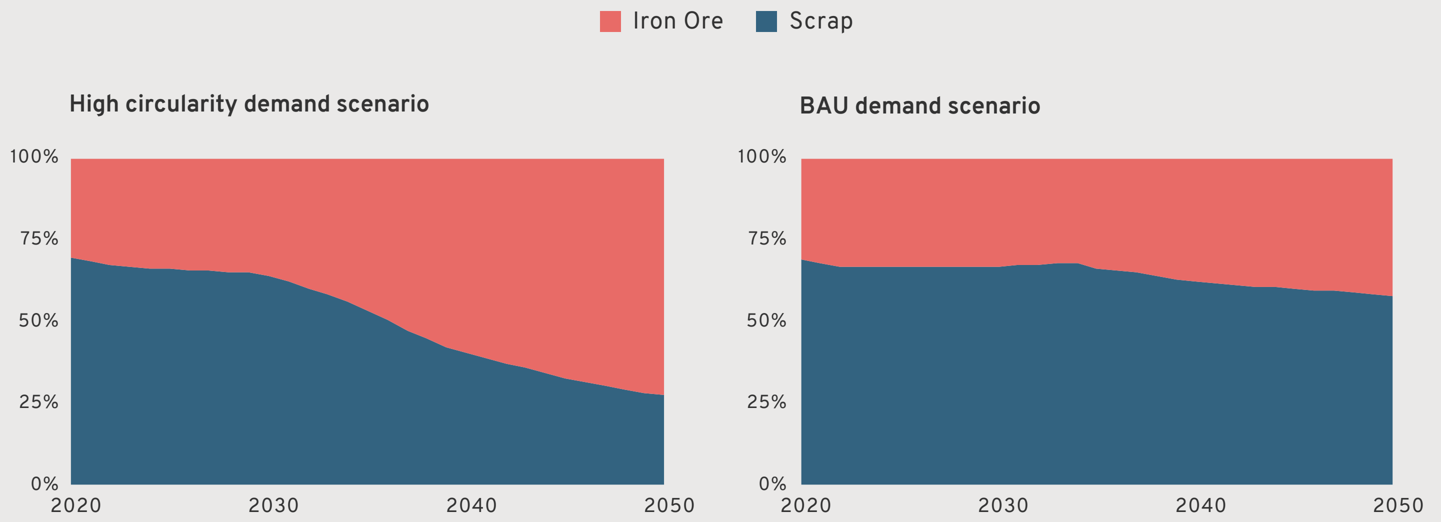
[i] Each strategy has a different rate of uptake and timing of maturity and can be expected to evolve dynamically between today and 2050. These strategies, to varying degrees, are limited by cost, technology readiness, behaviour, and availability of sustainable material substitutes.

[ii] Interactions are the sum of dynamics of linkages between demand levers.

Exhibit 6. Charge composition of iron ore and scrap steel by volume under different demand scenarios



Develop and Deploy Low-Emissions Steelmaking Technologies

Steelmakers can take steps to reduce some of their emissions immediately. These "transitional" steps can include energy efficiency improvements such as top gas recycling, utilising lower-emissions inputs where available (e.g., biogas, biochar), or switching to lower-emissions steelmaking processes (e.g., from blast furnace to DRI). Although these technologies are available today, they cannot eliminate all emissions. To (almost) completely remove emissions, breakthrough steelmaking technologies that utilise zero-carbon electricity, zero-carbon hydrogen,[i] or carbon capture technologies are required.

Collaborative research, development, and deployment initiatives, such as the Ultra-Low CO_2 Steelmaking (ULCOS) program,[ii] have advanced understanding of the possible technology pathways for decarbonising the steel sector. The technologies considered in this report are in Box 1.

There are key decision points that represent critical opportunities to transition to lower-carbon steelmaking technologies. Marginal emissions reductions can be achieved over the course of a plant's operating lifetime, but the most significant (and economic) decarbonisation opportunities come when furnaces near the end of their working life. Refractory relinings are necessary every 20 years, and more major refurbishment occurs every 40 years on average. Half of all steel plants globally are due for their next major investment decision (e.g., relining) before 2030. If technologies compatible with (near-) zero emissions are not available for commercial deployment in time, the industry risks locking in high-emitting technologies for another 20 years or facing costly early closures of steel assets.

Based on expected timelines of technology maturity, eight of the 10 (near-) zero-emissions technologies modelled in ST-STSM are expected to be ready for commercial deployment at or before 2030.[iii] These technologies carry varying degrees of technological uncertainty and, with the exception of scrap-based EAF, have not been tested at commercial scale. Accelerating the deployment of technologies that are nearing technological readiness while continuing to pursue innovations across the full range of potential solutions will ensure that the sector's transition does not rest on any single technology's success. On top of technology readiness, robust policy frameworks and a willingness to finance and pay for low-CO_2 steel will need to be in place to incentivise the switch to (near-) zero-carbon technologies.

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[i] Zero-carbon hydrogen could be produced via the electrolysis of water using zero-carbon electricity ("green" hydrogen) or from steam methane reforming coupled with CCS ("blue" hydrogen). In our modelling, we assume all hydrogen used in steelmaking is green hydrogen.

[ii] ULCOS was a consortium of 48 European companies and organisations from 15 European countries, formed to oversee research and development initiatives that would enable significant CO_2 emissions reductions from steel production.

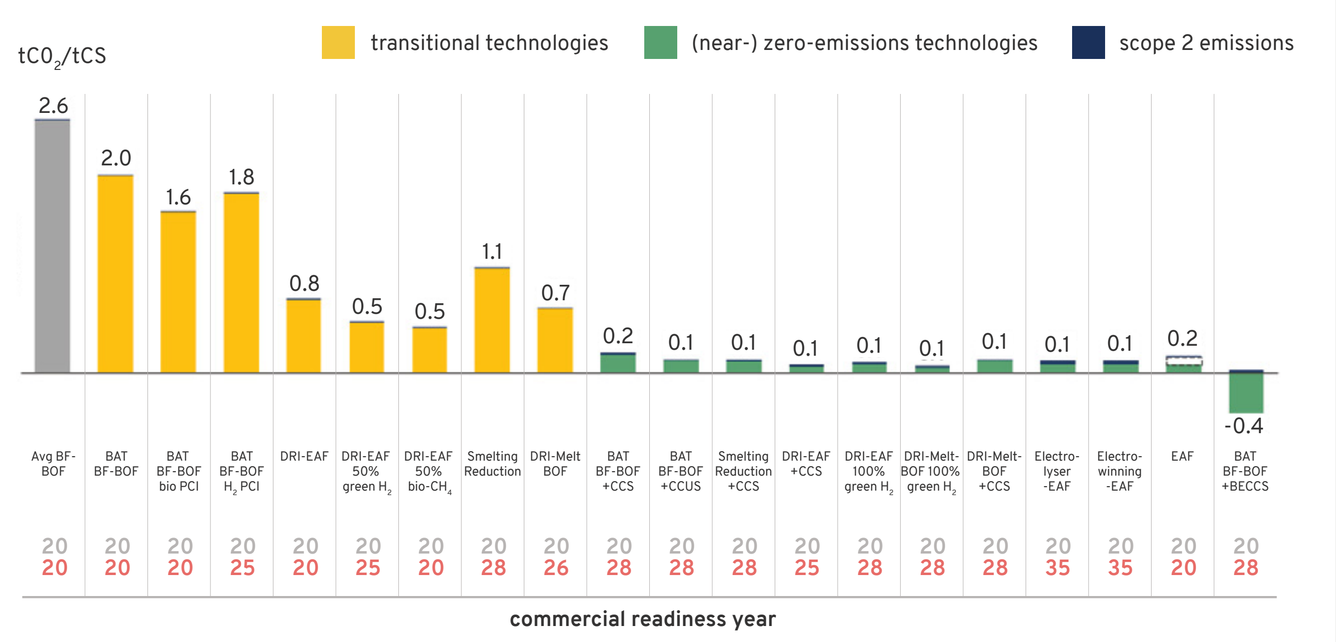
[iii] (Near-) zero-emissions technologies are classified as those with scope 1 emissions equal to or lower than BAT BF-BOF with CCUS. This equates to an emissions intensity of ≤0.2 tCO_2/tCS. The scope 2 emissions of these end-state technologies will also reduce to near zero as electrical power progressively decarbonises.

Box 1. Technology archetypes evaluated on the path to net zero

ST-STSM evaluates 20 steelmaking technology archetypes that are either in use today or expected to become available for commercial deployment prior to 2050. See Table 1 in the Technical Appendix for a detailed description of each technology archetype.

The 10 (near-) zero-emissions technology archetypes are based on zero-carbon electricity, zero-carbon hydrogen, or carbon capture. We consider the use of bioresources as a (near-) zero-emissions technology only when combined with carbon capture, given that bioresource use cannot completely replace fossil inputs in conventional BF-BOF. Carbon capture and utilisation (as opposed to storage) is only considered for BF-BOF, given that blast furnace gases are rich in H_2 and CO, making them suitable for use at large scale as a basic feedstock in organic synthesis.[10] For all other (near-) zero-emissions archetypes, captured carbon is assumed to be directed to storage.

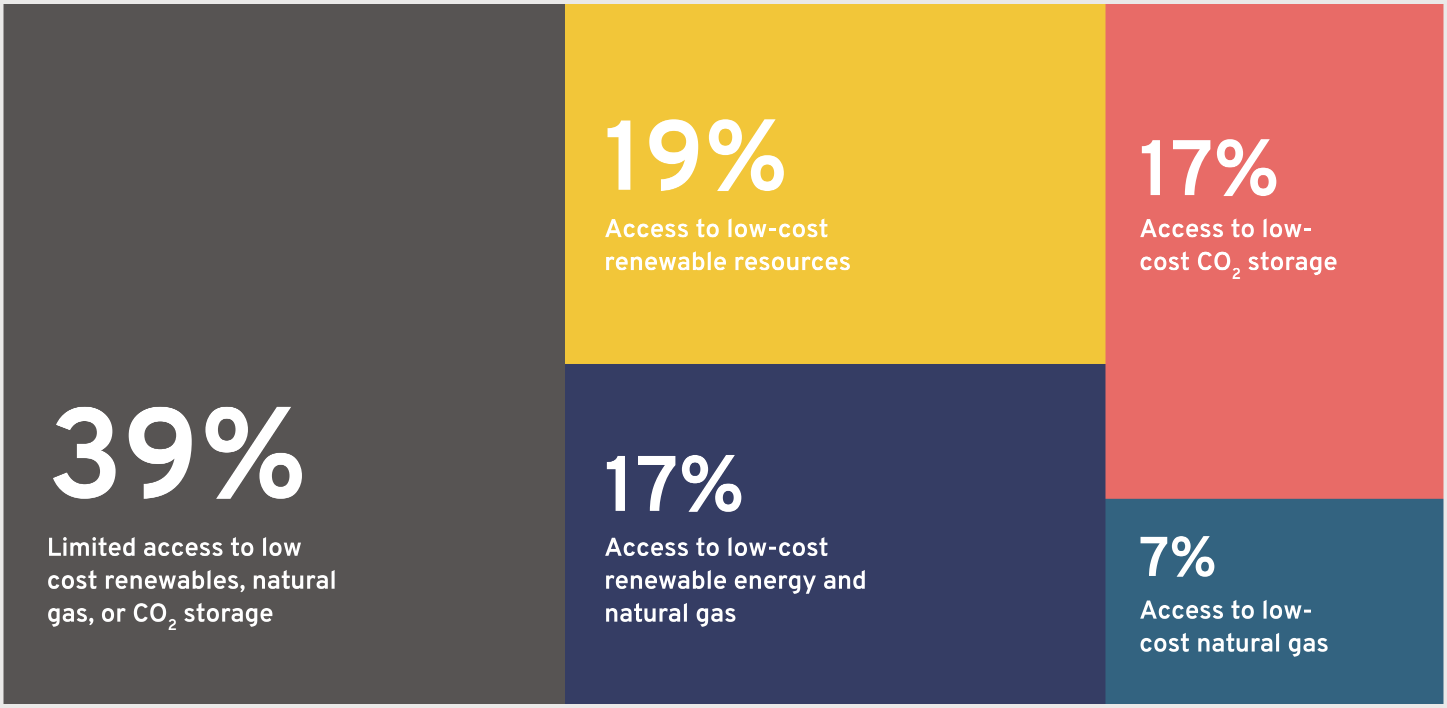
Exhibit 7. Summary of archetypes with associated emissions intensities (scopes 1 and 2) in 2050 and expected commercial availability



The transition to net-zero steel production will not look the same for every company or country, as specific technology choices will be driven by the regional context in which each steel plant operates. Historically, decisions over where to locate plants were driven by their proximity to coal and iron ore supplies. In a net-zero world, the most relevant regional context parameters will instead be the availability and cost of zero-carbon power, natural gas, and carbon storage. Proximity to industrial clusters, and therefore to potential users of waste gas streams, is also relevant when considering carbon capture and utilisation pathways. These context parameters dictate the cost of steelmaking for various technologies and are a vital component in determining a given plant's net-zero transition strategy.

Technologies based on zero-carbon electricity typically prevail where plants have access to low-cost zero-carbon power. Carbon capture technologies, on the other hand, are favourable when plants have access to CO_2 storage or are located near industrial clusters where captured carbon can be utilised as a feedstock for other industrial processes. Regions with low-cost natural gas and low-cost zero-carbon power are well-positioned for near-term shifts to transitional technologies, including DRI-EAF with increasing amounts of zero-carbon hydrogen.

Exhibit 8. Share of global steel plant capacity in 2020 (Mt) by access to regional context parameter[i]



Our analysis suggests that 37% of steel plants are in locations with access to low-cost renewable energy (including locations that also have access to low-cost natural gas), defined as the top quintile of locations globally from the perspective of the average solar PV and wind resource. Nevertheless, as many as two-fifths of today's steel plants may not be located in areas that are optimally suited to low-emissions steelmaking. A significant relocation of steel assets to locations with competitive advantages was considered unlikely by those interviewed for this report, owing to integrated downstream processing infrastructure and skilled workforces that have developed around existing plant locations. Nevertheless, the implications for local economies, jobs, and infrastructure planning would be significant if even a small proportion of those plants chose to relocate to greenfield sites.

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[i] We consider these the regional drivers most relevant to steel sector decarbonisation; however, this list is not exhaustive.

1.3 MODELLING A PATH TO NET ZERO

In this report, we explore potential pathways to reduce steel emissions. The analysis done in the Steel Sector Transition Strategy Model (ST-STSM) is informed by the valuable contributions that precede it, including the ULCOS project, the IEA's *Net Zero by 2050* roadmap, and extensive engagement with NZSI members and steel experts. The approach taken here is shaped by three main objectives:

- ✓ To provide a detailed reference point for the changes that will be needed over the next 30 years to underpin corporate target setting, Science Based Targets, and financial-sector alignment methodologies
- ✓ To inform priority actions, trade-offs, and decisions in the 2020s by stakeholders who will shape the steel markets, including industry leaders, governments, buyers of carbon-intensive materials, and financial institutions
- ✓ To underpin a coherent set of commitments to actions from stakeholders across the value chain, which together will unlock investment in zero-carbon solutions

Open-Access to Drive Actionable Insights

To promote transparency and collaboration, the model materials and analytics are open-access, such that the inputs and assumptions are available for enquiry, and future iterations may build off this effort. This open-access approach lends itself to regular refinement as data and insights evolve. Critically, it also ensures that the industry can align behind a strategy it considers technically and economically feasible, subject to appropriate value-chain collaboration, finance, and policy support. The Archetype Explorer tool that accompanies this report enables users to adjust different parameters in the model to reflect the circumstances faced in a particular geography, supporting real-world decision-making.

Scenarios Rooted in Technical and Economic Feasibility

The *Sector Transition Strategy* sets out two illustrative scenarios to achieve net zero by 2050. The scenarios describe which steel production processes (as shown in Box 1) are used to fulfil steel demand in a given year. They provide insight into the related emissions, energy consumption, and required investments. Both scenarios are based on bottom-up modelling of decision-making on investments at the level of individual steel plants, mapping all existing steel plants around the world and aiming to minimise the total cost of ownership within a given set of constraints.[i] The scenarios rest on two key principles:

1. The uptake of all emissions reductions levers is dictated by costs and technology availability at the point of each major capital investment decision, which traditionally happen every 20 years[ii]
2. Location-based circumstances determine the cost-optimal technology choice via implied local energy prices and availability of carbon storage sites (or utilisation opportunity)

The model differentiates the roles of primary and secondary steelmaking in the transition to net zero, an essential requirement for assessing the progress of individual steelmakers in decarbonising primary production. ST-STSM also provides the flexibility to assess the impact of different assumptions about technology availability, policy interventions, steel demand, and commodity pricing trends on the pace and nature of the transition.

As with any model, ST-STSM is an imperfect representation of the complex decision-making processes at play in the steel sector. It adopts a bottom-up, asset-by-asset approach that evaluates the business case for technology switches, constrained by achieving net zero by 2050. Critically, it is not a market model—it does not consider the price dynamics of fossil fuels in a decarbonising global economy or the impact of different speeds of transition on trade flows between geographies. ST-STSM does not consider the relocation of steel plants to newly competitive greenfield locations. And environmental impacts unrelated to GHGs have not been modelled. Understanding the critical regional dimensions of the steel sector transition will be vital for steel producers and policymakers alike. We will consider these dynamics in future updates.

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[i] Total cost of ownership is calculated based on the total cost of steel production, both capital and operating costs, over the lifetime of the steel plant.

[ii] Given inherent uncertainties over future feedstock and energy costs, as well as the productivity of currently commercially unproven technologies, the model considers a technology to be cost-competitive (and therefore available to be selected) when its total cost of ownership (TCO) is within 10% of the TCO of the most cost-competitive alternative in that location. This mitigates the risk that small differences in TCO between broadly cost-competitive technologies drive large differences in technology uptake.

Two Net-Zero Aligned Scenarios

Two different net-zero aligned scenarios, as well as a baseline, are modelled in the ST-STSM. The net-zero scenarios differ in the modelling constraint applied.

Carbon Cost Scenario

This scenario illustrates how the steel sector might decarbonise if coordinated action to support low-CO_2 steelmaking takes hold this decade. The Carbon Cost scenario assumes that, at each major investment decision, the steel asset switches to whichever technology offers the lowest total cost of ownership (TCO). A carbon cost is applied to each tonne of CO_2 emitted, rising linearly from $9 in 2023 to $250 in 2050. The same cost is applied to all scope 1, 2, and 3 emissions and all geographies.

The carbon cost acts as a proxy for the actions that are needed to close the competitiveness gap between (near-) zero-emissions and conventional steel production processes. Explicit carbon pricing schemes can be complicated to administer and, unless mechanisms are developed to coordinate across steel-producing geographies, uneven compliance costs pose a risk of carbon leakage. A variety of policy and value-chain levers can play an equivalent role to explicit carbon pricing, such as the creation of differentiated markets for low-CO_2 steel, targeted capital and operational expenditure subsidies for the deployment of (near-) zero-emissions technologies, and other regulatory measures that raise the cost of high-emissions technologies.

Tech Moratorium Scenario

The Tech Moratorium scenario takes an alternative approach by confining investments to (near-) zero-emissions technologies from 2030 onwards to reach net zero. As with the Carbon Cost scenario, the steel asset switches to whichever technology offers the lowest TCO at each major investment decision. In the absence of measures to incentivise their adoption in the 2020s, lower-emissions technologies are initially only built where they can compete on cost with conventional steelmaking process. From 2030 onwards, however, it is assumed that steel manufacturers will not be able to reinvest in high-emissions technologies.

With industry average relining cycles of 20 years for steel assets, this 2030 cutoff date ensures that no assets must be prematurely shut down for the industry to achieve net-zero emissions by 2050. This Tech Moratorium scenario could be realised in various forms, including government regulation on environmental standards for new plants, privately driven finance conditions, or industry initiatives that encourage the phaseout of high-carbon investments.

Baseline Scenario

To highlight the consequences of inaction, we also model a reference case in which a steel asset switches to the technology with the lowest TCO at each major investment decision, without a net-zero constraint. Although there is no net-zero constraint, the scenario should not be viewed as business as usual. It relies on the emergence of lower-emissions technologies in line with current expectations, as well as the availability of large quantities of zero-carbon electricity and hydrogen. Rather, Baseline represents the possible evolution of the steel industry in the absence of coordinated policy, finance, and value-chain support, where decarbonisation technologies are only used when and where they are economic.

Exhibit 9. Summary of scenarios modelled in ST-STSM

Scenario	Carbon Cost	Tech Moratorium	Baseline
Optimisation	Lowest total cost of ownership	Lowest total cost of ownership	Lowest total cost of ownership
Constraint	Carbon price starting at $9/tCO2 in 2023, rising linearly to $250/tCO2 in 2050	Only (near-) zero-emissions technology investments from 2030	-
Demand scenario	BAU	BAU	BAU
Achieves net zero	Yes	Yes	No

PART 2

Pathways to Net Zero by 2050

KEY HIGHLIGHTS

- It is technically possible for the global steel industry to reduce emissions by over 90% by 2050 compared to today without stranding existing assets if expected maturity timelines for breakthrough steelmaking technologies can be met. This is the case even if global steel demand grows by a third, as expected.

- Incremental technological progress and efficiency improvements in steelmaking technologies in the Baseline scenario result in 15% lower annual emissions than today in 2030 and 30% lower in 2050, but these changes are insufficient to deliver net zero in the sector.

- Fast and deep emissions reductions are unlikely to be driven by favourable economics alone. Strong policy interventions and supply chain coordination will be needed to support the business case for shifts to (near-) zero-emissions technologies in the 2020s and 2030s.

- A relatively modest carbon price could drive a larger reduction in annual emissions of 37% in 2030, reducing cumulative CO2 emissions from the steel sector by 35 Gt relative to Baseline by 2050. This is equivalent to saving 7% of the remaining global carbon budget for 1.5°C.

- These early investments in emissions abatement would entail a sharper rise in the average cost of steelmaking in the short term ($30/tCS over Baseline in 2030, excluding carbon price) and an additional $12 billion per year in investment above Baseline in the 2020s. At a project level, low-CO2 steel will cost considerably more. For example, zero-carbon hydrogen steelmaking is expected to cost at least $80/tCS more than conventional steel in 2030.

- Should conditions not be in place for significant deployment of (near-) zero-emissions steelmaking over the next decade, net zero could still be in reach if investments were confined to (near-) zero-emissions technologies from 2030 onwards. The consequence of delayed action is much larger cumulative emissions (by 25%), something the IPCC AR6 report makes clear we can ill afford.

- Steel produced using 100% zero-carbon hydrogen accounts for 40%–55% of primary steel production in 2050 under the two net-zero scenarios. The ramp-up in hydrogen production presents a major opportunity for the supply chain, with the steel sector demanding 18–22 Mtpa by 2030 and 35–55 Mtpa by 2050.

- To generate the zero-carbon electricity required for such large volumes of hydrogen and to power electrified steelmaking processes, policymakers will need to plan for a rapid scale-up in electricity generation and transmission capacity. Steelmaking will become more energy-efficient over time, but total electricity use in our scenarios grows 11 to 13 times compared to today.

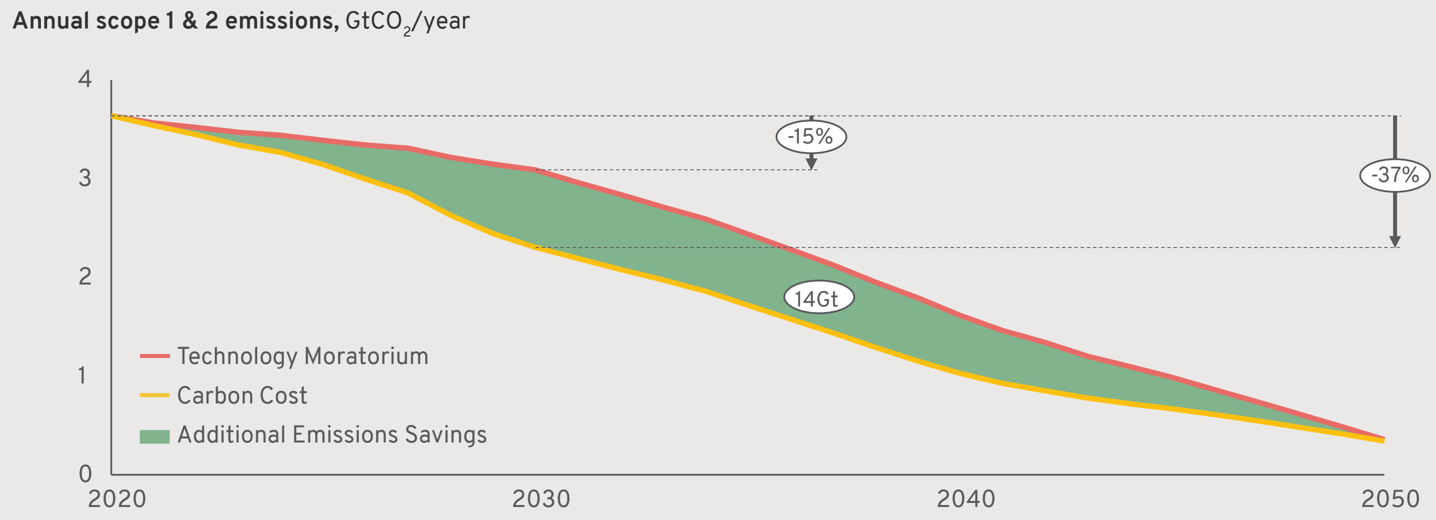
- In tandem, demand for metallurgical coal falls by 80%–90% by 2050, with associated scope 3 emissions savings from mining. This reflects the declining cost-competitiveness of BF-BOF with carbon capture technology relative to other (near-) zero-emissions technologies.

2.1 THE NET-ZERO “ENVELOPE” FOR STEEL

There are various pathways to reach net-zero emissions. The two core scenarios provide a perspective on how a net-zero transition could take place in the steel sector (Exhibit 10). Under these scenarios, the steel sector could reduce scope 1 and 2 emissions by 15%–37% by 2030 and 90% by 2050.[i] Together they form an envelope of pathways meeting net zero in 2050. Each scenario presents different implications for the evolution of steelmaking technologies, emissions, energy requirements, and financing needs, which we explore in detail in chapters 2.2 to 2.5 of this report.

While both scenarios reach net zero, early action is important. Climate change is driven by cumulative emissions in the atmosphere. Deploying breakthrough technologies earlier will raise investment costs and the cost of steelmaking in the short term, but the risks of overshoot associated with failing to act in this critical decade are far greater. Achieving the deeper emissions reductions in the 2020s in the Carbon Cost scenario would save 7% of the remaining global carbon budget between now and 2050 to limit temperature rise to 1.5°C (compared to Baseline).

Exhibit 10. Steel sector carbon emissions by scenario to net zero



2030	CARBON COST	TECH MORATORIUM
Policy framework	$72/tCO_2$	–
Near net-zero technology (% of primary production)	17	1
Electricity demand incl. H_2 production (TWh)	2,075	1,463
Additional investment	$119B	0

2050	CARBON COST	TECH MORATORIUM
Policy framework	$250/tCO_2$	(near-) zero-emissions tech only after 2030
Near net-zero technology (% of primary production)	100	100
Electricity demand incl. H_2 production (TWh)	5,417	4,853
Additional investment	$192B	$215B

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[i] These ranges do not include the implementation of negative emissions technologies to abate residual emissions by 2050.

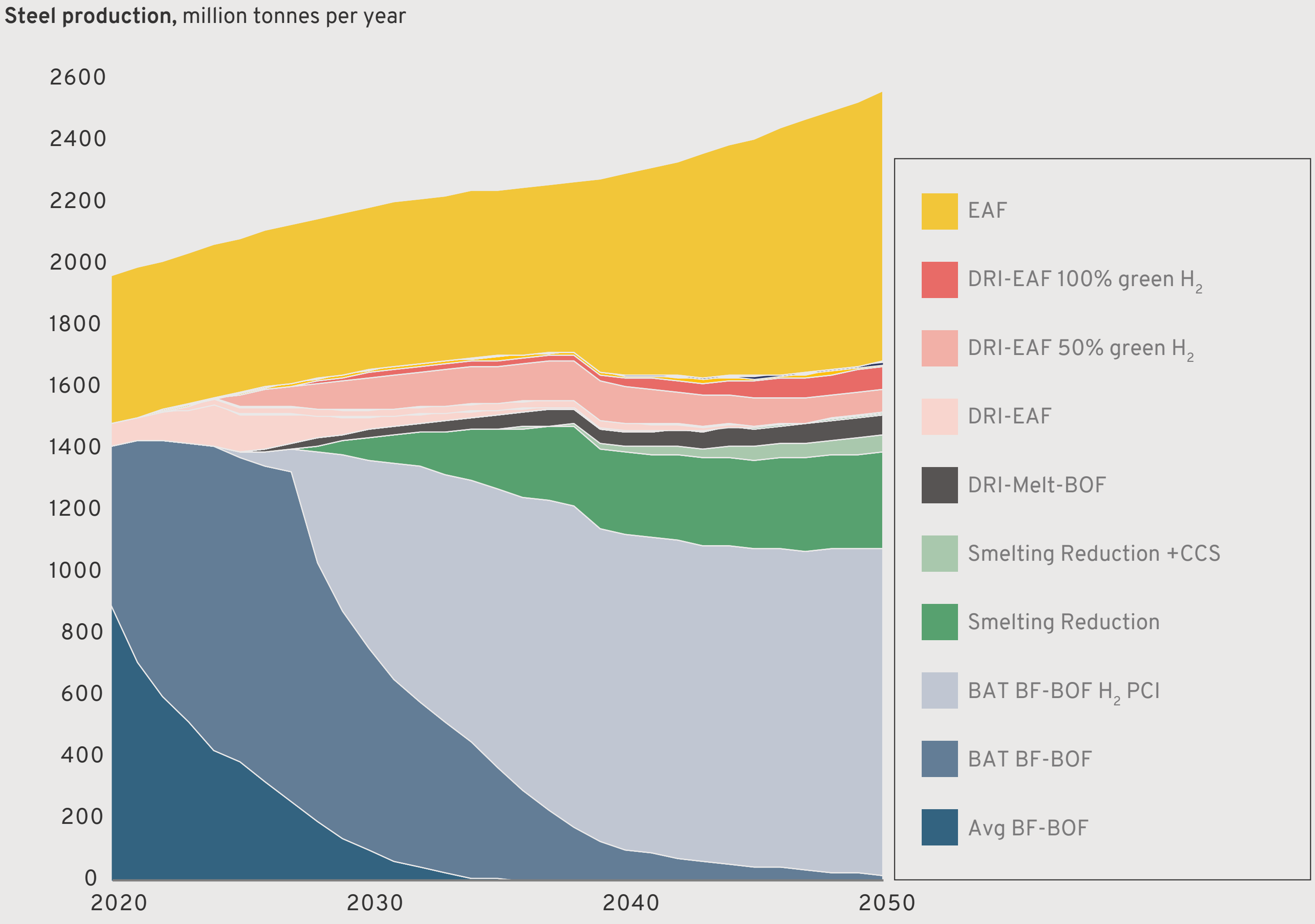
2.2 EVOLUTION OF STEELMAKING TECHNOLOGIES AND EMISSIONS

Steelmaking will diversify from three to up to 10 production routes in the transition to net zero, but the specific evolution of steelmaking technologies differs by scenario (see Exhibits 11, 12, and 13).

Baseline: Technology Cost Declines Alone Are Insufficient to Deliver Net Zero in Time

Our Baseline scenario, in which steel assets switch to whichever technology offers the lowest total cost of ownership at each major investment decision, indicates that few (near-) zero-emissions technologies are expected to be cost-competitive without policies and value-chain collaboration. BF-BOF remains the basis for primary steelmaking. Emissions reductions are primarily achieved through transitional fuel switching, particularly the use of hydrogen in combination with pulverised coal injection (PCI) in the blast furnace. CCS plays a negligible role in this scenario, as it represents a cost increase on top of production costs. Roughly 140 Mtpa (9%) of primary steel is produced with (near-) zero-emissions technologies in 2050 and annual emissions are only 27% lower in 2050 than in 2020. Cumulative emissions reach 90 $GtCO_2$, 18% of the global carbon budget to 2050.

Exhibit 11. Baseline scenario technology and production evolution



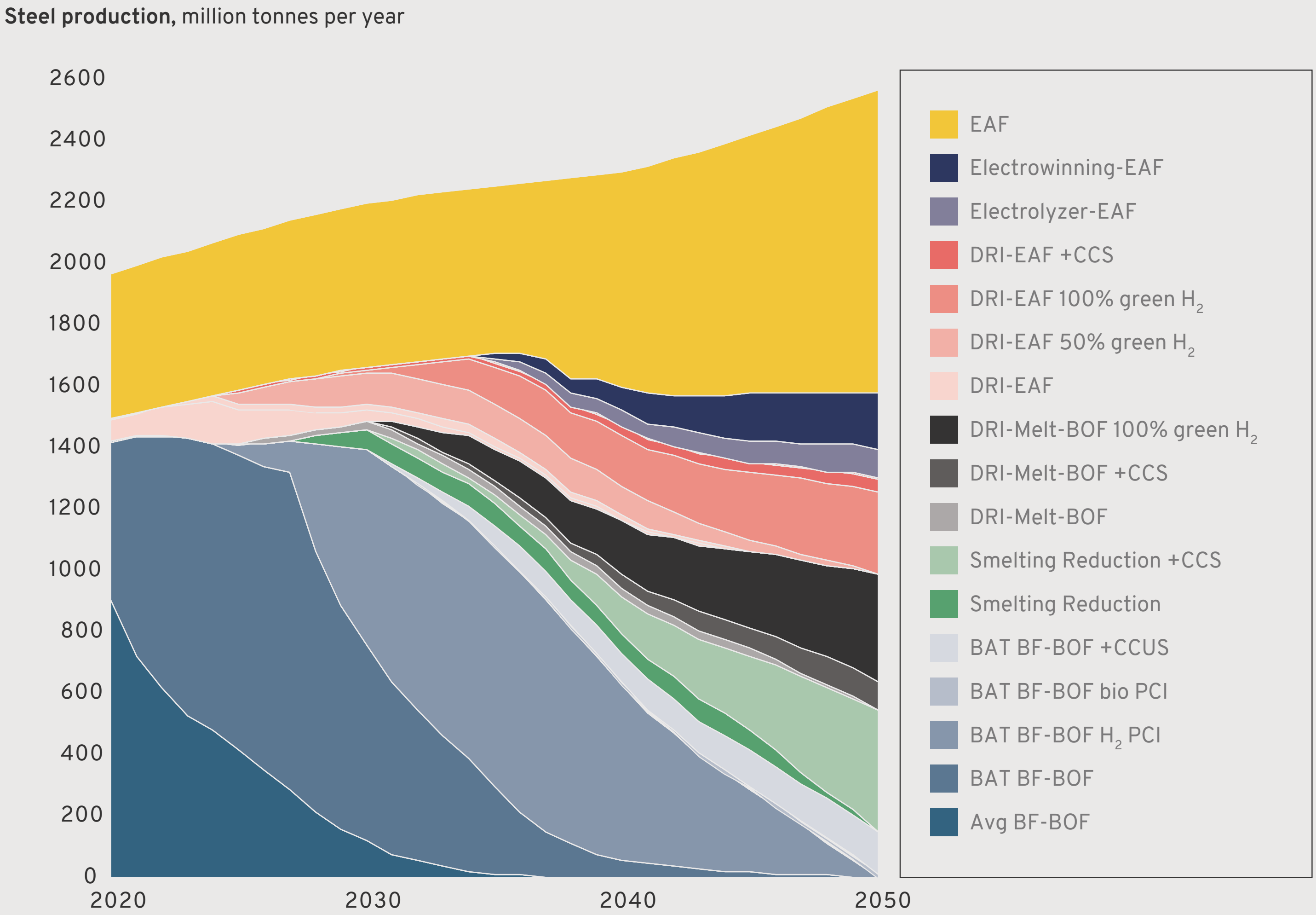
Tech Moratorium: A Range of Technologies Deliver Net Zero

Prior to 2030, the technology trajectory follows that of Baseline, as no constraints are assumed. Only transitional switches take place, such as upgrading blast furnaces to the best available technology and partial fuel switching to hydrogen injection. These improvements can mitigate up to 1.2 tCO_2/tCS (from an average BF-BOF archetype plant) and can be implemented as an intermediate upgrade prior to relining.

Even after 2030, existing plant infrastructure is maintained where possible while transitioning to net-zero compatible technologies, as these upgrades minimise capital and operating expenditures. For instance, existing BOF infrastructure can be coupled with newer (and less emissions-intensive) ironmaking technologies, such as smelting reduction or DRI, as an alternative to the conventional blast furnace ironmaking process. Natural gas is gradually replaced with hydrogen in DRI-EAF and DRI-Melt-BOF archetypes as zero-carbon hydrogen prices become competitive in favourable locations, accounting for 40% of primary steel production in 2050.

In regions with access to low-cost zero-carbon power, new electrolyser technologies coupled with EAFs may be a cost-competitive route for steelmaking once the technology matures, ultimately scaling to 15% of the 2050 primary steel technology mix. Archetypes utilising CCS or CCUS technologies account for the remaining 45% of primary steel production in 2050. The role of scrap-based production via EAF grows as large volumes of end-of-life scrap, particularly from China, become available.

Exhibit 12. Tech Moratorium scenario technology and production evolution

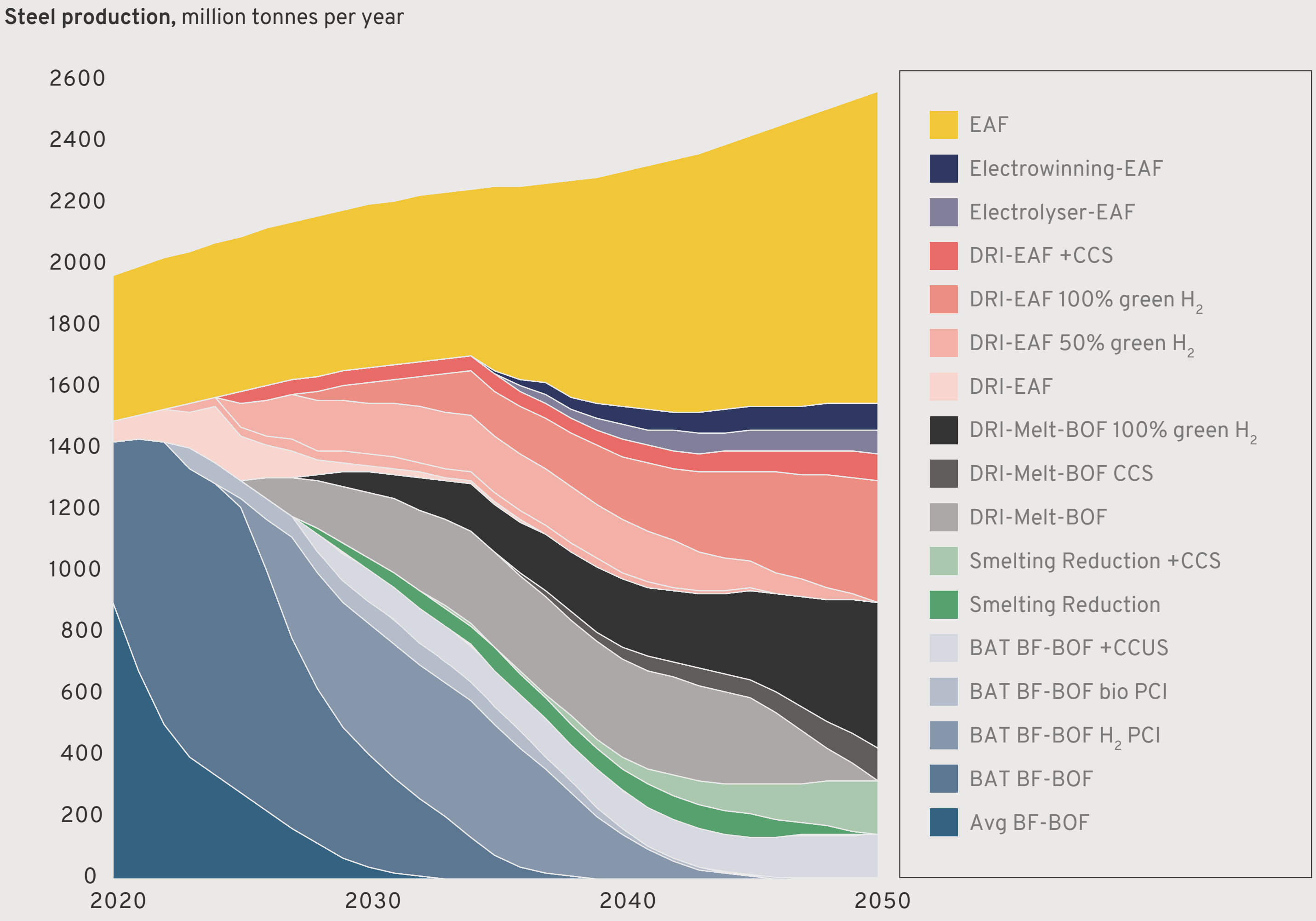


Carbon Cost: Earlier Technology Shifts and Greater Hydrogen Uptake

In this scenario, progressively rising carbon costs drive more fundamental technology switching in the next decade. Annual emissions are 0.8 Gt CO2 lower in 2030 than in Tech Moratorium. The faster trajectory reduces cumulative CO_2 emissions in 2050 by 14 Gt relative to the later transition in Tech Moratorium.

The best available technology (BAT) BF-BOF with CCUS is one the earliest (near-) zero-emissions technologies to scale, but its marginally higher emissivity and the falling cost of other (near-) zero-emissions technologies make it less favourable in later years. There is an early uptake of natural gas-based DRI production processes as these technologies can deliver immediate emissions reductions relative to unabated BF-BOF. By 2050, steel made with DRI accounts for two-thirds of primary steel production, 80% of which utilises zero-carbon hydrogen to deeply decarbonise. Marginal roles for smelting reduction with CCS and electrolysis-based technologies complete the 2050 technology mix.

Exhibit 13. Carbon Cost scenario technology and production evolution



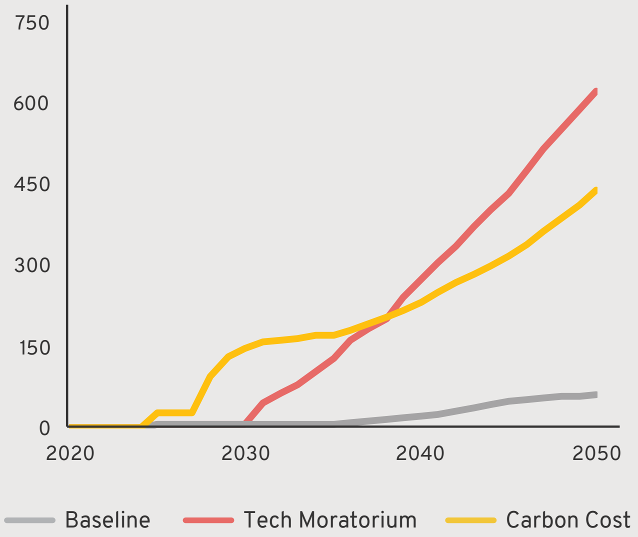
The Role of Carbon Capture

In either net-zero scenario, carbon capture facilities will need to scale rapidly. Over 140 Mtpa of CO_2 storage are needed by 2030 under Carbon Cost. For reference, 26 commercial CCS facilities (with average capture of ~1.5 Mtpa) are in operation today, and only one of these is associated with the iron and steel sector.[11] This scaling is necessary to capture the cumulative ~6 Gt of CO_2 from CCS-enabled archetypes by 2050. Demand for CO_2 storage capacity initially grows more slowly in Tech Moratorium (reaching 6 Mtpa in 2030) in the absence of a carbon cost. However, CO_2 storage capacity grows rapidly from 2030 onwards to capture 620 Mtpa by 2050.

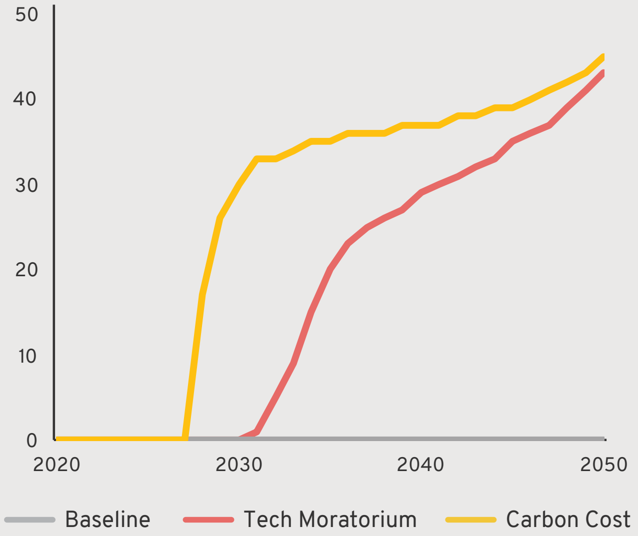
The balance of carbon storage versus carbon utilisation will depend in part on the future addressable market for CO_2. Captured CO_2 from the blast furnace could provide a valuable source of carbon for other heavy industry sectors, replacing virgin fossil fuel in applications where it can be sequestered long-term. ST-STSM assumes an addressable market of ~30 Mt of CO_2 in the late 2020s for applications such as concrete, long-lived plastics, and construction aggregate. Given this constraint, CCU technologies are likely to be favoured over CCS owing to relatively more attractive economics, but they will be forced to sequester the majority of the carbon they capture due to addressable market limits.

Exhibit 14. Annual CO_2 Storage and Utilisation

CO_2 stored, Mt per year



CO_2 utilised, Mt per year



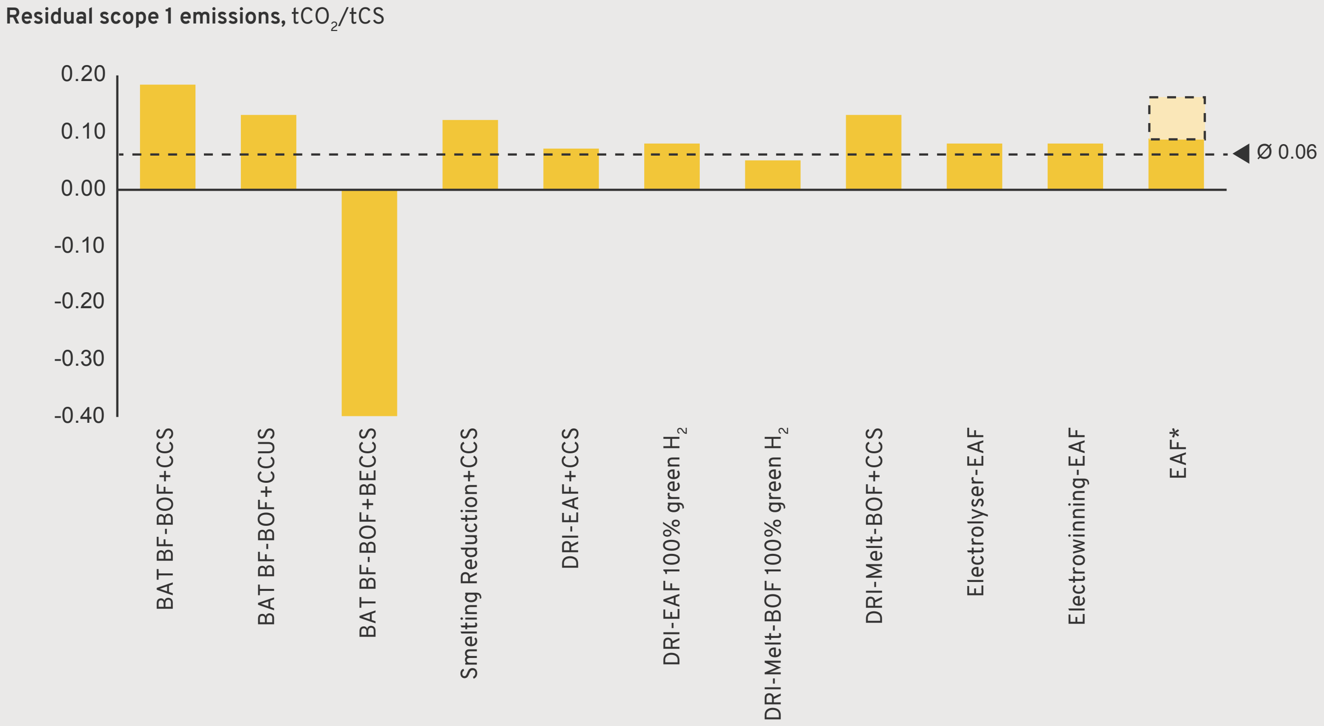
Box 2. Addressing Residual Emissions

To achieve net zero in the steel sector, any residual emissions that cannot be abated through technology developments will require offsetting. It is probable that the cost of purchasing or producing such offsets will fall to steel producers themselves. These costs should therefore be factored into decision-making when considering which technologies to pursue on the path to net zero and the overall cost of transition.

The potential scale of these residual emissions is significant. In both scenarios, ~350 Mtpa of residual CO_2 emissions (equivalent to 10% of steel sector emissions today) remain—primarily due to expected leakage from carbon capture technology, electrode degradation in EAFs, and emissions from regeneration fluxes. Unless further technology developments can be found, residual emissions are likely to require abatement through carbon removal technologies, such as direct air carbon capture (DACC). Finding truly sustainable and measurable natural carbon solutions can be challenging,[i] particularly given that they will be in high demand across other industries. The use of bioenergy coupled with carbon capture and storage (BECCS) could, in theory, generate negative emissions from steelmaking, but limits to the availability of truly sustainable biomass,[12] as well as competing requirements from other sectors, may restrict its use.

Based on a DACC price of $200/$tCO_2$ in 2050, offsetting these emissions could incur an additional $70 billion annually from 2050 onwards.

Exhibit 15. Residual emissions by technology in 2050



*Depends on presence of natural gas in preheating and finishing steps

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[i] Due to the risk of reversal of biogenic carbon storage and the difficulty of accurate measurement.

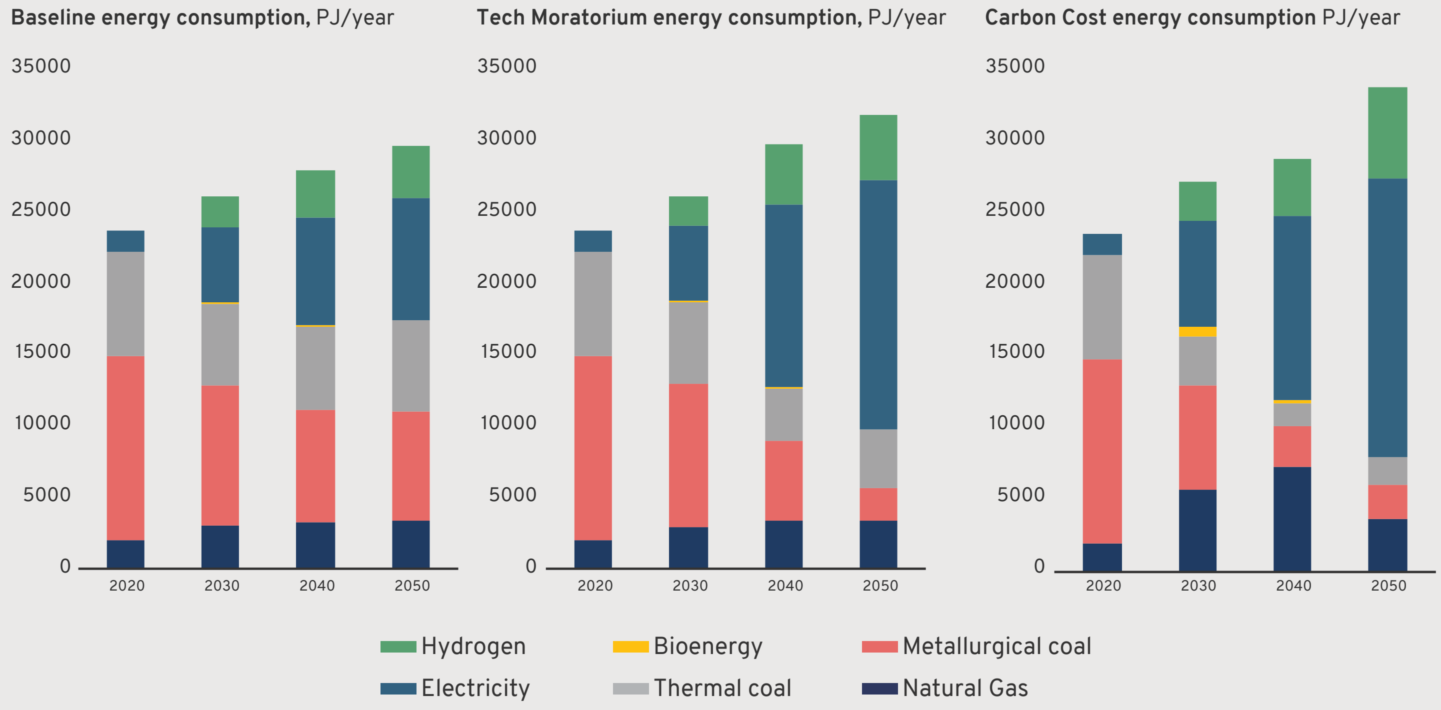
2.3 ENERGY USE: HYDROGEN AND ZERO-CARBON ELECTRICITY TO REPLACE COAL

The steel sector's primary energy consumption will decrease—and shift considerably—as the sector decarbonises (Exhibit 16). Declining total energy intensity of steelmaking (energy use per tonne of steel produced) largely offsets the increase in steel production. This is primarily due to the increased use of scrap (in the EAF archetype), which requires only ~13% of the energy required to produce steel from iron ore via the average BF-BOF process.

Metallurgical (coking) coal consumption decreases in all scenarios as hydrogen replaces it as a reductant. The continued use of thermal (low-grade) coal in Tech Moratorium reflects a greater role for the smelting reduction archetype, which can operate using lower grades of coal than blast furnaces. One consequence of the faster adoption of DRI-EAF technology in the Carbon Cost scenario is a sharp rise in the use of natural gas over the next two decades. Procurement of certified low-methane emissions natural gas will therefore be important to credibly demonstrate a reduction in supply chain emissions.

Steelmaking's direct electricity consumption increases by 2,600–2,800 TWh/year by 2050, as a growing proportion of steelmaking is reliant on EAF, high-heat electrical melting, carbon capture technology, or direct electrolysis. In addition to this increased direct electricity consumption, producing the volumes of zero-carbon hydrogen needed to facilitate net-zero steelmaking requires a further 1,700–2,400 TWh/year of electricity, if produced via electrolysis. For context, total electricity consumption in the EU today is approximately 2,800 TWh/year.[13] The 18–22 Mtpa of zero-carbon hydrogen required by 2030 may be feasible globally, though it equates to three times the hydrogen production target set out in the EU green hydrogen strategy of ~6.5 Mtpa by 2030.[14] Unless clean power and hydrogen infrastructure scale rapidly over the coming decade, they have the potential to delay the steel industry's transition.

Exhibit 16. Energy consumption under different scenarios



Baseline energy consumption, PJ/year

Tech Moratorium energy consumption, PJ/year

Carbon Cost energy consumption PJ/year

Exhibit 17. Consumption of coal and natural gas under different scenarios

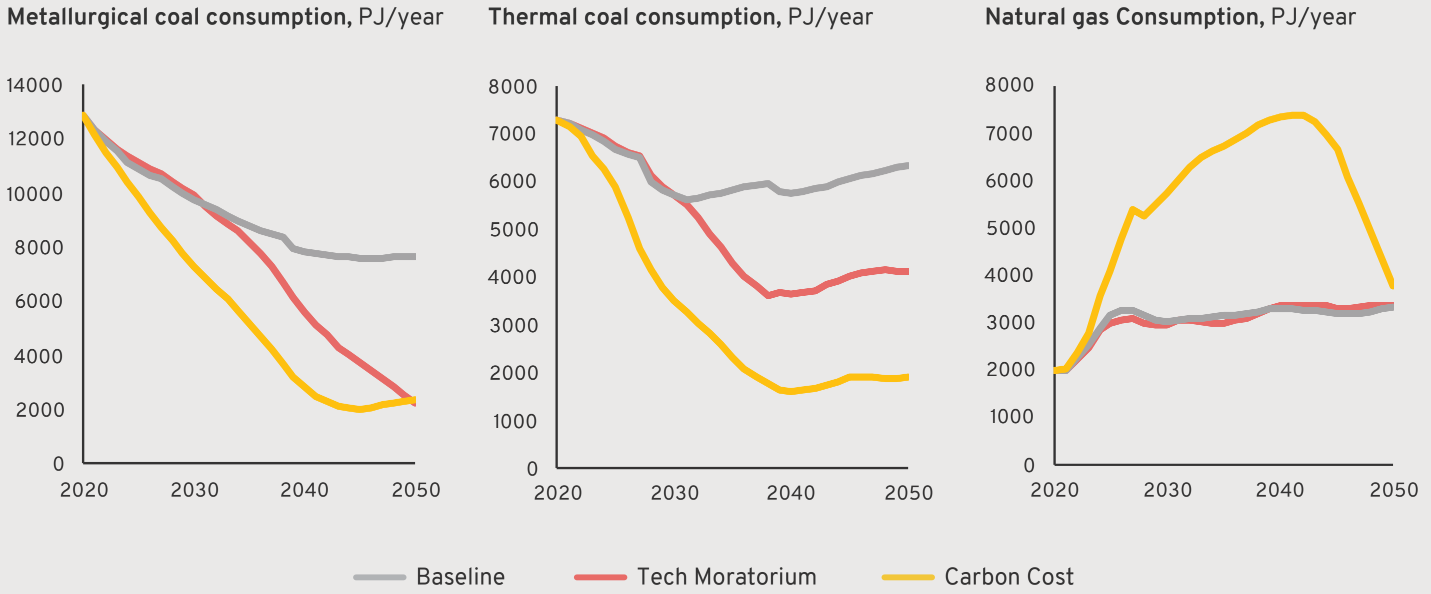
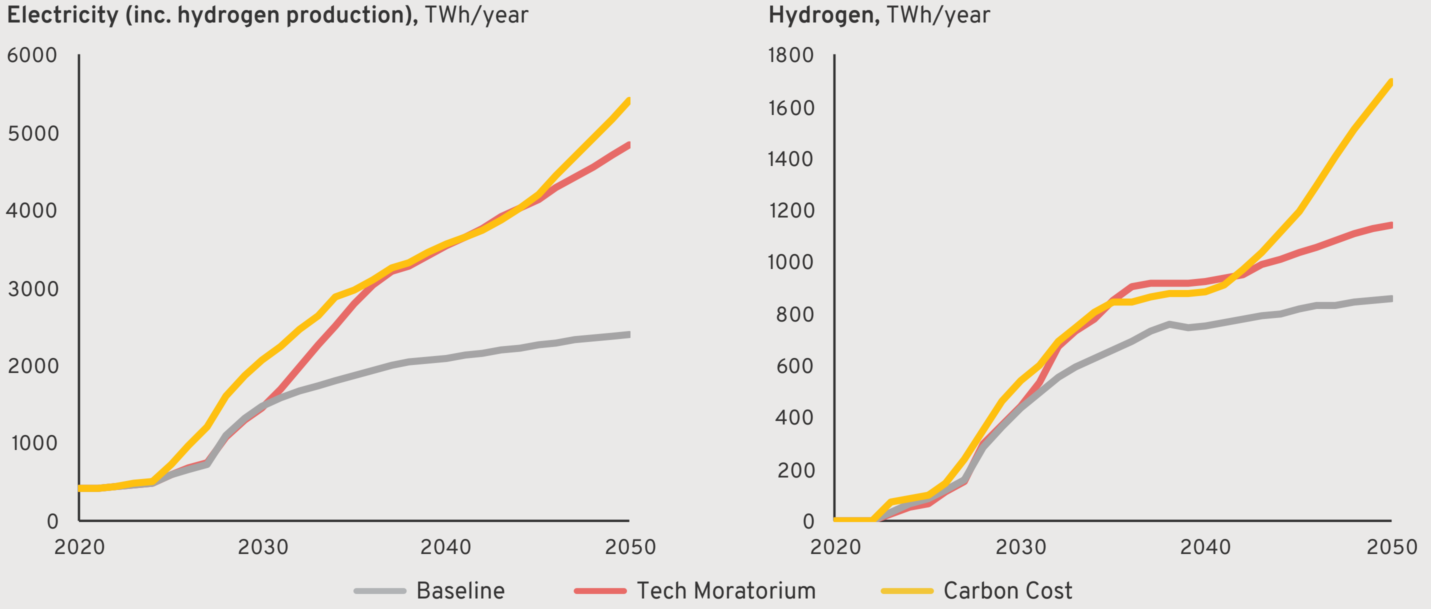


Exhibit 18. Electricity and hydrogen demand under different scenarios



Bioresources such as biochar, biogas, and biomass currently appear to have a limited but valuable role to play in the steel sector's transition. The use of bioresources within existing technology routes provides a cost-competitive way to unlock early emissions reductions before end-state technologies become available. Feeding bio-coal into the BAT BF-BOF route can reduce CO_2 emissivity by ~20% relative to coal, while replacing natural gas with biogas in the DRI-EAF route offers an emissions savings of ~40%.

However, limited availability of truly sustainable bioenergy means that such resources will need to be prioritised for sectors that lack viable alternative decarbonisation pathways over the medium term, such as aviation. The Energy Transitions Commission estimates the supply of truly sustainable bioresources available without major changes in land use, technology, and consumer behaviour at 40 EJ/year.[15] ST-STSM indicates that the steel sector might require 0.2–0.6 EJ/year of bioenergy at its peak in the early 2030s, less than 2% of this sustainable supply. Beyond this point, demand for biomass declines in all scenarios as alternative decarbonisation technologies become available.

2.4 FINANCE: THE MASSIVE INVESTMENTS REQUIRED WILL ONLY BE UNLOCKED IF "GREEN PREMIUM" IS BRIDGED

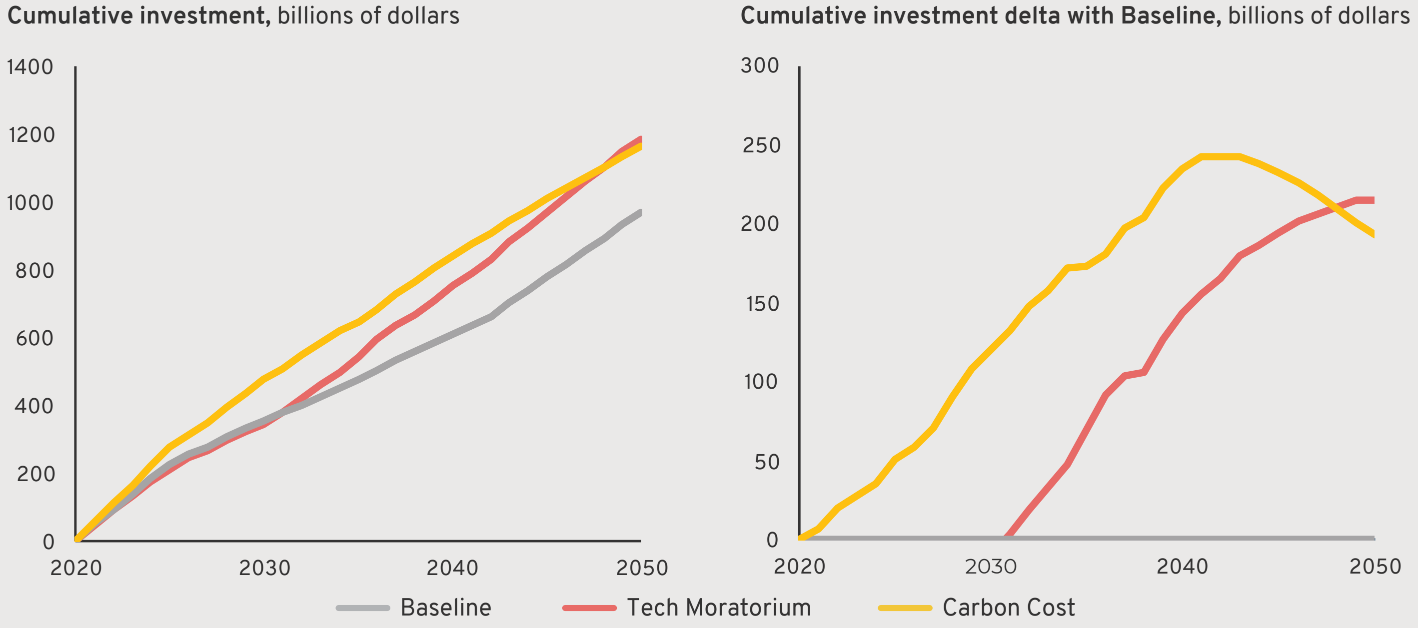
An Additional $6 Billion a Year in Capital Expenditures

Steelmaking is very capital intensive. A new BF-BOF integrated steel plant using best available technology requires approximately $1.4 billion in capital expenditures per million tonnes of steel capacity. While renovations to existing assets require about a quarter of the capital expenditure of building new plants, Baseline indicates that the steel sector will need an average $31 billion in investment annually to meet growing steel demand over the next 30 years and maintain the existing sites, even in the absence of a major transformation.

Even in this context, the financing challenge for the steel sector's transition is significant. Transitioning global steel assets to net-zero compatible technologies requires an additional $6 billion annually on average compared to Baseline, or $200 billion by 2050. Achieving the faster deployment of (near-) zero-emissions technologies under Carbon Cost, including more capital-intensive carbon capture technology archetypes, requires $12 billion in additional investment annually in the 2020s compared to the slower Tech Moratorium, though this deployment costs no more in the long run. If evaluated in terms of an investment in CO_2 emissions reductions, the 35 Gt of cumulative emissions avoided by following the Carbon Cost trajectory come at a capital expenditure cost of only $6/t$CO_2$ avoided.

Investment in enabling infrastructure such as CO_2 pipelines, hydrogen infrastructure, and zero-carbon electricity production is likely to dwarf that of the steel assets themselves. For example, delivering sufficient zero-carbon electricity to meet the needs of the steel sector, including the generation of the necessary volumes of green hydrogen, will take approximately $2 trillion in cumulative investment over the next three decades. That equates to 3% of the total expected investment in electricity generation, transmission, and distribution in a net-zero economy.

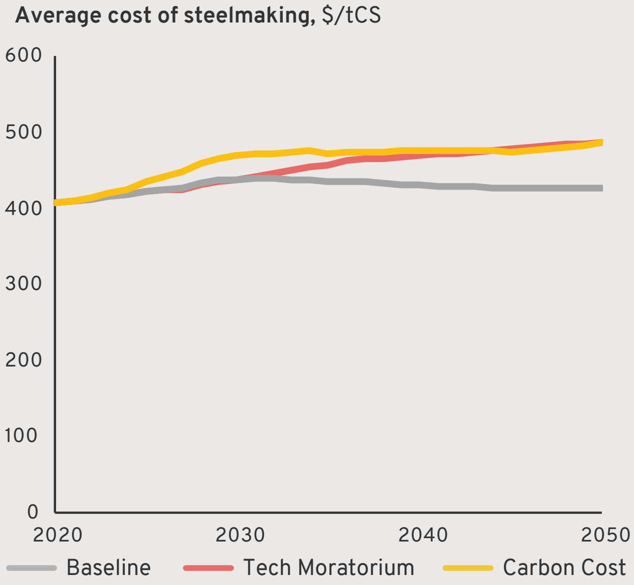
Exhibit 19. A faster transition will require greater investment over the next 20 years



Measures to Bridge the "Green Premium"

At the aggregate level, the transition to net-zero emissions in the steel sector will increase the average cost of steelmaking by less than 15% in 2050 (Exhibit 20).[i] However, there is a short-term trade-off between the pace of transition and the average cost of steelmaking. In the Carbon Cost scenario, the cost of steelmaking is $30/tCS (7%) above Baseline in the early 2030s, whereas the slower transition in the Tech Moratorium scenario sees the average cost of steelmaking climb in steadier fashion.

Exhibit 20. Average cost of steelmaking (excluding carbon price)



These aggregate-level cost changes may not reflect the full extent to which the price of steel will need to rise to achieve net zero. Low-CO_2 steel is likely to be more expensive to produce than conventional steel in some locations even in 2050. Should hydrogen prices drop to $1.10/kg by 2050 in the favourable locations as modelled, steel produced using zero-carbon hydrogen via DRI-EAF could still cost up to 15% more than unabated steel made via BAT BF-BOF. Other technologies that utilise or store CO_2 will always add cost relative to their unabated equivalent in the absence of a carbon price. Differences in end-of-life timelines for assets, access to resources, and ambition levels across steelmaking geographies mean that end-state technologies will, in the absence of intervention, have to compete alongside incumbent technologies in wholesale steel markets. Therefore measures will be required to bridge the "green premium"—the cost differential between high- and low-CO_2 steel—during the transition.

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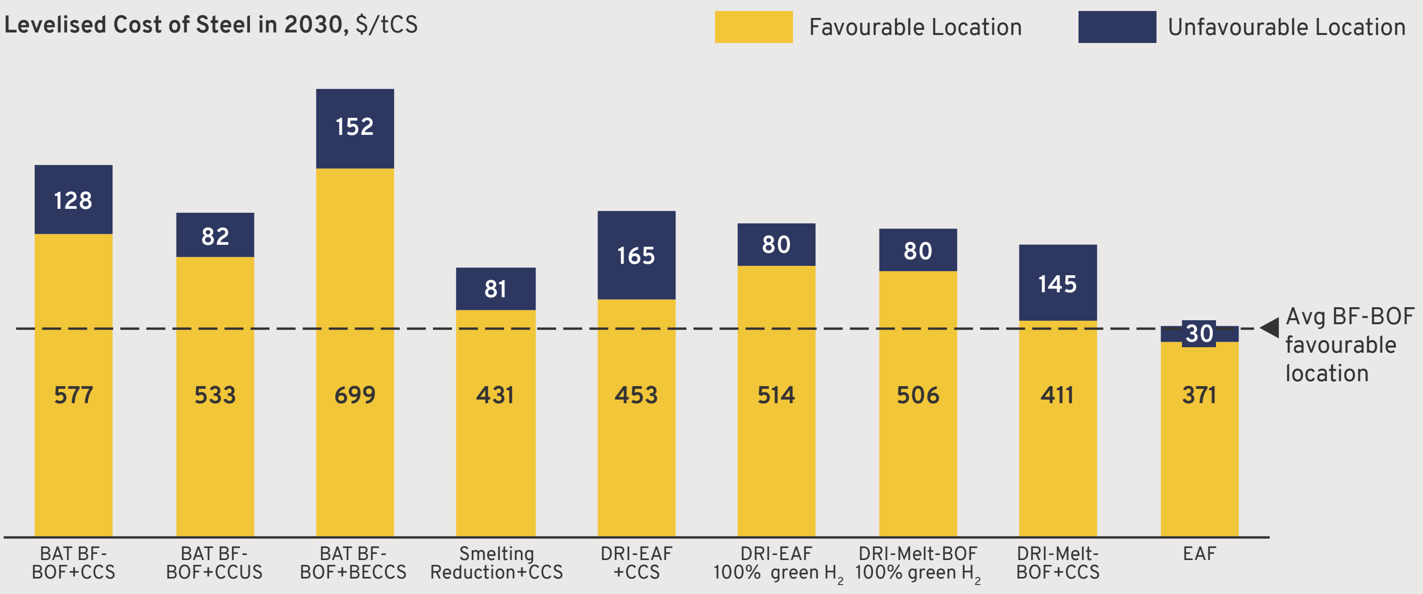
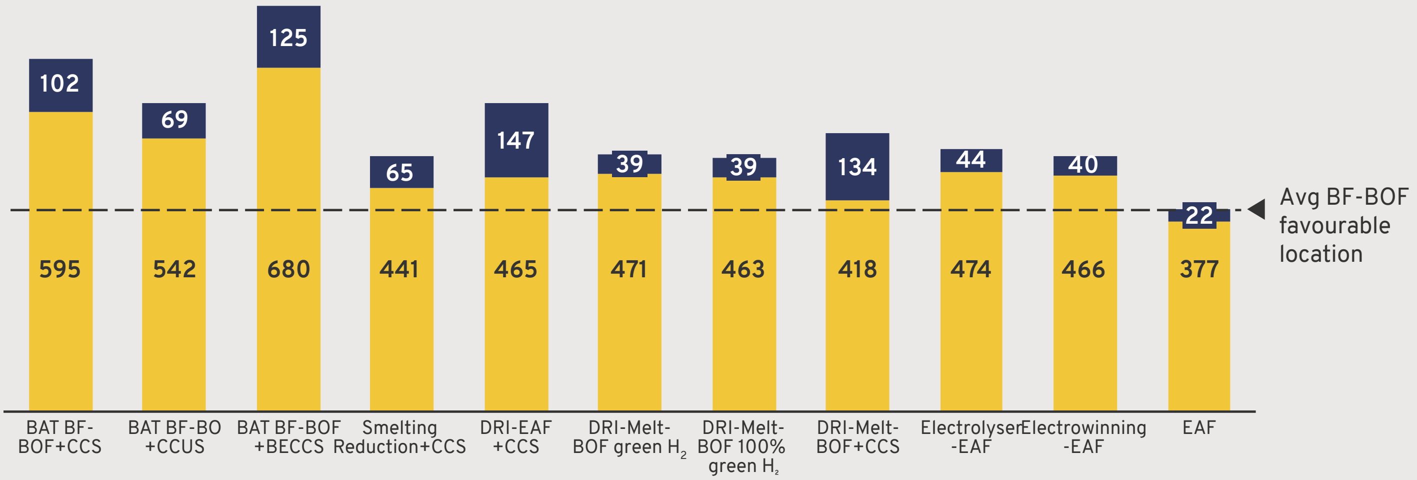
[i] We consider these the regional drivers most relevant to steel sector decarbonisation; however, this list is not exhaustive.

Exhibit 21. Levelised cost of (near-) zero-emissions technologies in 2030 and 2050

Levelised Cost of Steel in 2030, $/tCS



Levelised Cost of Steel in 2050, $/tCS



*Prices used in calculations are high-level averages for favourable and unfavourable locations, so there will be outliers where certain technologies may be much more or less competitive. This applies especially to BECCS, given the very local nature of biomass supply.

In the short term, voluntary demand signals could be designed specifically to support projects with large potential emissions reductions before they are cost-competitive, creating a differentiated market for low-CO_2 steel. Buyers may have to cover an initial green premium of $80/tCS in optimal locations (compared to the average BF-BOF in 2030) for zero-carbon hydrogen-based steel. While private-sector commitments to purchase the first volumes of low-CO_2 steel will be critical in building momentum, it is unlikely that voluntary commitments alone can achieve the volumes of off-take necessary to support low-CO_2 steel production at scale.

Carbon pricing offers one way to address this challenge at scale. By applying a cost to emissions, the cost of steelmaking for more emissive technologies increases relative to more abating technologies, enabling them to compete in the market. When including the tax on carbon emissions implied in the Carbon Cost scenario, the average cost of steelmaking peaks at $570/tCS in the early 2030s, $100/tCS higher than when technology costs alone are considered. Other regulatory measures, such as demand-side emissions standards that restrict the consumption of high-emissions steel, are likely to entail similar cost increases.

2.5 THE WHOLE STEEL ECOSYSTEM WILL HAVE TO ADAPT

Beyond the impacts examined above, there are a number of wider impacts that were not modelled within ST-STSM but which will be important considerations in any net-zero pathway.

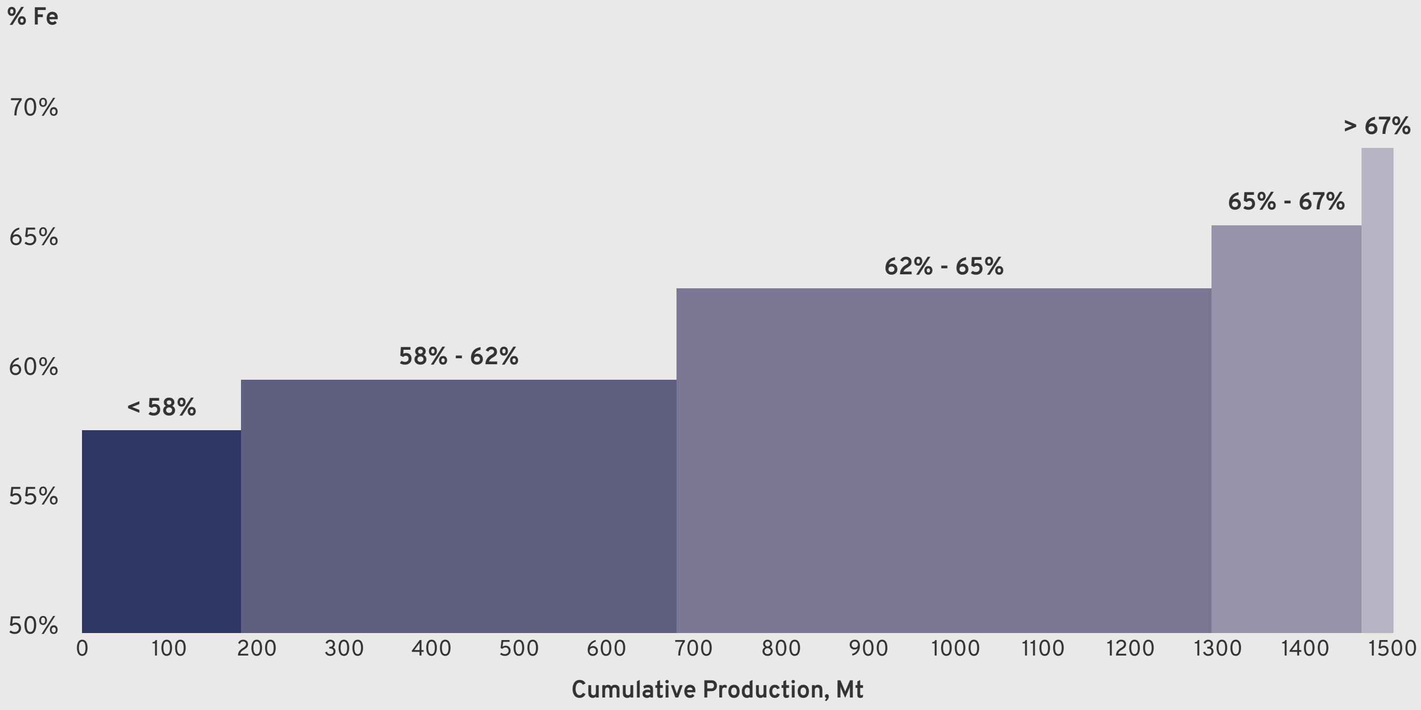
The Iron Ore Value Chain Will Need to Adapt

Today most seaborne iron ore is lower-grade ore that is well suited to BF-BOF production. Approximately 13% of seaborne iron ore is of “DR grade” (Exhibit 22), a grade with an iron content of more than 65% that is commonly used in DRI-EAF production. Today DRI requires high-grade ores, primarily to limit the amount of slag in the EAF process, which has no commercial value and therefore requires disposal in a landfill. Only a few producers can supply iron ore pellets at DR grade without further ore beneficiation, which adds cost and reduces iron ore yield.

The significant increase in DRI-based production suggested by both the Carbon Cost and Tech Moratorium scenarios will not be possible with high-grade ore alone unless significant new deposits are developed. Therefore, advances will likely be needed in beneficiation processes that minimise losses or in the development of DRI-based steel production routes that are compatible with lower-grade ores.

The DRI-melt-BOF archetype would make utilising lower-grade ores more feasible, thanks in part to the ease of removing impurities in the Basic Oxygen Furnace. However, processing higher-gangue ore would require more hydrogen in the shaft furnace. In a world where high-grade ores attract a significant price premium, the balance of DRI-melt-BOF and DRI-EAF technologies will be determined by the relative cost of removing impurities via beneficiation versus processing them in the shaft furnace and BOF.

Figure 22. Iron ore seaborne freight by grade[16]



Employment

The steel industry employs around 6 million people worldwide and is the source of an estimated 43 million additional jobs in other sectors.[17] Between 1920 and 2000, labour requirements in the industry decreased by a factor of 1,000, from more than three person-hours per tonne to just 0.003 person-hours.[18] The increased automation, digitalisation, and process electrification needed to make the low-CO_2 production routes competitive will likely continue this trend.

Based on our modelling results, almost no new steel capacity is needed until the 2040s, with refurbishment and redevelopment of existing sites sufficient to meet rising demand. This transition strategy does not model the relocation of greenfield assets to newly competitive locations. Policymakers should consider the combined effect of an expected falling labour intensity and the potential for relocation of steelmaking in industrial policies that deliver net-zero steel.

Other Environmental Considerations

While this transition strategy focuses on CO_2 emissions, it is also important to address the iron and steel sector's other environmental impacts. Steel production has a number of impacts on the environment, including airborne pollutants (CO, SOx, NOx, PM2.5), wastewater contaminants, hazardous wastes, and solid wastes. The transition away from fossil fuels to lower-carbon processes will reduce the overall environmental footprint of steelmaking.

However, there are risks that a singular focus on CO_2 may overlook other environmental issues such as methane leakage in natural gas use, solid waste arising from increasing EAF slag volumes, and the risks of airborne heavy metals from new production processes. These issues will need to be taken into consideration alongside the needs for net-zero emissions in the sector. The shift away from conventional blast furnaces may require new solutions for existing waste streams and co-products that have hitherto been utilised in the blast furnace, such as mill scale and waste gases.

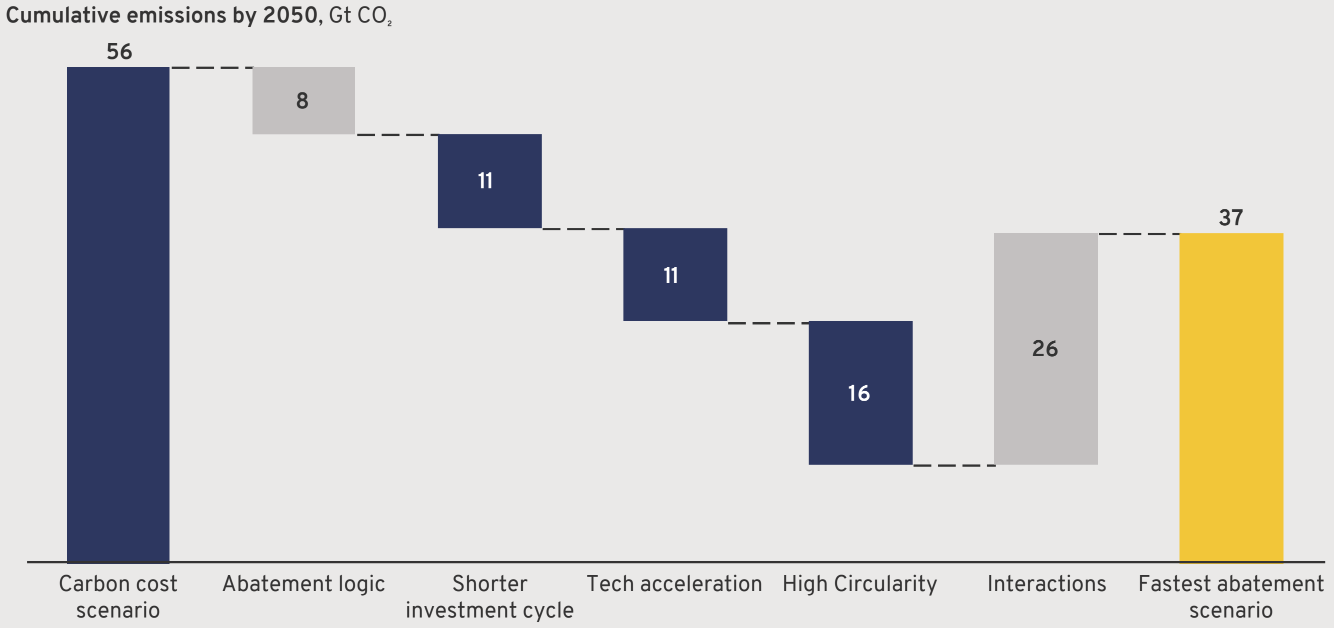
Box 3. A Faster Transition to Net-Zero Emissions in the Steel Sector

The Fastest Abatement scenario represents the ceiling of what might be technically possible by maximising the levers for decarbonisation, regardless of cost. The levers used are:

- Assume that each investment decision is optimised for the greatest abatement potential (instead of for lowest total cost of ownership). This results in the update of (near-) zero-emissions technologies as soon as the technologies are mature, irrespective of their economic competitiveness.
- Bring the maturity of low-CO_2 steelmaking technologies forward by two years.
- Shorten investment cycles from 20 to 15 years, allowing for a faster phaseout of high-emitting steel assets.
- Reduce (primary) steel demand from the BAU to the High Circularity scenario.

Pulling all of these levers could reduce cumulative emissions by a further 19 Gt relative to the Carbon Cost scenario once interactions between the different levers play out. These would come at significant additional costs, including the lost value of closing plants before the end of their useful life, significant increases in RD&D investments to bring breakthrough technologies to commercialisation sooner, and some additional cost to the scrap supply chain from enhanced circularity requirements. Most fundamentally, shifting to a focus on abating emissions irrespective of total cost of ownership would require a suspension of prevailing economic logic.

Exhibit 23. Levers to minimise cumulative emissions by 2050



PART

3

A Transition Strategy for a Net-Zero Steel Sector

3.1 PRIORITY ACTIONS THIS DECADE TO UNLOCK LONG-TERM PROGRESS

Together, the steel value chain, policymakers, and financial institutions can start on the path towards a net-zero steel sector. There are four key areas where interventions should be targeted in the 2020s to address the key challenges for steel decarbonisation, as identified in Part 1 of this report:

1. Develop (near-) zero-carbon steelmaking processes
2. Initiate switching to zero-carbon steelmaking early to avoid stranded assets
3. Cover the "green premium" on low-CO2 steelmaking
4. Level the global playing field

Example actions that stakeholders can take in the near term are described below. Each action relates to a specific challenge, although some actions impact several challenges at once. The prioritisation of these actions may need to change as technology readiness and national, regional, and global governance evolves.

1. Bring Forward Development of (Near-) Zero-Emissions Steelmaking Technologies

Steel producers are already making significant investments in efficiency improvements and breakthrough technologies. Accelerating the development and rollout of low-carbon steelmaking will need further strategic funding—particularly at later stages of commercial readiness—to crowd in capital at the scale and cost necessary to reach net-zero emissions by 2050.

Early investment in commercial-scale plants will build experience with new technologies and achieve learning curve effects that accelerate their adoption thereafter. However, technology and market risks make it difficult for steel manufacturers to raise capital for this type of investment and often entail a high cost of capital, which erodes overall project economics.

Green steel public procurement strategies, through which governments mandate or preferentially purchase steel based on carbon-related criteria, are a powerful tool in innovation policy to seed and underpin early markets, thereby providing partial de-risking of the investments. Collaboration to share and align practices across national governments, local authorities, and public agencies could accelerate the deployment of those mechanisms and help aggregate demand to send a clearer demand signal to the steel industry.

Voluntary commitments can provide important early demand for the first volumes of low-CO_2 steel, either via bilateral off-take agreements or public commitments from buyers to purchase a minimum volume of low-CO_2 steel. An increasing number of companies are setting emissions-reductions targets that cover upstream (scope 3) emissions in their supply chains. For example, in the automotive industry, both Toyota and Volkswagen are aiming to be carbon neutral by 2050, and Daimler and Jaguar Land Rover aim to reach neutrality by 2039.

Example targets in line with Carbon Cost scenario:

- Mature hydrogen PCI in BF-BOF and DRI-EAF with 50% hydrogen by 2025
- Multiple (near-) zero-carbon steelmaking technologies at commercial scale by 2030 (except electrolysis-based processes)

Key Actions

Industry	· Identify regions with access to low-cost zero-carbon electricity as priorities for early incubation and implementation of new green hydrogen-based and electricity-based technologies, such as those currently being demonstrated in the HYBRIT project.[19] An intermediate step, implementing DRI-based technologies, yields an immediate emissions reduction today compared to BF-BOF and sets steelmakers on a path towards future use of green hydrogen. · Partner with customers with stable demand (e.g., automotive or white goods) to enter long-term off-take agreements for low-CO_2 steel products to de-risk investment in net-zero compatible technologies.
Finance	· Private banks invest in low-carbon projects in concert with de-risking partners such as governments to bring forward commercial deployments with innovative approaches to project finance (using financial mechanisms that could also be offered to reward large buyers of low-CO_2 steel). This both promotes net-zero steel production and provides climate alignment benefits to the financial institution’s portfolio. · Collectively de-risk and scale new, low-carbon steelmaking technologies and the technologies that enable them, such that these technologies can become financeable by mainstream banks.
Government	· Prioritise funding for technologies and processes in early-stage R&D such as molten oxide electrolysis (MOE). Directing public funding towards electricity and zero-carbon hydrogen-based projects (and zero-carbon hydrogen production itself) can drive down costs and enable quicker adoption of (near-) zero-emissions technologies. · Implement instruments to provide loan guarantees for investments made in initial commercial installations by private capital providers and regional investment banks. Loan guarantees can protect against loss of capital for institutional investors and provide credit enhancement for the project. · Take strategic positions as “anchor” off-takers for the first volumes of low-CO_2 steel to encourage the necessary market confidence and crowd in private-sector investment. These opportunities could be prioritised where governments identify clear national strategic benefits and sufficient volumes of demand. · Establish clear procurement terms and conditions for low-CO_2 steel, which can be replicated by other large-volume private buyers.

2. Ensure the Supporting Energy Infrastructure Is Scaled by 2030

Accelerating the transition will also require a broader set of supportive policy measures to ensure that the necessary infrastructure—especially fossil-free energy provision and carbon transport and storage networks—is available on the scale required to meet the needs of the global steel industry. Green hydrogen, in particular, is highly sensitive to electricity prices, and access to cheap electricity will be critical to reducing the abatement costs of hydrogen-based steelmaking. Much of this will occur outside of normal sectoral boundaries, requiring new public-private and value-chain partnerships to deliver. There will be a major role for governments in planning and de-risking the financing of this energy infrastructure so that the large needs of the steel industry can be met.

Example targets in line with Carbon Cost scenario:

Infrastructure that should be in place by 2030 to support steelmaking includes:

- 2,100 TWh of zero-carbon electricity generated per year (including electricity for hydrogen production)
- 22 Mt of hydrogen produced per year
- 180 $MtCO_2$ of carbon transport and storage or utilisation

Key Actions

Industry	· Start planning for decarbonisation by identifying the earliest opportunity for a switch to zero-carbon steelmaking (e.g., the next relining). · Investigate the preferred options for decarbonisation of existing steel sites and engage other stakeholders in the conversation to get the needed infrastructure in place on time. · In regions with limited access to affordable zero-carbon electricity, undertake a suitability assessment for carbon capture retrofits.
Finance	· Develop and offer sustainable finance instruments to support steelmakers in committing to low-carbon pilot projects for primary production and to support governments in realising the required infrastructure. · Evaluate current risk management frameworks to identify opportunities for accelerating (near-) net-zero steelmaking technology in favoured regions (this should also consider the impacts of declining fossil fuel sources as a potential risk in maintaining high-carbon assets).
Government	· Develop a cross-sectoral perspective on decarbonisation that appropriately balances competing demands and identifies valuable synergies to reduce total infrastructure costs (such forward planning could also strengthen investor confidence). · Incentivise and/or legislate decarbonisation of existing power assets and significant scaling of zero-carbon electricity generation, as zero-carbon electricity is a critical prerequisite for a net-zero steel sector. · In regions with limited access to affordable zero-carbon energy, identify viable carbon storage and utilisation locations and establish a permitting process to encourage capture, transport, and storage infrastructure.

3. Bridge the "Green Premium"

There are various ways to close the "green premium," or cost difference between conventional steel and low-CO_2 steel. Consumers may be willing to pay a premium on a product made from lower-emissions steel. Financial support schemes could reduce the green premium, although these would need to cover the difference in production costs and not only the up-front investment in the site development, rebuild, or retrofit. These market and governmental mechanisms also require alignment around a workable definition for "green steel" (see item 4 below).

Another alternative is carbon pricing. To have the desired effect of catalysing investment in low-CO_2 steel production, the carbon price must be sufficiently strong and predictable to create an investment case. The scenarios suggest a green premium of $0–$150/tCS (when compared to an average BF-BOF in 2030) for zero-carbon hydrogen-based steelmaking. In most countries, the carbon cost faced by steelmakers is insufficient to advantage (near-) zero-emissions technologies over current steelmaking practices. The volatility of carbon prices in cap-and-trade schemes means that policy mechanisms that de-risk carbon price uncertainty may also be needed to bring forward the transition to breakthrough technologies.

Example targets in line with Carbon Cost scenario:

- The cost differential between ore-based (near-) zero-emissions steel and higher-emissions steel is on average $80 in 2030 (20% of the conventional steel price), equivalent to an average carbon price of $60/tCO2
- The green premium is bridged on 17% of total ore-based steel production in 2030

Key Actions

Industry	· Consider partnering with off-takers to seek potentially higher revenues on low-emissions products and/or oversupply of high-emissions products, as markets may develop an implicit carbon price if steel users are willing to pay a premium on low-emissions products.
Finance	· Develop practices required to scale a voluntary carbon market such as standardised accounting contract terms, digital exchanges, and registries. These practices have been outlined by the Taskforce on Scaling Voluntary Carbon Markets.
Government	· Where carbon pricing is not yet established, consider options to develop carbon markets (e.g., emissions trading schemes) or equivalent regulatory measures. · Consider developing carbon-based contracts for difference to support sufficiently high and predictable carbon pricing.

4. Level the global playing field

As the cost of abatement is passed through the value chain in the form of higher steel prices, competitive distortions with other markets should be avoided. Imposing equivalent carbon costs on both domestic and imported products is necessary to enable a domestic carbon price signal to take effect. These carbon costs can take the form of carbon border tax adjustments, regional carbon clubs, or a steel sector deal that aligns carbon pricing regimes at a multinational level.

Widely recognised, rigorous CO_2 standards can aid in identifying which steel products should be classified as “green” steel. These designations should be based on verifiable life-cycle carbon emissions assessment methodologies. While product standards can drive carbon-intensive products out of a market and assist in creating a global level playing field, they lack the efficiency of pricing mechanisms, which can drive a search for the optimal decarbonisation pathway, combining demand reduction, product substitution, recycling, and zero-carbon production technologies.

Example targets in line with Carbon Cost scenario:

- Two or more steel-producing regions have agreed on policies to align carbon taxes and/or other regulatory measures for steel production in 2025
- Standards are enforced across major steel-consuming regions that exclude or price out high-CO_2 steel products from 2030, while respecting asset life cycles

Key Actions

Industry	· Develop a joint definition of low-emissions steel with a stringent CO_2 emissions threshold that promotes end-state technology adoption. This could be done by defining a new standard level within the existing ResponsibleSteel framework to facilitate the implementation of appropriate demand signals. · Convene key players from across the steel value chain to facilitate greater collaboration and problem-solving at the national and multilateral level, building on the models pioneered by efforts such as the European Battery Alliance and the European Clean Hydrogen Alliance.
Finance	· Adapt existing carbon accounting, auditing, and verification frameworks to support a low-CO_2 steel market, in line with the methods and metrics specified by a standard-setting organisation.
Government	· Ensure that decarbonisation strategies (e.g., carbon pricing) do not disadvantage steelmakers within a government’s jurisdiction that are adopting low-carbon technologies, given the global trade of steel. A mechanism such as a carbon border adjustment (CBAM) could be one such strategy. · Provide reporting guidance and requirements for life-cycle emissions standards for key steel-using products. Applying these regulations on just a few steel-using value chains can be a key instrument to fast-track deployment of low-carbon steel and legitimise a differentiated product certification scheme.

3.2 THE WAY FORWARD

The steel industry finds itself at a historical juncture. It can and must rapidly decarbonise. The technologies required for net-zero steelmaking are known, and nearly all major steel producers are developing these low-CO_2 production technologies in pilot phase. Steel producers representing 20% of global primary production capacity, including half of the world's 10 largest producers, have set ambitious climate targets. Major steel-producing and -consuming regions, including the EU, United States, Republic of Korea, Japan, and China, are also committed to net-zero targets, leaving little choice but to invest in a low-carbon future for steelmaking.

Transforming these targets into reality will require stakeholder collaborations spanning the value chain from mine to buyer. The first wave of technology commercialisation will also require targeted and strategic decisions by first movers in the absence of market or technology certainty to provide the necessary proof points for the sector to transition at scale in the 2030s.

The foundations of such efforts are emerging, with a steadily growing volume of feasibility studies, risk-sharing partnerships, and pilot projects. These corporate efforts are supported by numerous collaborative initiatives that aim to create the conditions for investment in low-carbon solutions, such as efforts to develop steel standards and certification under ResponsibleSteel, as well as private-sector voluntary demand commitments through the Climate Group's "SteelZero" initiative. Other leading examples include the US government-backed First Mover Coalition, green public procurement efforts under the G7 Industrial Decarbonisation Agenda, and international collaboration on technology breakthroughs via the Clean Energy Ministerial. Finally, several initiatives focus on driving financial-sector interest in low-emissions steelmaking, such as the UN-convened Net-Zero Asset Owner Alliance and Net-Zero Banking Alliance, as well as the RMI Center for Climate-Aligned Finance's steel working group.

But there remains a needed solution to the "first mover disadvantage" that is created by wholesale steel markets, where prices are typically set by the marginal (and more emissive) producer. Multilateral solutions to existing and emerging regulatory asymmetries will be critical to unlocking the first wave of near-zero emissions steelmaking. An immediate priority is a new, high-ambition multilateral forum between net-zero aligned governments and steelmakers to explore and find solutions to this issue.

The Net-Zero Steel Initiative and its members will contribute actively to mobilising the steel value chain to enhance the environment for investment. NZSI stands ready to support financial institutions to design interventions that will help put the global steel sector, and its wider ecosystem, on a path to reach net-zero emissions. Together we can propel this committed community of stakeholders to act on the essential decisions required to deliver a sustainable future for this industry and the planet.

GLOSSARY

Abatement cost	The cost of reducing CO_2 emissions, usually expressed in US$ per tonne of CO_2
Archetype	A steelmaking production technology paired with its business case—which includes its fuel consumption, emissions, and cost. In ST-STSM, we model 20 distinct steelmaking archetypes. See table 1 in the Technical Appendix for a description of all technology groups and archetypes considered in this work
Bioenergy with carbon capture and storage (BECCS)	A technology that combines bioenergy with carbon capture and storage to produce energy and net negative greenhouse gas emissions (i.e., removal of carbon dioxide from the atmosphere)
Best available technology (BAT)	Technology designs and configurations that enable the lowest energy intensities practically achievable for a given process unit with commercial technology
Carbon capture and storage or utilisation (CCUS)	We use the term "carbon capture" to refer to the process of capturing the CO_2 produced from energy generation and industrial processes. Unless otherwise specified, we do not include direct air carbon capture (DACC) when using this term. The term "carbon capture and storage" refers to the combination of carbon capture with underground carbon storage, while "carbon capture and utilisation" refers to the use of captured carbon in carbon-based products in which CO_2 is sequestered over the long term (e.g., in concrete, aggregates, or carbon fibre)
Carbon budget	The remaining sum of global emissions that can be emitted in order to limit global warming to 1.5°C above preindustrial levels. This brief references IPCC's SR1.5, and subsequent 2019 emissions estimates, that find that in order to reach the 1.5°C target with limited overshoot at 50% probability, we must limit additional emissions to 580 $GtCO_2$ as of 2018, and 490 Gt as of 2020[20]
Carbon price	A government-imposed pricing mechanism, the two main types of which are a tax on products and services based on their carbon intensity, or a quota system that sets a cap on permissible emissions in the country or region and allows companies to trade the right to emit carbon (i.e., as allowances). This should be distinguished from companies' use of what are sometimes called "internal" or "shadow" carbon prices, which are not prices or levies, but individual project screening values
Crude steel	Steel as it emerges in its first solid state, before rolling and other finishing processes
Direct air carbon capture (DACC)	The extraction of carbon dioxide from atmospheric air. This is also commonly abbreviated as DAC
Direct emissions	CO_2 emissions that are directly attributable to the iron and steel sector as defined in this publication, including direct process emissions

Green hydrogen	Hydrogen produced via electrolysis using zero-carbon electricity
Hot metals	Molten iron produced in the blast furnace or smelting reduction furnace
Indirect emissions	CO_2 emissions from the generation of electricity and imported heat that are consumed in the iron and steel sector
Metallic inputs	The combined total of scrap and iron inputs to a steelmaking furnace
Net-zero emissions / Net-zero carbon / Net zero	The state in which the energy and industrial system as a whole, or a specific economic sector, releases zero net CO_2 emissions—either because it doesn't produce any or because it captures and utilises or stores the CO_2 it produces. In this state ("real net zero"), the use of offsets from other sectors should be extremely limited and used only to compensate for residual emissions from carbon capture leakage, unavoidable end-of-life emissions, or remaining emissions from the agriculture sector
Pellets	An enriched form of iron ore used as an input to DRI furnaces and blast furnaces
Primary production	Steel production that uses iron ore as its primary source of metallic input
Secondary production	Electric furnace production that is primarily fed by scrap, as opposed to pig iron or sponge iron
Scope 1 emissions	Direct emissions (scope 1) are estimated for the charge preparation, ironmaking and steelmaking stages, and on-site generation of electricity from off-gases for BOF routes
Scope 2 emissions	Indirect emissions (scope 2) are estimated from on-site electricity consumption (purchased power). The global average CO_2 intensity of electricity consumption is based on underlying data of the 2021 ETC report on grid decarbonisation.[21] Co-produced gas (generated directly by iron, coke, and steelmaking processes) for electricity generation is included in scope 1 in integrated routes
Scope 3 emissions	Supply chain emissions (scope 3) from raw material extraction, commodity production and use, and slag production are included
Technology Readiness Level (TRL)	Describes the level of maturity a certain technology has reached from initial idea to large-scale, stable commercial operation. The IEA reference scale is used, with 11 TRL increments grouped into six categories: concept (TRL 1–3), small prototype (TRL 4), large prototype (TRL 5–6), demonstration (TRL 7–8), early adoption (TRL 9–10), and mature (TRL 11)

TECHNICAL APPENDIX

Table 1. Technology group and archetype descriptions

Technology	(Near-) zero-emissions technology	Year of commercial availability (TRL 8)	Technology overview
Average blast furnace-basic oxygen furnace (BF-BOF)	N	2020	Feed consisting of iron ore and coke is prepared via pelletising and sintering, integrated with coke ovens. Feed is fed into a blast furnace, which undergoes a set of reactions ending in stripping iron ore of oxygen, thus producing molten iron (hot metal). Hot metal (HM) is purified in a basic oxygen furnace (BOF) using pure oxygen, which reacts with carbon and ore impurities, generating heat. Scrap steel is used as a coolant in the process and could also improve the economics of the process. Business case assumes a ~16.5% scrap ratio and 195 kg PCI/t HM.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF)	N	2020	Business case represents BF-BOF route with several improvements to its operations, including increased PCI ratio (230 kg/t HM), scrap ratio (30%), general heating efficiency gain (10%), and top gas recycling (TGR), allowing a reduction of solid carbon input to the blast furnace by ~15%.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with CCUS	Y	2027	BAT BF-BOF route in which CO and H_2 from the blast furnace is utilised for production of methanol/ethanol instead of being reutilised in the BF-BOF. The CO_2 sink is assumed to be sufficiently long-term to provide carbon credits due to either circulation of carbon in the economy or use in products with long lifetime. PCI is assumed to be fully replaced with carbon-dense plastic waste (i.e., polyolefins). Remaining CO_2 emissions from all major parts of the process are captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO_2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency is assumed to be 90%, constant across analysed period.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with CCS	Y	2027	BAT BF-BOF route in which CO_2 from all major parts of the process is captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency is assumed to be 90%, constant across the analysed period.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with biomass PCI	N	2020	BAT BF-BOF route in which pre-treated biomass replaces coal injection into the blast furnace. Wood charcoal assumed as reference.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with H_2 injection	N	2025	BAT BF-BOF route in which part of injected coal is replaced with green hydrogen. It is assumed that hydrogen replaces 120 kg coal/t HM (out of total 230 kg coal/t HM) due to endothermic nature of iron reduction with hydrogen, which may disturb the blast furnace temperature profile and render it inoperable.

Electric arc furnace (EAF)	Y	2020	Dominant steel recycling technology in which scrap steel is melted in an arc furnace using electric current. Preheating is assumed not to require natural gas, but finishing and casting assumed to require natural gas for temperature control. Power consumption in EAF is assumed to be ~1.9 GJ electricity/t liquid steel. EAF process decarbonisation was not modelled as part of this effort (aside from scope 2 emissions decrease due to power grid decarbonisation).
DRI-EAF	N	2020	Steelmaking process replacing coal as carbon source with natural gas in shaft furnace rather than blast furnace. Modelling based on MIDREX® technology in which natural gas is first converted via Steam Methane Reforming process to mixture of carbon monoxide and hydrogen which is then fed into the shaft furnace as reductant. Assumed ~10 GJ/t DRI (shaft furnace consumption) and 16.5% scrap ratio.
DRI-EAF with CCS	Y	2020	DRI-EAF route in which CO_2 emissions from shaft furnace and natural gas combustion are captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency assumed to be 90%, constant across the analysed period.
DRI-EAF with 100% green H_2	Y	2028	DRI-EAF route in which natural gas is replaced with green hydrogen as reductant. Since the reaction of hydrogen with iron ore is endothermic, additional heating of the shaft furnace is required, along with preheating of hydrogen feed. All additional heating requirements are assumed to be met with electric heating. Hydrogen consumption is assumed to be 63 kg/t iron, which is ~17% higher than theoretical requirement for reduction of hematite (54 kgH2/tFe) due to presence of impurities in ore, i.e., silica. Scrap ratio assumption is the same as in reference DRI-EAF business case (16.5%).
DRI-EAF with 50% green H_2	N	2025	DRI-EAF route in which 50% of shaft furnace natural gas feed is replaced with green hydrogen. Since the reaction of hydrogen with iron ore is endothermic, additional heating of the shaft furnace is required, along with preheating of hydrogen feed. All additional heating requirements are assumed to be met with natural gas. Hydrogen is mixed only with shaft furnace feed, remaining equipment uses 100% natural gas for heating. Scrap ratio assumption is the same as in reference DRI-EAF business case (16.5%).
DRI-EAF with 50% biomethane	N	2020	DRI-EAF route in which natural gas used across the plant is blended in equal proportions with biomethane.
DRI-Melt-BOF	N	2026	Combination of DRI shaft furnace with Basic Oxygen Furnace. DRI is made using natural gas, similar to the DRI-EAF route, then hot sponge iron is fed into the melter where it is melted using natural gas combustion. Liquid sponge iron is fed into BOF where it undergoes oxygen treatment similar to BF-BOF route. Given presence of melter and carbon content in sponge iron, it is assumed that scrap ratio can be as high as in case of BAT BF-BOF route (30%).
DRI-Melt-BOF with 100% green H_2	Y	2028	DRI-BOF route in which natural gas in shaft furnace is replaced with hydrogen. Since the reaction of hydrogen with iron ore is endothermic, additional heating of the shaft furnace is required, along with preheating of hydrogen feed. All additional heating requirements are assumed to be met with electric heating. Hydrogen consumption is assumed to be 63 kg/t iron, which is ~17% higher than theoretical requirement for reduction of hematite (54 kgH2/tFe) due to presence of impurities in ore, i.e., silica. Since there is no carbon in the sponge iron coming from Hydrogen DRI process, there is less heat generated during oxygen treatment in BOF. Hence scrap ratio is assumed to be the same as in DRI-EAF route (16.5%). In addition, heating in melter is assumed to come from electricity.

DRI-Melt-BOF with CCS	Y	2028	DRI-BOF route in which CO_2 emissions resulting from all major processes are assumed to be captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO_2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency assumed to be 90%, constant across the analysed period. Heating in melter is assumed to come from electricity.
Electrolyser-EAF	Y	2035	Molten Ore Electrolysis process in which iron is made via direct electrolysis of molten iron ore or a high-temperature (>1550°C) solution of it, similar to today's aluminium smelting. Molten iron is fed into EAF and a small amount of metallurgical coal (or pre-treated biomass) is added to supply carbon required to turn iron into steel. Power consumption in electrolyser is assumed to be ~13 GJ/t iron.
Electrowinning-EAF	Y	2035	Direct iron ore electrolysis process in which iron ore particles are suspended in aqueous alkaline solution in ~110°C. Current passing through the solution breaks down ore into oxygen and iron, which crystallises on cathode. Iron is fed into EAF where small amount of metallurgical coal (or pre-treated biomass) is added to supply carbon required to turn iron into steel. Power consumption in electrolyser is assumed to be ~12 GJ/t iron.
Smelting reduction	N	2028	Type of process in which liquid hot metal is produced from iron ore without coke. Business case is based on HIsarna, a type of smelting reduction in which iron ore fines are injected at the top of Cyclone Converter Furnace along with pure oxygen, while coal powder is supplied at the bottom. The process reduces iron ore into liquid pig iron without coke production and iron ore agglomeration steps. Pig iron is fed into BOF where it undergoes oxygen treatment similar to BF-BOF route. Coal consumption is assumed to be 12.7 GJ/t pig iron, scrap ratio is assumed to be similar to BAT BF-BOF (30%). BOF gases are assumed to be utilised on-site to generate a small amount of electricity (majority is supplied from grid).
Smelting reduction with CCS	Y	2028	Smelting Reduction process that takes advantage of the fact that CO_2 emissions from Cyclone Converter Furnace exit as concentrated stream (85-95% CO_2) which facilitates carbon capture. CCS technique used in the modelling is cryogenic distillation in which the CO_2-rich stream is liquefied and split into main constituents via distillation – it is assumed to consume ~2.2 GJ electricity/t captured CO_2.

Table 2. Key milestones and decision points for 2030

2030	Carbon Cost	Tech Moratorium	Baseline
Production technologies			
Share of secondary production in total steel production	24%	24%	24%
Share of primary steel with carbon capture production	9%	1%	1%
Share of primary steel production utilising H_2	44%	45%	44%
Share of primary steel with 100% H_2 production	8%	1%	1%
Emissions			
Total emissions (scopes 1 and 2) ($MtCO_2$)	2,304	3,090	3,061
Emissions intensity ($kgCO_2$/tCS)	1,059	1,421	1,407
Cumulative emissions, scopes 1 and 2 (Gt)	34	37	37
Electricity consumption (TWh/yr)	**2,075**	**1,464**	**1,471**
Cost of steelmaking incl. capital charges ($/tCS)	**547**	**437**	**438**
Cumulative investment (billion $)	**475**	**345**	**355**

Table 3. Key milestones and decision points for 2050

2050	Carbon Cost	Tech Moratorium	Baseline
Production technologies			
Share of secondary production in total steel production	40%	39%	34%
Share of primary steel with carbon capture production	33%	43%	4%
Share of primary steel production utilising H_2	57%	39%	72%
Share of primary steel with 100% H_2 production	57%	39%	4%
Emissions			
Total emissions (scopes 1 and 2) ($MtCO_2$)	342	355	2,551
Emissions intensity ($kgCO_2$/tCS)	134	139	1,002
Cumulative emissions, scopes 1 and 2 (Gt)	56	70	91
Electricity consumption (TWh/yr)	**5,417**	**4,853**	**2,395**
Cost of steelmaking incl. capital charges ($/tCS)	**527**	**487**	**427**
Cumulative investment (billion $)	**1,165**	**1,187**	**973**

ST-STSM Model Overview

Exhibit A. ST-STSM architecture overview[i]

Inputs

Steel demand
- Primary steel demand
- Secondary steel supply

Commodity data & prices
- Energy & materials
- Price projections for power and green H2 2020 – 2050
- Fuel emission factors

Global steel capacity
- Steel plants representing > 70% of global capacity

#20 steelmaking technology archetypes
- Technology operating characteristics
- Technology operating economics
- Technology-dependent non-combustion emissions

Decision parameters

Geospatial context
- Location-dependent resource availability and prices

Plant economics
- Investment and capital costs by technology archetype
- Operating expenditure by technology archetype
- Total cost of plant ownership per technology

Steel emission factors
- Scope 1 emissions factors per technology archetype (sum of fuel and non-combustion emissions)

Plant decision making

Net-zero 2050 end-state
- Model constrained to net-zero end-state compatible technology choices post 2030

Plant decarbonisation optimisation
- Scenario-based optimisation based on either abatement, total cost of plant ownership or capex

Timing of technology switching
- Refurbishment based on maintaining core furnace technology type
- End-of-life process switching evaluation

Output

Plant-level and infrastructure investment
- Tech / switches/ renovations per plant and associated plant level infrastructure
- New capacity

Commodity and energy consumption
- Total consumption of energy and materials per year 2020-2050

Cost of steelmaking
- Global average cost of steelmaking 2020-2050

Steel making emissions
- Primary and secondary steel scope 1 and 2, and simplified scope 3 trajectories for steel
- Emission intensity per tonne of primary and secondary steel

[i] Based on Global Energy Monitor's Global Steel Plant Tracker. https://globalenergymonitor.org/projects/global-steel-plant-tracker/

The Steel Sector Transition Strategy Model (ST-STSM) calculates pathways to net-zero emissions by 2050 for the steel sector. The model does this by assessing the business case for switching to a new technology archetype each time a steel plant faces a major investment decision (e.g., relining). Twenty technology archetypes are considered in the model. Business cases for each of these archetypes consider feedstock, fuel, and energy consumption, associated emissions, and operating and capital expenditures from publicly available data sources.

Direct and indirect (scope 1 and 2, respectively) emissions are the focus of the model. Scope 3 emissions illustrate the sector's broader effects on system dynamics and include scope 3 emissivities from natural gas, iron ore, and thermal and metallurgical coal mining. The scope and boundaries of emissions are detailed in Exhibit B. The boundaries align with those of the World Steel Association and differ from those of the IEA, which uses direct and indirect emissions system boundaries in which on-site and off-site electricity generation are considered part of emissions in the global power system.

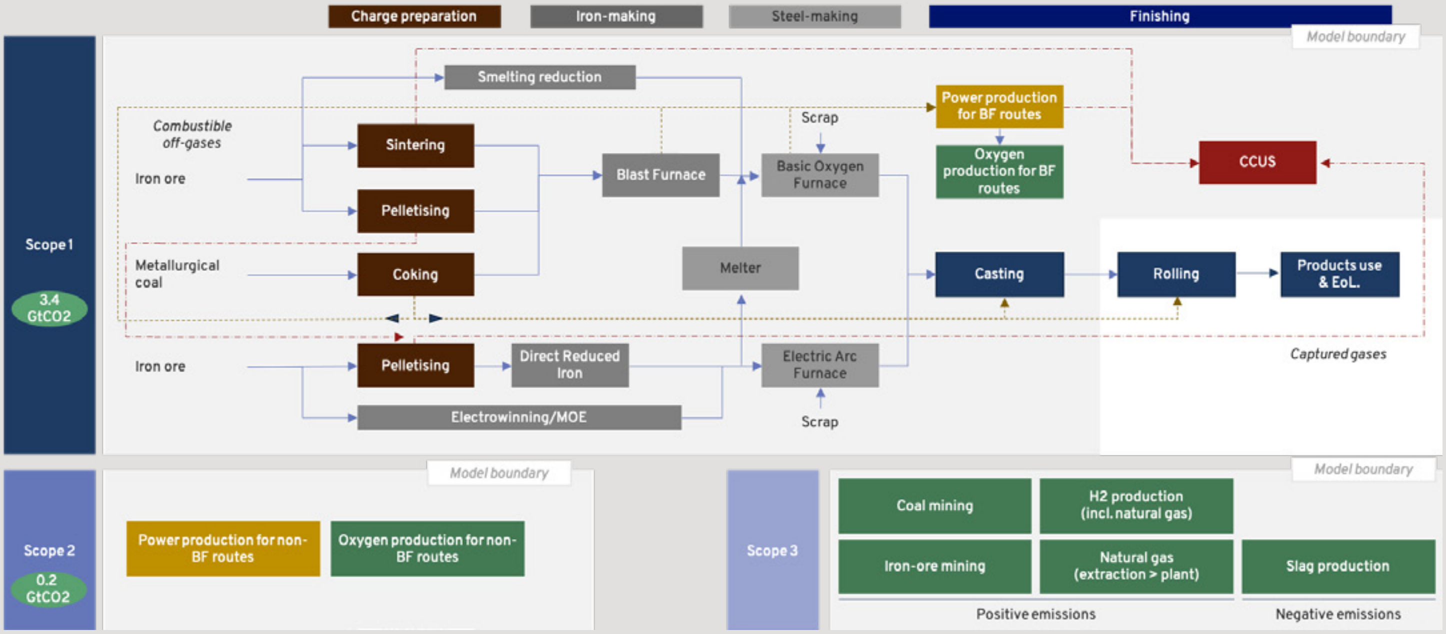
Two net-zero compatible scenarios are presented in comparison with a Baseline scenario. They optimise decision-making for the lowest total cost of plant ownership, with and without a carbon cost. To ensure the model achieves net zero by 2050, a forcing mechanism is applied. In the Tech Moratorium scenario, the range of technologies that can be chosen is limited from 2030 onwards to those classified as "(near-) zero-emissions." In the Carbon Cost scenario, a steadily rising carbon cost is applied to improve the competitiveness of end-state technologies relative to more emissive technologies. Each of the scenarios is also constrained by technology availability (TRL greater than 8) and plant relining schedules. A number of sensitivities can then be applied to each scenario, such as shorter investment cycles, faster innovation timelines, or reduced steel demand, to assess their impact on speed and pathway to net zero.

The model consists of four stages:

1. The model takes inputs that inform the economic parameters and emissions data for the 20 technology archetypes
2. Geospatial context parameters moderate the underlying costs of feedstock and other commodities, depending on whether a given plant is in a favourable location for that technology. This drives the plant economics (cost of steelmaking) and emissions profile that ultimately determine which technologies are more or less favourable
3. At each investment decision point, the technology that has the lowest TCO is selected
4. By aggregating all of these plant-level decisions, the model provides a detailed picture of the technologies, feedstock and energy inputs, emissions trajectories, and cost implications for the steel sector's transition

The simplified modelling architecture is detailed in Exhibit A.

Exhibit B. Scope and emissions boundaries



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