MAKING NET-ZERO STEEL POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

STEEL TRANSITION STRATEGY / SEPTEMBER 2022

MISSION POSSIBLE PARTNERSHIP

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At current emissions levels, staying within the global carbon budget for 1.5°C might slip out of reach already in this decade. Yet efforts to slow climate change by reducing greenhouse gas (GHG) emissions run into a central challenge: some of the biggest emitters of greenhouse gases into the atmosphere – transportation sectors like aviation, shipping, and trucking, and heavy industries like steel, aluminium, cement/concrete, and chemicals manufacturing – are the hardest to abate. Transitioning these industries to climate-neutral energy sources requires complex, costly, and sometimes immature technologies, as well as direct collaboration across the whole value chain, including companies, suppliers, customers, banks, institutional investors, and governments.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonise these industries. Led by the Energy Transitions Commission, the Rocky Mountain Institute, the We Mean Business Coalition, and the World Economic Forum, MPP has as its objective 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 heavy industry and transport. MPP will orchestrate high-ambition disruption through net-zero industry platforms for seven of the world's most hard-to-abate sectors: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals.

The foundation of MPP's approach: 7 Sector Transition Strategies

Transitioning heavy industry and transport to net-zero GHG emissions by 2050 – while complying with a 1.5°C target – will require significant changes in how they operate. MPP facilitates this process by developing **Sector Transition Strategies** for all seven hard-to-abate sectors.

A Sector Transition Strategy

is a suite of user-friendly tools (including a report, an online explorer, and an open-source model) aiming to inform decision makers from the public and private sectors about the nature, timing, cost, and scale of actions necessary to deliver net zero within the sector by 2050 and to comply with a 1.5°C target.

The market penetration of viable decarbonisation measures each sector can draw on is modelled in line with industry-specific replacement cycles of existing assets (steel plants or aircraft) and the projected increase in demand.

The objectives of the MPP Sector Transition Strategies are:

1. **To demonstrate industry-backed, 1.5°C-compliant pathways to net zero,** focusing on in-sector decarbonisation and galvanising industry buy-in across the whole value chain.

2. **To be action-oriented with clear 2030 milestones:** By quantifying critical milestones for each sector in terms of its required final energy demand, upstream feedstock resources, and capital investments, MPP wants to lay the foundation for tangible, quantitative recommendations of how these milestones can be achieved through collaboration between industry, policy makers, investors, and customers.

3. **To be transparent and open:** MPP's long-term goal is to fully lay open the internal machinery of the Sector Transition Strategies, that is, to make its Python models open source and all data inputs open access. In addition, MPP is developing online web interfaces that bring the Sector Transition Strategy reports to life: individual users will be able to explore the results of the reports and to customize model input assumptions, explore the impact of individual levers, and dive deeper into regional insights.

4. **To break free from siloed thinking:** The transition of a sector to net zero cannot be planned in isolation since it involves interactions with the broader energy system, (e.g., via competing demands for resources from multiple sectors). All MPP Sector Transition Strategies are based on similar assumptions about the availability and costs of technologies and resources like electricity, hydrogen, or sustainable biomass. By providing a harmonized, cross-sectoral perspective, we intend to inform decision makers with a fair, comparable assessment of transition strategies for all seven sectors.

On the basis of its Sector Transition Strategies, MPP intends to develop practical resources and toolkits to help operationalize industry commitments in line with a 1.5°C target. Among others, the quantitative results of the Sector Transition Strategies will inform the creation of standards, investment principles, policy recommendations, industry collaboration blueprints, and the monitoring of commitments. These will be developed to expedite innovation, investments, and policies to support the transition.

Goals of the MPP Steel Sector Transition Strategy

This report explores potential pathways to reduce emissions from the steel industry. The analysis that follows builds on the first edition of the Steel Sector Transition Strategy (published in October 2021) and the Steel Sector Transition Strategy Model (ST-STSM) upon which it was based. These efforts were informed by the valuable contributions that preceded them, including the Ultra-Low CO_2 Steelmaking (ULCOS) project, the International Energy Agency's *Net Zero by 2050* roadmap, and extensive engagement with Net-Zero Steel Initiative (NZSI) members and steel experts.[i] As in the first edition, the approach taken here is shaped by three main objectives:

1. To provide a detailed reference point for the changes that will be needed over the next 30 years to underpin target-setting across the steel value chain and its financiers.

2. To inform priority actions, trade-offs, and required decisions needed in the 2020s to get to net zero for stakeholders who will shape steel markets, including industry leaders, governments, buyers of carbon-intensive materials, and financial institutions.

3. To underpin a coherent set of commitments to actions from stakeholders across the value chain, which together will unlock investment in zero-carbon solutions.

i 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.

While the first edition of the Steel Sector Transition Strategy already fulfilled those objectives, the decision was taken to publish an updated version to address five key areas:

A. Inclusion of a 1.5°C-aligned pathway, ensuring that the Steel Sector Transition Strategy mirrored those written for other MPP sectors.

B. An expanded Global Steel Plant Tracker (GSPT) data set, which serves as a key input to the modelling. The updated GSPT covers an additional 32% of tracked capacity compared to the 2021 release.[1]

C. The ability to resolve important regional differences within the global steel industry, addressed by redesigning the ST-STSM to model the industry across 11 unique regions and enable deeper and more granular insight. Previously, the ST-STSM had only been able to model the industry at a global level.

D. The globalised nature of steel markets, taken into account by updating the ST-STSM with a function to model international trade, allowing it to better simulate the reality in which the industry operates.

E. Changes to market fundamentals, such as the jump in fossil fuel prices as a response to the ongoing war in Ukraine.

This updated Steel Sector Transition Strategy includes valuable additions that address these points. However, the key messages of the original edition remain substantially the same. Modifications to the modelling and analysis have understandably caused some details to shift, but the original findings have shown their robustness by remaining directionally unchanged in the face of these modifications.

To promote transparency and collaboration, the model materials and analytics will be made open source and open access, such that the inputs and assumptions are available for enquiry and future iterations may build upon this effort. This open-access approach lends itself to further 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. This open-source approach also enables users to adjust different parameters in the model to reflect the circumstances faced in a particular geography, supporting real-world decision-making.

Industry support for MPP's Steel Transition Strategy

This report constitutes a collective view of participating organisations in the Steel Sector Transition Strategy, foremost the NZSI community. Participants have generally 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 limiting global warming to 1.5°C, the importance of reaching net-zero GHG emissions in steel by mid-century, and share a broad vision of how a 1.5°C-aligned transition scenario could be achieved. The companies recognize that actions to support this broad vision should be pursued expeditiously.

The fact that this agreement is possible among the industry leaders listed below should give decision makers across the world confidence that it is possible to simultaneously meet rising steel demand, reduce emissions from the sector to net zero by 2050, and comply with a 1.5°C target. 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.

Unless otherwise stated, the report is based on publicly available, open access input assumptions and endorsers have not provided commercially sensitive information for technologies under development. While assumptions have been developed through a consensus view of participants, there are significant risks and uncertainties particularly related to cost, performance, and rate of implementation for technologies and actual results may differ materially from those indicated by these forward-looking assumptions.

ArcelorMittal, TATA STEEL, bp, CSN Companhia Siderúrgica Nacional, DANIELI, RioTinto, HSBC, IBERDROLA, Linde, LIBERTY, ResponsibleSteel standards & certification, SSAB, thyssenkrupp *, VATTENFALL, VALE

* thyssenkrupp Steel Europe

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Mission Possible Partnership (MPP)

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% of emissions: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030 in a Business-as-Usual scenario. 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**

Energy Transitions Commission (ETC)

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 organizations – 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

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. **rmi.org**

World Economic Forum

The World Economic Forum is the international organization for public–private cooperation. The Forum engages the foremost political, business, cultural, and other leaders of society to shape global, regional, and industry agendas. Learn more at **www.weforum.org**.

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EXECUTIVE SUMMARY

TEN CRITICAL INSIGHTS ON THE PATH TO A NET-ZERO STEEL SECTOR

1. Bringing the iron and steel sector on a path to net-zero emissions by 2050 is technically and economically possible. Achieving it will require deployment of multiple available and emerging technologies.

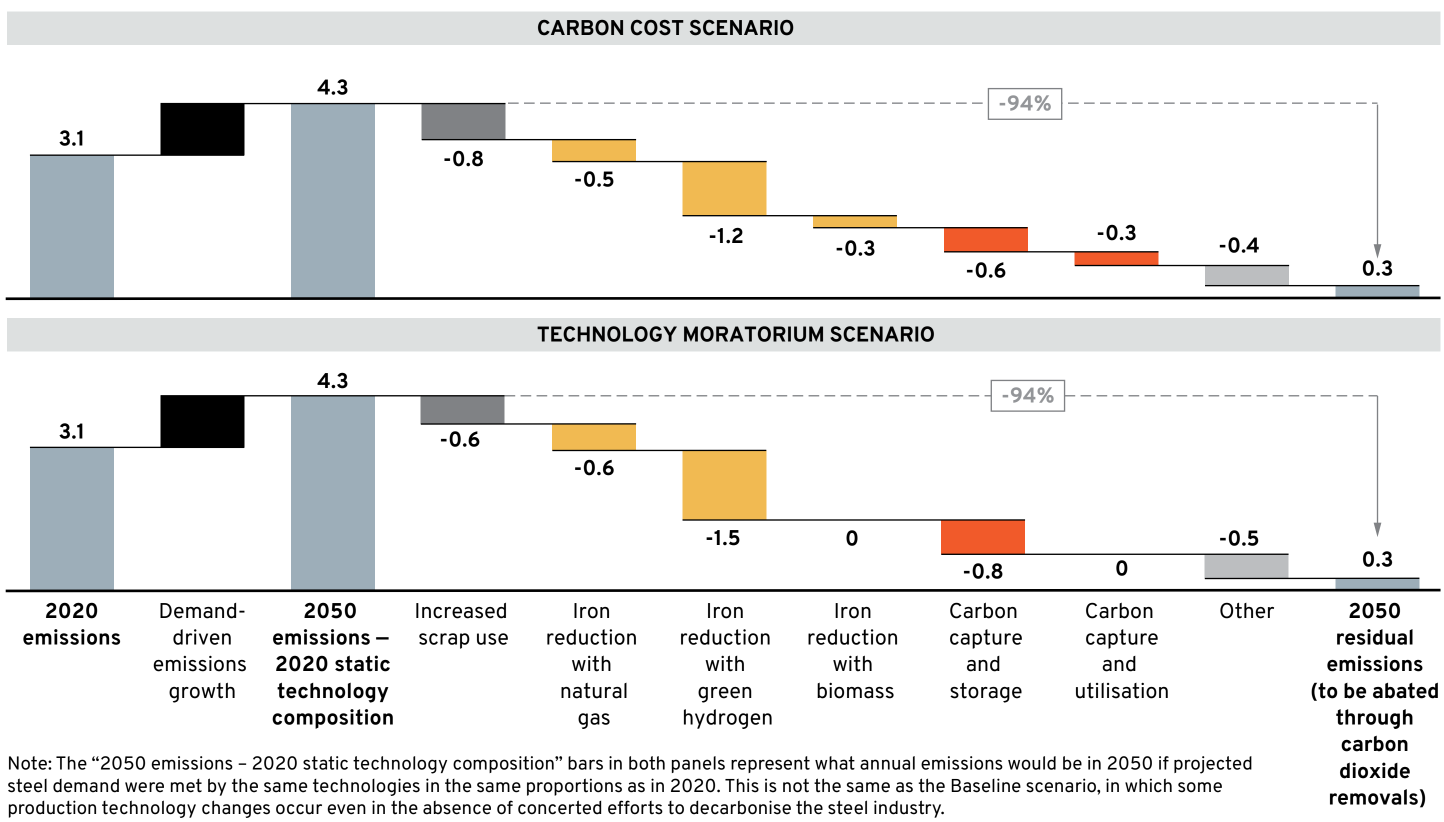
In 2020, the global iron and steel industry was responsible for more than 3.1 gigatonnes of carbon dioxide (Gt CO_2) emissions, about 7% of the total global greenhouse gas (GHG) emissions. In contrast to a Baseline scenario,[ii] two net-zero scenarios show different perspectives to reach net-zero emissions by 2050.

The pace of progress in the 2020s will depend on the extent to which policy and company decisions can bring forward investments in low-emissions steelmaking over the next decade, when the majority of capacity is expected to undergo major investment. The Carbon Cost scenario illustrates how the sector might decarbonise if coordinated action to support low-CO_2 steelmaking takes hold this decade. The Technology Moratorium scenario assumes limited progress this decade, before constraining investments to near-zero-emissions technologies from 2030 onwards. In both scenarios, residual emissions from these technologies remain in 2050 at levels of less than 10% of current emissions and requiring mitigation through carbon dioxide removals (Exhibit A).

EXHIBIT A

Key emissions reduction levers to achieve net zero in the steel industry

Annual emissions (Scope 1 and Scope 2), in Gt CO_2



Note: The "2050 emissions – 2020 static technology composition" bars in both panels represent what annual emissions would be in 2050 if projected steel demand were met by the same technologies in the same proportions as in 2020. This is not the same as the Baseline scenario, in which some production technology changes occur even in the absence of concerted efforts to decarbonise the steel industry.

Source: MPP analysis

ii A Baseline scenario acts as a reference case in which steelmaking assets switch to the technology with the lowest total cost of ownership at each major investment decision, without a net-zero constraint.

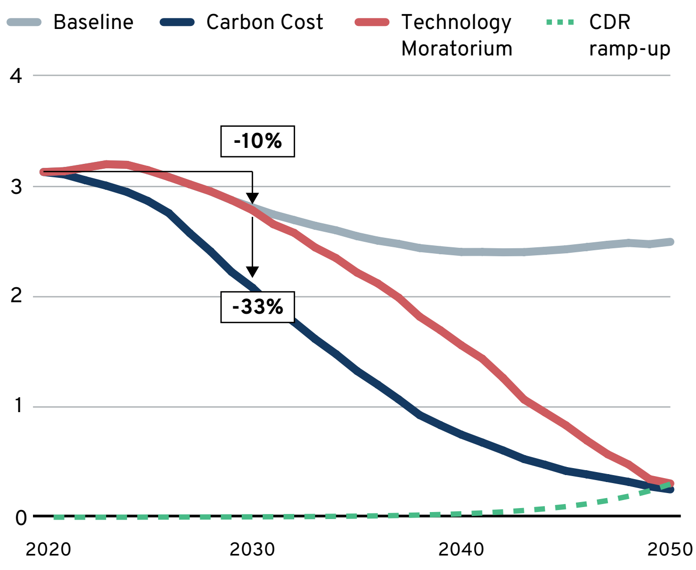
2. Although the pathways of both scenarios reach net zero by 2050, early progress in the 2020s is essential if the steel sector is to stay within its sectoral carbon budget.

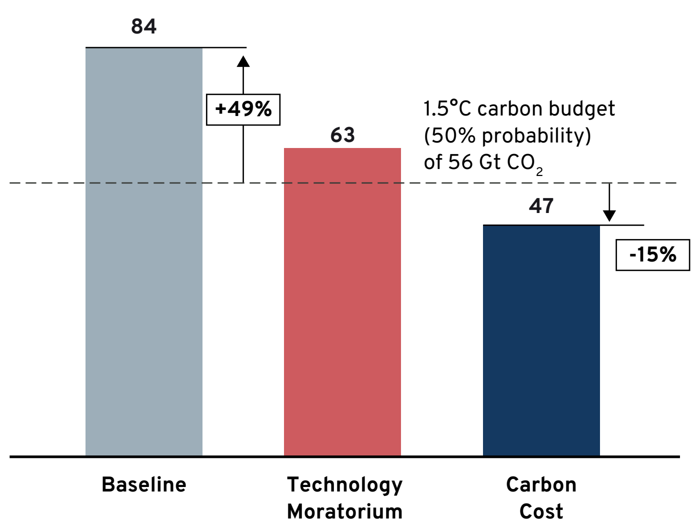
Incremental improvements in existing steelmaking technology and progressive decarbonisation of power grids could deliver 10% emissions reductions in 2030 compared to 2020 at little additional cost. But incentivising early switches to technologies with greater abatement potential could achieve much sharper reductions this decade and radically lower cumulative emissions.

Under the Carbon Cost scenario, up to 1 Gt of annual CO_2 emissions could be avoided in 2030 (a 33% reduction compared to 2020) if carbon pricing globally were to reach around $52 in 2030 or equivalent mechanisms were implemented.[iii] Following this faster trajectory would help ensure the industry remains within a 1.5°C-aligned carbon budget of approximately 56 Gt CO_2, in contrast to the Technology Moratorium scenario in which action is delayed to 2030 (Exhibit B).[iv] This level of decarbonisation would require a major ramp-up in low-CO_2 steelmaking investments in the 2020s, approaching 170 million tonnes (Mt) of annual primary steel production by 2030, equivalent to about 70 near-zero-emissions steel plants.

EXHIBIT B

Annual emissions trajectories and cumulative emissions in the steel industry





Note: The left panel includes the ramp-up of carbon dioxide removals (CDRs) required to abate residual industry emissions by 2050 and ensure the sector reaches net zero.

Source: MPP analysis

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

iv The sectoral 1.5°C carbon budget is calculated as of the beginning of 2020 at a 50% probability of achieving a 1.5°C target. It has been broken down from a global carbon budget provided by the IPCC to individual sectors following an average of the sectoral allocations of BloombergNEF *New Energy Outlook*, the International Energy Agency's *Net Zero by 2050*, and the One Earth Climate Model.

3. Progress in the 2020s has implications for the mix of steelmaking technology in 2050.

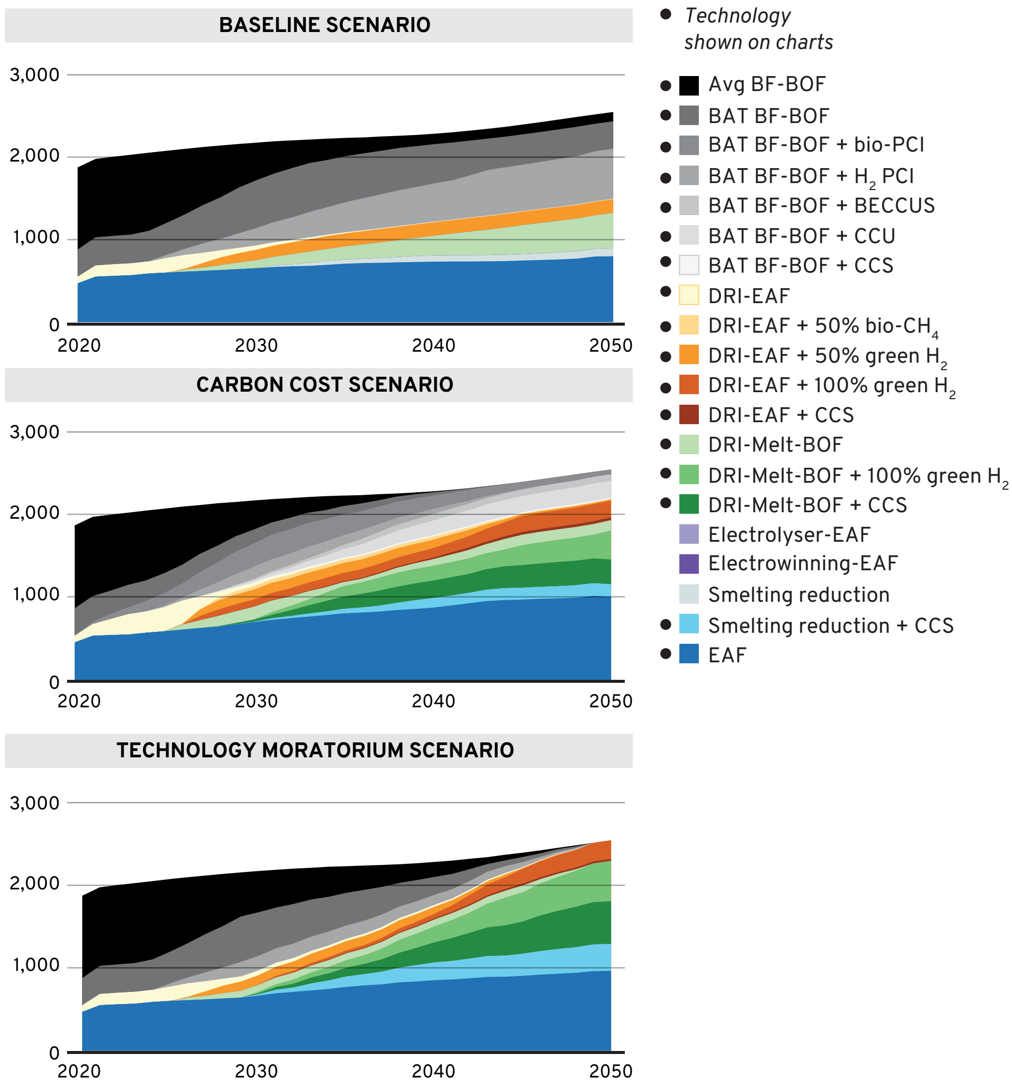
Given the typically 40-year asset life spans of steel plants, investment decisions in the 2020s will shape technology composition into the 2050s. In the Carbon Cost scenario where a cost of carbon is introduced early in the 2020s, the emissions reduction offered by secondary production is leveraged – within the limits of regional scrap availability – in advance of decarbonised primary steelmaking technologies becoming commercially available. This sees scrap-based steelmaking exceed 40% of total production by mid-century.

Additionally, production technologies coupling blast furnaces with bioenergy and carbon capture, utilisation, and storage (BECCUS) become cost-competitive by the late 2020s. This enables blast furnaces to provide 15% of total steelmaking capacity and retain a role in the industry in 2050 and beyond. In the Technology Moratorium scenario, delayed action sees greater uptake of direct reduced iron (DRI)–melter technology as a means to sharply reduce emissions in the 2030s–2040s and make the global industry compatible with a net-zero economy. Crucially, although the path to net zero in 2050 looks different between the two scenarios, early emissions abatement using lower-emissions transitional technologies is needed to deliver a net-zero outcome that is 1.5°C-aligned (Exhibit C).

EXHIBIT C

Evolution of the steel production technology mix

Crude steel production, in Mt



Note: The technology configurations comprise variations on two key processes, ironmaking and steelmaking. Ironmaking routes available today include conventional blast furnaces (BFs) or direct reduced iron (DRI) technologies. Electrolyser and electrowinning are novel ironmaking technologies that are not yet commercially available. These ironmaking technologies are then paired primarily with either a basic oxygen furnace (BOF) or an electric arc furnace (EAF) for steelmaking, both common today. Smelting reduction is an innovative technology that remains in development. Within these overarching routes there are additional subvariations: BF-BOFs can be designated as average or best available technology (BAT), or include the pulverised coal injection (PCI) process supplemented by additional feedstocks. Similarly, DRI technology can be made to work with a BOF by adding a melter (Melt) to the process. Lastly, all fossil fuel–based technologies can be paired with carbon capture, utilisation (CCU), and storage (CCUS) systems, which can derive their inputs from bioenergy (BECCUS). Please see the Glossary for additional details of the different production technology archetypes and their corresponding acronyms.

Source: MPP analysis

4. There is no silver bullet for decarbonising steelmaking, but a greater role for scrap and material efficiency, disruption of the blast furnace, and significant build-out of direct reduced iron–based steelmaking are likely.

A portfolio of solutions is needed to decarbonise steelmaking because different technologies will be cost-competitive in different locations. Most of today's primary steelmaking is in places that have historically offered affordable 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, low-carbon electricity and hydrogen, bioenergy, carbon capture and storage (CCS) infrastructure and sequestration sites, competitively priced natural gas, and proximity to industrial clusters 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:

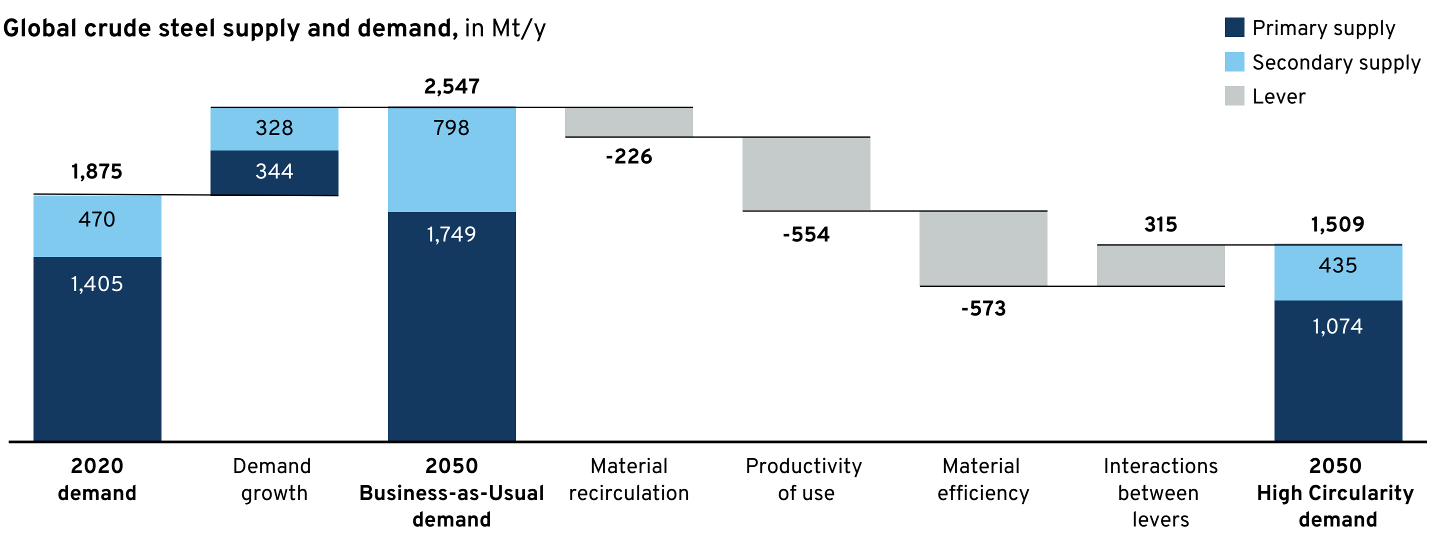
Scrap-based production, material efficiency, and circularity will play a critical role in decarbonising the industry, but large volumes of primary steel will still be needed to 2050 and beyond.

EXHIBIT D

Key levers to reduce primary steel demand

HIGH CIRCULARITY SCENARIO

Global crude steel supply and demand, in Mt/y



Note: The Interactions lever refers to how preceding levers support and rely on one another to achieve the greatest possible impact.

Source: MPP analysis

Steel scrap will play an increasingly important role in decarbonising the sector, both as an input to secondary steelmaking (which relies heavily on electricity and will decarbonise in tandem with the decarbonisation of the power sector) and as an input to primary steelmaking that can help lower the carbon intensity of production.[v] Growth in the global supply of steel scrap, particularly in China, will see its utilisation increase from around 670 Mt/y today to almost 1,180 Mt/y by 2050, replacing iron ore (although the extent of this replacement will likely vary substantially from region to region).

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

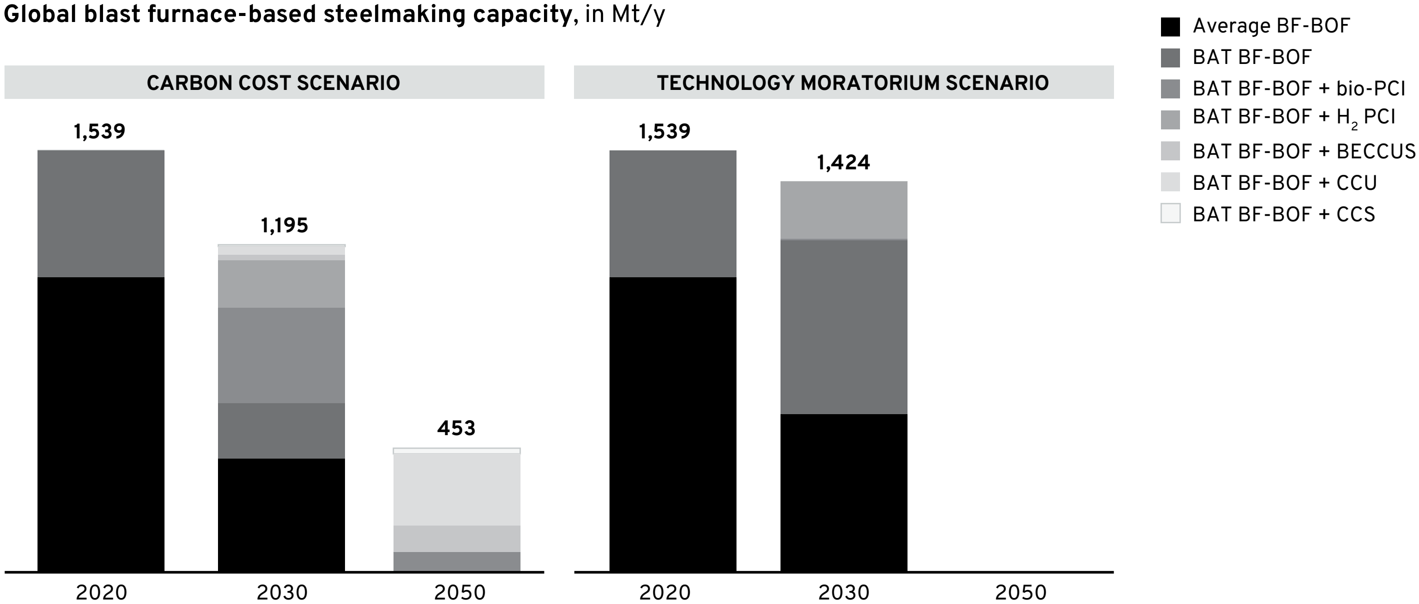
Future demand for primary (ore-based) steel can be further reduced through measures that improve scrap recirculation, productivity of steel use, and material efficiency across steel production and use. Recognising that there are diverging views on future steel demand, our Business-as-Usual (BAU) demand projection foresees an increase from 1,875 Mt in 2020 to more than 2,500 Mt in 2050, driven by demand growth in a number of developing regions. However, if material circularity measures are deployed maximally, they could reduce steel demand by up to 40% by 2050 relative to this projection, avoiding 18 Gt of steel production over the next three decades (Exhibit D). Even with these measures, not all steel demand can be met by recycling scrap, meaning primary steel must also decarbonise to achieve deep decarbonisation in the sector.

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

EXHIBIT E

Evolution of blast furnace steelmaking capacity

Global blast furnace-based steelmaking capacity, in Mt/y



Source: MPP analysis

Retrofitting existing blast furnace–basic oxygen furnace (BF-BOF) technology with carbon capture, utilisation, and/or storage (CCUS) may not be a competitive long-term strategy (Exhibit E), particularly in regions where hydrogen can be produced at highly competitive costs. 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 blast furnaces 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 at less than $1.70/kg, depending on the emissions profile of the existing furnace.[vi] 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 technology with CCS and natural gas–based DRI with CCS in combination with an electric arc furnace (EAF).

As the Carbon Cost scenario suggests, 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 syngas (short for synthesis gas) for the production of feedstocks 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.

vi Based on levelised cost of steelmaking in 2030 assuming a plant with a production capacity of 2.5 Mt/y and a utilisation factor of 80%.

Direct reduced iron–based steelmaking's share of primary production could grow from 5% today to between 70% and 80% by 2050, with implications for iron ore markets and emissions.

The DRI steelmaking process using natural gas provides an immediate emissions savings of about 1 tonne of CO_2 per tonne of crude steel (t CO_2/t CS) compared to an average BF-BOF of 2.4 t CO_2/t CS. In markets where gas prices are economically competitive for steelmaking, developing brownfield DRI capacity (by converting existing BF-BOFs) can help companies reach 2030 emissions reduction targets. These facilities can be set up to utilise a growing share of green hydrogen as supplies become available or can be fitted with CCUS technology, either of which can deliver near-zero-emissions steelmaking. They can also be 100% powered with gasified biomass, making DRI much more flexible in terms of feedstock than blast furnaces.

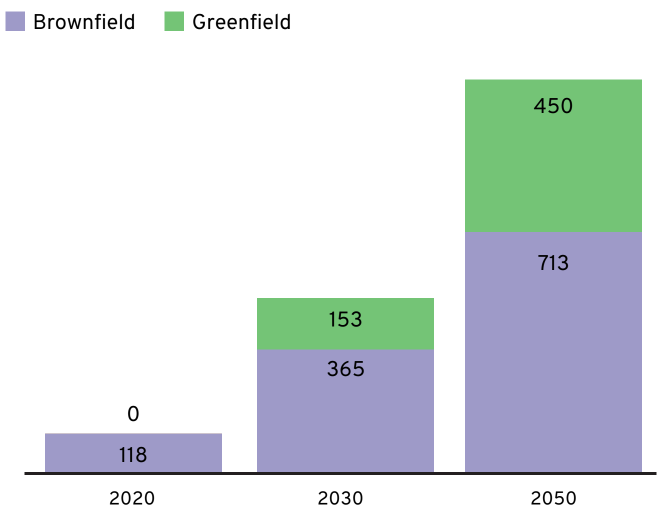
Only 13% of iron ore shipped today is of a suitable grade to use in DRI-EAF steelmaking. If DRI becomes the dominant ironmaking process, as this report suggests (Exhibit F), demand would need to be met through the development of new ore deposits, greater pre-processing of lower-grade ores to achieve sufficient purity, or the development of new melter technologies that enable lower-grade ores to be utilised in DRI-based steelmaking. Given the foreseeable development of new deposits and melter technologies, significant ore processing capacity is likely to be needed. Addressing the scaling of DRI demand will have cross-value-chain implications, creating opportunities and challenges in upstream iron mining activities.

EXHIBIT F

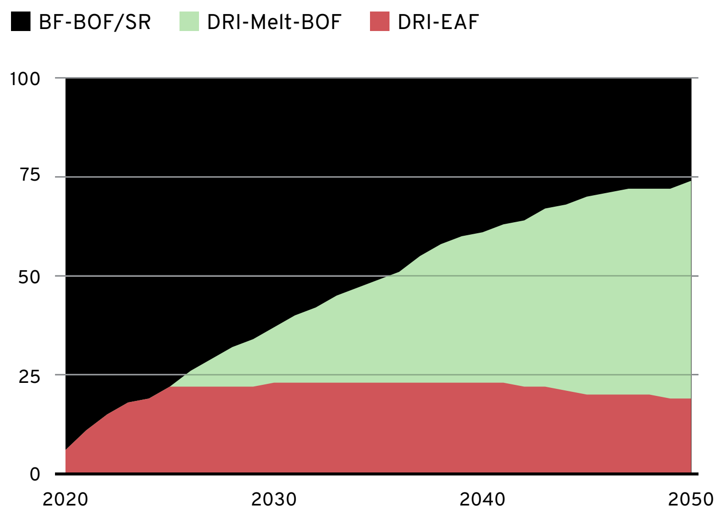
Evolution of DRI steelmaking and iron ore consumption

CARBON COST SCENARIO

Global DRI-based steelmaking capacity, in Mt/y



Global iron ore consumption, percentage



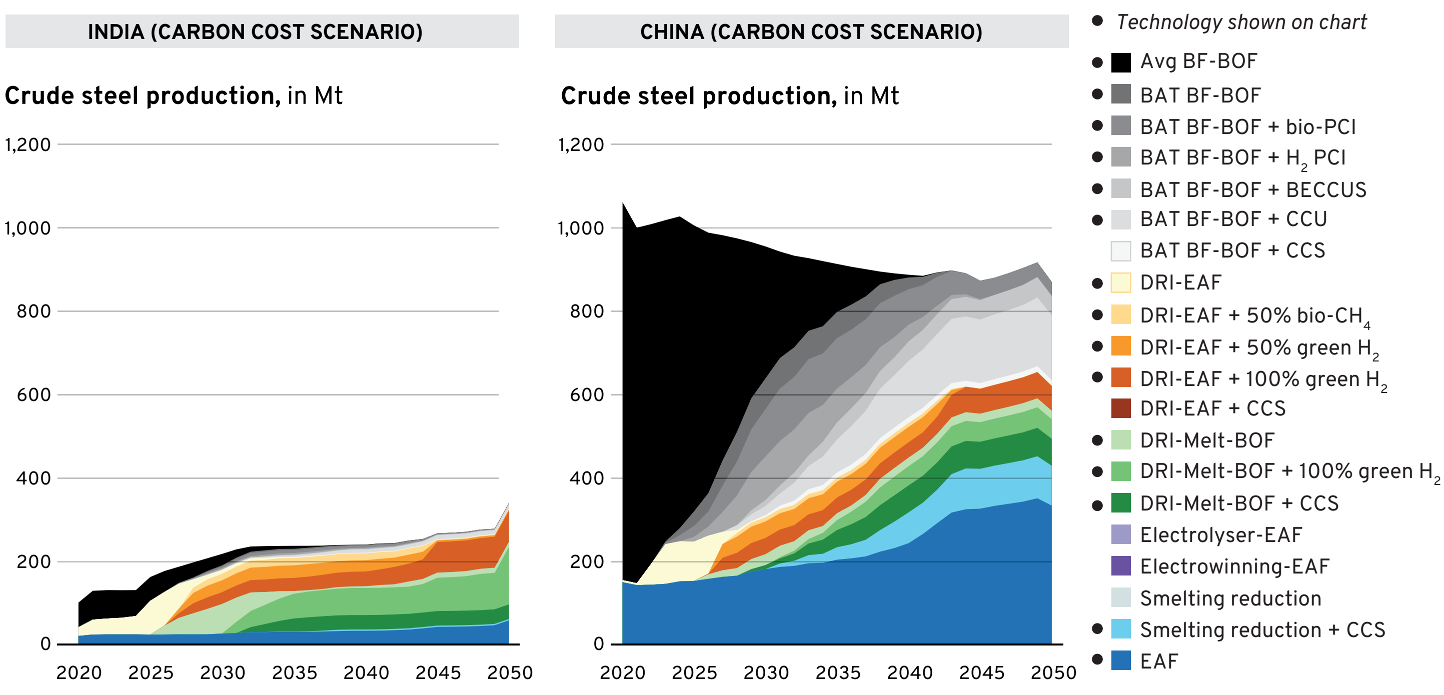
Source: MPP analysis

5. Decarbonisation trajectories for critical steel-producing regions will be shaped by existing assets, energy resource availability, policies, and regional demand for steel. Peak steel demand and increasing scrap availability in China combined with rising demand and increasingly affordable green hydrogen in India will do the most to shape steel sector emissions on a path to 1.5°C.

The technology and emissions pathway to a net-zero steel sector for each major steel-producing region will vary markedly. The technology composition and overall trajectory will be shaped by factors that affect the timing of investment decisions (such as regional demand shifts, the age of existing assets, or political decisions on whether to make or import steel) as well as those that affect the competitiveness of the different technology options available at those decision points (such as the infrastructure of existing assets, the availability of scrap steel, or local energy resources). Two trends will do most to shape a 1.5°C-aligned GHG trajectory of the sector (Exhibit G). China, leveraging an expanding domestic supply of scrap steel, invests heavily in secondary steelmaking capacity, which could account for almost 40% of domestic production by 2050. In India, rising demand and lower scrap availability will likely result in scale-up in primary capacity to meet burgeoning domestic demand. Low hydrogen prices in India mean that the majority of this primary capacity is centred on DRI technology utilising hydrogen.

EXHIBIT G

Regional evolution of the steel production technology mix



Source: MPP analysis

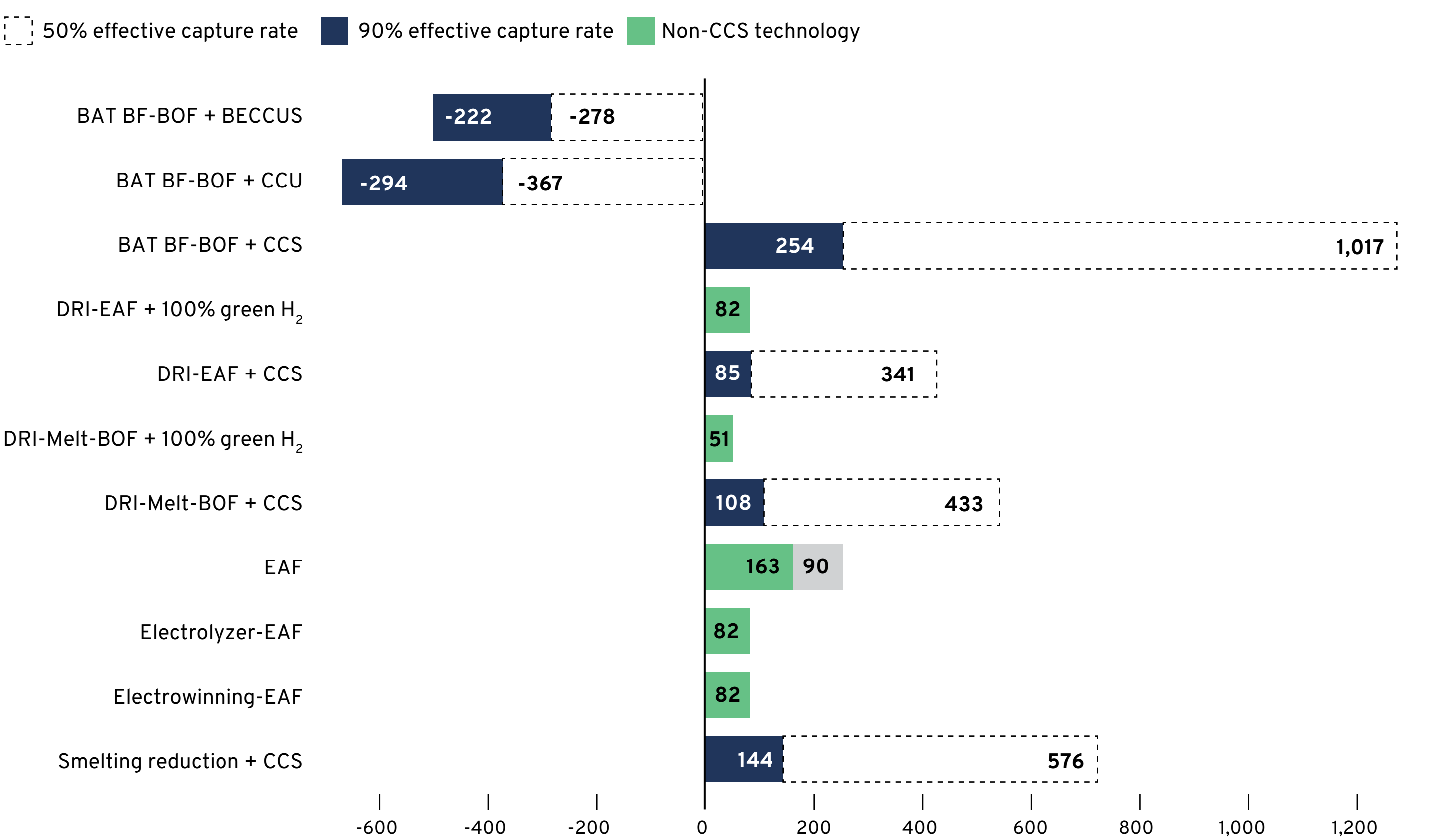
6. Almost all technologies will have residual emissions, which will need to be addressed to achieve net zero by 2050.

Except for technology archetypes that combine bioenergy resources with CCUS and deliver negative emissions, all near-zero-carbon production technologies will have residual emissions (Exhibit H). As a result, even if global power grids fully decarbonise, there will still be up to 0.3 Gt of residual CO_2 emissions from the steel sector (equivalent to ~10% of the steel sector's emissions today) in 2050. This is primarily due to expected uncaptured carbon dioxide from carbon capture technology (assuming a 90% effective capture rate) and electrode degradation in EAFs. The industry's remaining Scope 3 emissions, particularly in upstream feedstock production such as methane from coal mining and gas production, should also not be neglected. These will need to be managed by the industry and Scope 1 residuals alone may add a significant cost ($60 billion) annually from 2050 based on a $200/t$CO_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.

EXHIBIT H

Residual emissions of net-zero-compatible steelmaking technologies

Residual Scope 1 Emissions in 2050, in kg CO_2/t CS



Note: The range of residual emissions from EAF production depends on the presence of natural gas in the preheating and finishing steps. Both the BAT BF-BOF + CCU and BAT BF-BOF + BECCUS archetypes achieve negative emissions through bioenergy use.

Source: MPP analysis

7. Commercialisation and deployment of technologies to achieve net zero will require major investment inside and outside the steel industry, totalling $170–$200 billion annually.

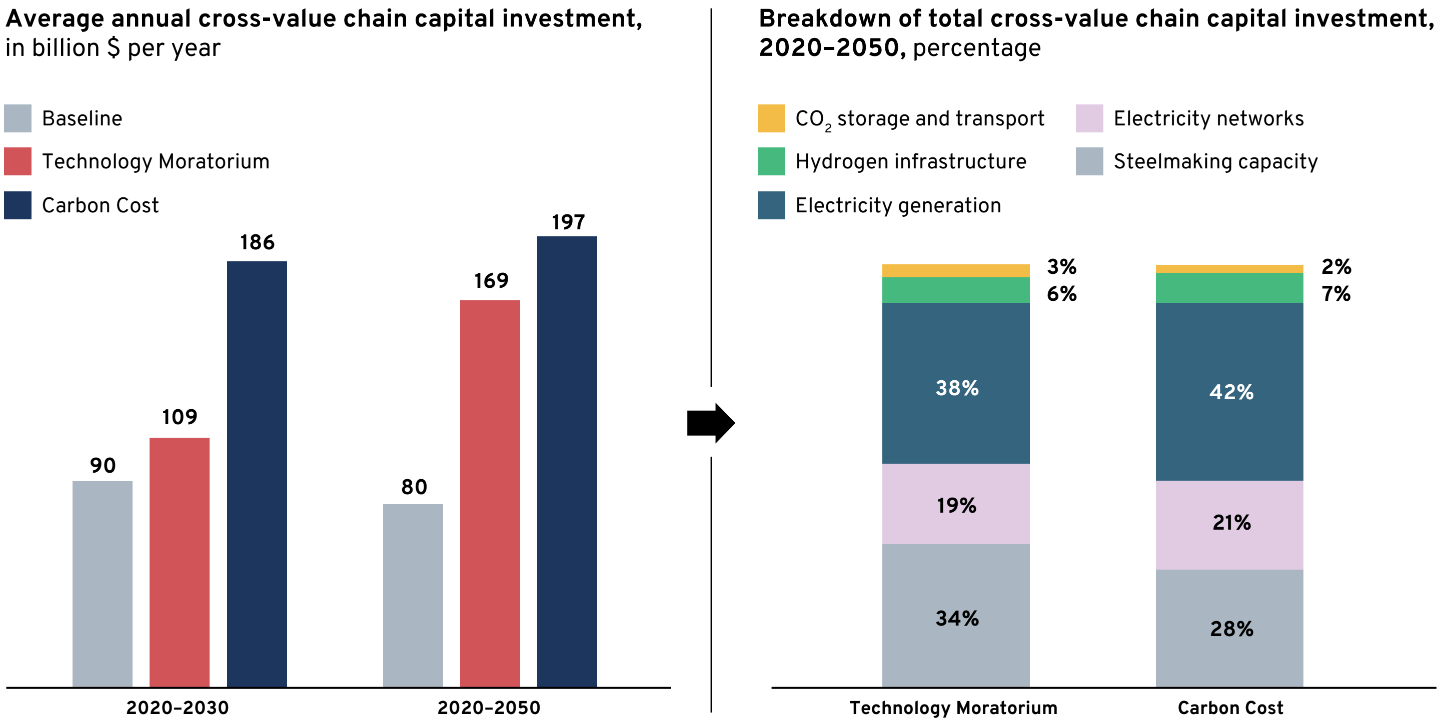
Even without major transformation, the steel sector is projected to need approximately $47 billion in investment annually to meet growing demand over the next 30 years and maintain existing sites. Transitioning the global steel asset base to net-zero-compliant technologies will require an additional $8–$11 billion investment annually – equal to $235–$335 billion of additional investment cumulatively by 2050. Initiatives to focus greater flows of capital towards those companies that align with a net-zero pathway will help accelerate these shifts.

The scale of investment needed in accompanying infrastructure could ultimately dwarf the needs of steel plants themselves (Exhibit I). Hydrogen use in the steel sector could grow to 52–75 Mt/y by 2050, eventually all coming from low-carbon energy sources. Electricity demands, both to generate sufficient volumes of green hydrogen and to meet the needs of an increasingly electrified asset base, could increase to 5,700–6,700 terawatt-hours per year (TWh/y) by mid-century.

In areas where competitively priced zero-carbon electricity is not available, carbon capture facilities will need to scale rapidly because storage for 550–750 Mt/y of CO_2 may be needed before 2050. In total, a net-zero steel sector will require cumulative investment between $5.2 and $6.1 trillion, with more than two-thirds of investment falling outside the steel plants.

EXHIBIT I

Summary and breakdown of the total investment involved in the net-zero steel transition



Source: MPP analysis

8. Lower- and near-zero-emissions primary steel will cost more. Public policies and value-chain coordination will be needed to address this premium, especially in the 2020s.

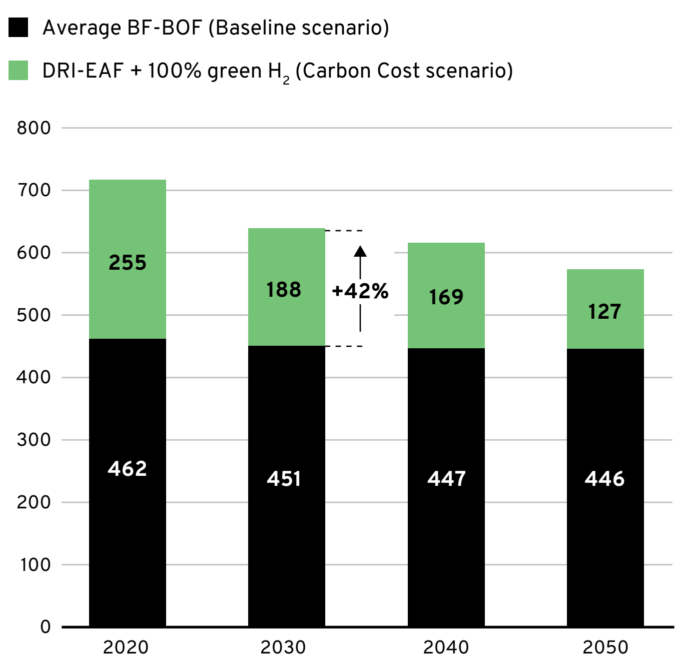
By 2050, the average cost of steelmaking (excluding capital charges) in a deeply decarbonised world could still be 15% higher than in a world without concerted efforts to decarbonise the steel industry. However, the impact of this on the final consumer would be comparatively smaller, given that intermediate steel products often account for only a portion of the cost of many of the final goods or services in which they are used (Exhibit J). If these costs were passed through to end-use markets and consumers, they would likely represent a premium lower than the prevailing market price volatility for basic materials. Moreover, this premium would reduce over time as near-zero-emissions technologies experience economies of scale and lower technology risk, making them increasingly competitive with conventional processes.

The cost difference between high- 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, green public procurement, and bilateral off-take agreements between steel producers and steel buyers. In the medium term, these initial measures may need to be strengthened with 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 introduced with coordination across steel-producing regions (recognising differences between individual 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 for coordinated global action.

EXHIBIT J

Impact of near-zero-emissions primary steelmaking on production costs and final consumer goods

Global average levelised cost of steelmaking, in $/t CS



Price difference of consumer goods produced with near-zero-emissions hydrogen steel vs. conventional primary steel, %

Consumer good	2030	2040	2050
Passenger car	+0.5%	+0.4%	+0.3%
Building	+2.1%	+1.9%	+1.4%
White good	+1.5%	+1.4%	+1.0%

Note: To provide a more illustrative comparison, the figures for average BF–BOF exclude any sort of carbon pricing, which would raise its production costs as a carbon intensive technology and further narrow the gap to near–zero-emissions alternatives.

Source: MPP analysis; ETC and Material Economics, **https://www.energy-transitions.org/publications/steeling-demand/**; McKinsey & Company and ETC, **https://www.mckinsey.com/business-functions/sustainability/our-insights/net-zero-steel-in-building-and-construction-the-way-forward**

9. The transition to net zero will have significant resource implications, with large increases in required hydrogen, electricity, and natural gas inputs, but a stark decline in coal.

Hydrogen: This analysis suggests production technologies using 100% green hydrogen could be responsible for 35%–45% of primary steel production in 2050, driving the consumption of zero-emissions hydrogen to 52–75 Mt/y (between 7% and 15% of potential global demand) by mid-century (Exhibit K).[vii] Supporting the growth of hydrogen-based steelmaking could help drive down the cost of green hydrogen production, unlocking its use in a wide range of other industrial applications where direct electrification is challenging.

Electricity: The 5,700–6,700 TWh/y of clean electricity the global steel sector would require by mid-century would be more than double the total power production of European Union member states in 2020. Delivering a resilient, secure supply of these enormous amounts of clean power represents a critical factor in unlocking decarbonisation for the steel industry and will require an extensive build-out of the necessary infrastructure. Given the high level of planning necessary for this infrastructure, for both transmission and distribution networks as well as generation assets, preparation must begin now.

Natural Gas: In addition to the growth of hydrogen, the uptake of DRI technology brought on by steel decarbonisation also sees a significant increase in the use of natural gas, with consumption more than tripling current levels in both net-zero scenarios. Procurement of certified low-methane-emissions natural gas will be important to credibly demonstrate a reduction in supply chain emissions where this fuel is used. This is particularly salient for the Carbon Cost scenario, where faster adoption of DRI technology precipitates a sharper increase in the use of natural gas over the next decade and a half. In both net-zero scenarios, CCUS plays an important role in ensuring that continued natural gas consumption is consistent with the sector's decarbonisation goals.

Bioenergy: Bioresources such as biochar, biogas, and biomass have a limited but valuable role to play in the steel sector's transition. Early action in the Carbon Cost scenario sees the use of bioresources within existing technology processes becoming cost-competitive, unlocking early emissions reductions of up to 40%–60% per tonne of crude steel compared to natural gas and coal. This early action sees the steel sector's bioresource use peak at 2.4 exajoules per year (EJ/y) in the 2030s, equivalent to less than 5% of global sustainable supply.[viii]

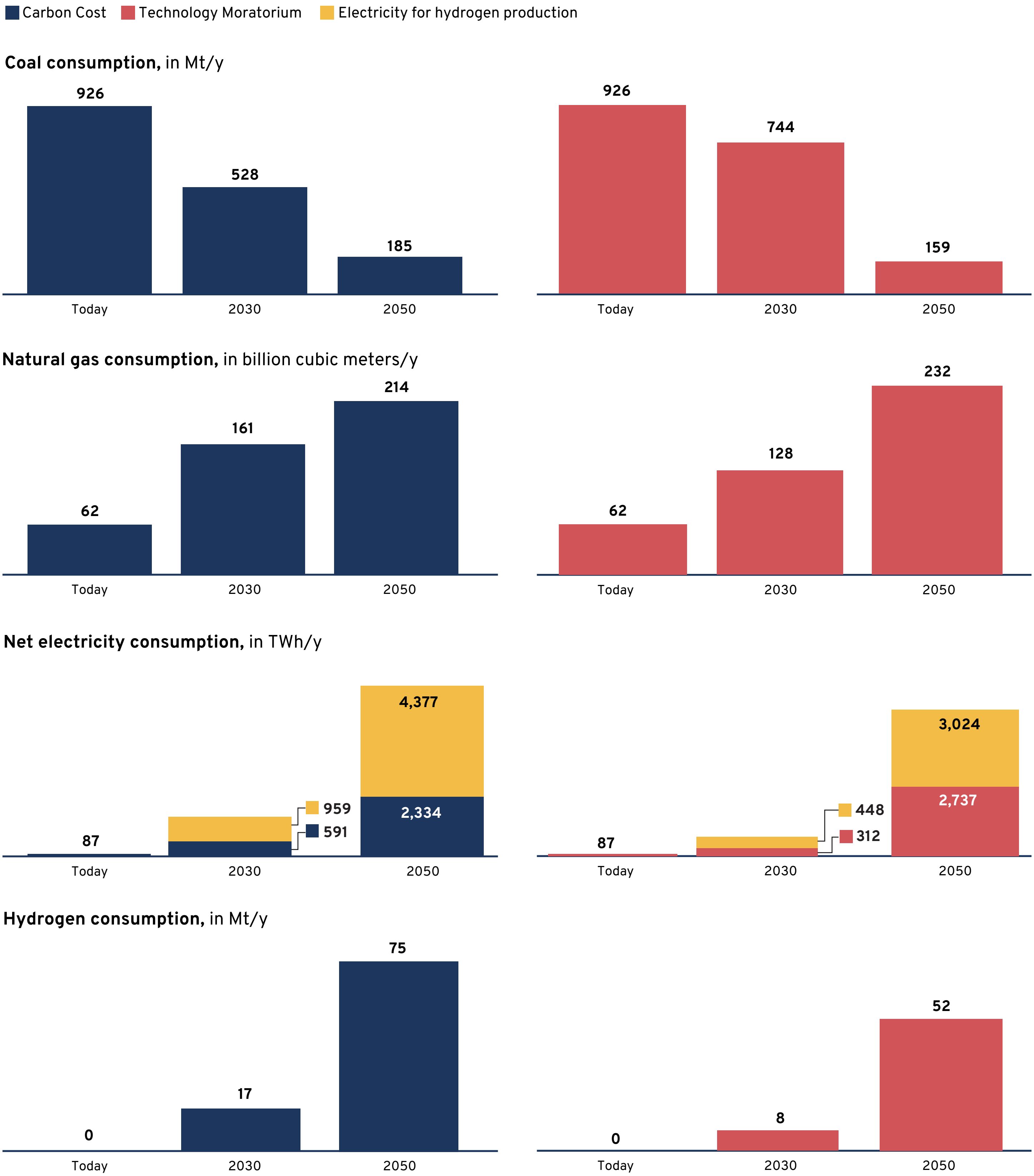
Coal: The replacement of blast furnaces with DRI-based steelmaking and smelting reduction techniques, which do not require metallurgical coal to reduce iron ore into molten iron, will trigger a major decline in demand for metallurgical coal. Use of thermal coal follows a similar trajectory, though its continued role in smelting reduction technology paired with CCUS sees it decline less sharply. Consequently, total coal consumption by the steel sector is expected to fall by more than 80% by 2050.

vii Energy Transitions Commission (ETC), *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy,* April 2021, https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/.

viii Energy Transitions Commission (ETC), *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach*, July 2021, https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-emissions-economy/.

EXHIBIT K

Energy consumption shifts driven by the net-zero steel transition



Source: MPP analysis

10. The key action this decade is to expand the pipeline of near-zero-emissions primary steelmaking. To accomplish this, policymakers need to create a level playing field and support a first wave of projects, industry needs to ramp up supply of and demand for near-zero primary steel, and finance must direct capital towards near-zero-emissions projects.

A narrow but clear window of opportunity is opening. Large swathes of existing steelmaking capacity will need major reinvestment decisions in the coming years and there is a risk of capacity-maintaining investment in high-emissions technology or delayed investment. The business case for low- and near-zero-emissions steel projects now represents the critical challenge that must be overcome.

Policymakers should urgently establish an international forum to debate and resolve the issue of how to create a level playing field and create markets for low-emissions steel production. In parallel, they must develop mechanisms to support deployment of near-zero-emissions industrial technologies and associated infrastructure (Exhibit L).

Industry must progress from the demonstration phase to final investment decisions for industrial-scale projects that will enter operation in the late 2020s. A redrawing of the steel value chain and supplier networks will require new partnerships to be forged. The demand side must also play a part in helping to pull those projects to market through premiums and signalling demand for material volumes of low-emissions steel.

Banks, institutional investors, and public-sector financial institutions must take a more hands-on approach to help manage the project and enterprise risk and direct capital towards first-mover projects and away from carbon-intensive investments. Widespread implementation of climate-aligned investment principles will be an important first step.

EXHIBIT L

Key actions in the 2020s to bring the iron and steel sector on a path to net-zero emissions by 2050

POLICY

Multilateral solutions

- **Level playing field**: Establish an international forum/alliance to debate and resolve the issue of how to create a level playing field and create markets for low- and near-zero-emissions steel production
- **Definitions:** Develop stable and ambitious trade- and transaction-grade standards for low-emissions steel production

National/regional supply incentives

- **Regulatory reforms:** Accelerate and improve permitting procedure for steel and supporting infrastructure
- **Investment:** Combine concessional, blended finance, credit and loan guarantees, and CAPEX grants for first-of-a-kind (FoaK) commercial-scale projects
- **Infrastructure:** Coordinate plans and strategies for necessary infrastructure and raw materials

National/regional demand incentives

- **Demand creation:** Extend green public procurement to support industrial strategy and lead market creation

INDUSTRY

Supply side

- **Projects:** Plan and deploy +70 near-zero-emissions primary steel mills by 2030
- **Target setting:** Set robust emissions reduction targets that are aligned with the goal of limiting global temperature rise to 1.5°C
- **Industry consortia:** Forge new partnerships across the steel value chain and upstream energy system
- **Common policy position:** Set out a joint high-ambition position to policymakers that reflects the role of international steel producers with assets in multiple geographies

Demand side

- **Green premiums:** Agree to long-term off-take with a green premium that is proportional to production cost increment and associated risks for both supplier and buyer

FINANCE

Capital allocation

- **Capital allocation:** Provide sufficient capital to enable at least $100 billion of additional investment in low-emissions steelmaking (and supporting infrastructure) each year until 2030
- **Business case innovation:** Co-develop strategies to manage the market, credit, liquidity, operational, and policy risks for FoaK projects

Climate alignment

- **Investment principles:** Implement 1.5ºC-aligned investment principles and plan and support a moratorium of non-climate-aligned steel investment from 2030

Source: MPP analysis

CONCLUSION

Bringing the iron and steel sector on a 1.5°C-aligned path to net zero is possible. It would require substantial annual investments in the order of $200 billion/y, of which more than two-thirds would fall outside the steel industry and into electricity, hydrogen, and CO_2 infrastructure, with large-scale implications across the wider value chain.

A course towards 1.5°C and net zero will require new levels of partnership between policymakers, industry leaders, and financial institutions. Early action in this decade is required to unlock technological innovation and economies of scale and to enable large-scale GHG emissions reductions in the 2030s and 2040s.

In a joint effort by actors across the value chain, we can make this mission possible.

MAIN REPORT

MAKING NET-ZERO STEEL POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

DECARBONISING STEEL: CHALLENGES AND SOLUTIONS

BOX 1

Key highlights

A. 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 up to 60% of steel in 2050 will likely need to come from primary, ore-based production in the absence of major materials and circularity breakthroughs. Therefore, new 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. Some of these technologies are already technically proven but not yet deployed at scale.

B. Progress this decade is essential, and steelmakers are stepping forward. As of the end of 2021, companies representing 20% of global steel production have set net-zero-compatible targets. Major steel-producing and -consuming regions, including the European Union (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. However, the necessary investment in low-CO_2 steel production will require a strong business case and policies that take global competition fully into account.

C. 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.

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

Source: MPP analysis, corporate announcements, government announcements

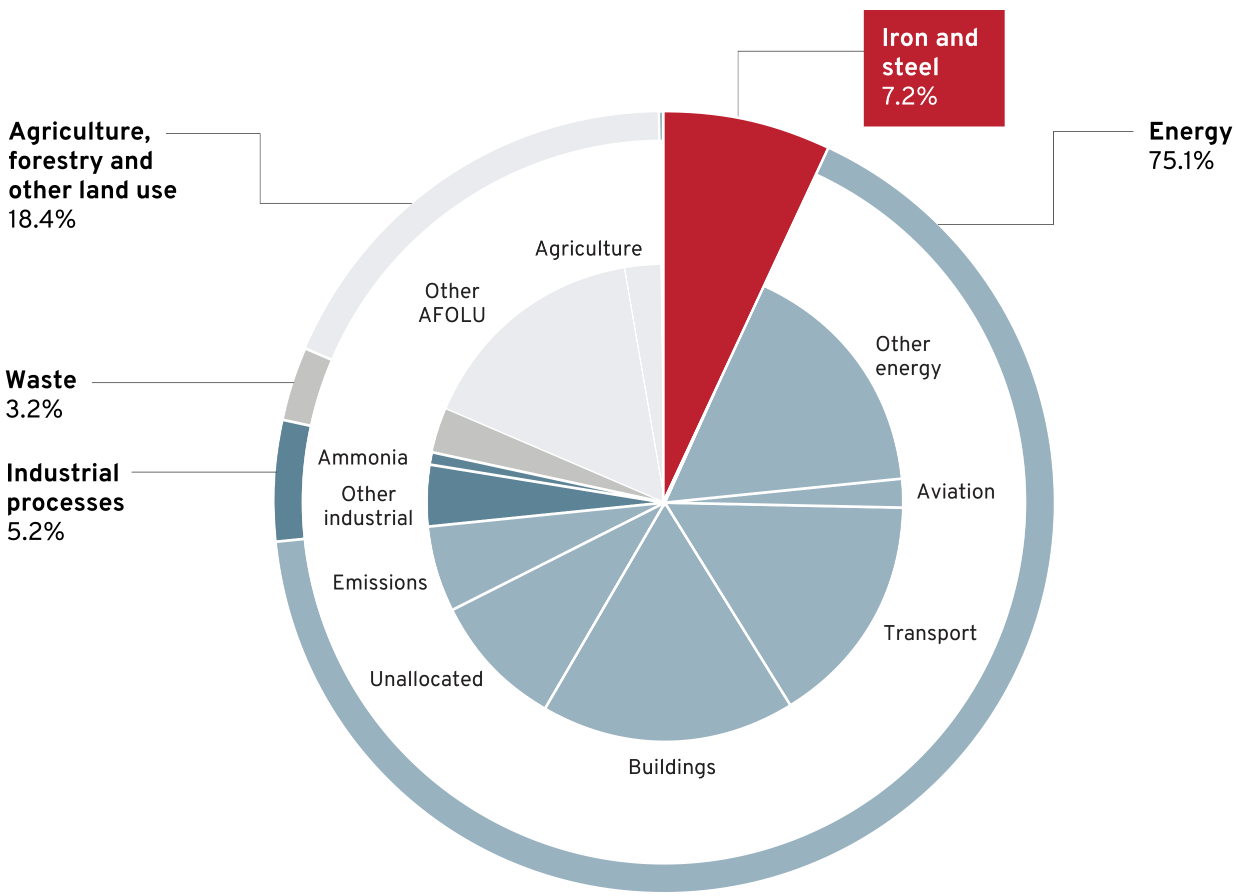
1.1 Global steel and its decarbonisation challenge

Steel is essential 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.[ix] Production of both primary and secondary steel emitted approximately 3.1 gigatonnes of carbon dioxide (Gt CO_2) in 2020,[x] and accounted for about 7% of global GHG emissions (Exhibit 1.1).[2] As the power sector decarbonises, steelmaking is expected to become the single largest source of industrial emissions.

EXHIBIT 1.1

Steel within the context of global greenhouse gas (CO_2e) emissions



Source: Hannah Ritchie, Max Roser, and Pablo Rosado, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

ix 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.

x Referring to both Scope 1 and Scope 2 emissions, the latter associated with electricity generation. Accounting methodologies for emissions can vary. The International Energy Agency 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. The Steel Sector Transition Strategy Model follows the worldsteel approach.

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.[3] Today, nearly all the world's steel is made through one of three main production routes:

1. **Blast furnace–basic oxygen furnace (BF-BOF):** Iron ore is reduced in the blast furnace to molten iron, which is subsequently refined to crude steel 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 fuels. About 70% of the world's steel was produced via this process in 2020, which emits an average of 2.1 tonnes of CO_2 per tonne of crude steel (t CO_2/t CS).

2. **Electric arc furnace (EAF):** The EAF route, accounting for 25% of global production in 2020, 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 0.5 t CO_2/t CS.

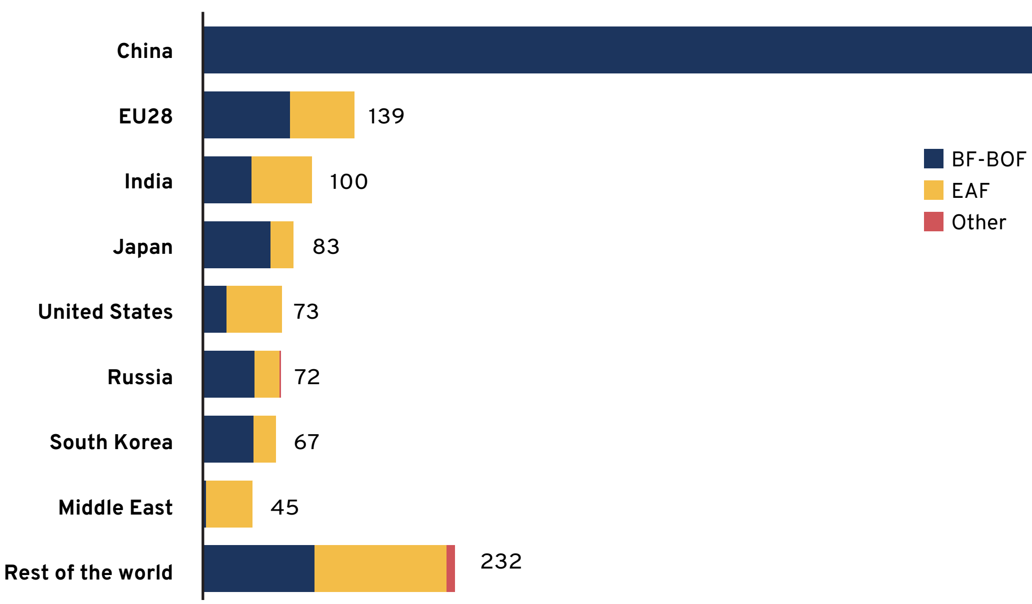
3. **Direct reduced iron–electric arc furnace (DRI-EAF):** Direct reduction is the process of reducing iron ore without melting it, using a reducing gas (typically a blend of hydrogen and carbon monoxide derived from natural gas). The solid product, DRI, is mainly used as feedstock in an EAF. About 5% of the world's steel is produced via this process, which emits 1.2 t CO_2/t CS on average when using natural gas.

The mix of these technologies varies significantly by region (Exhibit 1.2). 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 is a larger share. In locations with abundant and low-cost natural gas, such as the Middle East, DRI-EAF technology typically plays a larger role.

EXHIBIT 1.2

Crude steel production by process in 2020

Crude steel production in 2020, in Mt



Note: DRI-produced iron is used in both blast furnace and EAF routes and was equal to 106 million tonnes (Mt) in 2020.

Source: worldsteel, **https://worldsteel.org/steel-by-topic/statistics/world-steel-in-figures/**

Although they do they do not reach the same scale as the industry's combined Scope 1 and 2 emissions, addressing the ~0.7 Gt CO_2e/y of Scope 3 (supply chain) emissions linked to the steel sector presents another important challenge. Scope 3 emissions from steelmaking include upstream emissions from iron ore and energy supply, 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.

Why is steel hard to abate?

- **Projected demand growth:** Global crude steel production capacity has more than doubled over the past two decades. The BAU projection in this report, and those of industry and other experts, sees steel production increasing by a third by 2050 from 1,875 million tonnes (Mt) today, driven by growing urbanisation, particularly in developing countries.

  Even with incremental technology performance and material efficiency improvements, such growth will see cumulative CO_2 emissions of 84 Gt by 2050 in the absence of targeted measures and technology breakthroughs. This is about 16% of the 500 Gt the Intergovernmental Panel on Climate Change (IPCC) estimates is the maximum cumulative future emissions permissible if we are to have a 50/50 chance of limiting global warming to 1.5°C.[4]

  Even in analyses where demand is projected to plateau globally, the evolution of demand in different regions, combined with a preference for localised production, leads to a geographic shift in the carbon footprint of steelmaking.[5] Ensuring these growing markets do not simply build out low-cost but carbon-intensive primary steelmaking capacity poses a real challenge.

- **High costs:** Low-carbon production technologies for primary steel currently impose additional costs relative to existing methods and are expected to be cost-adding on average until 2050. This challenge is particularly acute in the current decade, where the costs of near-zero-emissions primary steelmaking facilities could be up to 90% higher than conventional plants.

Why is it particularly challenging to kick off the transition to net zero this decade?

- **Low technology readiness levels (TRLs):** Today, technologies that have the potential to produce steel with lower carbon emissions (such as scrap-fed EAF) and to incrementally reduce the emissions of carbon-intensive production (such as pulverised charcoal injection into BFs) already exist. However, while potential end-state, near-zero-emissions primary production technologies are already known and technically proven, none has yet reached a technology readiness level (TRL) of 9 and been deployed at a commercial scale.[xi] Most of these technologies are only expected to become commercially available in the second half of the 2020s or later.

- **Long industry time frames:** Given the capital-intensive nature of steelmaking, the most opportune moment to refurbish a steel plant and switch its production technology to a low-carbon alternative is towards the end of the plant's investment cycle.

  The length of this cycle for a BF-BOF is around 20 years, dictated by the "campaign life" of its furnaces. Lengthy asset lifetimes such as these mean not all steel plants will be eligible for a low-carbon refurbishment in the coming decade (and those plants that are eligible risk being locked into carbon-intensive pathways if alternative technologies are not available in time).[6] Although greenfield low-carbon steel projects would not face the same obstacles, the considerable lead time needed to plan and build new steelmaking assets means it would still be challenging to take action quickly in this way.

- **Competitive wholesale market:** The steel industry operates in a highly globalised and commoditised wholesale market, meaning even small increases in the costs faced by steelmakers can weaken their market competitiveness. This could create a first-mover disadvantage for steelmakers looking to take early action on decarbonisation because they may become subject to a relatively significant green premium that their slower-moving rivals would not face.[7]

1.2 Decarbonisation solution portfolio

This section provides a high-level overview of the available decarbonisation levers to get to net-zero CO_2 emissions by 2050 while complying with a 1.5°C carbon budget – based on the following definitions of a "1.5°C carbon budget" and "net zero".

xi Please see the Glossary for an explanation of the TRL scale.

BOX 2

What is the 1.5°C carbon budget for steel?

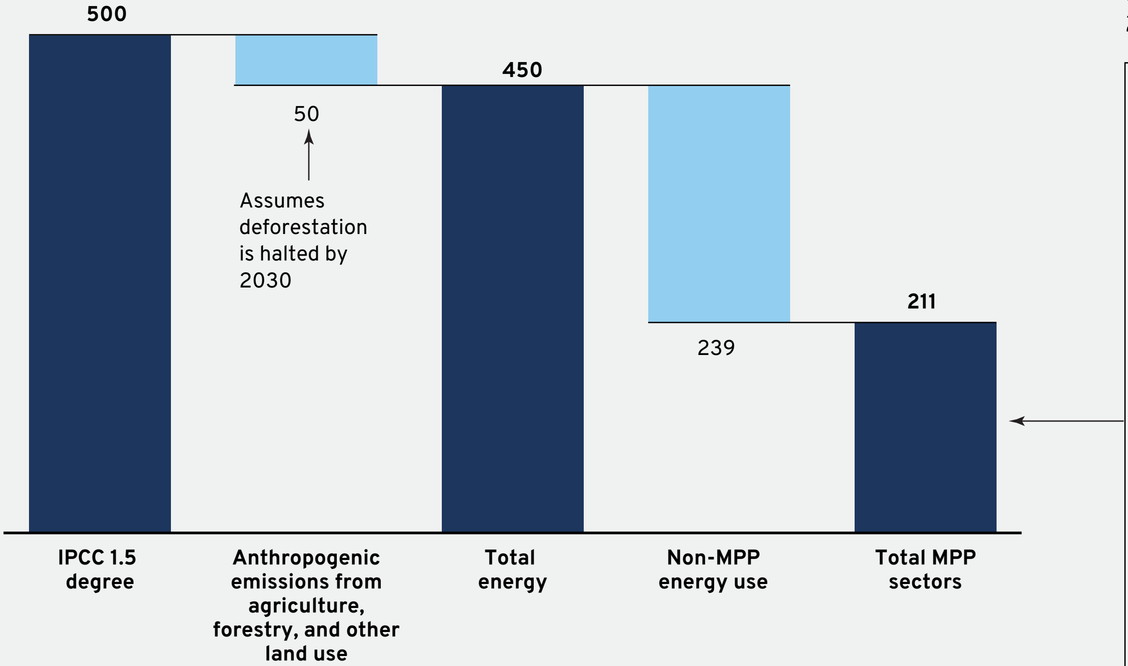
The IPCC estimates the global carbon budget to limit global warming to 1.5°C with a probability of 50% is about 500 Gt CO_2 from the beginning of 2020.

From that, about 50 Gt CO_2 of net anthropogenic emissions from agriculture, forestry, and other land use (AFOLU) are subtracted. That leaves roughly 450 Gt CO_2 for all energy sectors, which needs to be allocated to individual sectors according to their decarbonisation complexity. Hard-to-abate sectors are limited in their decarbonisation speed, whereas other sectors like power or automotive could switch to low-carbon technologies more quickly.

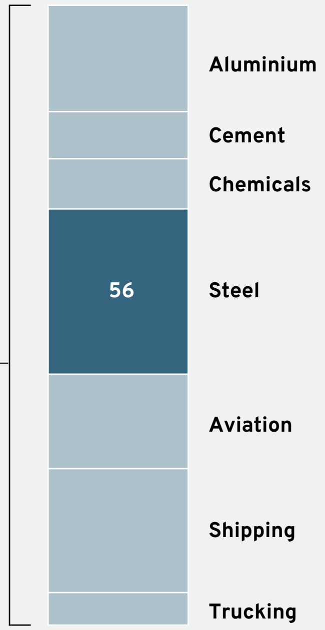
In a preliminary assessment of the MPP, roughly 50% of the 450 Gt CO_2 have been allocated to the seven MPP sectors (aluminium, chemicals [ammonia and petrochemicals], concrete/cement, steel, aviation, shipping, and trucking). The sectoral allocation is based on the cumulative sectoral emissions from the International Energy Agency's *Net Zero by 2050* report and the BloombergNEF *New Energy Outlook 2021* report (and for some sectors, the *One Earth Climate Model*) between 2020 and 2050, which serve as a proxy of how difficult it is to abate each individual sector.

Following this methodology, global steel has a 1.5°C carbon budget of about 56 Gt CO_2 from the beginning of 2020. Given the variety of other potential sectoral allocation methods, this value should not be taken as the absolute truth, but rather as an indicative figure for a 1.5°C carbon budget for global steel.

Global carbon budget 2020-2050, in Gt CO_2



MPP sectors carbon budget 2020-2050, in Gt CO_2



Source: MPP analysis; IPCC, **https://www.ipcc.ch/sr15/**; IEA, **https://www.iea.org/reports/net-zero-by-2050**; BloombergNEF, **https://about.bnef.com/new-energy-outlook/**

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 would reduce the need for steelmaking inputs (such as iron ore and energy) and increase the likelihood the transition would be sustainable, affordable, and achievable within the required timeline. The 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 thus focuses on reducing emissions by changing the steel production process. Only with those levers can emissions from the steel sector reach net zero.

1.2.1 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.[8] It is therefore essential to assess how total demand for primary 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 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.[xii] Much of this growth will be in low-income and emerging economies – India's demand is expected to reach 445 Mt by 2050 from 120 Mt today – more than offsetting declining demand in China, Europe, Japan, and the Republic of Korea (Exhibit 1.3).

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 the contribution of scrap in the total steel charge could grow to 45% in 2050 from 34% today.[xiii]

BOX 3

What is net zero?

The world needs to get to net-zero greenhouse gas emissions by 2050 to avoid the most harmful effects of climate change. Thereby, *net zero* means priority in-sector decarbonisation, complemented by carbon dioxide removals (CDRs).

- **About 90%–95% of current emissions in each sector need to be reduced by in-sector measures.** This is in line with the Science Based Targets Initiative (SBTi), which prescribes "long-term deep decarbonization of 90–95% across all scopes before 2050" as the single most important target for a net-zero world. Due to the uncertainty surrounding Scope 3 emissions, this report focuses on achieving net zero in terms of Scope 1 and 2 emissions.

- **The remaining 5%–10% of residual emissions that cannot be reduced by in-sector decarbonisation need to be neutralised by CDR,** the potential of which is described in a recent report from the Energy Transitions Commission.

Source: SBTi, **https://sciencebasedtargets.org/net-zero**; ETC, **https://www.energy-transitions.org/publications/mind-the-gap-cdr/**

xii The BAU scenario closely mirrors demand outlooks from other prominent sources, including the International Energy Agency Stated Policies Scenario, and was intentionally modelled to represent a near-consensus view.

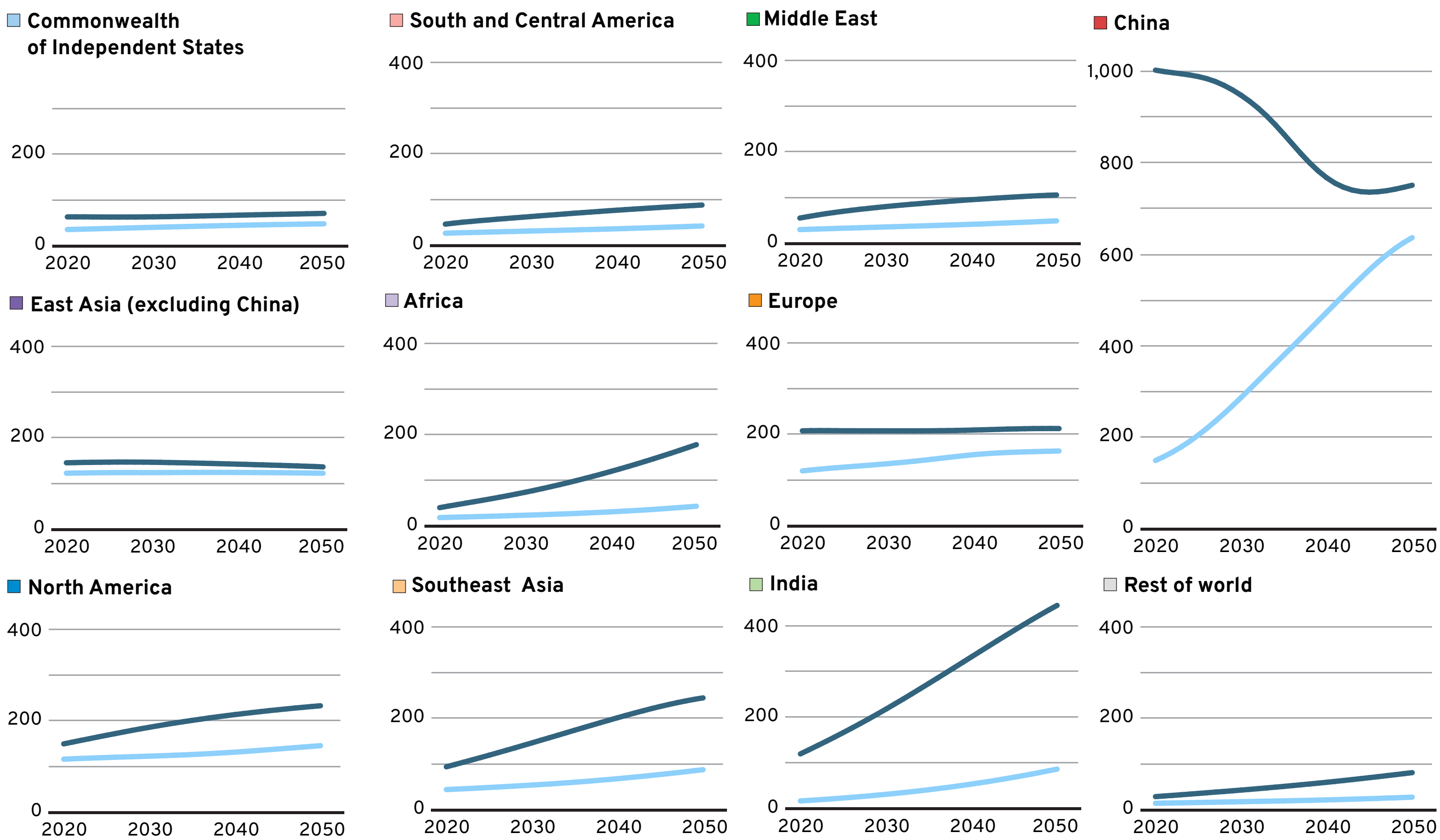
xiii Based on equivalent iron (Fe) content.

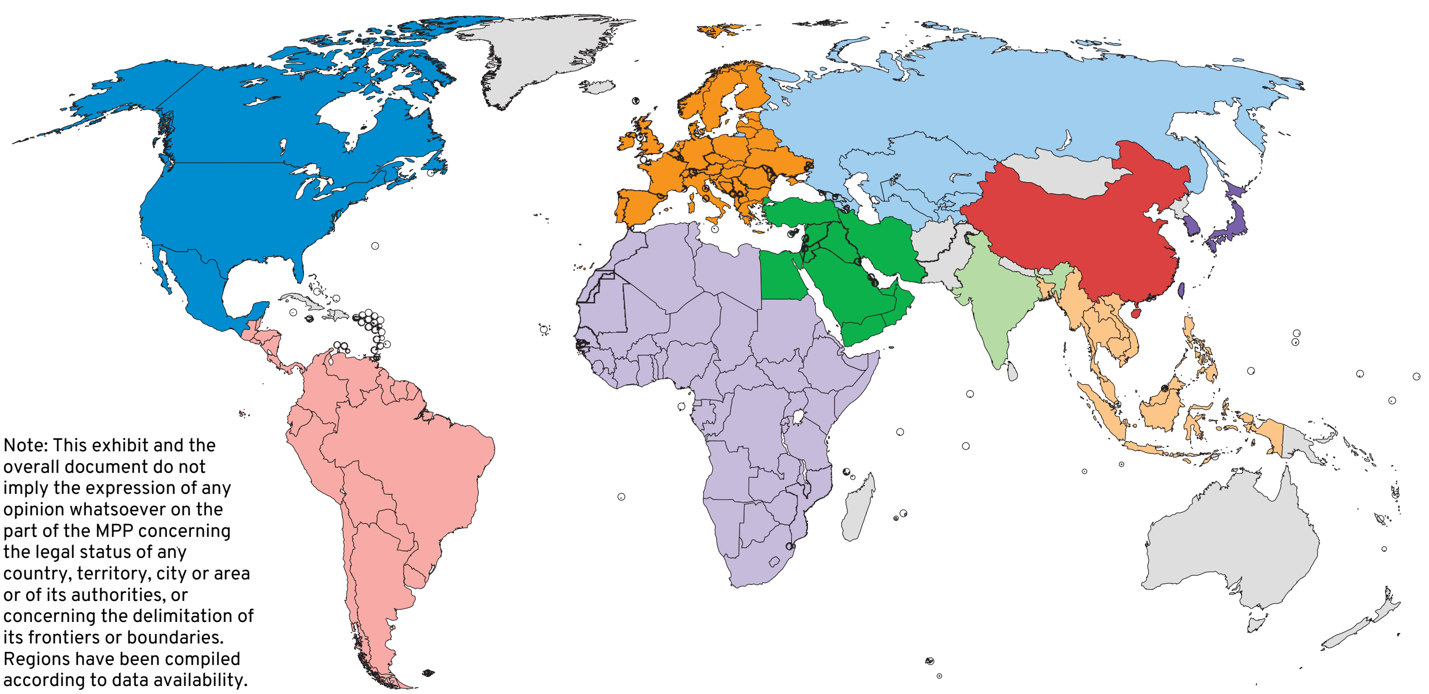
EXHIBIT 1.3

BAU demand for crude steel and scrap availability by region

Million metric tons

Crude steel demand — Scrap availability





Note: This exhibit and the overall document do not imply the expression of any opinion whatsoever on the part of the MPP concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Regions have been compiled according to data availability.

Source: MPP analysis of public data, 2022

BOX 4

Material efficiency strategies

Material efficiency strategies could lead to greater emissions savings by reducing primary demand. 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 the ST-STSM considers three categories of levers for material efficiency:

1. **Material recirculation:** These levers 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
2. **Productivity of use:** These levers 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
3. **Material efficiency:** These levers 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

In the High Circularity scenario, three categories of levers (Box 4) 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 (Exhibit 1.4). Scrap's share of total steel charge in 2050 remains similar to BAU at around 45%, but lower steel demand and greater scrap recirculation combine to reduce iron ore consumption by 60% (Exhibit 1.5). This would avoid 19 Gt of cumulative Scope 1 and Scope 2 CO_2 emissions by 2050 at little or no cost to end consumers. Annual Scope 3 emissions (such as those associated with iron ore and coal mining) would also decline by about a third relative to BAU, with further associated environmental benefits to air quality and resource use.

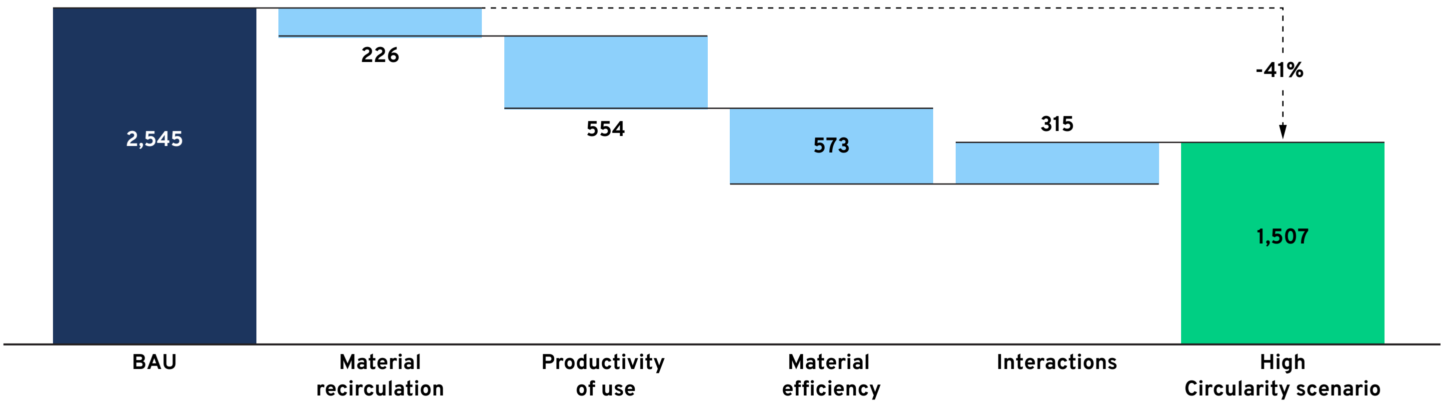
Even in a maximal scenario such as High Circularity, where greater material efficiency and secondary steelmaking combine to reduce demand for primary steel by almost 60% compared to BAU, limits to the quantity and quality of available scrap mean that decarbonising ore-based production remains critical to a net-zero future.

In India, crude steel demand reaches 295 Mt 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 meet large proportions of steel demand in some regions, notably China, Japan, the Republic of Korea, and 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 1.4

Circular economy impacts on global crude steel demand in 2050 in the High Circularity scenario

Crude steel demand, in Mt



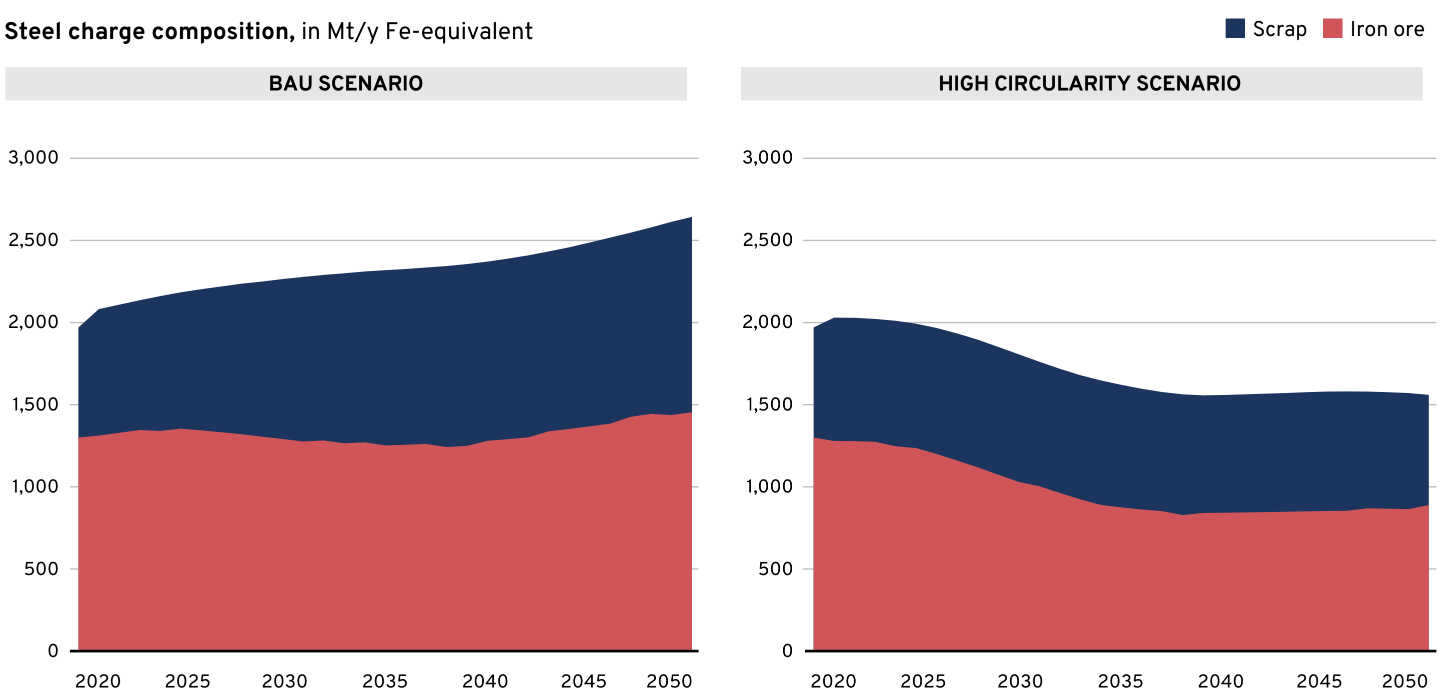
Note: Each strategy has a different rate of uptake and timing of maturity and can be expected to evolve dynamically between today and 2050. These strategies, to varying degrees, are limited by cost, technology readiness, behaviour, and availability of sustainable material substitutes. Interactions are the sum of dynamics of linkages between demand levers.

Source: MPP analysis

EXHIBIT 1.5

Charge composition of iron ore and scrap steel under different demand scenarios

Steel charge composition, in Mt/y Fe-equivalent



Source: MPP analysis

1.2.2 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 where competitively priced natural gas is available). Although these technologies are available today, they cannot eliminate all emissions. To (almost) completely remove emissions, breakthrough steelmaking technologies must either avoid emissions or manage them in a way that prevents them from entering the atmosphere.[9]

Accelerating the deployment of technologies that are nearing technological readiness while continuing to pursue innovations across the full range of potential solutions will ensure the sector's transition does not rest on any single technology's success.

Avoiding emissions is centred on utilising zero-carbon electricity and hydrogen to eliminate emissions from the energy usage and processes of steelmaking.[xiv] Both vectors offer carbon-free alternatives to meet the energy needs of the different steps of the steelmaking process, such as generating high-temperature heat. Crucially, both vectors can also eliminate the sizable process emissions of ironmaking. Zero-carbon hydrogen offers a clean feedstock for producing DRI, while zero-carbon electricity can power electrolyser and electrowinning ironmaking technologies. These solutions avoid emissions that would otherwise be generated from DRI production with natural gas or if ironmaking were carried out in a BF.

1.2.3 Capture emissions that cannot be avoided

If avoiding emissions is not economical, steelmaking technologies can be near-zero emissions if they effectively capture their carbon emissions and prevent them from entering the atmosphere. Much like carbon-free production methods, solutions centred on CCUS can address both the energy and process emissions of steelmaking. CCUS technologies can be affixed to the fossil fuel power generation assets that supply energy to steel plants, as well as to emissive process equipment such as natural gas DRI plants and coal-fed BFs.

Even if emphasis were placed on avoiding emissions as much as possible, carbon capture solutions will still have a role to play in addressing the residual emissions that will remain even in a net-zero steel industry. Carbon dioxide removal (CDR) solutions, such as direct air carbon capture (DACC), or some other method of abating residual emissions will be essential in bringing the industry's emissions fully down to zero.

Collaborative research, development, and deployment initiatives, such as the Ultra-Low CO_2 Steelmaking (ULCOS) programme, have advanced understanding of the possible technology pathways for decarbonising the steel sector, both in terms of avoiding as well as managing emissions. The technologies considered in this report are in Box 5.

Regardless of the chosen technological route, key decision points 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 are 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.[10]

Based on expected timelines of technology maturity, 9 of the 11 near-zero-emissions technologies modelled in the Steel Sector Transition Strategy Model (ST-STSM) are expected to be ready for commercial deployment at or before 2030.[xv] 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 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.

xiv 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.

xv Near-zero-emissions technologies are classified as those with Scope 1 emissions equal to or lower than best available technology BF-BOF with CCUS. This equates to an emissions intensity of ≤ 0.25 t CO_2/t CS. The Scope 2 emissions of these end-state technologies will also reduce to near zero as electrical power progressively decarbonises.

BOX 5

Technology archetypes

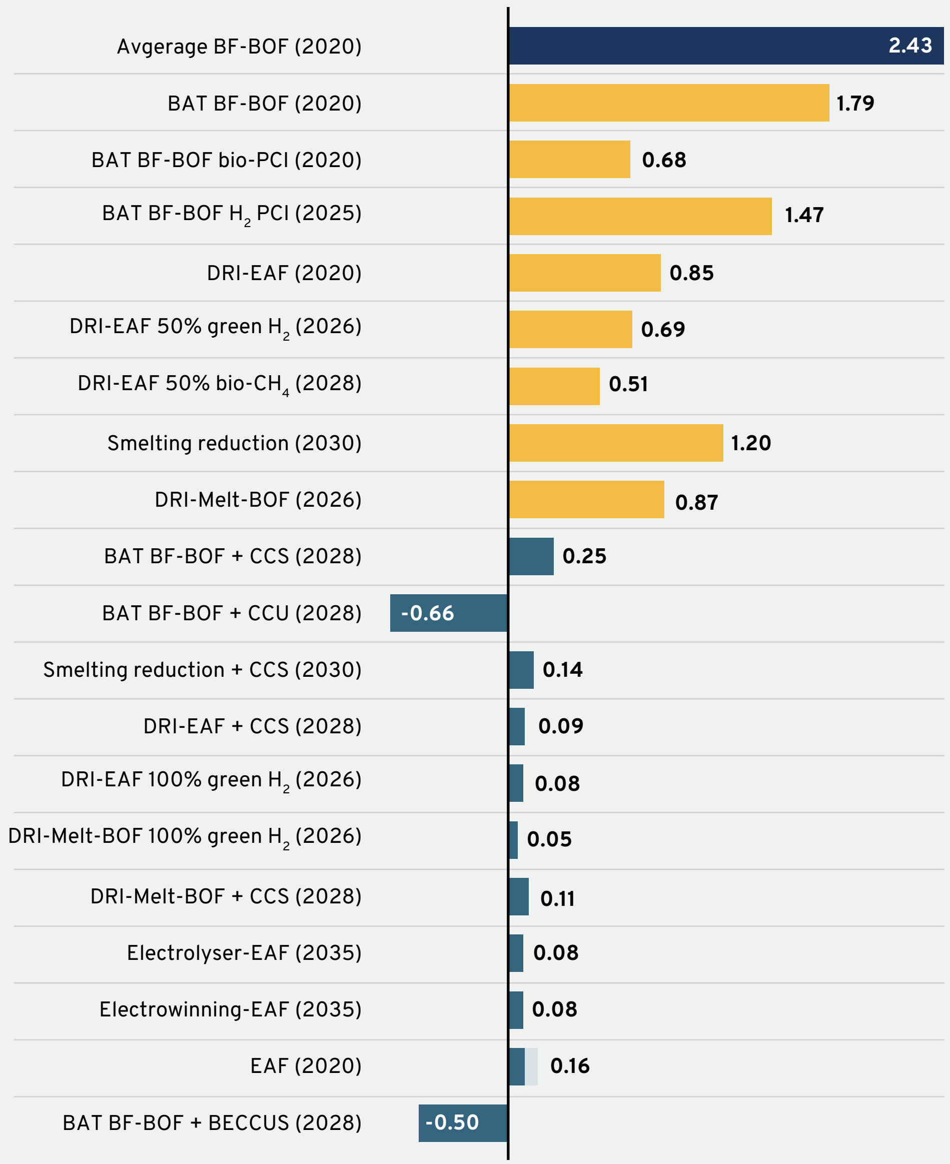
The ST-STSM evaluates 20 steelmaking technology archetypes that are either in use today or are expected to become available for commercial deployment prior to 2050. See the Glossary for additional detail on each archetype.

The 11 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 a 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. For all other near-zero-emissions archetypes, captured carbon is assumed to be directed to storage.

Summary of technology archetypes evaluated in the ST-STSM with associated emissions intensities (Scopes 1 and 2) in 2050 and dates of expected commercial availability

Emissions intensity in 2050 (Scope 1 & 2), in t CO_2/t CS

Transitional technologies
Near-zero-emissions technologies



Source: MPP analysis; Clarke Energy, https://www.clarke-energy.com/steel-production-gas/

1.3 Regional differences and solution availability

The transition to net-zero steel production will not look the same for every company or country because 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 could 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 (CCU) 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.

Not all steel plants benefit from these conditions and many plants may therefore not be located in areas that are optimally suited to low-emissions steelmaking. As a result, it is possible that parts of the iron and steel value chain may be subject to some relocation. For example, while integrated downstream processing and skilled workforces may limit the relocation of steelmaking, separate production of DRI (then shipped in sponge iron form) may well become significant, creating economic and employment opportunities in some locations but threats in others. Implications for local economies, jobs, and infrastructure planning could be significant even if only a small proportion of existing activities are relocated to greenfield sites.

1.4 Industry collaboration and wider benefits of the transition

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 (from iron mining and energy supply upstream to customers downstream) as well as supportive finance and policy environments. Four challenges in particular must be addressed:

A. **Develop near-zero-emissions steelmaking processes:** Most steelmaking today is dependent on fossil fuels 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 emissions. The challenge for steelmakers is to find an economic and carbon-free replacement for fossil fuels or to capture and store the generated greenhouse gases.

B. **Enable 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. Only one or two investment cycles remain to align on technologies compatible with net-zero trajectories and avoid stranded assets.[xvi] 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.

C. **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.[11] Ultimately, the cost increase will need to be borne by end-use markets in the form of higher steel prices.

D. **Level the global playing field:** Because 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 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.

Wider benefits of the transition

Steel could provide concentrated demand and certainty of off-take for zero-carbon hydrogen. A single steel plant using hydrogen rather than fossil fuels to reduce iron ore would utilise about 300,000 tonnes of hydrogen, absorbing the output of 5 gigawatts of electrolysers.[xvii] 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 blast furnaces 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 construction aggregates, concrete, and 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 are available.

xvi 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.

xvii 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.

ACHIEVING NET ZERO: POSSIBLE TRAJECTORIES

BOX 6

Key highlights

A. It is possible for the global steel industry to reduce Scope 1 and 2 emissions by more than 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 by this analysis.

B. Incremental technological progress and efficiency improvements in steelmaking technologies in the Baseline scenario result in 10% lower annual emissions than today in 2030 and 20% lower in 2050, but these changes are insufficient to deliver net zero in the sector.

C. 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 end-state technologies in the 2020s and 2030s.

D. A relatively modest carbon price trajectory could drive a larger reduction in annual emissions of 33% in 2030, reducing cumulative CO_2 emissions from the steel sector by 36 Gt relative to Baseline by 2050. This is equivalent to saving 7% of the remaining global carbon budget for 1.5°C.

E. These early investments in emissions abatement would entail a sharper increase in the average cost of steelmaking in the short term ($15/t CS or 4% over Baseline in 2030, excluding carbon price and capital charges) and an additional $100 billion per year in cross-value-chain investment above Baseline in the 2020s. At a project level, low-CO_2 steel will cost considerably more. For example, zero-carbon hydrogen steelmaking is expected to cost at least $175/t CS (40%) more than conventional steel in 2030.

F. 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 33%), something the IPCC Sixth Assessment Report makes clear we can ill afford.

G. Steel produced using 100% zero-carbon hydrogen accounts for 35%–45% 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 8–17 Mt/y by 2030 and 52–75 Mt/y by 2050.

H. 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. Net electricity consumption in steelmaking will grow to between 5,700 and 6,700 terawatt-hours per year (TWh/y).

I. In tandem, demand for coal falls by 80% 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.

Source: MPP analysis

2.1 Scenario definition

The Sector Transition Strategy sets out two illustrative scenarios to achieve net zero by 2050. The scenarios describe which steel production processes (Box 4) 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.[xviii] 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 occurs approximately every 20 years (depending on plant operating characteristics and technology).[xix]

2. Location-based circumstances determine the cost-optimal technology choice via implied local energy prices and availability of carbon storage sites (or utilisation opportunities).

The model underpinning the scenarios 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. The 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.

The ST-STSM has undergone important updates since the first edition of the Sector Transition Strategy. First, it has moved from a global approach to modelling steel plants to modelling them within 11 geopolitical regions. Each region is built on unique assumptions around factors such as crude steel demand, energy prices, and political preferences around making versus importing steel, adding greater nuance to the decision-making of the plants modelled there.

Additionally, to reflect the highly globalised and commoditised nature of the steel market, the ST-STSM now includes a trade module that simulates import/export dynamics. The module enables steelmaking regions to consider their cost-competitiveness relative to other regions and determines whether that region expands its production capacity or turns to imports to meet local demand.

Aside from general political preferences around sovereign steel production, it is important to note that the trade module is entirely cost-based and ignores other sources of noneconomic friction such as changing tariff regimes. Although this may be less representative of reality in the short term than alternative approaches (such as those employed by gravitational trade models), it at least provides a consistent long-term outlook that is designed to be resilient to short-term shocks. As the recent war in Ukraine has demonstrated, anticipating these shocks and their precise effects borders on impossible, meaning a view on trade centred on noneconomic factors (particularly shifting geopolitical conditions) falls apart in the long term as circumstances shift.

As with any model, the 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 fully fledged market model. The ST-STSM does not consider the relocation of steel plants to newly competitive greenfield locations and environmental impacts unrelated to greenhouse gases have not been modelled. However, the ST-STSM continuously undergoes development and improvement, so these dynamics may be considered in future updates.

Two different net-zero-aligned scenarios, as well as a baseline, are modelled in the ST-STSM (Exhibit 2.1). 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 price is applied to each tonne of CO_2 emitted, increasing linearly from $0 in 2023 to $200 in 2050. The same price is applied to all Scope 1 and 2 emissions in all geographies.

  The carbon price 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

xviii 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.

xix 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.

in place of 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.

Regardless of the actions the carbon price can be assumed to represent, a crucial driver of its effect in the scenario is its predicable future trajectory. This effect manifests when a steel plant faces an investment decision and the TCOs of different options are weighed across a 20-year horizon. The TCO considerations factor in not only the carbon price at the time of the investment decision, but also the future impact of the price as it steadily rises.

- **Technology Moratorium scenario:** The Technology 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 processes.

  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 Technology Moratorium scenario could be realised in various forms, including government regulation of 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 it assumes 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. 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 2.1

Scenario overview

	Baseline	Carbon Cost	Technology Moratorium
Demand scenario		**BAU**	
Carbon pricing	**No**	**Yes:** Starting at $0/t CO_2 in 2023, rising linearly to $200/t CO_2 in 2050	**No**
Market entry of novel production technologies		**(See Box 5)**	
Explicit technology constraint	**No**		**Yes:** Only near-zero emissions technologies permitted from 2030 onward
1.5°C aligned	**No**	**Yes**	**No**
Model logic		**Selects technology with lowest total cost of ownership (TCO)**	

Source: MPP analysis

2.2 What it will take to achieve a net-zero consistent steel sector

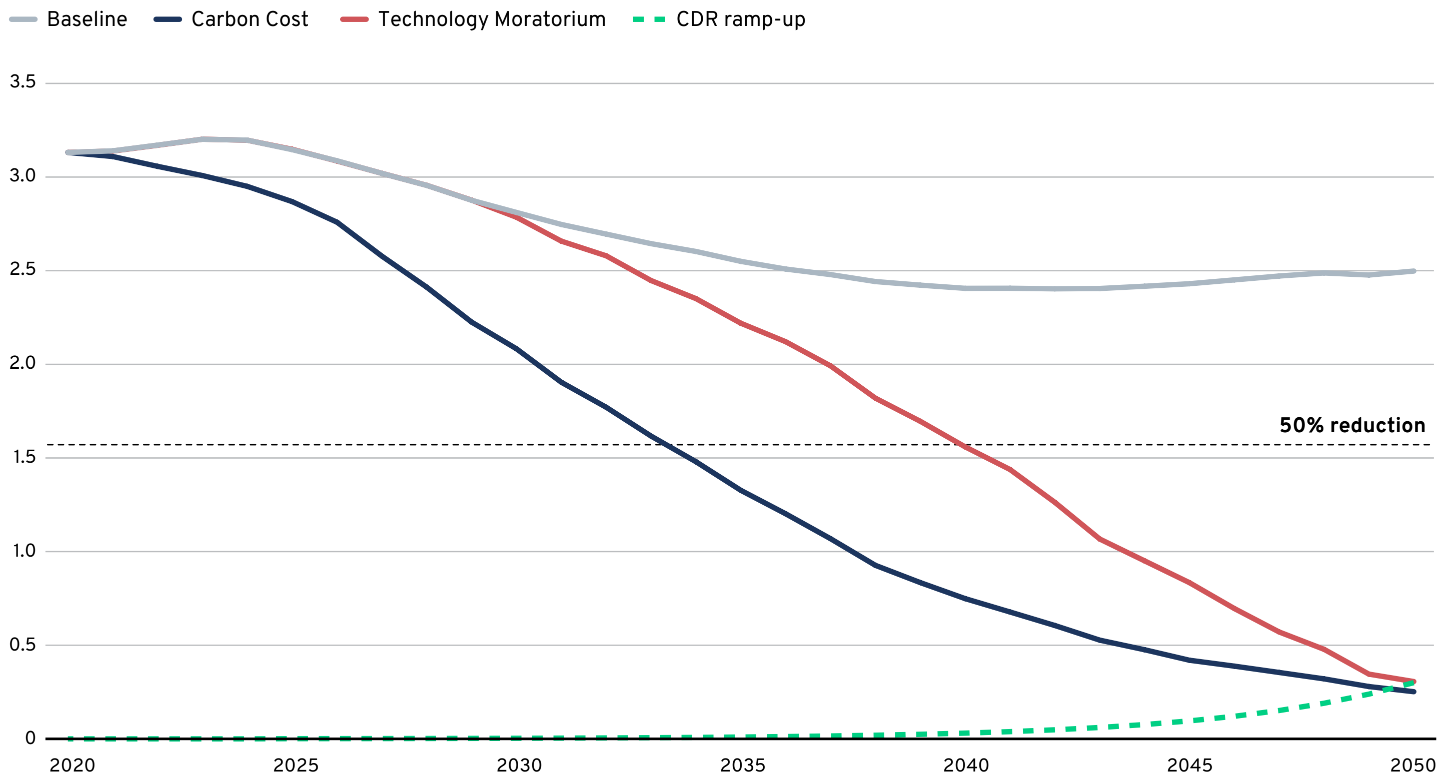
2.2.1 Reducing emissions in the 2030s and halving them by 2040

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 2.2). Under these scenarios, the steel sector could reduce Scope 1 and 2 emissions by 10%–33% by 2030 and by 90% by 2050.[xx] 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 throughout the rest of this section.

EXHIBIT 2.2

CO_2 emissions trajectories and the net–zero envelope

Annual emissions (Scope 1 & 2), Gt CO_2/y



Note: The chart includes the ramp-up of carbon dioxide removals (CDRs) required to offset residual industry emissions by 2050 and ensure the sector reaches net zero.

Source: MPP analysis

xx These ranges do not include the implementation of carbon removal technologies to abate residual emissions by 2050.

2.2.2 Compatibility with the 1.5°C carbon budget

Although both scenarios reach net zero, early action is important. Climate change is driven by cumulative emissions in the atmosphere. Deploying breakthrough technologies earlier will increase 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 ensure the global steel industry remains within its 1.5°C-aligned carbon budget, while the delayed action implied in Technology Moratorium sees that scenario exceed this budget (Exhibit 2.3).

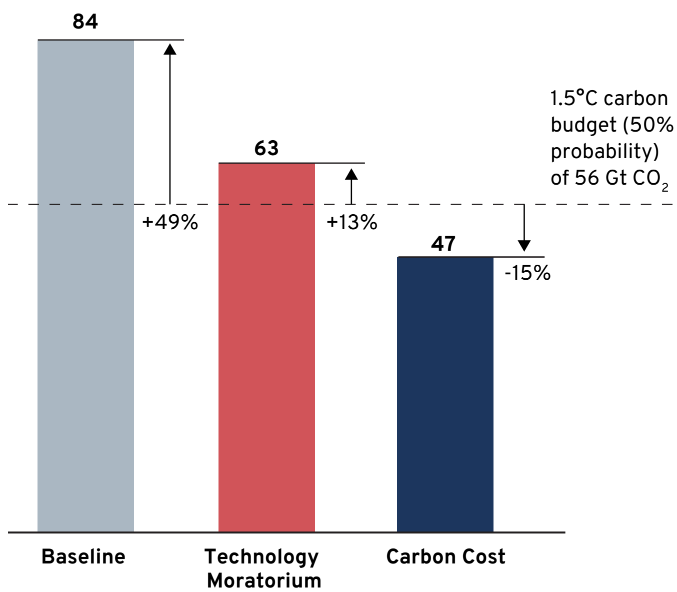
2.2.3 Evolution of steelmaking technologies and emissions

Steelmaking will diversify from 3 to up to 12 production routes in the transition to net zero, but the specific evolution of steelmaking technologies differs by scenario.

EXHIBIT 2.3

Comparison of 1.5°C carbon budget with the cumulative emissions of modelled scenarios

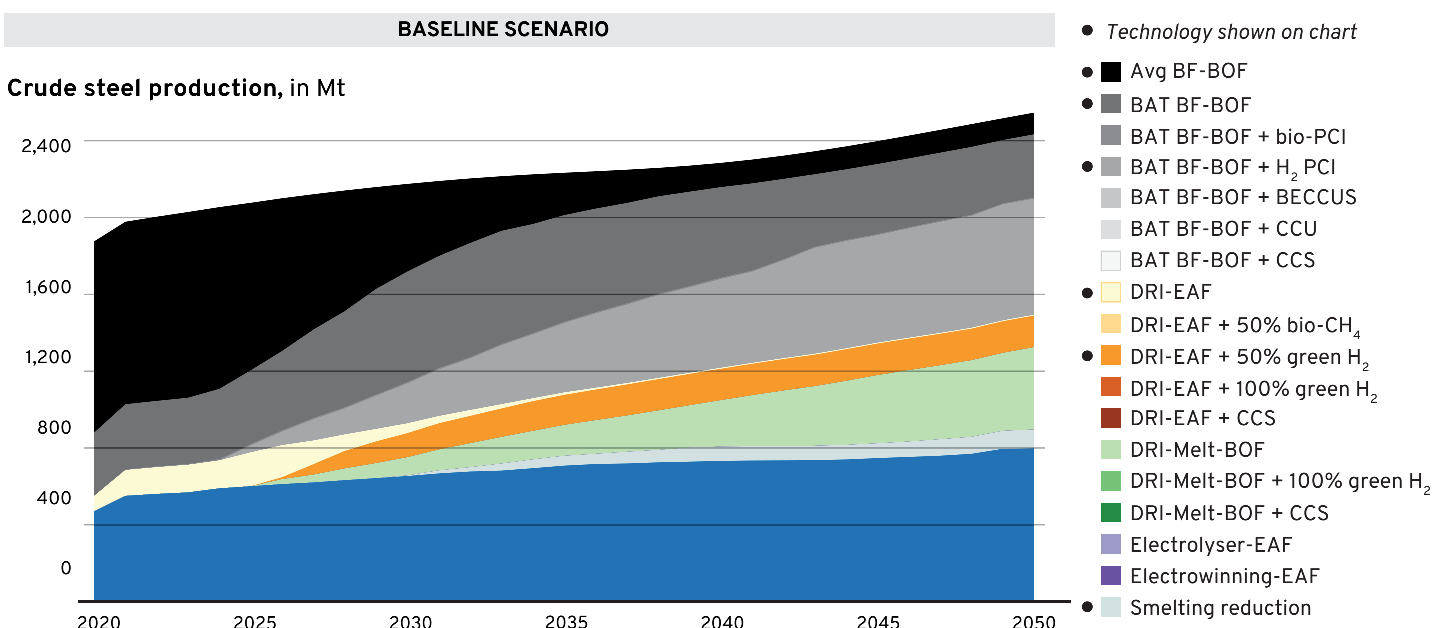
Cumulative emissions (Scope 1 & 2), 2020-2050, Gt CO_2



Source: MPP analysis

EXHIBIT 2.4

Baseline scenario technology and production evolution



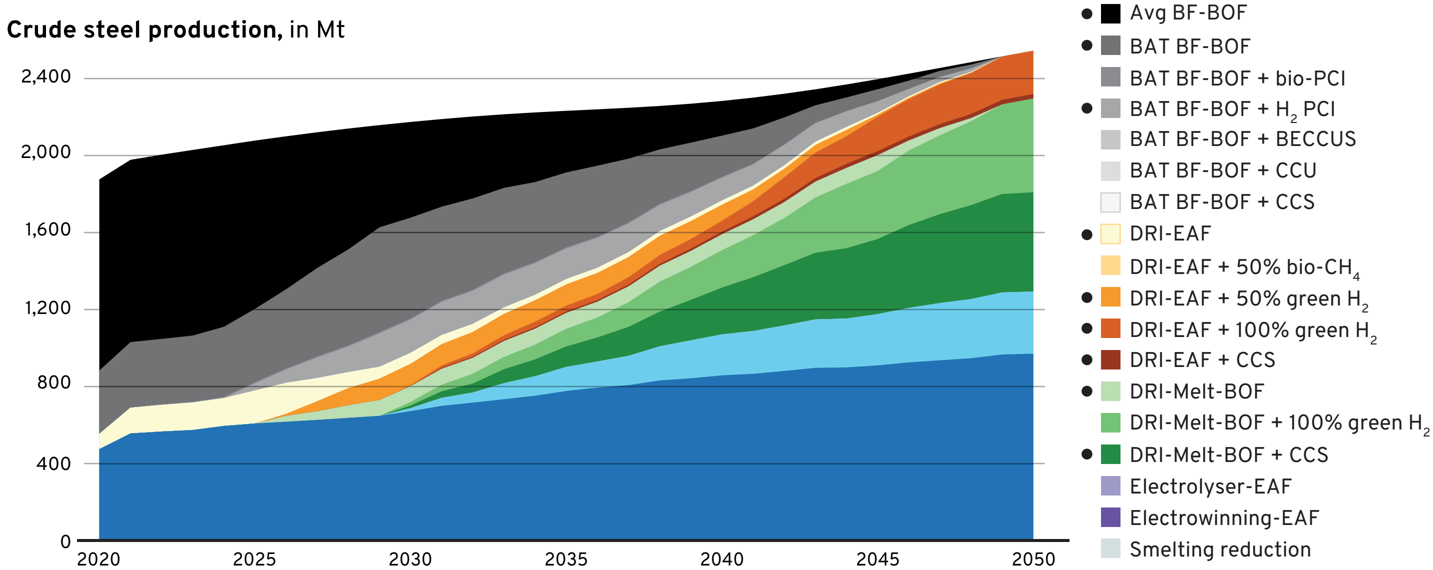
Source: MPP analysis

The Baseline scenario, in which steel assets switch to whichever technology offers the lowest TCO at each major investment decision, indicates that few end-state technologies are expected to be cost-competitive without policies and value-chain collaboration (Exhibit 2.4). BF-BOF retains the largest share of 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. Carbon capture and storage (CCS) plays a negligible role in this scenario because it represents a cost increase on top of production costs. Fewer than 1 Mt of primary steel is produced with near-zero-emissions technologies in 2050 and annual emissions are only 20% lower in 2050 than in 2020. Cumulative emissions reach 84 Gt CO_2, 16% of the global carbon budget to 2050.

EXHIBIT 2.5

Technology and production evolution

TECHNOLOGY MORATORIUM SCENARIO



Source: MPP analysis

Prior to 2030, the Technology Moratorium trajectory follows that of Baseline because no constraints are assumed (Exhibit 2.5). Only transitional switches take place, such as upgrading blast furnaces to the best available technology (BAT) and partial fuel switching to hydrogen injection. These improvements can mitigate up to 1 t CO_2/t CS of Scope 1 emissions (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 because 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-Melter-BOF archetypes as zero-carbon hydrogen prices become competitive in favourable locations, accounting for 45% of primary steel production in 2050.

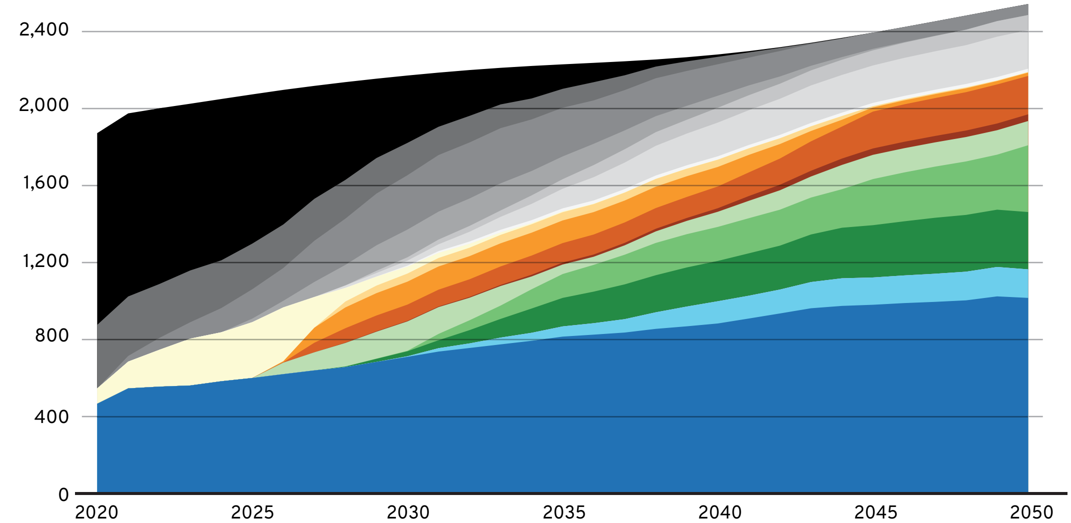
Archetypes utilising CCS technologies account for 55% of primary steel production in 2050. The role of scrap-based production via EAF grows as large volumes of end-of-life scrap, particularly from China, become available.

Technology and production evolution

EXHIBIT 2.6

CARBON COST SCENARIO

Crude steel production, in Mt



Source: MPP analysis

In the Carbon Cost scenario, progressively rising carbon prices (or equivalent actions) drive more fundamental technology switching in the current decade (Exhibit 2.6). Annual emissions are 0.7 Gt CO_2 lower in 2030 than in Technology Moratorium. The faster trajectory reduces cumulative CO_2 emissions in 2050 by 15 Gt relative to the later transition in Technology Moratorium.

In this scenario, there is an early uptake of natural gas–based DRI production processes because these technologies can deliver immediate emissions reductions relative to unabated BF-BOF. By 2050, steel made with DRI accounts for almost 70% of primary steel production, more than half of which utilises fully zero-carbon hydrogen to deeply decarbonise. In parallel, the scenario's rising carbon price increasingly rewards technologies capable of achieving negative emissions, making BAT BF-BOFs with bioenergy and CCUS competitive in certain locations. The BAT BF-BOF with bioenergy and carbon capture, utilisation, and storage (BECCUS) and BAT BF-BOF with CCU (which also consumes bioenergy) configurations create an opportunity for the continued use of blast furnaces through 2050 and account for 11% of primary production by mid-century. A marginal role for smelting reduction with CCS completes the 2050 technology mix.

BOX 7

Electrolysis and electrowinning

Despite reaching a TRL of 9 in 2035, electrolysis-EAF and electrowinning-EAF archetypes do not enter the steel production mix in the Technology Moratorium or Carbon Cost scenarios, where assets follow 20-year industry investment cycles and investments are optimised for cost. These archetypes remain costlier on a levelised cost basis relative to other production technologies. This is driven by two factors:

1. Ironmaking involving direct electrolysis of iron ore requires large continuous electricity loads (3.8 MWh/t of iron in 2035) and therefore requires a constant supply of electricity. Hydrogen ironmaking archetypes also have substantial power requirements – driven by green hydrogen production (4.5 MWh/t of iron in 2035) – but the ability of hydrogen electrolysers to operate in unison with variable electricity generation avoids the need for a more expensive stable power supply. In each of the modelled regions, the cost of electricity does not fall to a level where direct iron ore electrolysis technologies become cost competitive with competing technologies.

2. Electrolysis-EAF and electrowinning-EAF archetypes attain TRL 9 in 2035, whilst all other near-zero-emissions technologies become commercially available in the preceding decade. By this year, cost reductions and the need for capacity investment before 2035 lead to pathway dependencies in which transitional investments within furnace groups (e.g., blast furnace, direct reduction) create an additional hurdle to the adoption of direct iron ore electrolysis archetypes.

For direct iron ore electrolysis to reach cost-competitiveness with hydrogen steelmaking on a levelised cost basis, power prices would need to fall below $25/MWh by 2035, more than 35% below the average prices modelled in the most favourable regions in the core scenarios. However, these results should not be interpreted as direct iron ore electrolysis archetypes being economically unviable. Electrolysis and electrowinning archetypes enter the steel production mix in the Fastest Abatement scenario, where investment cycles are shortened, TRL development is accelerated, and investment decisions are optimised for abatement rather than lowest TCO (see Box 10). In this scenario, electrolysis and electrowinning archetypes offer the potential for deeper emissions reductions as soon as sufficient clean electric power is available.

The Technology Moratorium and Carbon Cost scenarios assume that electrolysis and electrowinning archetypes require grid-sourced electricity. Taking a higher-resolution view of location-specific opportunities, it is probable there will be locations that offer a combination of low cost and stable power at costs below regional averages.

Factors that could improve the competitiveness of these archetypes in favourable locations include dedicated, coupled solar and wind power generation or power purchase agreements with generators offering better economics than power grids. Similarly, the modularity of these archetypes offers a distinct advantage, enabling plants that use the technology to progressively scale their capacity over time in smaller increments than competing technologies. Electrolysis could also offer the potential to process iron ore deposits that are geographically stranded, presenting a unique business case for these resources.

Source: MPP analysis

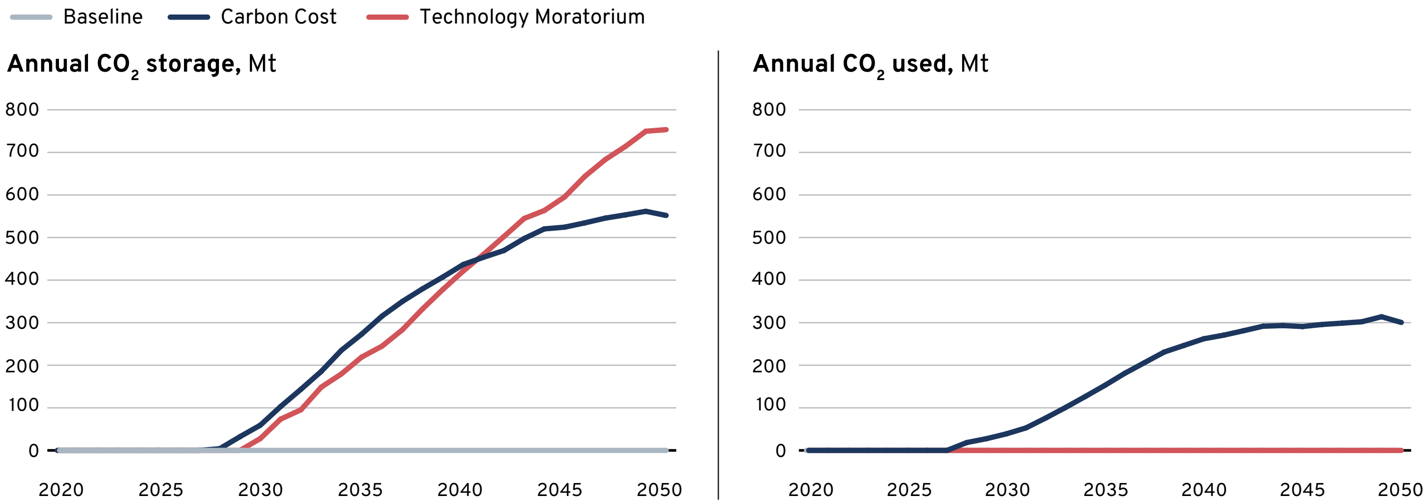
In either net-zero scenario, carbon capture facilities will need to scale rapidly. More than 60 Mt/y of CO_2 storage is needed by 2030 under Carbon Cost. For reference, as of the end of 2021, only 26 commercial CCS facilities (with average capture of ~1.5 Mt/y) were in operation, and only one of these was associated with the iron and steel sector.[12] This scaling is necessary to capture the cumulative ~8 Gt of CO_2 from CCS-enabled archetypes by 2050. Demand for CO_2 storage capacity initially grows more slowly in Technology Moratorium (starting with 27 Mt/y in 2030) in the absence of a carbon cost. However, CO_2 storage capacity grows rapidly from 2030 onwards to capture 750 Mt/y 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 fuels in applications where it can be sequestered long term, such as concrete, long-lived plastics, and construction aggregate. The same result could be achieved with DRI technology equipped with oversized biomass gasification, which the latest version of the ST-STSM does not currently model. An additional benefit of using biomass-based DRIs would be eliminating coke use, which may not be possible with blast furnaces where coke is required to provide mechanical support for the reactions in a way that may not be replicable with bio-based alternatives.

These market opportunities for captured carbon, combined with rewards for negative emissions, create attractive economics for CCU and BECCUS technologies in the Carbon Cost scenario, which sees more than 300 Mt/y of CO_2 from the steel industry utilised elsewhere by 2050 (Exhibit 2.7). There is, however, substantial uncertainty over the future addressable market for CO_2 and the share the steel industry could capture, meaning higher levels of carbon sequestration could be expected.

Annual CO_2 storage and utilisation

EXHIBIT 2.7



Note: Virtually no CO_2 is captured, used, or stored in the Baseline scenario.
Source: MPP analysis

BOX 8

Negative emissions and carbon credits

The Carbon Cost scenario illustrates how using sustainable biomass in steelmaking could be attractive because of the potential to claim emissions credits (under a price of carbon) for supplying bio-based carbon for applications and processes that currently rely on fossil fuel carbon. On the basis of sourcing sustainable biomass feedstocks, the ST-STSM assumes that each tonne of carbon sourced from bioresources would be replenished with new biomass stock within a year.

Complex issues could arise when a tonne of biocarbon moves from sector to sector. Irrespective of what form of carbon accounting protocol is assumed, it would be vital to ensure that two or more sectors cannot claim emissions credits for the same tonne of biocarbon. This is particularly important in cases where the biocarbon is burnt, releasing its carbon in the form of CO_2.

According to carbon accounting norms, emissions from biofuels are considered carbon neutral based on biomass crediting. This implies that if the biofuel producer takes credit for biomass used, the same credit cannot later be claimed by, for example, the aviation industry, which would need to account for the emissions from burning the biofuel in full. As carbon neutrality is the main selling point of biofuel, it would be difficult to imagine a situation where an actor such as the aviation industry would pay more for biofuels only to have to treat them as regular kerosene from an emissions perspective.

The Carbon Cost scenario assumes that the steel sector claims full credit for biocarbon supplied to the market. This implies that it is not converted into fuels but into products that provide long-term storage opportunities (e.g., plastics, construction aggregates) where there is no expectation that all or part of the emissions credit is transferred to the buyer.

To explore what might happen in a scenario where the steel sector could not claim full credit for biocarbon supplied to the market (for example, where the biocarbon is used for biofuel production as well as embedded in long-lived products), we can assume a scenario where the steel producer could claim only 50% of the credit associated with biocarbon supply. Halving the credit sees steel production in 2050 from the BAT BF-BOF + CCU/BECCUS archetypes decline by 30% in the Carbon Cost scenario, from 278 Mt/y to 194 Mt/y. The BAT BF-BOF + CCS archetype sees some growth in their place, but it is primarily hydrogen steelmaking technologies that fill the gap.

The sensitivity of negative-emissions steelmaking technologies to the value of carbon credits suggests that the at-scale adoption of biomass as a feedstock in the steel industry may be dependent on the development of cross-sectoral carbon accounting and associated regulation. It highlights the need to develop a globally consistent set of carbon accounting rules; otherwise, there is a risk of different actors claiming biocarbon credits multiple times as the carbon moves along value chains and across accounting regimes.

Source: MPP analysis

BOX 9

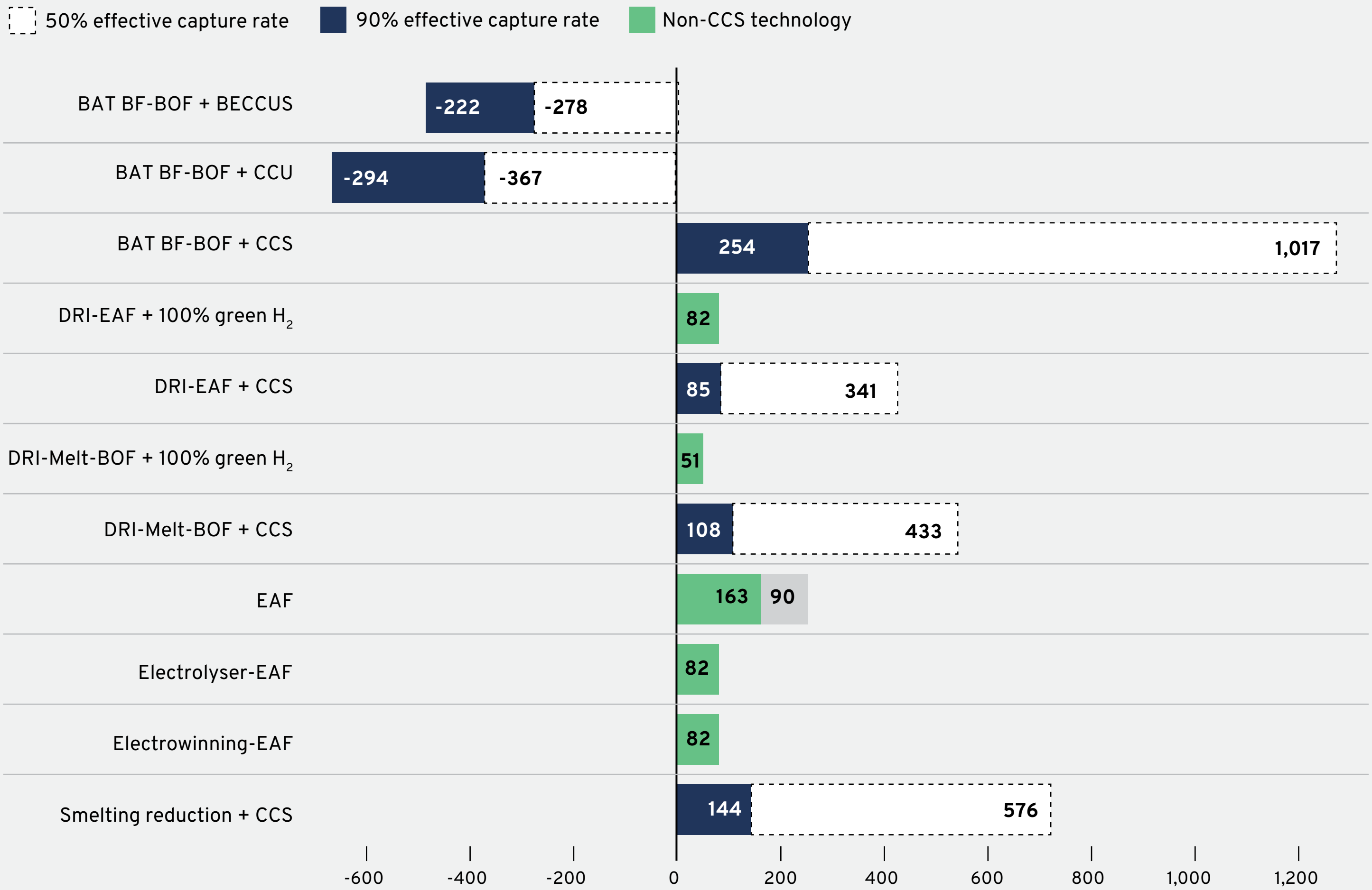
Addressing residual emissions

To achieve net zero in the steel sector, any residual emissions that cannot be abated through technology developments must be counterbalanced by permanent removals. It is probable that the cost of purchasing or producing such removals 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 the net-zero scenarios, up to ~300 Mt/y 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 DACC, that would require investment and scale-up well in advance to be a viable solution by 2050. Finding truly sustainable and measurable natural carbon solutions can be challenging, particularly given they will be in high demand across other industries. The use of bioenergy coupled with CCS could, in theory, generate negative emissions from steelmaking, but limits to the availability of truly sustainable biomass, as well as competing requirements from other sectors, may restrict its use.

Based on a DACC price of \$200/t CO_2 in 2050, abating these emissions could incur an additional \$60 billion annually from 2050 onwards.

Residual Scope 1 emissions in 2050, in kg CO_2/t CS



Note: The range of residual emissions from EAF production depends on the presence of natural gas in the preheating and finishing steps. Both the BAT BF-BOF + CCU and BAT BF-BOF + BECCUS archetypes achieve negative emissions through bioenergy use.

Source: MPP analysis; ETC, https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-emissions-economy/

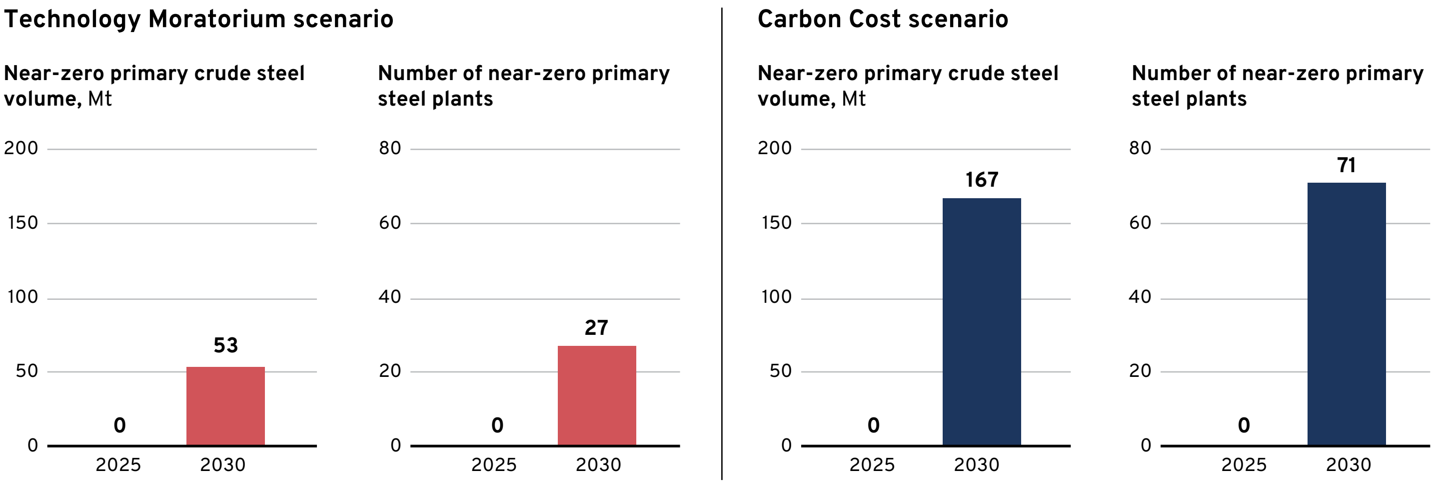
2.2.4 Milestones in the 2020s to kick off the transition to net zero

By 2030, more than 160 Mt/y of crude steel demand must be met by near-zero-emissions primary plants for the sector to be on a credible 1.5°C-aligned pathway as laid down by the Carbon Cost scenario (Exhibit 2.8). Meeting that demand would require at least three times as much production capacity as the current pipeline to 2030 of low-carbon steel projects (Exhibit 2.9). Given the long investment cycles associated with steel assets and lengthy lead times for greenfield projects, planning for the ~70 near-zero-emissions primary plants needed must begin now. Existing assets should switch to end-state-compatible production technologies at the end of their current investment cycle and greenfield project planning should commence immediately.

It is still possible for the steel industry to achieve net zero by 2050 with more modest goals in the 2020s. Meeting over 50 Mt/y of steel demand in 2030 with near-zero-emissions production as needed in the Technology Moratorium scenario would only require that low-carbon steel capacity currently in the pipeline be converted to end-state production technologies before the end of the decade (Exhibit 2.10). Crucially, however, aspiring to these more modest goals would likely put the industry's emissions trajectory out of alignment with its 1.5°C carbon budget.

EXHIBIT 2.8

Growth of near-zero primary steel production and steel plants

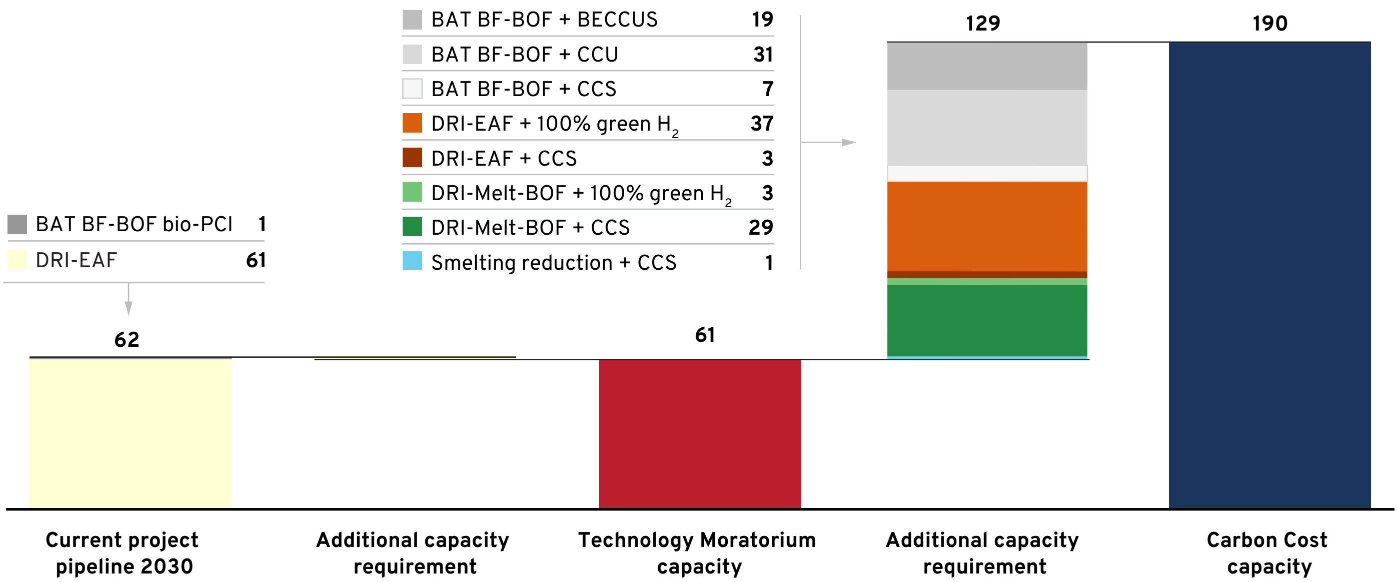


Source: MPP analysis

EXHIBIT 2.9

Near-zero-emissions primary capacity shortfall to meet 2020s milestones

Near-zero primary steel capacity in 2030 vs. potential capacity, in Mt/y (illustrative scenario)

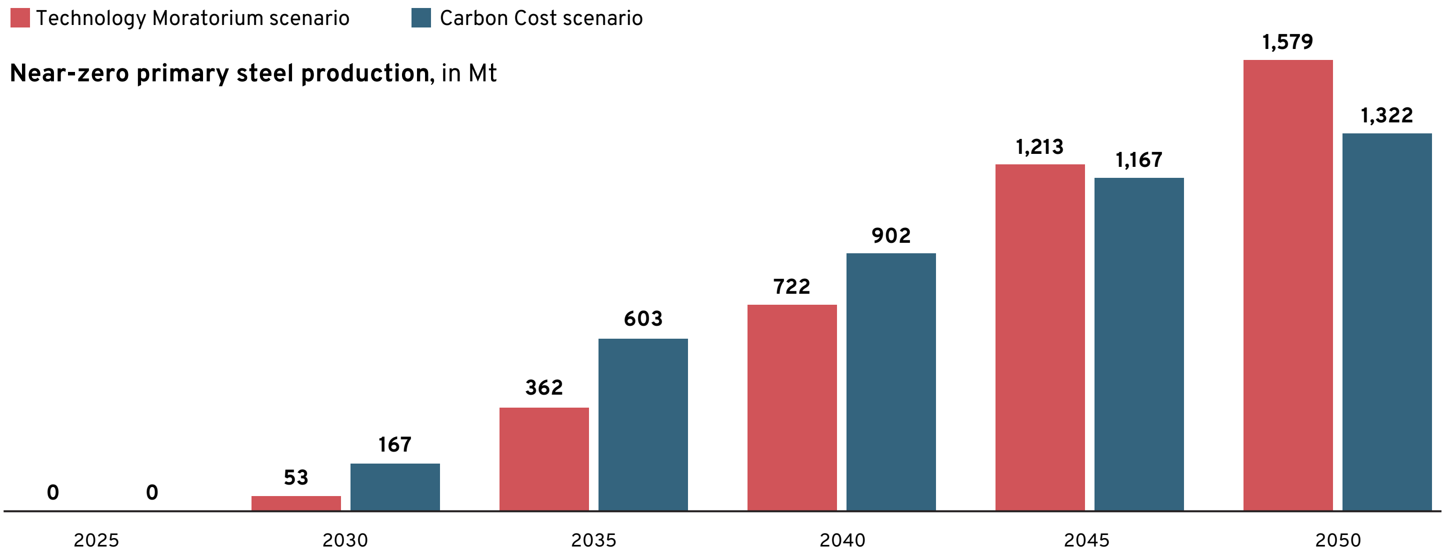


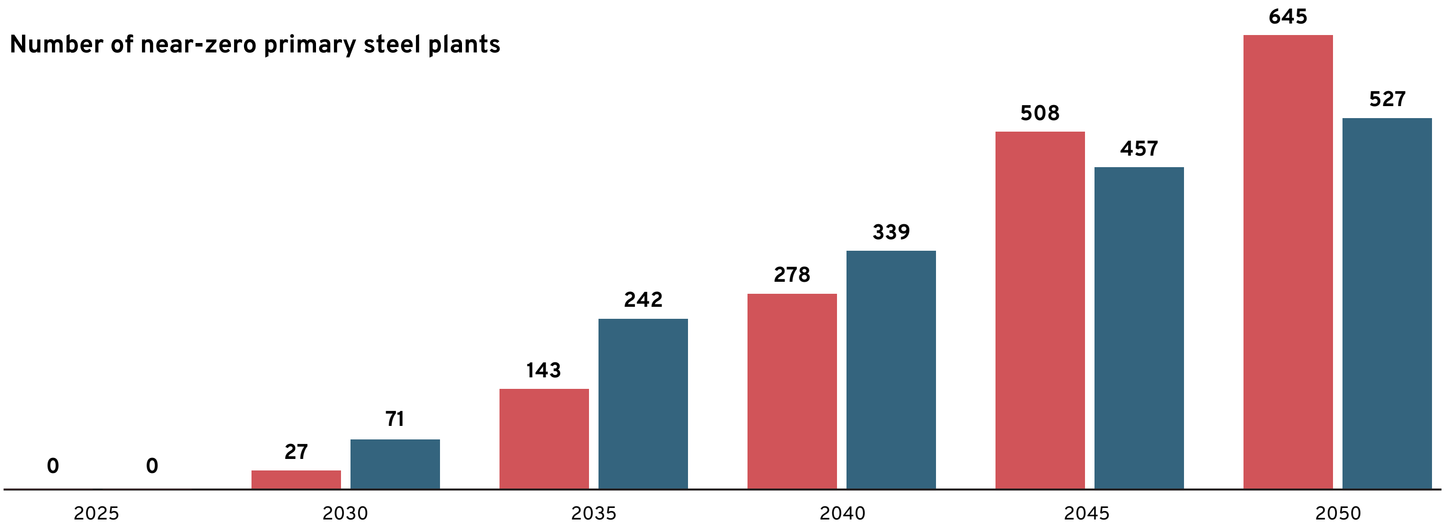
Note: First bar: Current low-carbon primary steel project pipeline. Right four bars: Illustrative supply capacity scenario for near-zero primary steel in 2030. Note that the required capacity figures are higher than the production figures in Exhibit 2.8, which reflects how steel plants cannot normally utilise their full capacity at all times. Almost all the capacity in the low-carbon steel pipeline is not based on end-state technology. However, in the four right bars, this pipeline is treated as near-zero-emissions production capacity for illustrative purposes. The pipeline is treated this way because it is primarily composed of DRI-EAF capacity, which could reasonably be transitioned to an end-state technology by fuel switching to 100% green hydrogen or by retrofitting CCUS systems.

Source: MPP analysis; Agora Energiewende, **https://www.agora-energiewende.de/en/service/global-steel-transformation-tracker/**; Leadership Group for Industry Transition (LeadIT), **https://www.industrytransition.org/green-steel-tracker/**

EXHIBIT 2.10

Growth of near-zero primary steel production and steel plants





Source: MPP analysis

BOX 10

A faster transition to net zero

The ST-STSM also models a Fastest Abatement scenario to represent the ceiling of what might be technically possible by maximising the levers for decarbonisation, regardless of cost. The levers used are:

A. Reduce (primary) steel demand from the BAU to the High Circularity scenario.

B. Shorten investment cycles from 20 to 15 years, allowing for a faster phaseout of high-emitting steel assets.

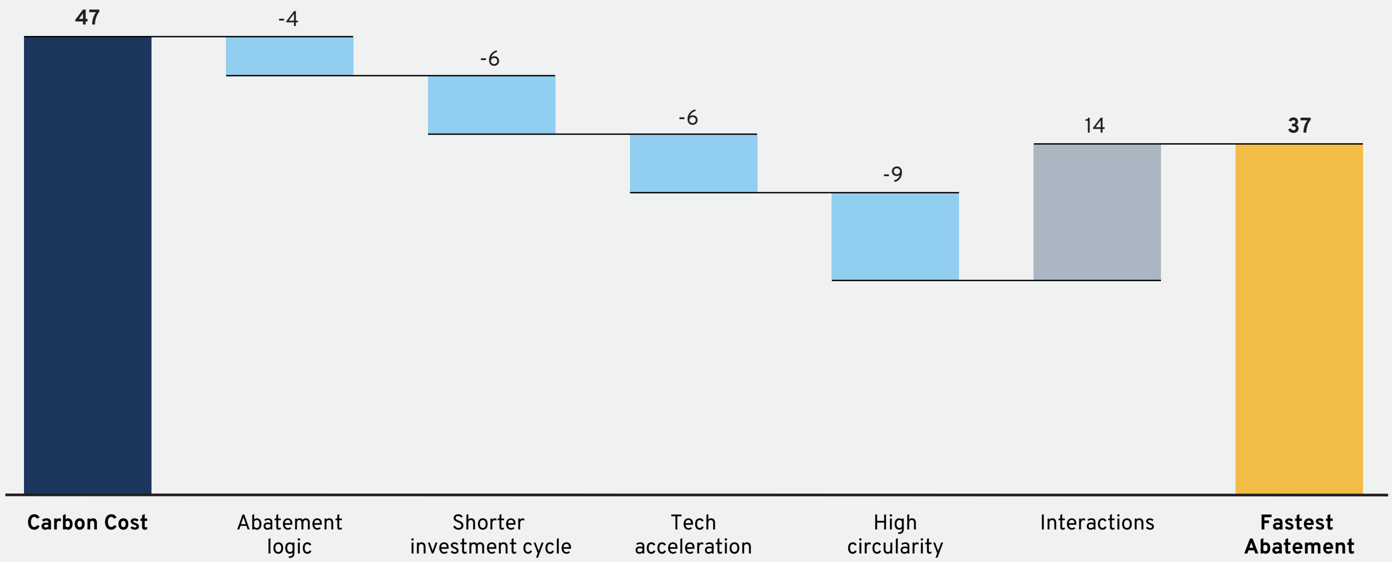
C. Bring the maturity of low-CO_2 steelmaking technologies forward by two years.

D. Assume that each investment decision is optimised for the greatest abatement potential (instead of for lowest TCO). This results in the uptake of near-zero-emissions technologies as soon as the technologies are mature, irrespective of their economic competitiveness.

Pulling all these levers could reduce cumulative emissions by a further 10 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 R&D investments to bring breakthrough technologies to commercialisation sooner, and some additional cost to the scrap supply chain from enhanced circularity requirements.

Results of the Fastest Abatement scenario

Cumulative CO_2 emissions (Scope 1 & 2) between 2020 and 2050, in Gt



Source: MPP analysis

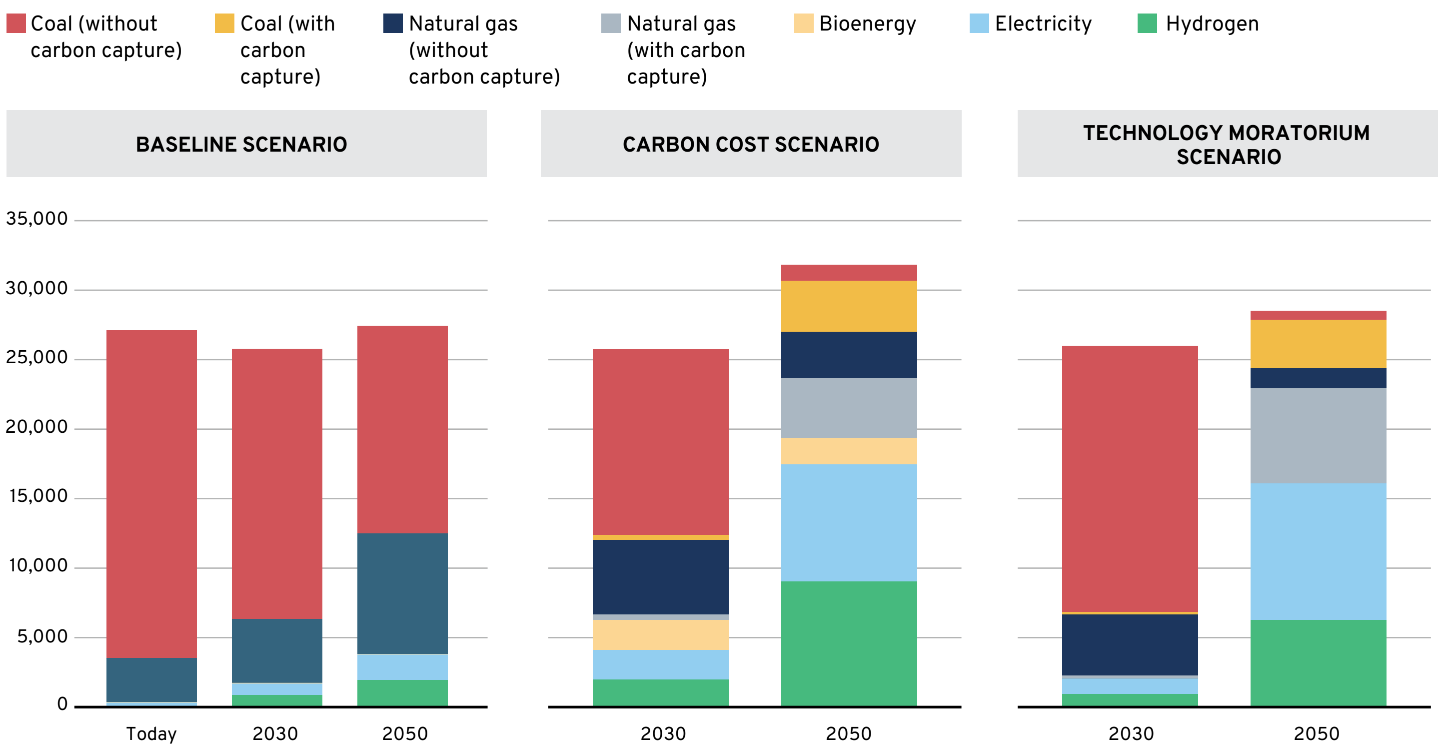
2.2.5 Energy requirements and prerequisites

The steel sector's primary energy consumption will shift considerably as the sector decarbonises (Exhibit 2.11). Declining total energy intensity of steelmaking occurs in the early stages, primarily due to the increased use of scrap (in the EAF archetype), which requires much less energy than producing steel from iron ore via the average BF-BOF process. However, this trend changes course in both net-zero scenarios when novel primary steelmaking technologies begin to take hold.

EXHIBIT 2.11

Fuel consumption shifts across scenarios

Net energy usage, in PJ/year

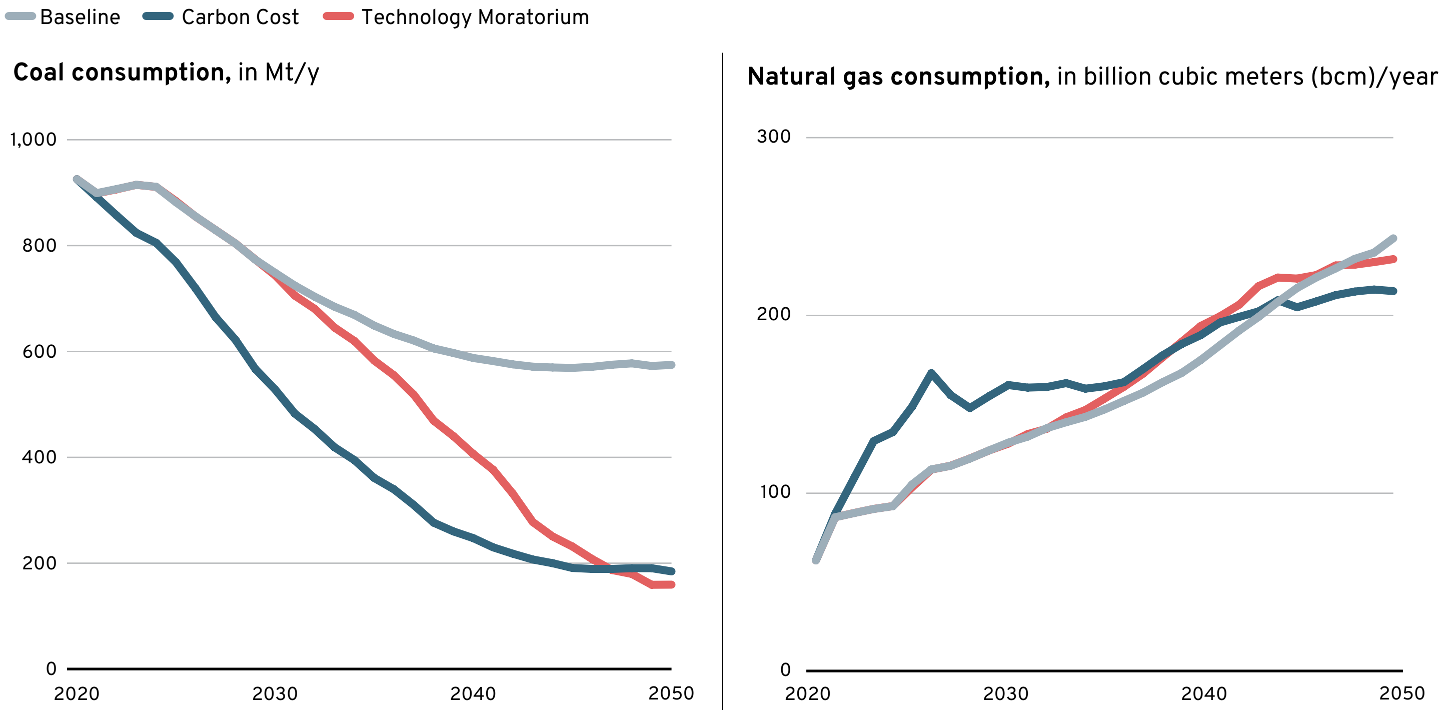


Source: MPP analysis

Coal consumption decreases in all scenarios as hydrogen replaces metallurgical (coking) coal as a reductant. The greater continued use of thermal (low-grade) coal in both net-zero scenarios reflects the 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 technology in the Carbon Cost scenario is a sharper increase in the use of natural gas over the next decade and a half (Exhibit 2.12). Upstream Scope 3 emissions from natural gas production are not modelled in detail by the ST-STSM and assuming a leakage factor of ~1.5% sees no more than 0.1 Gt CO_2e of annual emissions in any modelled scenario. However, recent research into methane emissions (particularly around 'super-emitting' events centred on the large, uncontrolled release of methane due to the malfunction of equipment and infrastructure) suggests that uncertainty around these emissions points upward to higher leakage factors. Procurement of certified low-methane-emissions natural gas will therefore be important to credibly demonstrate a reduction in supply chain emissions.

EXHIBIT 2.12

Evolution of fossil fuel consumption



Source: MPP analysis

BOX 11

Coal mining and Scope 3 emissions

Although coal consumption declines starkly in both net-zero scenarios, the continued use of coal by the steel industry in 2050 and beyond has implications for the sector's upstream Scope 3 emissions.

In 2020, methane emissions from coal mining amounted to 0.3 Gt CO_2e, equivalent to just under 10% of steel sector Scope 1 and 2 emissions in that year. As the industry progresses toward net zero in the Carbon Cost scenario, declining coal consumption brings the associated methane emissions down to 0.06 Gt CO_2e by 2050. However, by this point, coal mining emissions represent a proportionally greater challenge, equivalent to 24% of steel sector Scope 1 and 2 residual emissions in 2050.

Even with the application of CCUS technologies, the potential for continued use of coal past 2050 highlights the importance of addressing Scope 3 emissions to ensure all emissions associated with the steel industry fully reach zero. Abating methane emissions from coal mining in 2050 through CDR could add a further $12 billion annually to the cost of addressing residual emissions in the Carbon Cost scenario based on a DACC price of $200/t CO_2e. If this abatement cost were borne by the coal mining industry and passed through, steelmakers could see the price of coal rise by $65/t in 2050.

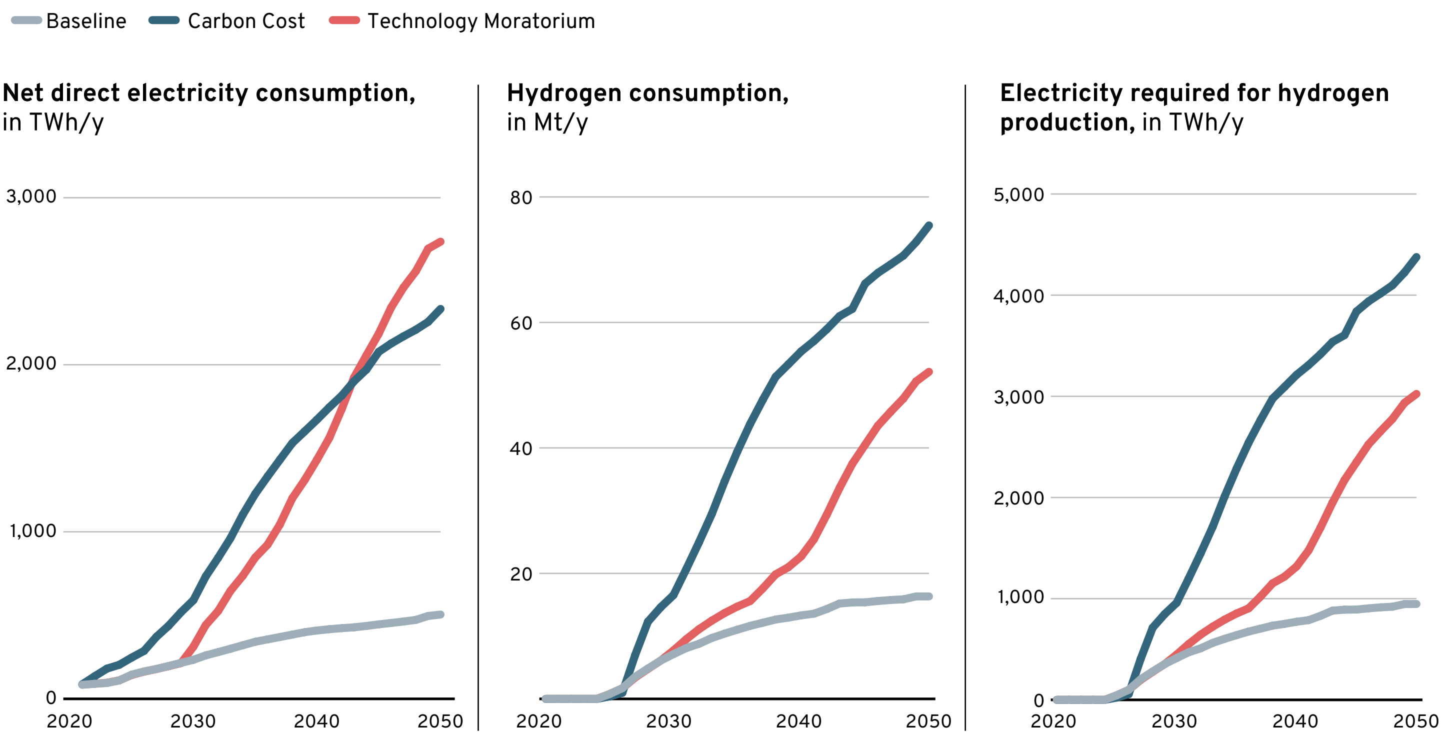
While further research is needed to address this issue in full, it is clear that collaboration between steelmakers and their suppliers (particularly in key coal-producing regions such as China, India, Indonesia, the United States, and Australia) will be needed to ensure these Scope 3 emissions are addressed.

Source: MPP analysis

Steelmaking's direct net electricity consumption increases by 2,300–2,700 TWh/y by 2050 because a growing proportion of steelmaking is reliant on EAF, high-heat electrical melting, or carbon capture technology (Exhibit 2.13). In addition to this increased direct electricity consumption, producing the volumes of zero-carbon hydrogen needed to facilitate net-zero steelmaking requires a further 3,000–4,300 TWh/y of electricity, if produced via electrolysis.
For context, total electricity consumption in the EU today is approximately 2,800 TWh/y.[13] The 8–17 Mt/y of zero-carbon hydrogen required by 2030 may be feasible globally, though the upper end of the range equates to almost three times the hydrogen production target set out in the EU green hydrogen strategy of ~6.5 Mt/y by 2030.[14] Unless clean power and hydrogen infrastructure scale rapidly over the coming decade,

EXHIBIT 2.13

Evolution of net electricity and hydrogen consumption



Note: The third panel assumes all hydrogen consumed is green hydrogen produced via electrolysis.

Source: MPP analysis

they have the potential to delay the steel industry's transition. 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 Scope 1 CO_2 emissions by ~60% 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 (ETC) estimates the supply of truly sustainable biomass available without major changes in land use, technology, and consumer behaviour to be at least 50 exajoules per year (EJ/y).[15] The ST-STSM indicates that the steel sector might require up to 2.4 EJ/y of biomass at its peak in the 2030s, no more than 5% of this sustainable supply. Beyond this point, demand for bioresources present in the modelled scenarios declines as alternative decarbonisation technologies become increasingly competitive.

2.2.6 The cost of the switch to near-zero-carbon solutions

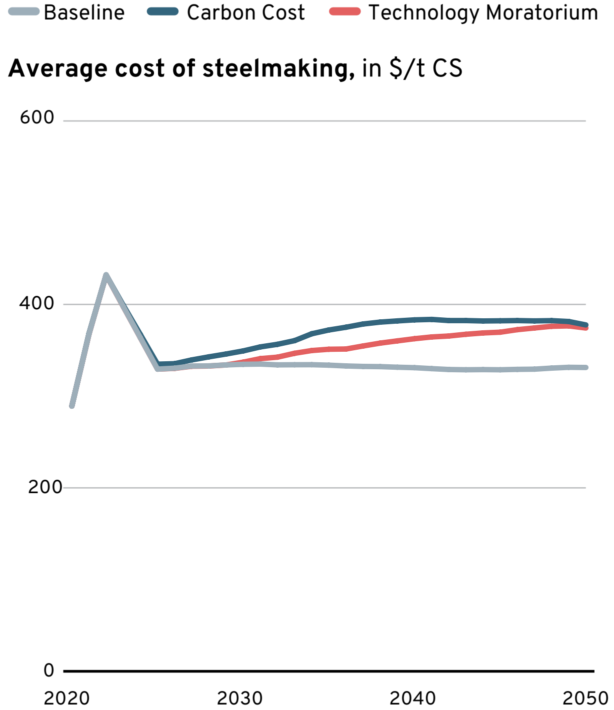
At the aggregate level, the transition to net-zero emissions in the steel sector will increase the average cost of steelmaking (excluding capital charges) by less than 15% in 2050 (Exhibit 2.14). However, there is a short-term trade-off between the pace of transition and the average cost of steelmaking. In the Carbon Cost scenario, the cost of steelmaking already reaches $25/t CS (8%) above Baseline in the early 2030s, whereas the slower transition in the Technology Moratorium scenario sees this cost climb in a steadier fashion.

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 (Exhibit 2.15). Even if hydrogen prices were to drop to as low as $0.60/kg by 2050 (as modelled in the most favourable regions), the levelised cost of steel produced using zero-carbon hydrogen via DRI-EAF could still be up to 17% 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, need 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.

EXHIBIT 2.14

Average cost of steelmaking over time



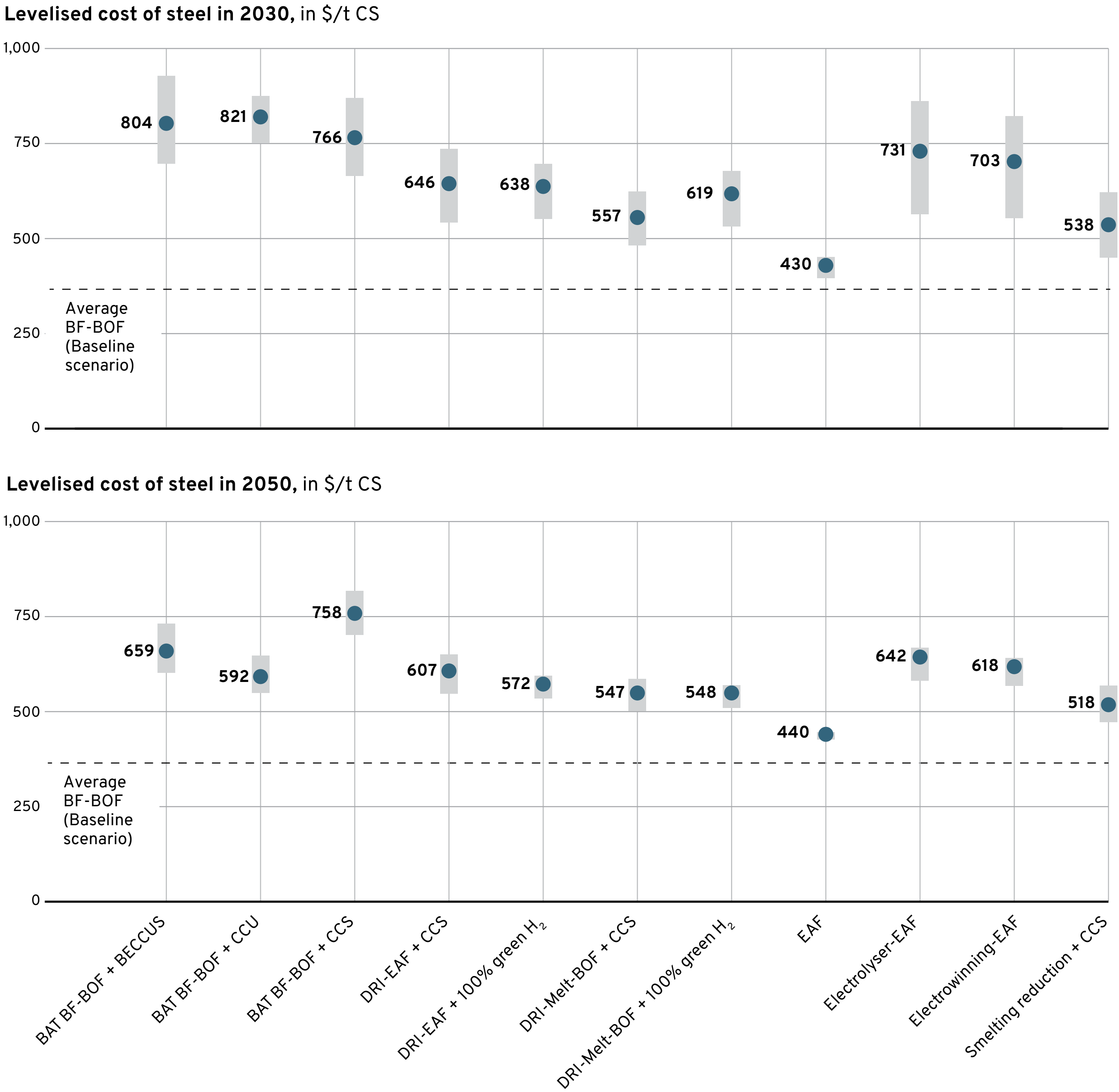
Note: Excludes carbon pricing and capital charges. The peak in the early 2020s is caused by a spike in global fossil fuel prices, largely a response to the war in Ukraine.

Source: MPP analysis

EXHIBIT 2.15

Levelised cost of near-zero-emissions steelmaking technologies

CARBON COST SCENARIO



Note: Charts include carbon pricing except in the Average BF-BOF reference lines. The figure associated with each technology represents a high-level global average based on country-level averages. The bars indicate the range of country-level figures for each technology, with the lower and higher ends representing cost at the most and least favourable locations, respectively. Because the figures comprise high-level averages, there will no doubt be outliers where a certain technology may be much more or less competitive. This applies especially to BECCUS, given the very local nature of biomass supply. All figures assume a plant with a capacity of 2.5 Mt/y and a capacity utilisation factor of 80%.

Source: MPP analysis

Although there will be green premium on near-zero-emissions steel to a greater or lesser degree for the foreseeable future, the impact of this premium on end consumers should be manageable. Decarbonisation will increase the average cost of steelmaking over time, but the reality that steel only forms a portion of the total cost of the goods in which it is used means higher steel costs will result in only minor increases to the price of those goods. Even in 2030, cost increases will be only around 0.5% for passenger cars and 1.5% for white goods, with the highest increase of around 2.1% in construction. By 2050, these cost penalties will fall to 0.3% for cars, 1% for white goods, and around 1.4% for buildings (Exhibit 2.16). These cost increases could be lower still if a higher price of steel stimulates product redesign to reduce required steel inputs.

EXHIBIT 2.16

Comparing price difference of consumer goods across scenarios

Price difference of products containing steel produced by an average DRI-EAF fed with 100% green hydrogen (Carbon Cost scenario) compared to steel produced by an average BF-BOF (Baseline scenario)

Consumer Good	2020	2030	2040	2050
Passenger car	~$37,500	+0.5%	+0.4%	+0.3%
Building	~$0.8m	+2.1%	+1.9%	+1.4%
White good	~$400	+1.5%	+1.4%	+1.0%

Note: Percentage values show how much steel input prices would increase the final consumer price if the remaining bill of materials for the product remained the same as in 2020 with no inflation, assuming higher steel input costs do not induce any changes in product design.[xxi] The goods in question are assumed to require only crude steel. In reality, consumer products such as these would require finished or speciality steel products. However, the decarbonisation of steelmaking is expected to have a less significant impact on the cost of finishing processes and specialty steelmaking than on crude steel production. Consequently, the additional costs associated with steps beyond crude steel manufacturing have been excluded.

Source: MPP analysis; ETC and Material Economics, https://www.energy-transitions.org/publications/steeling-demand/; McKinsey & Company and ETC, https://www.mckinsey.com/business-functions/sustainability/our-insights/net-zero-steel-in-building-and-construction-the-way-forward

Although end consumers may be able to absorb the cost increases of steel decarbonisation, without bridging the green premium at the wholesale level steelmakers may be unable to pass that premium all the way through. Given the highly globalised and commoditised nature of wholesale steel markets, producers who bear the costs of decarbonisation may find they become less competitive relative to their carbon-intensive peers, rendering them unable to sell their near-zero-emissions products and thereby pass on costs. Bridging the green premium at this point in the value chain is important to allow a market for near-zero-emissions steel to flourish.

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 need to cover an initial green premium of $175/t CS or 40% (compared to the average BF-BOF in 2030) for zero-carbon hydrogen–based steel. Although 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.

xxi The remaining bill of materials for these consumer goods is kept constant for the purpose of illustrating the cost impact of steel decarbonisation specifically. In practice, the cost of the remaining bill of materials is likely to rise, driven by factors such as inflation and the decarbonisation of the industries responsible for producing those materials. Acknowledging inherent uncertainties, taken in aggregate, the cost rises implied by the decarbonisation of all of the materials that go into vehicles, buildings, white goods, and other consumer products could lead to substantial price increases.

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 price on carbon emissions implied in the Carbon Cost scenario, the average cost of steelmaking (excluding capital charges) peaks at ~$385/t CS in the early 2040s, $55/t CS (16%) 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.

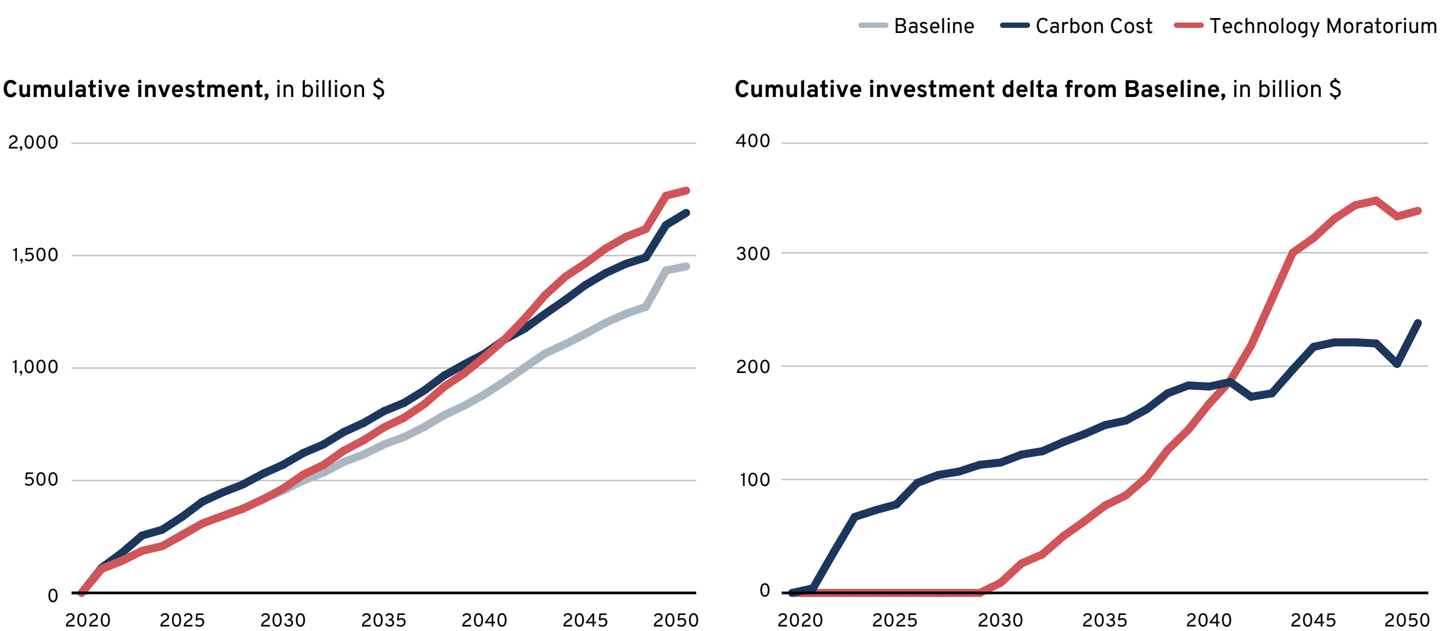
2.2.7 Investment needs for the transition to net zero

Steelmaking is highly capital-intensive. A new BF-BOF integrated steel plant using BAT requires approximately $1.2 billion in capital expenditures per million tonnes of steel capacity. Renovations to existing assets require about a quarter of the capital expenditure of building new plants, but Baseline indicates the steel sector will need an average $47 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 $9 billion annually on average compared to Baseline, or $290 billion by 2050. Achieving the faster deployment of end-state technologies under Carbon Cost, including more capital-intensive carbon capture technology archetypes, requires $10 billion in additional investment annually in the 2020s compared to the slower Technology Moratorium. However, cumulative investment in Technology Moratorium eventually surpasses Carbon Cost because delayed action sees fewer transitional technologies deployed in the 2020s and forces the industry to undergo a costlier asset overhaul from 2030 onwards (Exhibit 2.17). If evaluated in terms of an investment in CO_2 emissions reductions, the 36 Gt of cumulative emissions avoided by following the Carbon Cost trajectory come at a capital expenditure cost of only $7/t CO_2 avoided.

EXHIBIT 2.17

Investment in steelmaking capacity



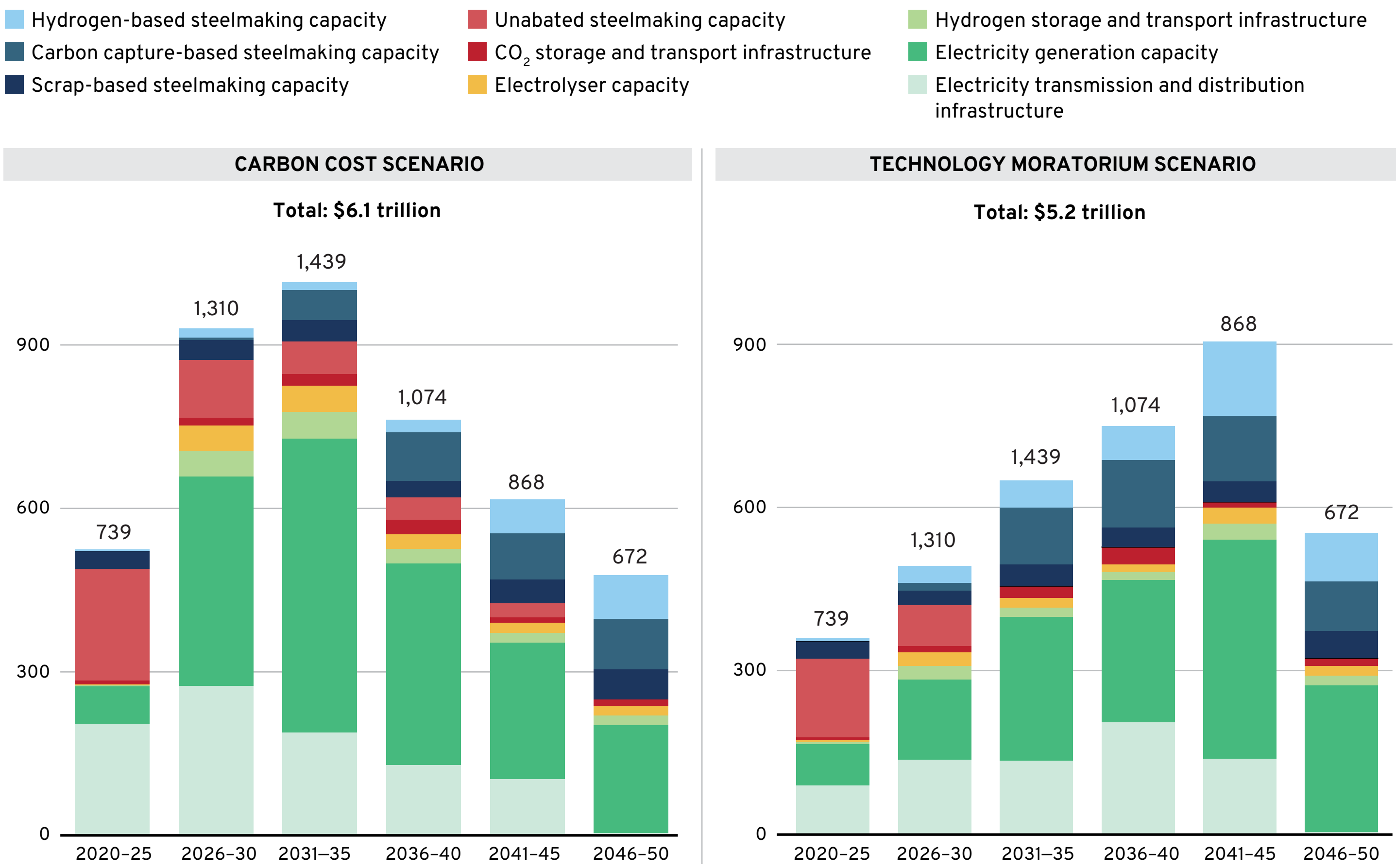
Source: MPP analysis

Investment in enabling infrastructure such as CO_2 storage, 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 and all the accompanying electricity network infrastructure, will take approximately $3–$3.8 trillion in cumulative investment over the next three decades (Exhibit 2.18). That equates to 3%–5% of the total expected investment in electricity generation, transmission, and distribution in a net-zero economy.

EXHIBIT 2.18

Total system-wide capital investment to achieve net zero

Cross-value-chain investment, in billion $



Note: Uncertainty surrounding the precise location of future steel plant development (especially greenfield capacity) means the industry's requirements in these areas can only be approximated and the corresponding investment needs will likely vary.

Source: MPP analysis; ETC, **https://www.energy-transitions.org/publications/carbon-capture-use-storage-vital-but-limited/**; ETC, **https://www.energy-transitions.org/publications/making-clean-electricity-possible/**; ETC, **https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/**

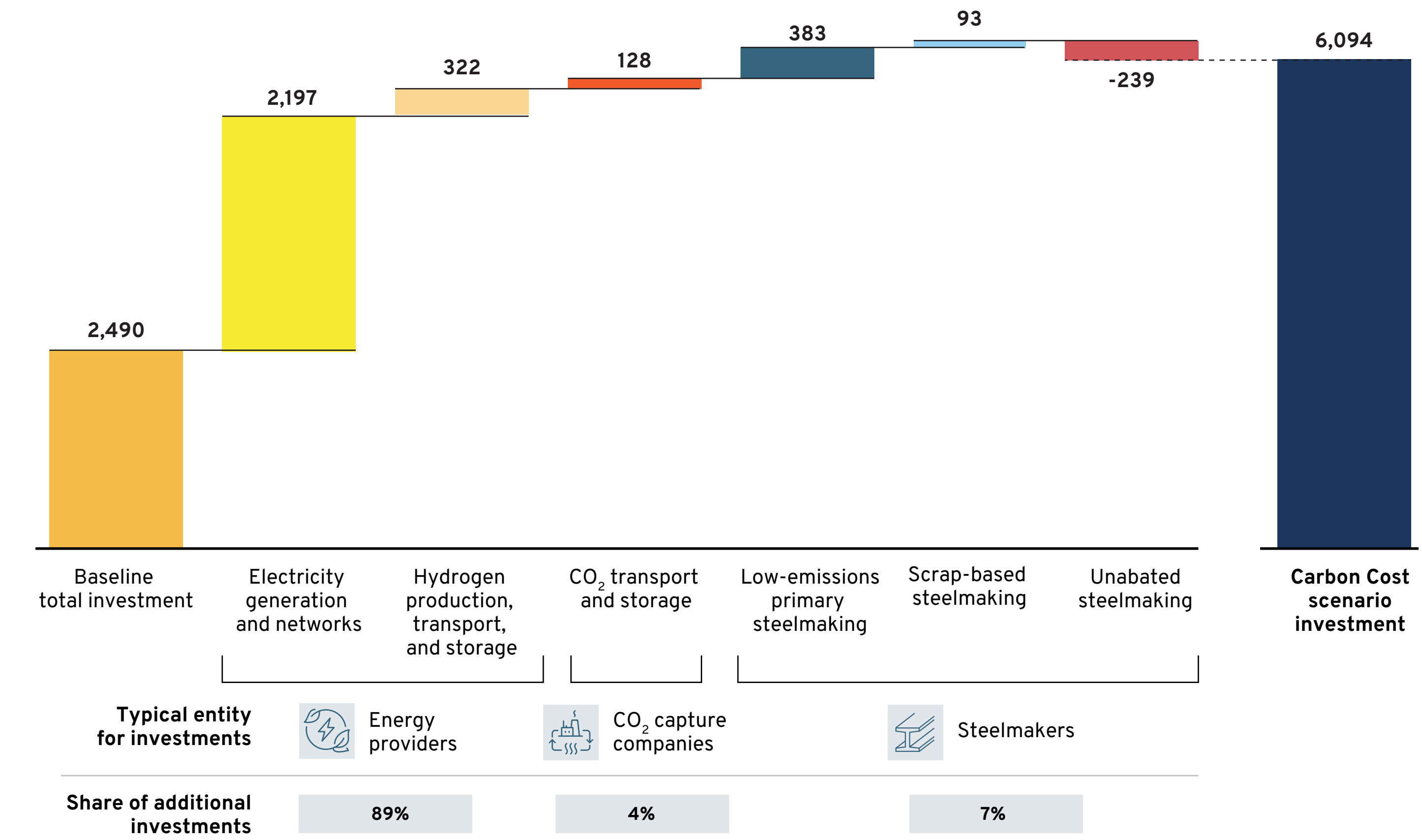
The importance of the investment in enabling infrastructure becomes all the more apparent when focusing on the *additional* investment required by a decarbonising steel sector. Although total system investment in both net-zero scenarios is significant (Exhibit 2.18), a sizable proportion of that investment would take place as a matter of course in the Baseline scenario, particularly the expenditure on steelmaking assets themselves. When the difference in system investment between the Carbon Cost and Baseline scenarios is disaggregated, the additional expenditure on enabling infrastructure is more than 10 times the amount needed for steelmaking assets (Exhibit 2.19).

EXHIBIT 2.19

Total additional system investment from Baseline required to achieve a 1.5°C-aligned, net-zero steel industry

CARBON COST SCENARIO

Global cumulative cross-value-chain investment, in billion $



Source: MPP analysis; ETC, https ://www.energy-transitions.org/publications/carbon-capture-use-storage-vital-but-limited/; ETC, https://www.energy-transitions.org/publications/making-clean-electricity-possible/; ETC, https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/

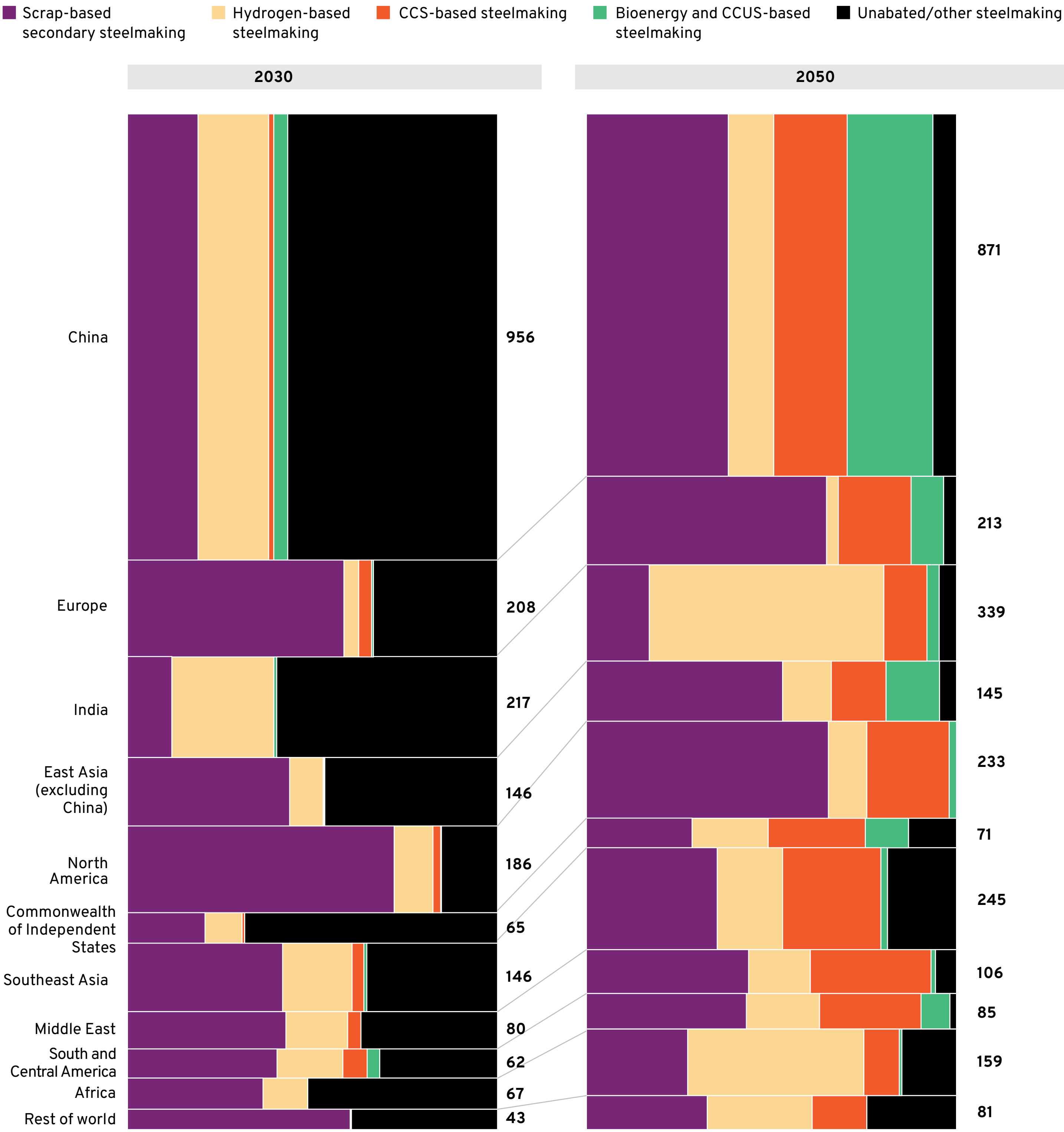
2.2.8 Regional pathways and differences

The capability of the updated ST-STSM to model the steel industry at the regional level enables more sophisticated modelling of the sector and more granular insight. To begin with, all the key trends identified at the global level manifest to some extent in each region in both net-zero scenarios. The blast furnace undergoes significant disruption because it is displaced by DRI as the primary technology for ironmaking (although this disruption unfolds at different speeds in different regions). Similarly, steelmaking based on hydrogen and CCUS technologies emerges in all regions, alongside growth in secondary steelmaking (Exhibit 2.20).

EXHIBIT 2.20

Regional evolution of global steel production

Production volume for the Carbon Cost scenario, in Mt



Note: Production from technologies that consume bioenergy but lack CCUS and are not end state, such as BAT BF-BOF with bio-PCI, fall into the Unabated/other steelmaking category.

Source: MPP analysis

However, common features across regions do not mean the global net-zero technology trajectories (Exhibits 2.5 and 2.6) should be treated as one-size-fits-all pathways for individual regions to follow. Local conditions create varying opportunities and challenges for the steel sector in different geographies, meaning each region takes a relatively distinct route in making its contribution to achieving net zero globally.

Numerous factors vary by region and shape the steel industry. The following key factors have a significant impact on steelmaking investment decisions and are considered by the ST-STSM, although the set is not exhaustive and future development of the model may expand the list further:

A. **Age of existing asset base:** The relative age of the steel mills within a region is important given that the most opportune moment to make an investment decision about an existing asset is when it reaches the end of its current investment cycle. The age of the mills in a region will determine the timing of their refurbishment and, crucially, if and which near-zero production technologies are available at the time.

B. **Regional demand:** Changes in demand also shape the all-important timing of investment decisions. If demand is poised to outstrip local supply, steelmakers in the region will consider expanding their production capacity, and the moment they do so will similarly dictate the technology options available to them.

C. **Political preferences:** Steelmaking has historically been considered an industry of strategic national interest in many countries around the world. If the countries in a region express a preference for sovereign production over imports, that region may expand its production capacity even if foreign supply could satisfy demand more affordably.

D. **Technology of existing asset base:** When a steel asset is facing an investment decision, the attractiveness of investment options would be shaped by the plant infrastructure that is already in place. Certain options could be more favourable if they utilise some or all of the existing infrastructure. For example, switching a mill from a BF-BOF to a DRI-Melter-BOF would capitalise on its existing basic oxygen furnace and reduce the capital expenditures required for the switch. At the regional level, the technologies represented by the existing asset base at any given time influence the cost-optimal “end-state” technology solutions in a decarbonised steel sector.

E. **Input costs:** The price of key steelmaking inputs, namely, fossil fuels, electricity, and hydrogen, vary by region. Different steelmaking technologies become more or less attractive from an investment perspective depending on the resource consumption and associated operating expenditures they would incur in a given region.

The steel industry faces a relatively unique constellation of these factors in every region at any given point in time, resulting in regional trajectories that can vary substantially from the global pathways to which they contribute. The six regions below illustrate this clearly:

A. **Europe:** The location of notable advances in steel decarbonisation, both in terms of technology and policy. Crude steel demand is projected to plateau at just over 200 Mt/y across the modelled horizon. The region contains substantial fleets of both BF-BOF and EAF mills, and scrap availability is expected to grow slightly from an already high level.

B. **China:** The largest steelmaking region in the world today, accounting for more than half of global production and the largest blast furnace fleet of any region. There is a general consensus that steel demand is expected to peak and decline, driven by decreasing domestic consumption, but there is uncertainty and differing views on the timing of peak demand and the extent of its decline by 2050. One IEA estimate suggests domestic demand could fall to as low as 475 Mt/y, while analysis by RMI sees demand peaking at 1,100 Mt/y in 2024 before declining to 620 Mt/y by mid-century.[16] The BAU demand scenario utilised by the ST-STSM is more conservative, with domestic demand peaking at approximately present-day levels before declining to 750 Mt/y by 2050. Scrap availability in the country is expected to substantially increase.

C. **India:** Fleet of existing plants is relatively diverse, comprising blast furnaces, secondary EAF, and DRI-EAF capacity. Domestic steel demand is expected to almost quadruple, growing at a much faster rate than the local level of available scrap.

D. **South and Central America:** A region that is expected to see a significant increase in domestic demand. The region is well endowed with valuable resources for steel decarbonisation, namely, renewable energy sources and high-grade iron ore deposits.

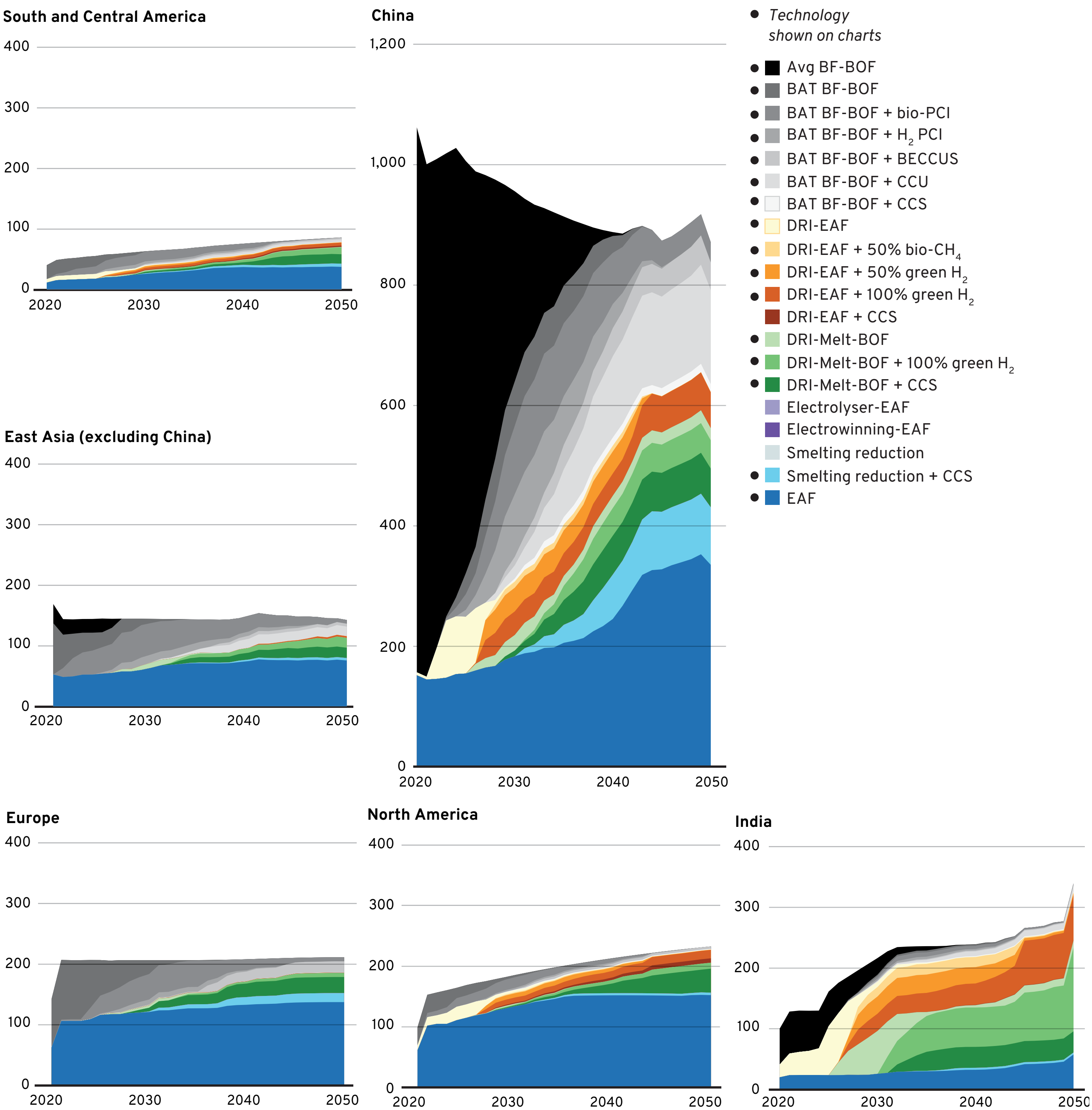
E. **North America:** The bulk of steel production from this region is accounted for by the United States, where secondary steelmaking already comprises the majority of steel production. The region is expected to benefit from comparatively lower electricity prices relative to other major steelmaking geographies.

F. **East Asia (excluding China):** Countries such as Japan and the Republic of Korea, possessing developed economies with mature steel industries. Like Europe, they possess large BF-BOF and EAF fleets, but the region is different in that local scrap availability is not expected to increase significantly.

Evolution of steel production by technology in six major steelmaking regions

EXHIBIT 2.21

Carbon Cost scenario crude steel production, in Mt



Note: Year-on-year production fluctuations visible at the regional level are driven by the international wholesale market, where shifts in the relative competitiveness of different steelmaking regions cause those regions to rapidly switch between local production and imports to meet domestic demand.

Source: MPP analysis

Regional differences produce notably distinct net-zero technology pathways across these six regions (Exhibit 2.21). North America leans into its existing EAF fleet and combines it with lower power prices and greater scrap availability to further expand its secondary steelmaking capacity. China similarly invests heavily in secondary steelmaking, leveraging an expanded domestic supply of scrap steel. As a result, scrap-based EAFs account for almost 40% of domestic production by 2050, an outcome not dissimilar to the findings of recent analysis by the IEA.[17]

Similarities between Europe and the East Asia (excluding China) region create parallels in their trajectories. Both leverage existing BF-BOF assets either by pairing them with bioenergy and CCUS or by switching blast furnaces for DRI-Melter combinations. A key difference between the regions is that higher growth in scrap availability allows Europe to expand its secondary steelmaking to proportionally higher levels.

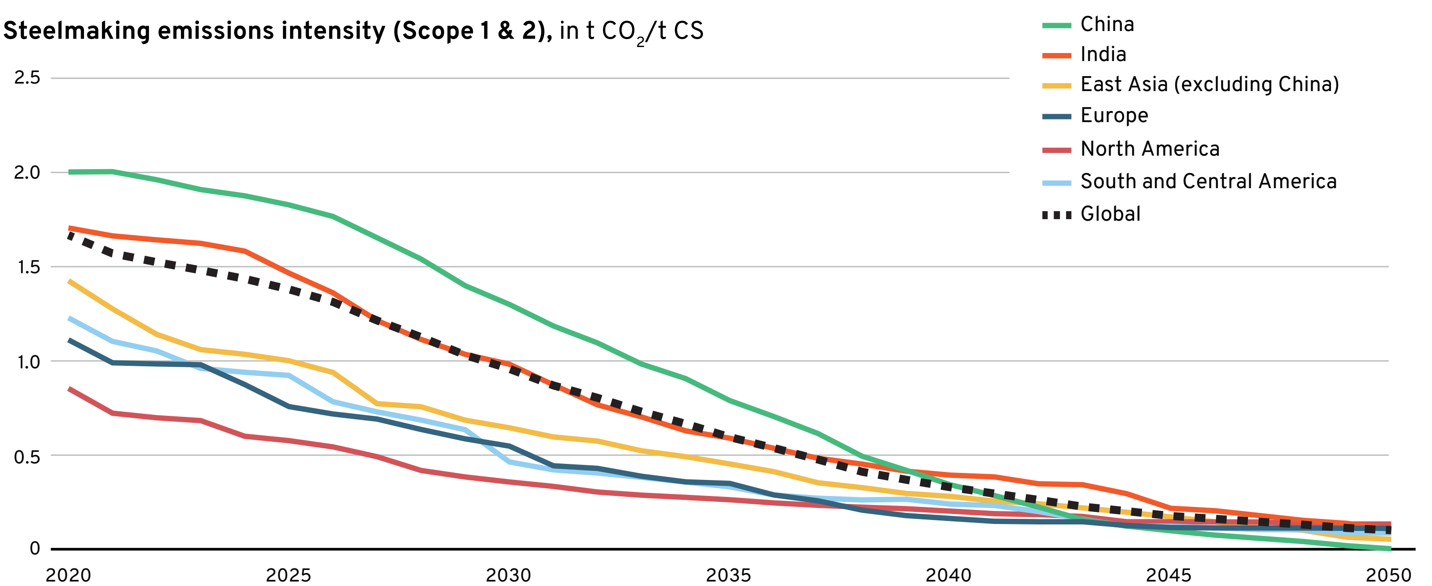
India also expands its EAF fleet, although a slower growth rate in its domestic scrap availability creates a much lower ceiling for its potential in the country.[18] Alongside political preferences for sovereign production, limits to secondary steelmaking drive a significant scale-up in primary capacity to meet burgeoning domestic demand. Low hydrogen prices in India mean the vast majority of this primary capacity is centred on hydrogen DRI. Lastly, South and Central America leverage low electricity prices to expand their EAF capacity, both secondary as well as primary (fed with DRI).

These regional differences will shape the decarbonisation of the global steel industry, and the cost-optimal decarbonisation pathway for each region will require context-specific policy responses. If conditions in a location favour hydrogen over CCUS as the solution for decarbonising primary steelmaking, then the relevant industry, policy, and finance stakeholders will need to prioritise their efforts accordingly. Such regional differences will also define the shape of the regional steel sector decarbonsation curves, and interim emissions reduction targets should vary as a consequence (Exhibit 2.22).

EXHIBIT 2.22

Emissions intensity of steelmaking globally and of six major steelmaking regions

CARBON COST SCENARIO



Note: For modelling purposes, the ST-STSM assumes that steel mills of a given production technology archetype do not display substantial operational differences across regions. For example, an average BF-BOF would have the same energy intensity and Scope 1 emissions intensity in one modelled region as it would in another. In practice, however, a given production technology archetype will display regional differences that could cause real-world steelmaking emissions intensity to vary from the chart above, particularly in the 2020s. For example, analysis shows India's current emissions intensity as higher than China's on account of how India's BF-BOF fleet is more energy-intensive.[19]

Source: MPP analysis

Equally important, if not more so, a regional view draws attention to how the footprint of steelmaking will shift over time and highlights what is important not only now but also in the future. Recognising the inherent uncertainty in and differing views on future demand across steelmaking regions, regional production can broadly be expected to fall into one of three categories: (1) decline (as anticipated in China), (2) plateau (as expected in Europe, Japan, and the Republic of Korea), and (3) growth (as predicted in India, North America, and South and Central America).

China may be the largest steelmaker in the world and a major focus for emissions at the moment, but emissions will no doubt reduce simply as a function of declining domestic demand. The steel sector in India and other developing regions may have a comparatively small carbon footprint for the time being, but their expected rise in production and emissions could more than outweigh any decline experienced by China. Consideration of these future shifts in the footprint of steelmaking is essential for ensuring decarbonisation happens early in growth markets. Failing to address this risks locking those regions into emissions-intensive assets and pathways that would put net zero and 1.5°C alignment out of reach for the industry globally.

2.2.9 The whole steel ecosystem will need to adapt

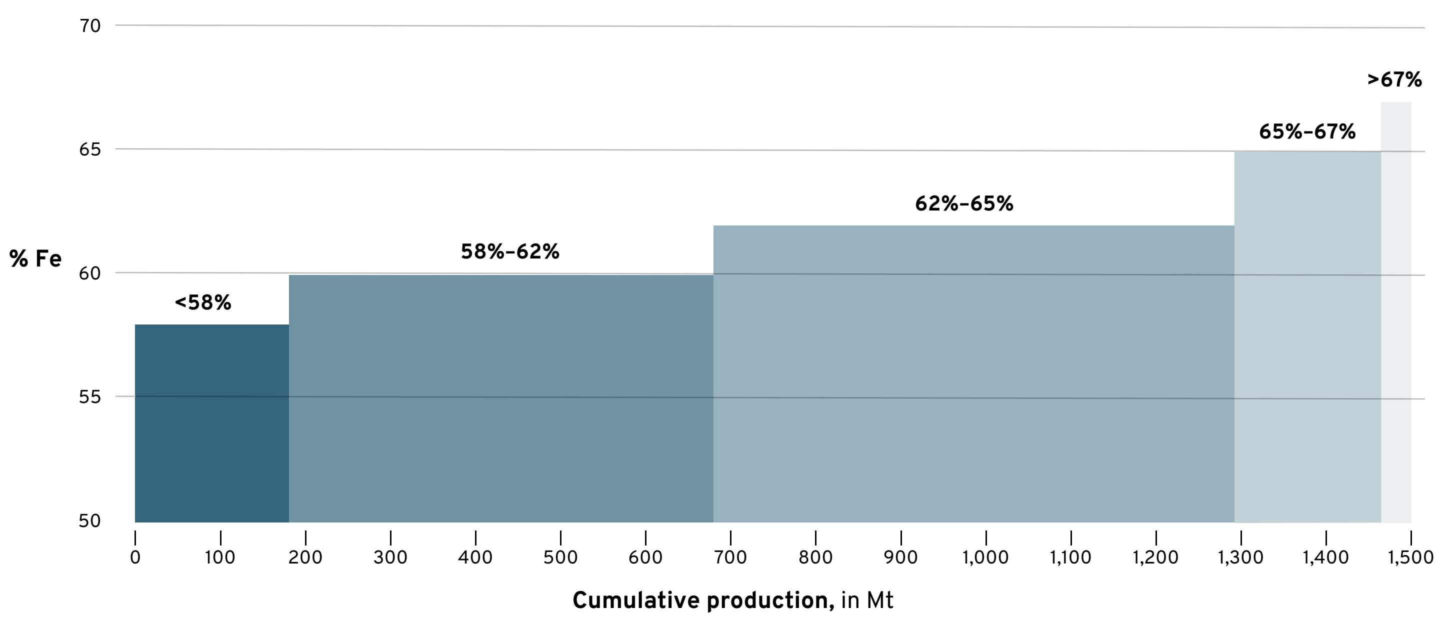
Beyond the impacts examined above, there are a number of wider repercussions that were not modelled within the ST-STSM but which will be important considerations in any net-zero pathway.

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 2.23), 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. This slag is not commercialised in many cases and frequently 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.

EXHIBIT 2.23

Seaborne iron ore freight by grade



Source: CRU, https://www.crugroup.com/analysis/market-outlooks/

The volume of high-grade ore required by the significant increase in DRI-based production suggested by both the Carbon Cost and Technology Moratorium scenarios can be addressed by the iron mining sector in two ways. The first is the development of significant new deposits of high-grade ore. The second involves advancement and expansion of iron ore beneficiation processes that improve lower-quality ores and make them eligible for DRI steelmaking.

A third option the steel industry can pursue is the development of DRI-based steel production routes that are compatible with lower-grade ores. The DRI-Melter-BOF archetype would make utilising lower-grade ores more feasible, thanks in part to the ease of removing impurities in both the melter and basic oxygen furnace compared to an EAF alone. However, processing higher-gangue ore may lead to some inefficiencies in the shaft furnace. In a world where high-grade ores attract a significant price premium, the balance of DRI-Melter-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 basic oxygen furnace.

Even if new high-grade ore deposits are developed and DRI-Melter-BOF capacity is scaled up, substantial iron ore beneficiation capacity is likely to be needed. In the Carbon Cost scenario, ore consumption by DRI steelmaking is set to increase from 130 Mt/y in 2020 to 1,625 Mt/y by 2050. However, the expansion of DRI-Melter-BOF capacity starting in the mid-2020s accounts for most of this demand growth, claiming almost 75% of DRI-grade ore in 2050. The demand for DRI-EAF-grade ore peaks in the late 2020s at just over 460 Mt/y and subsequently declines to 400 Mt/y by 2050.

In terms of high-grade ore deposits, data from Wood Mackenzie indicates a pipeline of planned mining projects due to begin production this decade with total capacity up to 213 Mt/y.[20,xxii] Adding this to the ore production levels needed to meet DRI-EAF output in 2020 still leaves a shortfall of at least 120 Mt/y of high-grade ore needed to reach peak DRI-EAF production. With ore processing left as the only option to cover this gap, significant iron ore beneficiation capacity would need to be developed to meet the needs of a steel sector en route to net zero.

Given the potentially significant impact of the availability of high-grade iron ore on steel decarbonisation, future development of the ST-STSM aims to address this issue by enabling the model to optimise for available ore grades in addition to the factors it already takes into account.

Employment

The steel industry directly employs around 6 million people worldwide and some estimates suggest it supports 43 million additional jobs in other sectors.[21] The decarbonisation of steel will have negligible consequences for indirectly supported employment and its impact on direct employment (whether positive or negative) will likely be small relative to other changes the sector is experiencing.[xxiii]

Between 1920 and 2000, labour requirements in the industry decreased by a factor of 1,000, from more than 3 person-hours per tonne to just 0.003 person-hours.[22] This trend is likely to continue to some degree in all three core modelled scenarios, influenced by the increased automation, digitalisation, and process electrification needed to make low-CO_2 production routes competitive.

It is possible, however, that the relocation of greenfield assets to newly competitive locations could result in more significant employment effects in specific localities. 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

This transition strategy focuses on CO_2 emissions, but 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, SO_X, NO_X, $PM_{2.5}$), 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, 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. Possible solutions include the commercialisation of waste products, such as the way EAF primary slag has historically been used to produce aggregates for road making in certain parts of the world. On a related note, the shift away from conventional blast furnaces may require new solutions for existing waste streams and coproducts that have hitherto been utilised in the blast furnace, such as mill scale and waste gases.

xxii There is significant uncertainty around the level of DRI-grade ore mining capacity that will be operational by the end of the current decade. The figure of 213 Mt/y is an upper boundary, with 20% of that capacity likely to yield ores with a grade suitable for DRI-EAF consumption where it is only "possible" that the remaining capacity would do the same.

xxiii Where decarbonisation is achieved via the addition of CCUS, total employment will likely be higher than under the Baseline scenario (all else being equal). Where decarbonisation is achieved via other technologies, small positive or negative changes to employment are possible.

CONCLUSION: FROM STRATEGIC THINKING TO ACTION IN THIS DECADE

In the Glasgow Climate Pact, agreed in 2021, the parties to the United Nations Framework Convention on Climate Change recognise "that limiting global warming to 1.5°C requires rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45% by 2030 relative to the 2010 level".[23] They add that this will require accelerated action this decade, on the basis of the best available scientific knowledge.

Although the steel sector is not expected to contribute to this goal in the same way as sectors with lower technical and economic challenges to decarbonisation, the steel value chain, policymakers, and financial institutions should start on the path towards a net-zero steel sector now. The following two sections highlight (1) key milestones that should be achieved before 2030, and (2) what key policy, industry, and finance actions can bring about these milestones.

3.1 Key milestones to 2030

Although reducing demand for primary steel (through greater material circularity and the expansion of secondary steelmaking) is a powerful lever for emissions reductions, achieving net zero will not be possible without mitigating emissions from primary steelmaking. **The commercialisation and expansion of near-zero-emissions primary steelmaking is the decisive task to lay the foundation for net-zero steel by 2050** (Exhibit 3.1).

EXHIBIT 3.1

Key milestones to unlock the transition to a 1.5°C-aligned, net-zero-emissions steel sector

	Key milestones until 2025	Key milestones until 2030
NEAR-ZERO PRIMARY STEEL PRODUCTION RAMP UP	**190 Mt/y** of near-zero emissions primary capacity in development to become operational by 2030	**170 Mt/y** of near-zero-emissions primary steel production
	First 5 near-zero-emissions steel projects achieve final investment decision (FID) status	**70 near-zero-emissions** primary steel mills in operation
	$125 billion of annual investments in plants and enabling infrastructure	**$185 billion** of annual investments in plants and enabling infrastructure
UPSTREAM ENERGY AND SUPPORTING INFRASTRUCTURE	**7 GW** of dedicated electrolyser capacity	**300 GW** of dedicated electrolyser capacity
	175 GW of dedicated renewable electricity generation capacity	**760 GW** of dedicated renewable electricity generation capacity
	0.9 EJ/y of sustainable biomass directed to the steel sector	Transport and storage capacity for **60 Mt/y of CO_2**
TRLS	**Commercial availability** of hydrogen DRI technology imminent	Carbon capture, utilisation, and storage (CCUS) technologies with **90% effective** capture rate commercially available for steel
POLICY	**Two or more** steel-producing regions agree on policies to align carbon taxes and/or other regulatory measures for steel production	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

Source: MPP analysis

Although there have been clear signs of progress in demonstrating the technical feasibility of near-zero-emissions primary steelmaking, the current low-emissions steel project pipeline to 2030 is insufficient to achieve the necessary milestones by the end of the decade (Exhibit 2.9). At the time of writing, no near-zero-emissions steel project anywhere in the world has secured final investment decision (FID) status. Expanding the project pipeline and accelerating projects towards FID status serve as useful focal points around which action towards the 2030 milestones can be directed.

3.2 Policy, industry, and finance action to achieve 2030 milestones

Together, the steel value chain, policymakers, and financial institutions can start on the path towards a net-zero steel sector. Accomplishing the mission of getting near-zero-emissions primary steel plants operational this decade rests on overcoming four key challenges:

A. Bringing forward the development of near-zero-emissions steelmaking technologies

B. Ensuring supporting infrastructure (particularly in energy) is scaled rapidly

C. Bridging the cost differential faced by low-CO_2 steelmaking

D. Levelling the global playing field

The key actions that stakeholders should take are outlined in detail in Exhibit 3.2 according to the category to which stakeholders belong. Grouping actions in this way is designed to help stakeholders better understand what they specifically can do but should not distract from the vital need for cross-value-chain collaboration. The prioritisation of these actions may need to change as technology readiness and national, regional, and global governance evolves.

EXHIBIT 3.2

Four key challenges to kick off the transition to net-zero steel in this decade and a non-exhaustive overview of potential high-impact solutions

Problem statement	High-potential solutions	Policy	Industry	Finance	Customers	Examples
TECHNOLOGY						
Near-zero-emissions primary steelmaking technologies have yet to become commercially available	Support R&D, particularly for earlier-stage technologies	✓	✓			• The HYBRIT project for hydrogen steelmaking in Sweden • Government loan guarantees • Blended finance involving development banks • steeluniversity, an initiative of worldsteel
	Incubate pilot projects in locations with favourable conditions (such as access to cheap renewable energy)	✓	✓			
	De-risk near-zero-emissions projects with public-private partnerships	✓		✓		
	Arrange “anchor” off-take agreements for breakthrough projects	✓			✓	
	Expand training and development to grow the necessary engineering capacity		✓			
ENERGY AND SUPPORTING INFRASTRUCTURE						
The energy and carbon infrastructure needed to underpin a net-zero steel industry is not yet in place	Legislate low-carbon electricity scale-up, alongside decarbonisation of power sector	✓				• Public targets and support for clean electricity build out, such as the Renewable Energy Directive of the European Union and the Inflation Reduction Act in the United States • Identification of prospective new industrial “hubs” centred on hydrogen or CO_2 pipelines and storage
	Channel capital towards clean energy and CO_2 infrastructure projects			✓		
	Forge cross-value-chain partnerships to position clean steel production as an “anchor” off-taker for clean energy or CCUS infrastructure		✓			
COST						
Near-zero-emissions steel is likely to face a green premium for the foreseeable future	Agree forward purchase commitments for the long-term off-take of near-zero-emissions steel at a premium to send clear demand signals to the market		✓		✓	• Demand-side initiatives such as First Movers Coalition (FMC) in the United States and SteelZero • The green public procurement commitments developed by countries party to the Clean Energy Ministerial (CEM) Industrial Deep Decarbonisation Initiative (IDDI) • Carbon pricing regimes (set by emissions trading schemes or alternative regulatory measures) potentially supported by carbon contracts for difference (CCFDs)
	Institute green public procurement requirements for steel	✓				
	Introduce carbon markets through appropriate regulatory measures	✓				
COMPETITION						
Varying steel abatement costs across regions can create competitive distortions	Set joint definition of near-zero-emissions steel		✓		✓	• Standards designed by ResponsibleSteel • Applying carbon border adjustment mechanisms such as the one put forward by the European Union • The Sustainable STEEL Principles for climate-aligned investment developed by the RMI Center for Climate-Aligned Finance
	Adopt policy mechanisms to counteract competitive distortions	✓				
	Establish multilateral agreements between major steel-producing countries	✓				
	Apply climate-aligned investment principles to steel financing (including collective frameworks)			✓		

Source: MPP analysis

3.2.1 Key policy actions in this decade

Decisive policy action will be needed to address all four key challenges. The combination of strategically important production bases, the size and scale of the industry, and the emissions-intensive and trade-exposed nature of steel manufacturing means policymakers have a critical role in unlocking decarbonisation of the sector. In the immediate term, an enabling environment that supports and fosters a pipeline of zero-emissions primary steel projects and enables progress to FIDs before the middle of the decade is essential.

The exact arrangement of the policy levers may need to change as national, regional, and global governance evolves. Nevertheless, it is important that key elements of a strong framework are put in place before 2025 (or at least announced), given the lead time major investment decisions require, the urgency of addressing reinvestment cycles, and bringing breakthrough technologies to commercial scales in the 2020s:

A. Policymakers can bring forward the development of near-zero-emissions steelmaking technologies by:

- Blending concessional and commercial capital, including but not limited to tailored credit, loans, and guarantees, alongside extending research, design, and development grant-making to first-of-a-kind (FoaK) commercial-scale projects in recognition of the risk and expense involved in integrating development technologies at commercial scale.
- Implementing regulatory reforms that accelerate and streamline permitting procedures for steel production assets and supporting infrastructure. Such reforms must be aligned with national climate and net-zero strategies and policy frameworks in addition to factoring in the long lead times for industrial assets.
- Repositioning public procurement of steel as a tool of innovation and industrial strategy to drive volumes of decarbonised steel to market. Such strategies, through which governments could mandate or preferentially purchase steel based on carbon-related criteria, could provide partial de-risking of FoaK steel investments.

Efforts by governments and other public entities to pursue blended finance innovations should leverage financial models and technical assistance to build their own organisational technical capacity and the expertise of their staff so that they can best structure, manage and execute these transactions.

B. Policymakers can ensure the necessary scale-up of supporting infrastructure by:

- Coordinating plans and strategies across borders and between sectors for the necessary energy, enabling infrastructure, and raw materials. This includes bio-based raw materials.
- Incentivising and/or legislating decarbonisation of power systems to significantly scale provision of clean power.
- Defining clear and unambiguous credit utilisation rules for CO_2 emissions considered permanently chemically bound in a product so they do not enter the atmosphere under normal use.

C. Policymakers can bridge the green premium on near-zero-emissions steel by:

- Developing or adopting stable and ambitious trade- and transaction-grade definitions for low-emissions steel. Such definitions can be promulgated to other large-volume private buyer groups. Collaboration to share and align practices across national governments, local authorities, and public agencies could aggregate demand and send an even clearer signal to this effect.
- Where carbon pricing is not yet established, consider options to develop carbon markets (e.g., emissions trading schemes) or equivalent regulatory measures.
- Designing, harmonising, and implementing carbon contracts for difference support schemes, providing stable revenue at levels offsetting the green premium.

Rigorous standards based on emissions thresholds can aid in identifying which steel products should be classified as “green” steel.[xxiv] Such definitions are necessary to enable differentiated product markets and for facilitating targeted policy support. These definitions need to adhere to the principles of consistency, universality of application, and transparency. Although product standards can drive carbon-intensive products out of a market and assist in creating a level playing field globally, they lack the effectiveness of pricing mechanisms, which can drive a search for the optimal decarbonisation pathway, combining demand reduction, product substitution, recycling, and zero-carbon production technologies.

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 policy mechanisms that de-risk carbon price uncertainty may also be needed to bring forward the transition to breakthrough technologies.

xxiv The term “green steel” is used sparingly in this document in recognition that the analysis is focused on GHG emissions and that any definition of green steel should also take into account broader environmental, social, and governance (ESG) issues. Please consult the *ResponsibleSteel Standard* for more information on these issues: **https://www.responsiblesteel.org/standard/**.

D. Policymakers can level the global playing field by:

- Establishing an international forum/alliance to debate and resolve the issue of how to create a level playing field and create markets for low- and near-zero-emissions steel.

- Defining reporting guidance and requirements for life-cycle emissions standards for key steel-consuming products. Applying these regulations on just a few steel-using value chains can be a key instrument to fast-track deployment of low-emissions steel and legitimise a differentiated product certification scheme.

Because 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.[24]

At the national level, the measures outlined above to address the first three challenges can be combined and staggered to maximum effect. Given the highly globalised nature of the wholesale steel market, addressing the fourth challenge will depend on multilateral solutions that go beyond what individual countries can achieve independently.

3.2.2 Key industry actions in this decade

Given that the entire steel value chain will need to evolve for the sector to achieve net zero, the key actions industry must take this decade will require cross-value-chain collaboration. The actions that follow involve steelmakers, and also upstream actors (ranging from iron miners, to energy suppliers, to steelmaking equipment manufacturers) and downstream customers:

A. Industry can bring forward the development of near-zero-emissions steelmaking by:

- Setting out a public decarbonisation strategy that identifies the necessary actions for transforming steelmaking, transforming energy use, the use of scrap, sourcing of clean power, and planning for managing residual emissions.[xxv] In regions with limited access to affordable low-carbon electricity, undertaking a suitability assessment for carbon capture retrofits will be necessary.

- Setting robust corporate targets for both near- and long-term emissions reductions. Such targets need be 1.5ºC-aligned, reach net-zero emissions by 2050, and be kept up to date to meet the expectations of investors, customers, and policymakers. Long-term CO_2 data collection will be an essential supplement to this.

- Expanding training and development programmes to grow the engineering capacity needed to deliver the required scale of near-zero-emissions primary steel production. This engineering capacity should include skills relating to the interaction between low-carbon energy systems and steelmaking.

B. Steelmakers can facilitate the scaling of the necessary enabling infrastructure by:

- Actively forging new partnerships and industry consortia across the steel value chain and upstream energy system to develop opportunities for steel production to be an "anchor" partner in clean power, hydrogen, and CCUS projects.

C. Industry can help bridge the green premium on near-zero-emissions steelmaking by:

- Agreeing to long-term off-take with a price premium that is proportional to the production cost increment and associated risks for both supplier and buyer. Buyers with robust upstream Scope 3 targets represent the critical first movers.

D. Industry can play a role in levelling the global playing field by:

- Developing a widely adoptable definition of low- and near-zero-emissions steel with a stringent CO_2 emissions threshold that promotes the adoption of net-zero-compatible production technologies. This could be achieved by defining a new standard level within the existing frameworks and complement efforts to create demand and demand signals.

- Working to agree on a joint high-ambition position on the need for international policy collaboration and coordination that reflects the role of international steel producers with assets in multiple jurisdictions and with exposure to multiple policy environments.

xxv The worldsteel 'Step Up' programme offers a useful starting point for steelmakers looking to develop decarbonisation strategies.

3.2.3 Key finance actions in this decade

The scale of the cross-value-chain investment required to decarbonise steel creates an enormous opportunity for the financial sector, whose actors are integral to achieving FIDs on low-emissions steel projects. Financial institutions can capitalise on this opportunity and help address all four key challenges as follows:

A. Financial institutions can bring forward the development of near-zero-emissions steelmaking technologies by:

- Supporting governments and steel sector efforts to avoid capacity-maintaining investment in high-emissions technology or delayed investment. The adoption of climate-aligned investment principles is an important first step.
- Actively codeveloping strategies to manage and lower the market, credit, liquidity, operational, and policy risks of FoaK projects. Blended finance provided in part by development banks could play a key role here.
- Providing sufficient capital to unlock at least $100 billion of additional investment in the steel sector each year until 2030.

B. Financial players can support the scaling of the necessary energy infrastructure by:

- Evaluating current risk management frameworks and institutional charters to identify opportunities to enable investment in low- and near-zero steelmaking projects. This should also take into consideration the impacts of declining fossil fuel sources as a potential risk in maintaining high-carbon assets.
- Providing sufficient capital to support a massive investment in clean power provision and other critical upstream energy infrastructure.

C. Financial institutions can bridge the green premium on near-zero-emissions steelmaking by:

- Developing the methodologies and protocols 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.

D. The global finance sector can help level the global playing field by:

- Working with industry and regulatory bodies to adapt existing carbon accounting, auditing, and verification frameworks to develop consistent steel sector and cross-sectoral methodologies for assessing corporate and project-level emissions performance.
- Actively implementing the Financial Stability Board's Task Force on Climate-Related Financial Disclosures recommendations for steel investments and portfolios.

Capital providers can exert a strong levelling force by channelling their capital to companies and infrastructure projects that display high ambition towards steel decarbonisation. Climate-aligned investment principles can create clarity and transparency on which companies and projects are investable and which are not in line with net-zero and 1.5°C targets. Financiers can develop principles such as these on their own or join collective frameworks (Exhibit 3.3).[25] In either case, to effectively apply these principles, financial institutions will require a sector-specific methodology to measure and track alignment of their clients and reliable data sources for assessing progress. The Sustainable STEEL Principles, developed by the RMI Center for Climate-Aligned Finance (CAF), are a good example of a framework designed to address these issues by providing lenders with a fit-for-purpose, collective methodology crafted to harmonise across various standards, optimise for emissions reductions, and support client engagement.[26]

EXHIBIT 3.3

Elements of climate-aligned investment principles

Timeline

Private banks, institutional investors, and public sector banks commit to ensuring their investments in infrastructure assets and companies comply with climate targets. For example, the Sustainable STEEL Principles enable banks to measure the climate alignment of their steel lending portfolios and encourage them to set targets aligned with the emissions trajectory of the IEA NZE scenario.

Client engagement

Recommendations for how to engage with clients to support their decarbonisation efforts. The Sustainable STEEL Principles encourage signatories to:

- Inform clients of their alignment score, and company-specific Alignment Zone, which charts out the low-carbon transition against two net-zero scenarios.
- Encourage clients to adopt emissions reduction targets in line with best practices.
- Inquire as to whether clients have a transition plan to guide their company's low-carbon transition, and if not, encourage clients to create one.
- Discuss specific opportunities for transitional switches with clients, including financing tools available to support client decarbonisation.

Disclosure

Requirements to disclose the alignment of investment portfolios with decarbonisation trajectories and climate targets. For example, the Sustainable STEEL Principles require signatories to make public annual disclosures on their portfolio alignment scores, contextual information behind the scores, and forward-looking indicators (on an optional basis) for progress.

Exclusion criteria

Criteria to trigger divestments from non-1.5°C-aligned assets and companies, such as declining to provide loans to steel companies that do not meet minimum 1.5°C-aligned criteria by 2030 (such criteria cannot form part of a collective framework such as the Sustainable STEEL Principles but can be considered by individual financiers).

Inclusion criteria

Criteria to trigger new investments in 1.5°C-aligned assets and companies, such as channelling investment to steelmakers targeting to reduce their CO_2 intensity per tonne of crude steel by 30% by 2030 (such criteria cannot form part of a collective framework such as the Sustainable STEEL Principles but can be considered by individual financiers).

Source: MPP analysis; Poseidon Principles, **https://www.poseidonprinciples.org/finance/**; RMI CAF, **https://climatealignment.org/focus-areas/**

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. As of the second half of 2022, steel producers representing more than 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, Brazil, 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 Movers 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 Glasgow Financial Alliance for Net Zero as well as the Sustainable STEEL Principles.

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 primary 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. The Net-Zero Steel Initiative 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.

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 the ST-STSM, we model 20 distinct steelmaking archetypes
Bioenergy with carbon capture, utilisation, and storage (BECCUS)	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
Bioenergy	Renewable energy derived from biological sources in the form of solid biomass, biogas, or biofuels
Carbon budget	The remaining sum of global emissions that can be emitted to limit global warming to 1.5°C above preindustrial levels. This report references IPCC's SR1.5, and subsequent 2019 emissions estimates, that find that to reach the 1.5°C target with limited overshoot at 50% probability, we must limit additional emissions to 580 Gt CO_2 as of 2018, and 500 Gt as of 2020[27]
Carbon capture and storage or utilisation (CCUS)	The term *carbon capture* refers to the process of capturing the CO_2 produced from energy generation and industrial processes. Unless otherwise specified, direct air carbon capture (DACC) is not included when using this term. The term *carbon capture and storage* refers to the combination of carbon capture with underground carbon storage, and *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 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 (CS)	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 report, including direct process emissions
Green hydrogen	Hydrogen produced via electrolysis using zero-carbon electricity
Hot metal	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 does not 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
Scope 1 emissions	Direct emissions (Scope 1) 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) estimated from on-site electricity consumption (purchased power). Coproduced 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
Secondary production	Electric furnace production that is primarily fed by scrap, as opposed to pig iron or sponge iron
Technology readiness level (TRL)	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)

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MISSION POSSIBLE PARTNERSHIP

The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonise some of the world's highest-emitting industries in the next 10 years.