1.5°C STEEL

DECARBONIZING THE STEEL SECTOR IN PARIS-COMPATIBLE PATHWAYS

October 2021

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Steel production in a factory. Photo by Ant Rozetsky via Unsplash.jpg

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Executive Summary

If we are to achieve deep cuts in emissions in line with keeping a 1.5°C pathway in reach, there can be no sectoral exceptions. The steel sector has to rapidly decarbonize. Every year roughly 2 billion tons of steel are produced, contributing to around 7% of global greenhouse gas emissions. Currently demand is projected to increase to over 2.5 billion tons per year by 2050, with the bulk of growth in emerging economies.

This demand increase comes at a point when steel sector emissions need to fall fast to bring the sector in line with a Paris-compatible net-zero by 2050 trajectory. While momentum towards decarbonization is growing, the sector is currently not on track to significantly reduce its emissions. Accelerating steel decarbonization will require going further and moving faster on all available mitigation levers with concerted policy efforts at national and international levels underpinning this shift.

This study examines those challenges, unpacking for the first time at global and regional levels the implications for steel decarbonization of a 1.5°C compatible transformation pathway. Using the Global Change Analysis Model (GCAM)[1], we explore the gap between current policy trajectories and 1.5°C consistent pathways and the role of key technologies and demand-side measures in achieving accelerated steel decarbonization. We draw out policy implications at the global level and in the six largest steel producing regions: China, Europe, India, Japan, South Korea, and the US.

Key findings

- **Accelerated steel decarbonization is key to keeping 1.5°C alive**. In a cost effective 1.5°C pathway, steel sector emissions need to fall by at least 50% by 2030 and by 95% by 2050, on 2020 levels. A 10-year delay in action results in an additional 20 $GtCO_2$ being emitted from the steel industry between 2020 and 2050, accounting for about 5% of the remaining global total carbon budget[2] with a 67% probability of limiting global warming to 1.5°C.

- **Demand-side levers are critical for staying within the 1.5°C threshold.** The adoption of a suite of material efficiency measures alongside scaling up steel recycling accounts for 50% of steel sector mitigation in 2050 to meet a 1.5°C trajectory. Moreover, these solutions are readily deployable today, allowing for rapid progress on steel sector emissions in the next decade, buying time for breakthrough technologies to mature.

- **To avoid early retirement and stranded assets, no new blast furnaces without carbon capture, utilization, and storage (CCUS) should come online after 2025.** Nearly all blast furnaces without CCUS, which account for 61.3% of steel production today (Swalec & Shearer, 2021), are phased out by 2045 in an orderly 1.5°C transition. With an average lifetime of 20-25 years, this suggests

[1] GCAM is an open-source, global integrated assessment model. The source code and assumptions are available at https://github.com/JGCRI/gcam-core.

[2] According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, the estimated remaining carbon budget from 2020 to the year of reaching global net zero CO_2 emissions is 400 $GtCO_2$, in the case of 67% likelihood of limiting global warming to 1.5°C.

that any new blast furnaces without CCUS built as early as 2025 and by 2030 at the latest risk becoming stranded assets. This also goes for existing blast furnaces that are relined but not retrofitted with carbon capture technology in this time frame.

- **The global steel sector will need to see a large-scale shift in production capacity towards breakthrough near-zero emissions steelmaking technologies.** CCUS will be needed as early as 2025 to retrofit existing or equip new blast furnaces.[3] The share of blast furnaces, with and without CCUS, declines over time as other low-carbon steel production technologies come in at competitive costs. Steel produced from hydrogen-based direct reduced iron (DRI) expands gradually, coming online from the mid-2020s, and accounts for 19% of global production by 2050. DRI electric arc furnaces (EAFs) equipped with CCUS also increase, accounting for 18% of global production by 2050. Crucially, the groundwork for this shift has to be laid in the next 2-3 years with a major wave of reinvestment in steelmaking capacity expected in the next decade.

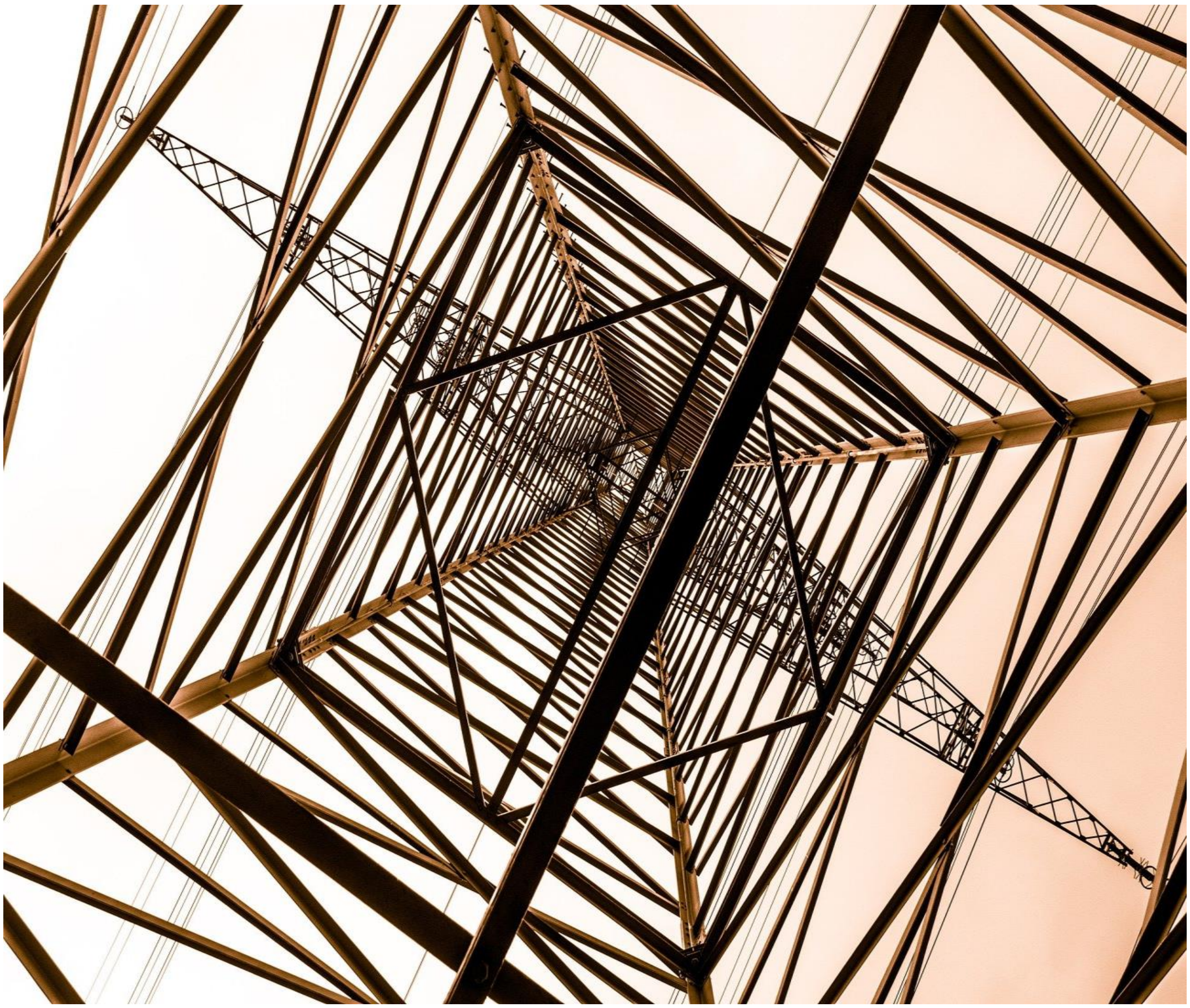
- **Phasing out coal and increasing the use of renewable-based electricity and hydrogen are necessary to make drastic emission reductions in the iron and steel industry.** In the 1.5°C orderly scenario, unabated coal only accounts for 2%, while electricity and hydrogen account for 65% of global fuel consumption in the iron and steel industry by 2050. Global electricity use in the iron and steel industry increases from 1300 TWh EJ in 2019 to 1900 TWh in 2050. Hydrogen use in the steel industry also sees considerable growth, reaching 4.5 EJ in 2050. Given the large increase in hydrogen and electricity, it is crucial for their upstream production to become cleaner than it is today, requiring a large build out of renewable energy capacity globally.

- **No leaders or laggards.** While regions face different challenges in steel decarbonization and will follow different technology pathways, all six of the major steel producers need to immediately step-up action on steel decarbonization. Regions with large existing steel capacity today, China, Europe, Japan, South Korea, and the U.S., reduce their steel sector emissions by 97-99% between 2020 and 2050 in the orderly 1.5°C scenario. India, with rapid steel capacity expansion, needs to reduce it steel sector emissions by 90% by 2050 from 2020 levels in an orderly 1.5°C future.

- **Far greater ambition in policymaking, technology deployment and circular economy approaches will be needed to shift the steel sector to a 1.5°C compatible pathway.** This will require urgent and concerted efforts from a wide set of stakeholders. Governments and steel producers will need to set ambitious steel decarbonization targets early on and pursue a rapid transition to near-zero emissions steel technologies via a combination of direct support and regulation to restrict carbon-intensive steel capacity expansion, e.g. phasing out the operation of blast furnaces without CCUS. Steel consumers and public bodies will need to step up procurement commitments to ensure near-zero emissions steel goes from a niche, premium

[3] Given uncertainties associated with CCUS deployment in the iron and steel sector, we conducted sensitivity runs excluding CCUS as an option to decarbonize the steel sector and unpack the implications in Box 3.2, concluding that steeper emissions reductions and earlier blast furnace retirement would be required if CCUS is not available in the iron and steel sector.

product to a mainstream commodity. Policymakers will need to introduce regulation to seize the full potential of circular economy and material efficiency solutions for steel. Finally, major steel producing countries will have to coordinate on research, development, and demonstration, green steel standards, certifications and other lead market creation instruments for green steel, transition finance, subsidies and trade policy to ensure a level playing field.



Acronyms and Abbreviations

BF	Blast furnace
BOF	Basic oxygen furnace
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon capture, utilization and storage
CCFDs	Carbon contracts for difference
CO_2	Carbon dioxide
COP26	26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change
DRI	Direct reduced iron
EAF	Electric arc furnace
ETS	Emissions trading system
EU	European Union
GCAM	Global Change Analysis Model
GDP	Gross domestic product
GHG	Greenhouse gas
IAM	Integrated assessment model
IEA	International Energy Agency
IDDI	Clean Energy Ministerial Industrial Deep Decarbonization Initiative
IPCC	Intergovernmental Panel on Climate Change
MDB	Multilateral development bank

Table of Contents

Chapter 1. Background: Steel Industry Transition

The Paris Agreement has transformed the policy debate around decarbonizing heavy industry. Unlike earlier climate accords, which left large volumes of national emissions unaccounted for, the Paris Agreement set a goal of limiting global warming to 1.5°C with a carbon budget that implies achieving a carbon neutral world by the middle of this century. Heavy industry sectors, including steel, cement and chemicals, are now expected to rapidly decarbonize, approaching net-zero by mid-century.

Steel is the largest industrial emitter. As a key input into infrastructure, buildings, wind turbines, home appliances and cars, steel is among the most widely used materials on the planet. It is responsible for 8% of global final energy demand and 7% of energy-sector carbon dioxide (CO_2) emissions (IEA, 2020). The vast majority (61.3%) of steel today is produced via the coal-based blast furnace-basic oxygen furnace (BF-BOF) route, in which metallurgical coal acts as both a source of heat and of carbon in the ironmaking process (Swalec & Shearer, 2021). The sector is highly reliant on coal, which meets 75% of its energy demand. Every ton of steel manufactured generates, on average, 2.2 tons of CO_2 (IEA, 2020).

Moreover, demand for steel is projected to continue growing. 1,878 Mt of steel were produced worldwide in 2020[4] (World Steel Association, 2021) and it is estimated that global demand will continue rising in the next three decades as emerging economies grow (IEA, 2020). Without targeted measures to reduce the carbon footprint of steelmaking, therefore, CO_2 emissions from the sector are likely to further increase.

From a technical perspective, there are an increasing number of solutions for reducing steel sector emissions. Shifts in design, efficient use of steel, and direct reuse of steel could lower demand for primary steel. Steel recycling in EAFs can emit less than 0.3 tons of CO_2 per ton of steel in indirect emissions today, about 85% lower emissions than the BF-BOF route. Emissions depend primarily on the source of electricity and can, therefore, be more easily mitigated than for primary steelmaking routes. Scaling up steel recycling in EAFs, which today account for roughly 20% of steelmaking capacity (Swalec & Shearer, 2021), is, therefore, a key mitigation lever. The potential to do this will vary across regions, as it relates to the current ratio of primary and secondary steel production, the availability and quality of scrap, average age of existing blast furnaces, and the balance of primary and scrap trade.

There are also a number of new ways of producing cleaner primary steel. Shifting to direct reduced iron (DRI) steel production using natural gas can be 66% less emissions-intensive than the BF-BOF route (Witecka et al., 2021). Experts view this as a key bridging solution as it is available today and can eventually be decarbonized without the need for additional retrofits: increasing shares of renewable-based hydrogen can be blended in over time. However, the risk of natural gas lock-in has to be managed.

Net-zero primary steelmaking processes are also under development, including electrolytic hydrogen-based direct reduced iron with EAFs (DRI-EAF-H2) where the electricity is sourced from renewable

[4] There is a minor reduction in steel demand in 2020, in response to the COVID-19 pandemic.

sources, steelmaking with carbon capture, utilization, and storage (CCUS), and iron ore electrolysis.[5] There is a lot of momentum around hydrogen direct reduction, in particular, with a string of pilots announced over the last year and companies projecting that hydrogen-based net-zero steel could be commercially available as early as 2025 (Henbest, 2021).

Increased optimism over the feasibility of steel sector transition has also seen an uptick in private sector commitments. The last year saw a steady stream of net-zero pledges from steel companies, which now cover over 20% of global steelmaking capacity (Swalec & Shearer, 2021). Front-runner steel consumers are also starting to shift. The emergence of buyers' club initiatives (e.g. SteelZero run by the Climate Group) has seen market participants show a willingness to pay a premium for green steel (Delasalle et al., 2021).

These efforts, however, still only cover a small share of the global steel market and there are worrying signs that the sector is not yet moving fast enough. The net-zero pledges being set are often vague, with companies banking on the bulk of emissions reductions to occur post-2030. Most steel companies with net-zero commitments have yet to lay out detailed roadmaps for how they expect to deliver their pledges (Gardiner & Lazuen, 2021).

Well-known barriers still stand in the way of steel sector decarbonization. Emissions-free steel is currently still expensive to produce and there is not yet a sizable, guaranteed market for it. Steelmaking is a capital-intensive industry with investment cycles typically lasting several decades resulting in a high degree of inertia. Global overcapacity in the sector has depressed steel prices in some locations and dampened appetite for investment at a time when steel companies are under pressure to replace existing capacity with low-emissions alternatives. That has also made it difficult for new players to enter the market and compete with larger companies. Finally, steel is globally traded and faces harsh price competition, making it harder for steel producers to pass through the additional costs of investing in cleaner technologies without impacting their competitiveness.

Moreover, the necessity of rapid steel decarbonization stands in stark contrast with current and planned steelmaking capacity. Three-quarters of steel capacity currently under construction is based on the most polluting coal-based BF-BOF route (Swalec & Shearer, 2021). Given the long lifetime of these plants (roughly 20-25 years or more depending on the location), any additional blast furnaces built today will lock-in high emissions, making it more difficult to keep warming below 1.5°C. It is, therefore, crucial that policymakers responsible for industrial and economic planning consider a faster transition of the steel sector in their respective countries and adjust policies accordingly.

Rapid transition is needed to set the steel sector towards 1.5°C consistent pathways. A big wave of steel capacity reinvestments (>50% of current BF-BOF capacity) is expected in the coming decade. The key question is what technology pathway plant owners will opt for in the immediate future. The right policy signals are needed now to give plant owners the confidence to invest in breakthrough technologies, rather than locking in carbon-intensive production via refurbishments, or see these sites shut down.

[5] Iron ore electrolysis is not considered in this study as it is still at an early stage of development. However, it is included in the IEA's 2020 Steel Technology Roadmap and could yet play an important role in steel sector decarbonization.

For decision-makers, more insights are needed into the required speed, pathways, and policies for 1.5°C compatible steel sector decarbonization. The goal of this report is to fill in some of those gaps, providing reliable and detailed information on the implications of meeting a 1.5°C compatible trajectory for steel decarbonization globally and in key regions: China, Europe[6], India, Japan, South Korea, and the US.

[6] Europe in this report includes Andorra, Austria, Belgium, Bulgaria, Channel Islands, Cyprus, Czech Republic, Denmark, Estonia, Falkland Islands (Malvinas), Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Hungary, Ireland, Isle of Man, Italy, Latvia, Lithuania, Luxembourg, Malta, Monaco, Netherlands, Poland, Portugal, Romania, Saint Helena, Saint Pierre and Miquelon, San Marino, Slovakia, Slovenia, Spain, Sweden, Turks and Caicos, United Kingdom, Vatican, Virgin Islands (British), and Wallis and Futuna.

Chapter 2. Methodology and Scenarios

2.1 Methodology

To understand changes in steel demand, production technologies, and emissions, we use the Global Change Analysis Model (GCAM) in this study (Bond-Lamberty, 2021). GCAM is a global, multi-sector, integrated model of human and earth system dynamics, and has been used in all the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). GCAM contains representations of the energy system, water, agriculture and land use, the economy, and the climate, and can be used to explore and quantify the behavior of and interactions between them through scenario analysis. GCAM includes 32 geopolitical regions, 384 land use regions, and 235 water basins. Each region carries its own set of assumptions, such as existing infrastructure, resource availability, and technology cost and efficiency. The model runs in five-year time steps through to the end of the century and is calibrated to historical data through 2015. The main advantage of using GCAM is that it captures the interactions between the steel sector and the rest of energy, economic, and environmental systems, and provides insights into how changes in upstream and downstream sectors would affect steel decarbonization, and vice versa.

GCAM operates on the principle of market equilibrium and iterates on a set of prices until supply and demand are equal across all markets in the model. Prices and other relevant information are used to make decisions about the allocation of resources. The model is dynamic recursive, so agents do not know the future when making a decision in the current period. After it solves each period, the model then uses the resulting state of the world to perform the same iteration process in the next period. Key input assumptions include population and GDP, technology costs and performance, water and land requirements, resource availability, and climate policies. Model outputs include energy supply and demand, technology deployments, prices in each sector, land use, water demand, and greenhouse gas emissions.

Technologies in GCAM compete for market share based on their characteristics, input costs, and output prices. The cost of a given technology has three components: non-energy cost, efficiency, and price of fuel inputs. Non-energy cost includes levelized capital, fixed, and variable costs incurred over the lifetime of the equipment. Efficiency measures the required input to produce a unit of output. Fuel price is endogenously calculated within the model in each period and specific to each region. Technologies in GCAM, including technologies used in electricity generation, refining, industry, buildings, and transportation, are vintaged. Existing plant or equipment continues operating until the end of physical life, unless the price falls to the point that operation cost exceeds the vintage of capital, at which point the plant or equipment would be retired. For this study, the lifetime of steel plants is assumed to be 20 years for developed regions and China and 25 years for India and other emerging economies. New technologies are introduced based on a logit choice function. The logit function has been widely used to determine market shares of discrete technologies and accounts for non-modeled factors, such as social, behavioral, and institutional factors, that can affect technology choices (J. F. Clarke & Edmonds, 1993).

GCAM is a high-resolution integrated assessment model (IAM) with fully coupled economic, energy, land, water, and climate systems. Compared to most existing steel sector models and energy system models, GCAM can capture complex interactions and feedbacks across systems and how changes in one system could affect others. For example, the use of hydrogen in the steel sector competes with hydrogen use in other sectors such as aviation and shipping and is constrained by hydrogen production and transportation, which is further affected by upstream sectors such as gas production and electricity generation. Similarly, the use of biomass-based blast furnace is bounded by the availability of energy crops that compete with food crops and forest for land as well as bioenergy consumption in other parts of the energy system. In this study, the global consumption of bioenergy is capped at 100 EJ, to address sustainability concerns (Creutzig, 2015). At the same, GCAM has its limitations. While GCAM, or IAMs in general, are valuable tools to explore cost effective 1.5°C pathways, they do not fully consider political and social constraints associated with rapid system transitions or measure economic damages and reduced growth due to climate change.[7]

The version of GCAM used for this work contains a detailed representation of the iron and steel sector, which includes eight competing technologies for steel production (Figure 2.1). These include existing technologies, such as BF-BOF and EAF using either steel scrap or direct reduced iron as the main raw material, as well as innovative technologies that have the potential to fully decarbonize the iron and steel sector, such as CCUS and hydrogen-based DRI in combination with EAF (see the table in Appendix 1 for detailed technology descriptions).

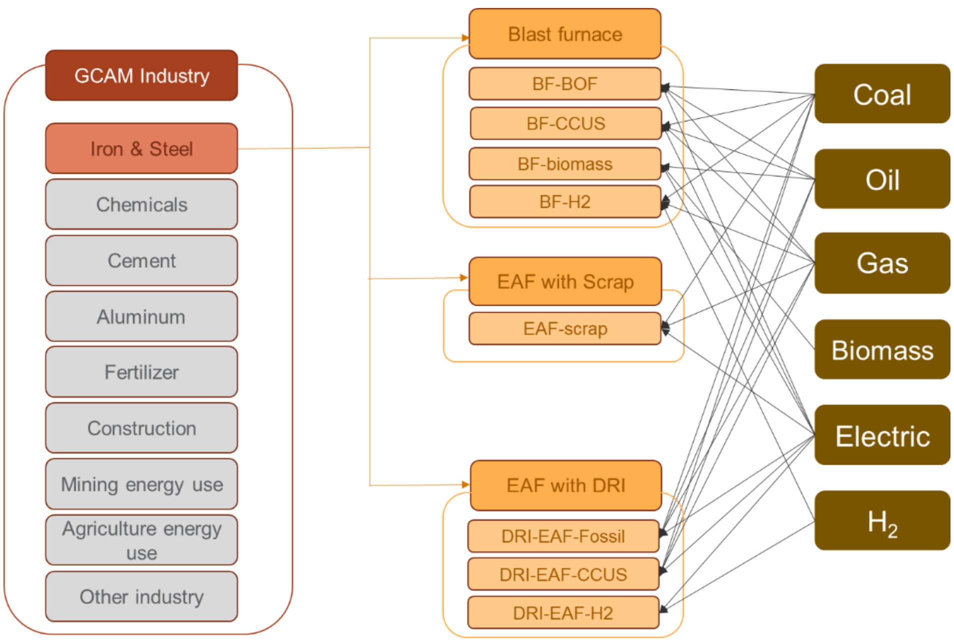


Figure 2.1 Iron and steel sector in GCAM

[7] GCAM documentation is available at https://jgcri.github.io/gcam-doc/. For more information on advantages and disadvantages of IAMs, please see AR5 WGIII Chapter 6.2: Assessing Transformation Pathways, https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter6.pdf (L. E. Clarke et al., 2015); and "How 'integrated assessment models' are used to study climate change", https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change (Evans, 2018)

2.2 Scenario design

The scenarios explored in this study consider two key issues. First, what is the gap between current policy trajectories and 1.5°C consistent pathways? Second, what are the roles of key technologies and demand-side measures in transforming the steel sector in a 1.5°C future?

To understand the gap, we start with three global emissions pathways. The reference emissions pathway largely relies on current policies and technologies. This serves as a counterfactual pathway that can be used to demonstrate the impact of mitigation policies and is a commonly used approach by IPCC assessment reports and other modeling studies. There are different pathways to limit the global temperature rise to 1.5°C. To understand the implications of different pathways for steel sector transition, we examine two 1.5°C pathways: an immediate and a delayed transition. The 1.5°C results discussed in Chapters 3 and 4 are based on global cost-effective pathways to achieve emissions trajectories depicted in Figure 2.2.

- **Reference (Ref)**. The reference pathway assumes no new policies taken by countries after 2020. This provides a baseline against which we examine the impact of policy actions and mitigation actions.
- **An orderly 1.5°C transition (1p5)**. In the orderly 1.5°C transition pathway, global emissions start to decline immediately and countries collaboratively reach net zero CO_2 emissions by 2050. In this pathway, the estimated cumulative carbon emissions between 2020 and 2050 (i.e. the net zero year) are 470 $GtCO_2$, which is roughly consistent with carbon budget for 50% probability of limiting the global temperature rise to 1.5°C with no or low overshoot (Masson-Delmotte, 2021).
- **A delayed 1.5°C transition (1p5 delay)**. In the delayed 1.5°C transition pathway, global emissions continue to increase up to 2030 and then countries start to collaboratively reduce emissions to zero or well below zero. The orderly and delayed 1.5°C pathways are designed with the same cumulative emissions between 2020 and 2100, but the delayed transition portrays a high-overshoot 1.5°C pathway due to higher peak-temperature budget – 770 $GtCO_2$ between 2020 and 2050.

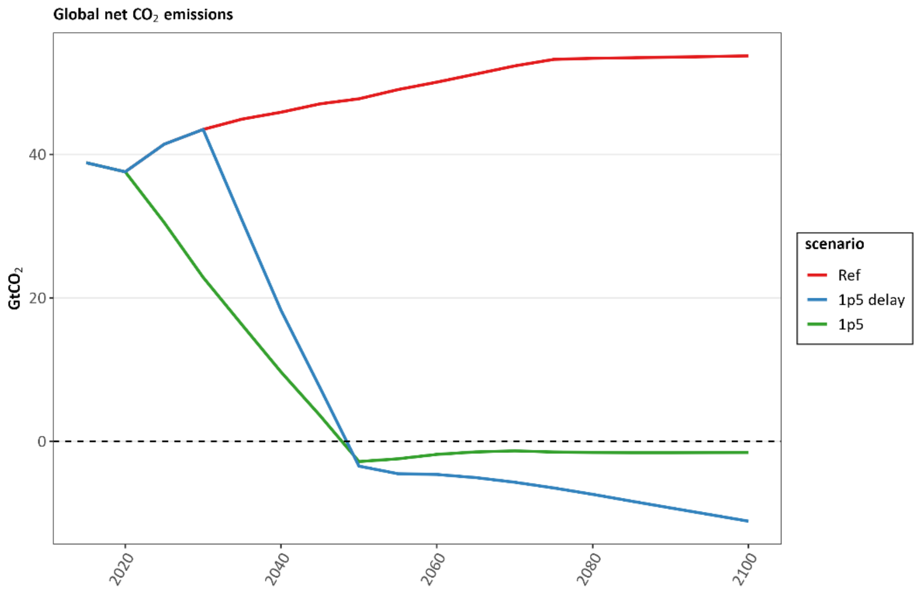


Figure 2.2 Global total net CO_2 emissions pathways under current policies, 1.5°C, and 1.5°C delayed transition pathways

Multiple measures can be taken to reduce emissions from the steel sector. We examine both demand and supply side measures and their interactions and tradeoffs in reference and 1.5°C consistent pathways. These measures demonstrate different stages of technology maturity and have different levels of mitigation potential.

- **Energy efficiency**. Energy efficiency improvement, although not able to fully decarbonize the steel sector, can reduce steel sector emissions at relatively low cost. The International Energy Agency (IEA) estimates that upgrading to best available technologies on average could improve energy efficiency of steel producing technologies by 20% (Oki & Salamanca, 2021).
- **Material efficiency**. Material efficiency measures can reduce demand for steel while providing the same material services, contributing to emissions reductions. These can include demand side measures, such as extending building lifetimes and lightweighting vehicles, as well as supply side measures, such as improving manufacturing yields. We consider eight different measures to improve material efficiency (see Box 3.1) and assess the impact of material efficiency improvement on steel decarbonization globally and in key regions.
- **Recycling**. Large emissions reductions can be achieved by improving material recycling and scrap use in steel production. EAF-scrap, coupled with power sector decarbonization, has significant potential to reduce emissions at competitive cost but is currently limited by the availability and quality of scrap. The opportunity could grow in the coming decades as the amount of available scrap increases and with developments in scrap sorting and decontamination.
- **Hydrogen**. Hydrogen, considered as one of the key strategies to decarbonize steel, can be used in two ways: as an auxiliary reducing agent in the BF-BOF route or as the sole reducing agent in the EAF-DRI route. As GCAM is an integrated assessment model, we consider the production and distribution of hydrogen and the use of hydrogen in other sectors (e.g. chemicals and

freight transportation), and assess how these factors affect the use of hydrogen in the steel sector.

- **Carbon capture, utilization, and storage**. CCUS could play an important role in decarbonizing steel, especially in regions with large, young BF-BOF facilities. Capture technologies can be applied at a steel plant or in the production of fuel consumed by a steel plant, e.g. hydrogen, electricity, and refined liquids. GCAM considers both sectoral-specific carbon capture technologies and regional-specific transportation and storage capabilities. Different types of utilization and reservoir are considered, including enhanced oil recovery, coal, oil, and gas basins, and deep saline formations (Li et al., 2009). The potential deployment of CCUS in steel hinges on capture costs as well as the availability and costs of CO_2 pipelines and storage sites.

Energy efficiency, material efficiency, improved recycling and scrap use, hydrogen, and CCUS are all needed to achieve deep emissions reductions in the steel sector. The availability of zero-carbon electricity will be a key factor across a number of these levers (recycling, hydrogen, and CCUS). In addition, technology costs, fuel prices, availability of resources, raw materials and key infrastructure, existing facilities and steel production capacities, and regional-specific policies will affect technology portfolios and fuel transition and shape the steel sector transition in a 1.5°C future.

To examine the impact of specific measures in reducing steel sector emissions and explore different transition pathways, we develop a total of 15 scenarios for the steel sector that consider the interactions between the above mitigation strategies and emission pathways (see Appendix 2). For most of this report, we focus on the orderly 1.5°C scenario with advanced deployment of all five mitigation strategies listed above, which depicts an immediate transition to net-zero emissions with proactive implementation of readily available mitigation measures and rapid development and deployment of innovative technologies.

Chapter 3. Global 1.5°C Steel Transition Pathways

The steel sector faces several critical challenges in deep decarbonization. The capital-intensity of the sector, the fact that low carbon steel making technologies are still in the process of reaching maturity, and the trade-exposed nature of global steel value chains, all contribute to the image of steel as a "hard-to-abate" sector (Davis et al., 2018). However, recent years have seen a proliferation of studies pointing to the feasibility of the steel sector transition.[8] Moreover, a set of increasingly ambitious steel decarbonization pathways from global and regional studies have started to flesh out possible decarbonization trajectories for the sector.[9]

Our report builds on these studies to set out a detailed examination of 1.5°C compatible steel decarbonization pathways and their implications for key steel producing regions (See Appendix 3 for a comparison of our study to IEA pathways). This chapter sets out the findings from our orderly 1.5°C scenario for the steel sector at the global level using our reference scenario as a benchmark and our delayed 1.5°C transition scenario for comparison. We first outline the overall emissions trajectory, then our projections for steel demand and production and the impact of material efficiency, before diving into the contribution of each mitigation lever, the implications for energy use and infrastructure deployment, and, finally, the risk of delayed action at the global level.

3.1 Steel sector emissions consistent with 1.5°C pathways

Shifting to a Paris-compatible 1.5°C consistent pathway, will require global steel emissions to fall by at least 50% by 2030 and by 95% by 2050, on 2020 levels. An accelerated reduction in emissions along these lines will require the transformation of production sites and supply chain infrastructure on a far greater scale than has been achieved to date. The challenge is particularly acute for existing integrated steelworks (BF-BOF) which cannot be fully decarbonized and must either be retired, retrofitted, or closed. According to the Global Steel Plant Tracker, approximately 61.3% of today's global crude steel capacity uses the BF-BOF route (Swalec & Shearer, 2021).

Hitting this pathway will require accelerated action across key steel producers. India overtakes China to become the largest steel emitter globally by 2050 (Figure 3.1). China sees significant demand reduction and a huge transition in steelmaking technology but remains a major emitter in 2050. India and China together account for 55% of the remaining 100 $MtCO_2$ emissions from the steel sector by 2050 in 1.5°C scenarios, while producing 55% of global steel. At the same, both regions see significant steel emissions reductions between 2020 to 2050, their total emissions decrease from 2400 $MtCO_2$ to 60 $MtCO_2$. Other major producers today, including Europe, Japan, South Korea, and the US, all reduce steel emissions significantly with advanced deployment of all mitigation levers, with only 1-5 $MtCO_2$ residual emissions left by 2050. Emerging economies, in particular developing countries in Asia (excluding China

[8] Material Economics: Industrial Transformation 2050; McKinsey & Company: Decarbonization challenge for steel, OECD: Low and Zero emissions in the steel and cement industries.

[9] Recently published steel sector decarbonization roadmaps include the IEA's Iron and Steel Technology Roadmap and Net-Zero by 2050; TERI: Towards a Low Carbon Steel Sector; RMI China: Pursuing Zero-Carbon Steel in China, Mission Possible Partnership: Net-Zero Steel Sector Transition Strategy, IDDRI: Global Facility Levels Net-Zero Steel Pathways.

and India), will play an increasingly important role in steel production and account for 14% of global steel emissions by 2050 in 1.5°C scenarios.

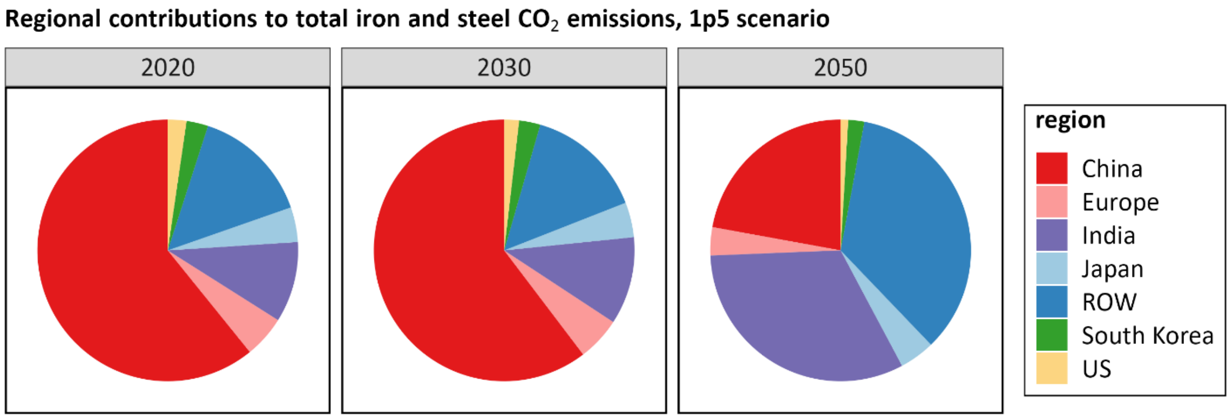


Figure 3.1 Key regions' contributions to global iron and steel CO_2 emissions in 2020, 2030, and 2050 in orderly 1.5°C pathways. Global iron and steel CO_2 emissions in 2020, 2030, and 2050 are projected at 3.4, 1.7, and 0.10 $GtCO_2$, respectively.

3.2 Future steel demand and production

Future steel production by region

Steel is a key input across a vast array of sectors, supplying components used in infrastructure, clean energy technologies, white goods, and the transport sector. There are currently few readily available alternatives to steel that can perform to a similar standard in many of its end uses, making it fundamental to modern economies. As a result, steel demand closely tracks the stage of economic development in any given country. The bulk of steel demand growth is expected to happen in emerging markets, driven by infrastructure expansion, urbanization, and increased consumer demand (World Steel Association, 2021). This demand growth is expected to continue through the mid-century and possibly longer. By contrast, steel demand in most advanced economies either reaches the saturation level or is expected to peak and decline in the near future. A key driver of steel demand in advanced economies will be the continued expansion of renewable energy infrastructure (Audenaerde, 2017; IEA, 2020).

Globally, the combination of increasing steel demand in emerging economies and relatively stable demand in advanced economies results in increasing global production through 2050. **In our reference scenario, global steel production increases by nearly 35% in the next three decades, from 1,864 Mt in 2020 (World Steel Association, 2021) to around 2,500 Mt in 2050.**

Three key trends underpin the regional dynamics in steel production (Figure 3.2). First, steel production in China peaks around 2025 and is on a declining trajectory thereafter, as China shifts towards a less resource-intensive economic growth model. Although China remains the largest steel producer by 2050, its share in global steel production declines from 54% in 2020 to 30% in 2050. Second, steel production in developed economies, such as Europe, Japan, South Korea, and the US, levels off, either stagnating or slightly declining over the coming decades. The share of steel production from these four regions combined declines from 22% in 2020 to 15% in 2050. Third, emerging economies are the main driver for the growth in steel demand and production by 2050. In particular, India's steel production increases from 117 Mt in 2020 (6% of global production) to around 570 Mt (23% of global production) in 2050. Other developing regions also see rapid growth. For example, steel production in Indonesia increases to around 60 Mt in 2050, which accounts for 2.5% of global total steel production.

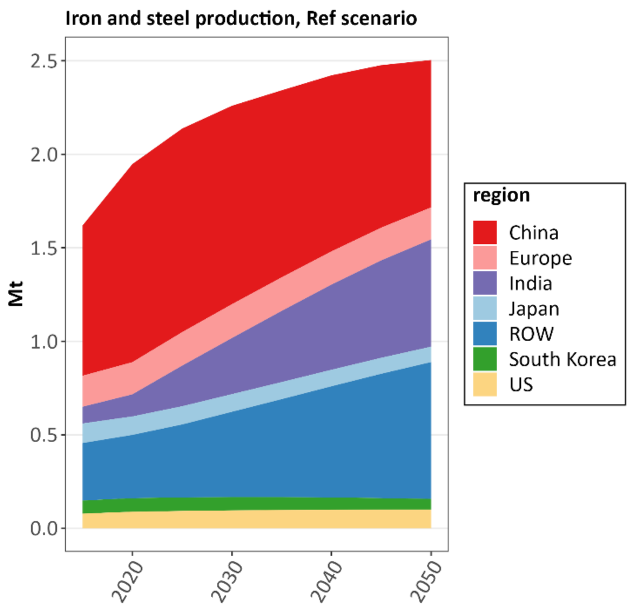


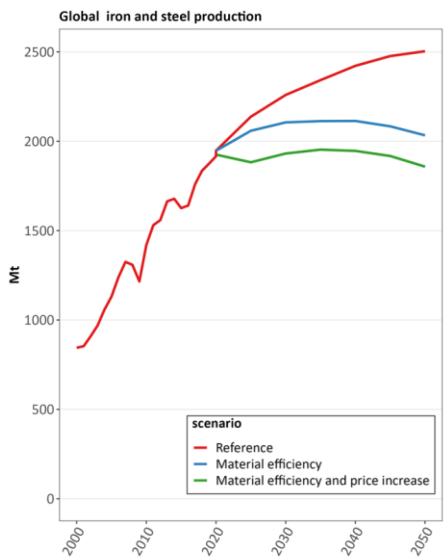
Figure 3.2 Iron and steel production in the reference scenario

Impact of material efficiency on future steel production

Ambitious material efficiency strategies can significantly reduce global steel demand and production. Steel demand can be reduced, sometimes by more than 40% in a given instance, by making changes in design, using higher-quality steel, and extending the lifetime of steel-intensive products and buildings (see Box 3.1 for material efficiency measures considered in this study). **The adoption of a suite of aggressive material efficiency measures in our orderly 1.5°C scenario reduces global steel production by 470 Mt by 2050, compared to the reference scenario (Figure 3.3a).** This contributes to 21% of the required emissions reduction by 2050, making it one of the key levers for staying within the 1.5°C threshold.

The impact differs by region. Developed economies with more infrastructure buildup and in-use stock see more impact from material efficiency improvements. Aggressive material efficiency strategies lead to 22-26% reduction in steel production relative to the reference scenario by 2050 in Europe, Japan, South Korea, and the US, compared to an 18-19% reduction in China and India. However, given the volume of future steel production and consumption expected in India, China, and Africa, deploying the full potential of demand-side approaches in key growth markets, will be essential if the sector is to reach net-zero emissions. Action on material efficiency, however, depends on the cooperation and motivation of a set of actors that goes far beyond the steel supply chain, encompassing architects, auto-makers, engineers, and consumers.

Panel a. Global iron and steel production



Panel b. Contribution of material efficiency measures to total global reduction

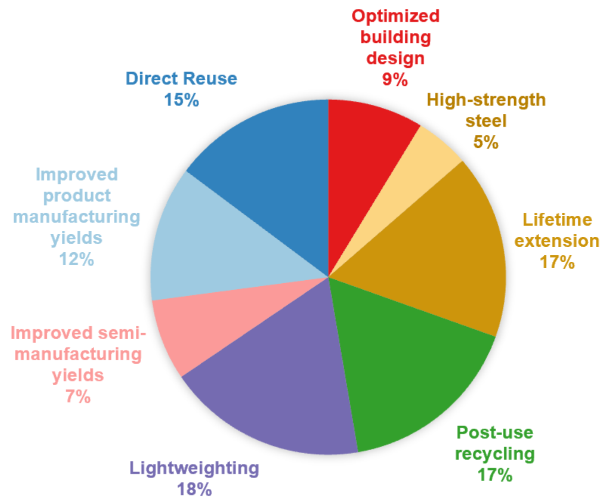


Figure 3.3 Global iron and steel production and the impact of material efficiency.

In addition to material efficiency, steel demand and production are affected by price. In 1.5°C scenarios, the global average steel price increases by 17% by 2050 compared to the steel price in the reference scenario. Price increases derive from increasing carbon prices (from approximately \$100/tCO_2 in 2025 to \$1300/tCO_2 in 2050) and the use of more expensive fuels and technologies in steel production. Increased steel prices bring down global steel production further, to 1860 Mt by 2050, a 25% reduction compared to the reference scenario.

Box 3.1 Impact of material efficiency on steel production

We consider eight different material efficiency measures in this study The contributions of these measures are calculated based on IEA assumptions and data on existing steel stocks (Pales, Teter, Abergel, & Vass, 2019; Pauliuk, Wang, & Müller, 2013). Implementing all these measures can reduce global steel production by 470 Mt by 2050. Out of these measures, lightweighting, post-use recycling, and lifetime extension, have the most significant impacts (Figure 3.3b).

- Building lifetime extension
- Optimized building design
- Post-use recycling in buildings
- Use of high-strength steel
- Lightweighting vehicles
- Improved semi-manufacturing yields
- Improved product manufacturing yields
- Direct reuse

3.3 Contributions across mitigation levers

Shifting to a 1.5°C compatible pathway, with net-zero emissions by 2050, will require going further and moving faster on all available mitigation levers. Our orderly 1.5°C scenario sees around 95% of emissions reduction by 2050, with 100 $MtCO_2$ remaining emissions, via a combination of existing and emerging technologies and solutions. As noted above, a more circular economy with increased material efficiency and improved recycling can significantly lower steel emissions, but this will not be sufficient. Innovative near-zero emissions technologies, such as CCUS and hydrogen, will be critical to tackling the remaining emissions in the steel sector to pave the path for a 1.5°C future (Figure 3.4).

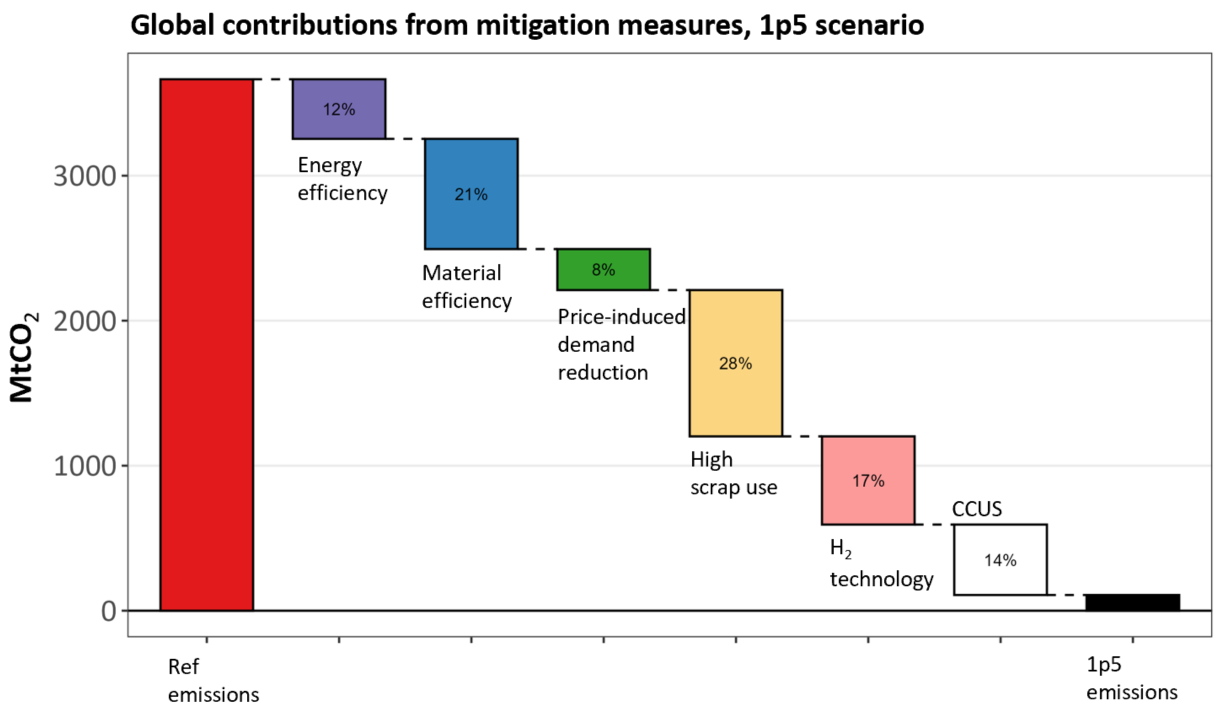


Figure 3.4 Contribution of different mitigation strategies to global steel emissions reduction in 2050

Improving energy efficiency, material efficiency, and scrap use can reduce steel emissions by 61% by 2050 in 1.5°C consistent pathways. By 2050, the predominant production method is EAF with scrap, producing about 47% of steel from nearly 1000 Mt of scrap metal (Figure 3.5). This represents a sizeable shift in the ratio of primary to secondary steel production from roughly 70:30% in 2020 to 50:50% in 2050.

The share of EAF-scrap in steel production differs by region, depending on existing infrastructure and availability of scrap. Regions like the US can reach up to 72%, whereas India has 36% of steel produced by EAF-scrap in 2050 (Figure 3.6).

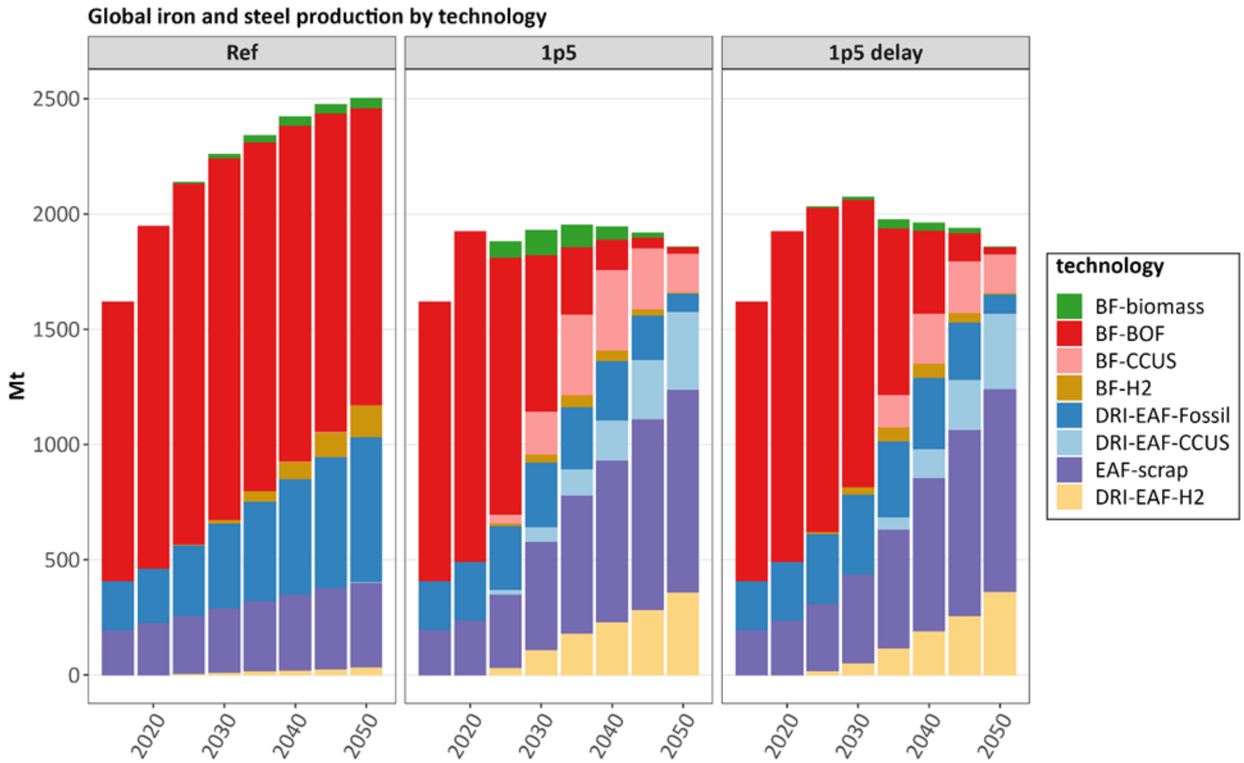


Figure 3.5 Global steel production technologies in reference, orderly 1.5°C, and delayed 1.5°C scenarios

Breakthrough technologies are essential to fully decarbonize the steel sector. In orderly 1.5°C scenarios, nearly all unabated blast furnaces (blast furnaces without CCUS), which account for 61.3% of steel production today, are phased out around 2045. For regions with large stocks of newer blast furnaces, CCUS will be critical to preventing early retirement of these facilities (Swalec & Shearer, 2021). Blast furnaces will need to be retrofitted or equipped with CCUS as early as 2025 to avoid early retirement (Figure 3.6). The share of blast furnaces, with and without CCUS, declines over time, as other low-carbon steel production technologies come in at competitive costs. Steel produced from hydrogen-based DRI starts to be commercially available around 2025 and gradually grows to 19% of global production by 2050. EAF-DRI-CCUS also increases, accounting for 18% of global production by 2050.

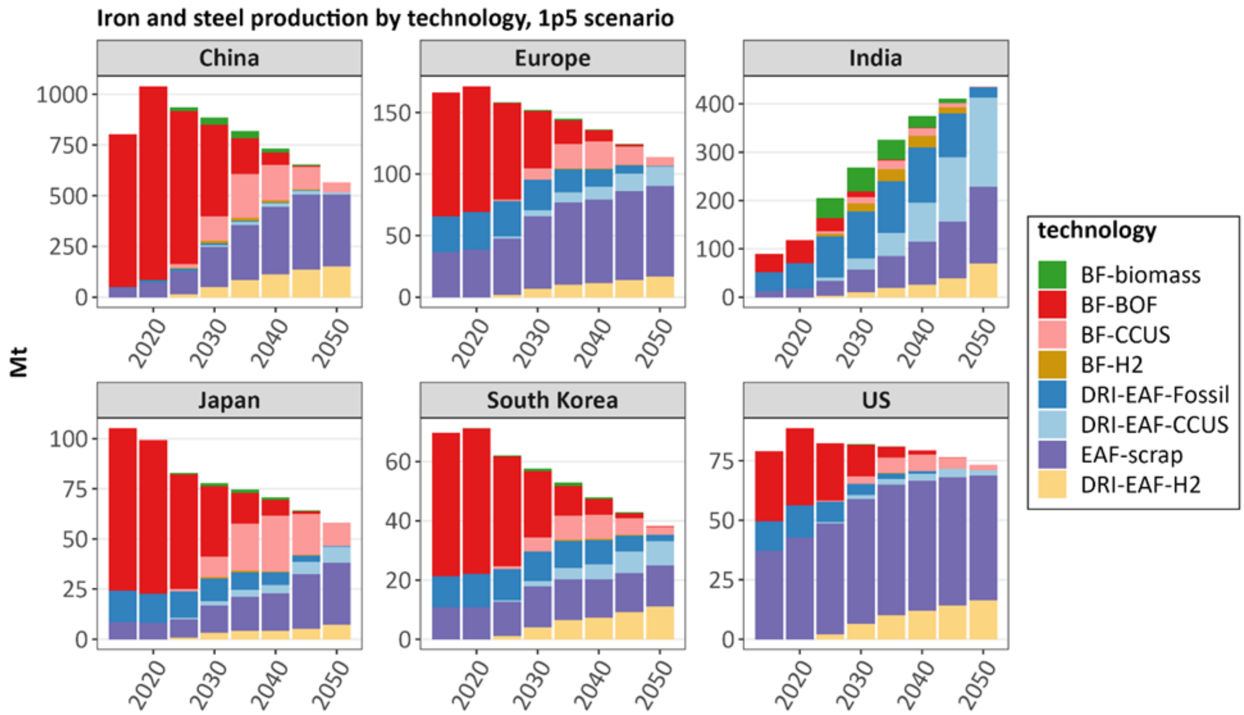


Figure 3.6 Steel production technology transitions in an orderly 1.5°C pathway

Box 3.2 Role of CCUS in Steel Decarbonization

CCUS is still at the demonstration stage today and requires significant efforts globally on deployment, business model development, and the roll-out of transport and storage infrastructure. As of September 2021, there are just four iron and steel CCUS demonstration projects globally with relatively low capture rates (Global CCS Institute, 2021). Moreover, among steel companies currently pursuing low-carbon steel projects, none are considering commercial-scale projects using post-combustion CCS with blast furnaces. While CCUS remains an important mitigation lever and plays a significant role in this study, in practice there is slow progress in deploying CCUS in steel facilities.

Given the uncertainties associated with CCUS deployment in the iron and steel sector, we conduct sensitivity runs that exclude CCUS as an option to decarbonize the steel sector. In this case, although global emissions still reach zero around 2050 to achieve the 1.5°C target, there are trade-offs within the steel sector and between steel and other sectors. Steeper emissions reductions and earlier blast furnace retirement would be required if assumptions about the contribution from CCUS prove to be optimistic.

Specifically, without CCUS in the steel sector, there would be:

- More scrap (47% of global steel production with CCUS vs. 57% without CCUS) and hydrogen (19% of global steel production with CCUS vs. 31% without CCUS) use by 2050, which also implies scrap imports for countries like India;

- More expensive steel in near-to-medium term for regions that have a large amount of existing steel facilities (e.g. 5-20% higher steel prices in China and 5-15% higher steel prices in Europe during 2030-2040 without CCUS than with CCUS);
- Higher steel sector emissions in near-to-medium term (15-25% higher global steel CO_2 emissions during 2035-2045 without CCUS than with CCUS) that need to be offset by the power and other sectors.

The retirement of unabated coal and increased use of electricity and hydrogen are necessary to make drastic emissions reductions in the iron and steel industry. In the 1.5°C orderly scenario, the share of electricity and hydrogen in the steel sector increases rapidly, accounting for 65% of fuel consumption globally by 2050 (Figure 3.7). Global electricity use in the iron and steel industry increases from about 1300 TWh in 2019 to 1900 TWh in 2050. Hydrogen use in the steel industry also sees considerable growth, reaching 4.5 EJ in 2050. In most regions, unabated coal is phased out by 2050. Fuel switching varies across regions, depending on resource and technology availability. For example, gas with CCUS is projected to account for about 20% of energy consumption in steel production in Europe in 2050, compared to less than 1% in India (Figure 3.8).

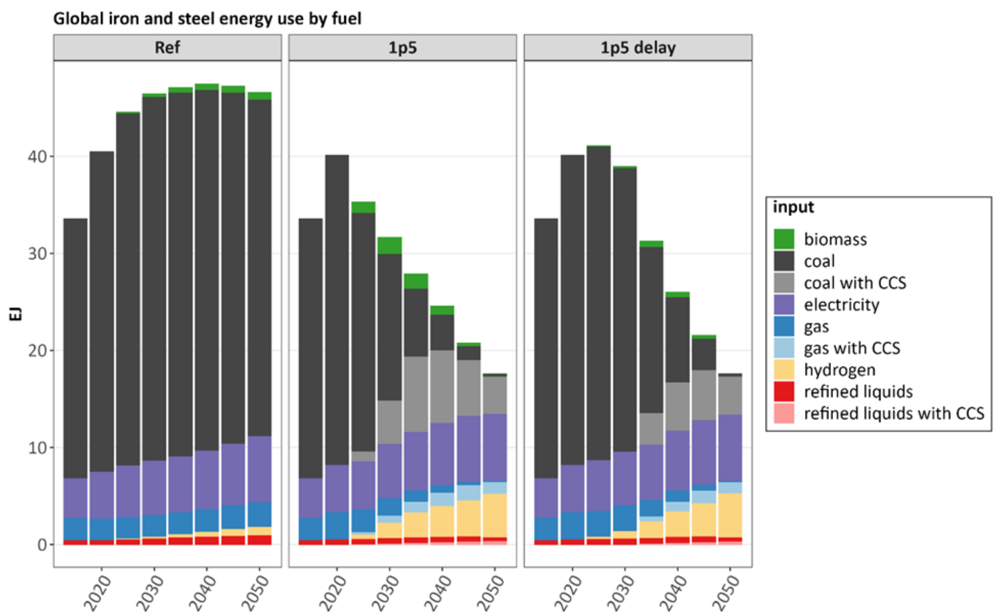


Figure 3.7 Global steel sector fuel use in reference, orderly 1.5°C, and delayed 1.5°C scenarios

Given the large increase in hydrogen and electricity, it is crucial for their upstream production to become cleaner than it is today. Indirect emissions from the iron and steel industry are shown in Box 3.3. Currently, about 35% of electricity is generated from low-carbon technologies; in the 1.5°C scenario, nearly 100% of electricity generation by 2045 is carbon free[10]. Over 80% of hydrogen is currently

[10] Electricity generated from solar, wind, hydro, geothermal, biomass, nuclear, and fossil fuels with CCUS is considered carbon free or clean in this study.

produced with unabated fossil fuels. By 2050, almost 99% of hydrogen production is powered by renewables or uses carbon capture technology (Box 3.3).

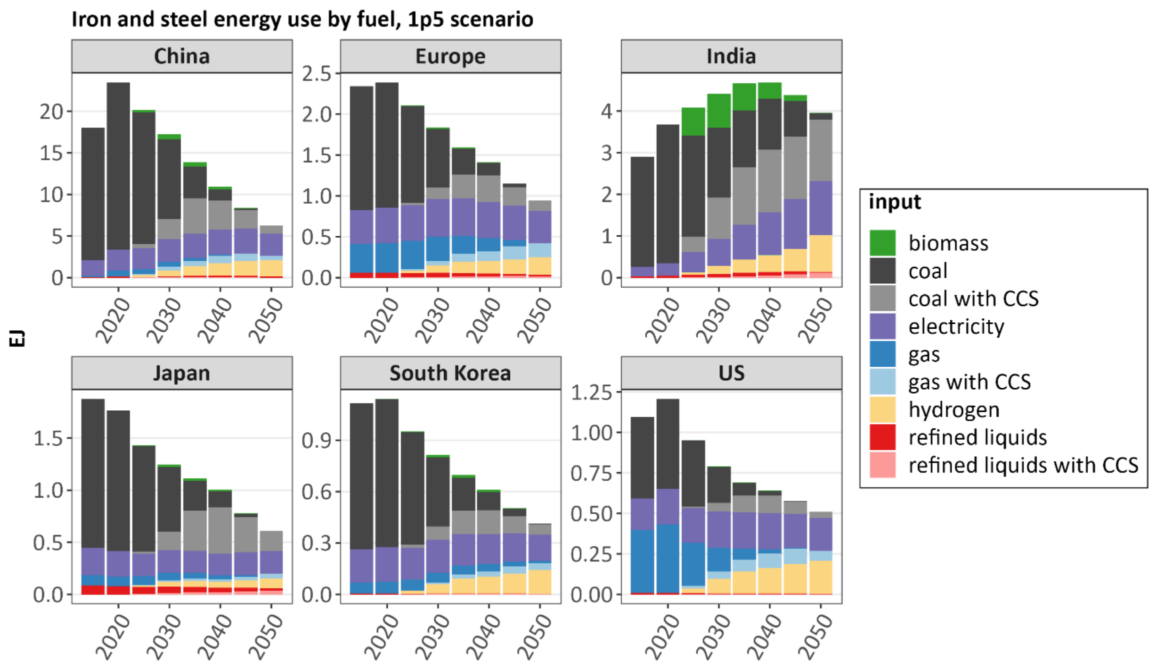
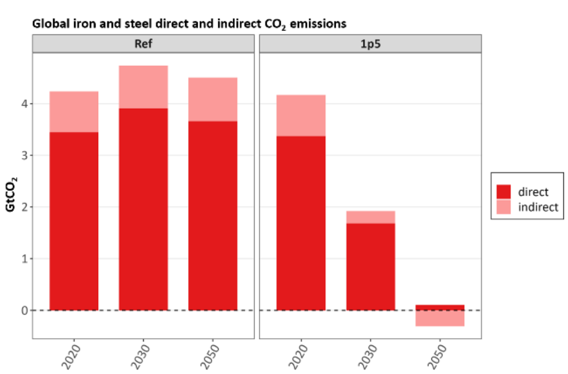
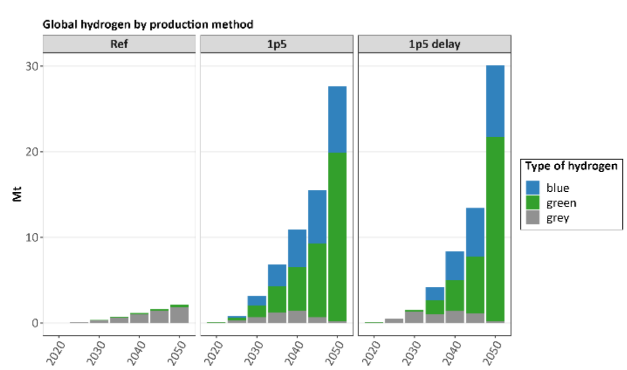


Figure 3.8 Fuel switching in key regions in an orderly 1.5°C pathway

Box 3.3 Technology transition in upstream sectors

To achieve the 1.5°C target, the entire economy needs to be decarbonized by 2050, which requires that both the steel sector and its upstream sectors reach near-zero emissions. Indirect iron and steel emissions from electricity and hydrogen remain at about 0.80 $GtCO_2$ per year through 2050 in the reference scenario. With changes in upstream hydrogen and electricity production in the 1.5°C orderly scenario, indirect iron and steel emissions from these two sectors become negative by 2050, with changes in electricity generation and hydrogen production technologies. With increasing deployment of renewables, nuclear, and bioenergy with CCUS, net CO_2 emissions from





the electricity sector become negative by 2045. Global hydrogen production increases to nearly 30 EJ, about 71% production is green and 28% is blue[11].

3.4 Implications of delayed actions

Delayed actions result in an additional 20 $GtCO_2$ being emitted from the steel industry by 2050. The difference accounts for about 5% of the remaining global carbon budget with 67% probability of maintaining the global temperature rise to 1.5°C. Across all sectors, delayed actions result in an additional 300 $GtCO_2$ being emitted by 2050, making the peak temperature higher than 1.5°C.

The large difference between cumulative CO_2 emissions with delayed actions can be attributed to slower coal retirement in the near-to-medium term. In the steel industry, 48% of energy is sourced from unabated coal in the 1.5°C orderly scenario, compared to 75% in the 1.5°C delayed scenario in 2030. By 2040, unabated coal still provides over 34% of energy used in the iron and steel industry in the delayed action scenario, compared to about 15% in the orderly scenario.

To meet net zero targets, blast furnaces will need to be almost entirely phased out by 2050. With an average lifetime of 25 years, this would suggest that any blast furnaces built after 2025 risk becoming stranded assets. Based on this assumption, delayed action could result in approximately 560 Mt of stranded blast furnace capacity by 2050, compared to only 200 Mt in the orderly scenario.

[11]Hydrogen production technologies considered in this study include natural gas steam reforming with and without CCS, biomass gasification with and without CCS, thermal splitting from nuclear, electrolysis from both grid connected electricity generation and onsite renewable generation, and coal-based hydrogen with and without CCUS (only in selected regions). Biomass, thermal splitting, and electrolysis production are considered green and production from fossil fuels with CCUS is classified as blue.

Chapter 4. 1.5°C Transition Pathways for Key Regions

This chapter explores the implications of a 1.5°C compatible steel decarbonization pathway for the six largest steel producing countries and regions: China, Europe, India, Japan, South Korea, and the US, which together account for 77% of global steelmaking capacity (see Table 4.1) and will play a key role in determining the future direction of the global steel sector (see Appendix 4 for emissions pathways and contributions of mitigation levers in these six regions). We unpack their respective decarbonization pathways, country-specific challenges, and policies and immediate actions they can take to transition their steel sectors to a 1.5°C pathway.

Table 4.1 1.5°C Scenario emissions reductions and contributions from mitigation measures by region in 2050

	Current Production Capacity				Steel Emissions ($MtCO_2$)		Contribution by mitigation lever in orderly 1.5°C scenario ($MtCO_2$)					
Region	Crude steel production (tt pa)	BF-BOF (%)	EAF (%)	Mixed/ unknown (%)	2050 Reference	2050 1p5 scenario	Energy efficiency	Material efficiency	Price-induced demand reduction	High scrap use	H2	CCUS
China	1,023,671	77	4	19	1500	23	-150 (-10%)	-230 (-16%)	-150 (-10%)	-570 (-39%)	-270 (-18%)	-100 (-7%)
Europe	171,747	69	29	2	170	4	-24 (-14%)	-51 (-30%)	-14 (-8%)	-42 (-25%)	-19 (-11%)	-21 (-13%)
India	90,125	63	24	13	1100	33	-97 (-8.8%)	-280 (-25%)	-91 (-8%)	-240 (-22%)	-200 (-17%)	-200 (-18%)
Japan	117,083	73	15	12	120	5	-14 (-12%)	-24 (-21%)	-10 (-9%)	-34 (-30%)	-10 (-9%)	-21 (-19%)
South Korea	70,260	25	37	38	71	2	-9.6 (-13%)	-19 (-27%)	-9.0 (-12%)	-9.0 (-10%)	-16.3 (-24%)	-8.8 (-13%)
United States	84,151	42	58	0	82	1	-16 (-20%)	-26 (-32%)	-5.9 (-7%)	-4.9 (-6%)	-19 (-24%)	-9.1 (-11%)

Note: Production capacity and shares from Global Steel Plant Tracker, Global Energy Monitor, February 2021.

4.1 China: Cornerstone of global steel decarbonization

As the world's largest producer and consumer of steel, China is absolutely central to the decarbonization trajectory of the steel sector globally (Ji Chen, 2021). China accounts for more than half of all steel output globally, and over 60% of global carbon emissions from steel plants (Swalec & Shearer, 2021). Since the 1990s, rapid development of the Chinese economy has led to massive increases in the country's steel production and consumption. However, there are signs that growth is beginning to slow as the central government attempts to cut production (Financial-Times, 2021).

China's steel industry is predominantly made up of large conglomerates, most of which are owned by local governments or the state. Production is heavily weighted towards coal-based BF-BOF processing which accounts for over 77% of steel output. As a result, the energy and emissions intensity of Chinese steelmaking is among the highest globally. The steel sector is responsible for more than 30% of total coal use in China and has been the main source of growth in demand for coal (Shanshan, 2021). Moreover, China's steel sector is also characterized by a fairly young fleet of blast furnaces (on average 13 years), raising the risk of stranded assets as the sector transitions (Ji Chen, 2021).

The Chinese steel sector currently emits over 2 $GtCO_2$ annually, accounting for around 17% of the country's carbon emissions (Ren et al., 2021). Swift actions will be necessary if the steel sector is to be brought in line with the country's stated target of carbon neutrality by 2060 and peak CO_2 emissions before 2030. In March 2021 a state-run news outlet reported that Beijing is developing plans for steel industry emissions to peak within four years. Major steel producers, Baowu Steel and HBIS, have put forward plans to achieve carbon neutrality in 2050, aiming to peak emissions in 2023/2022 and to reduce emissions by 30% and 10% in 2025, respectively.

However, these plans stand in contrast to recent political dynamics surrounding steel production restrictions. Local authorities in major steel hubs reversed restrictions on steel production in early 2020 to help bolster the economy in its COVID-19 recovery. Steel production in 2020 was 40% higher than projected in the previous five-year plan in 2016 (Myllyvirta, 2021).

To stay on track with the 1.5°C target, China's steel sector emissions need to be reduced by 50% by 2030 and 99% by 2050, compared to today's levels. This requires a major reduction in emissions intensity, from today's levels of 2.15 tons CO_2/ton of steel produced (Hasanbeigi, Arens, Cardenas, Price, & Triolo, 2016) to 1.1 tCO_2/t in 2030 and 0.04 tCO_2/t in 2050 - spelling deep structural changes for the Chinese steel supply chain and more broadly the national economic development model.

Demand-side levers, in particular, steel recycling, play a major role in China's steel transition. In 2050 56% of China's steel production capacity is covered by EAF-scrap production, reducing emissions by 39% relative to the reference scenario . Increasing the share of scrap-based EAF production is also a stated government aim with the Ministry of Industry and Information Technology calling for a shift away from BF-BOF steelmaking. This, however, stands in stark contrast with current and planned steelmaking capacity. BF-BOF makes up 93% of steelmaking capacity under construction in China, compared to just 7% for EAF steelmaking (Swalec & Shearer, 2021).

Material efficiency and price-induced steel demand reduction reinforce the shift to EAF-scrap, further bringing down China's steel demand. Material efficiency improvements alone bring production levels down 19% compared to the reference scenario, to 650 Mt/yr in 2050. Steel prices rise in the 1.5°C scenario, further bringing demand down, to 560 Mt/yr.

Capturing the full potential of these demand-side levers will require concerted policy efforts to curb primary steel production, incentivize recycling, improve collection and sorting of steel scrap, and extend the lifetime of steel-intensive assets. Steel production curbs, while critical, could prove challenging to implement, given the key role steel output has traditionally played in China's economic growth, including in the COVID-19 recovery (Lo, 2021).

In addition to reductions in primary steel production, China's 1.5°C steel decarbonization trajectory sees a major shift in primary steelmaking technologies. In our 1.5°C orderly scenario, blast furnaces produce approximately 10% of China's steel by 2050, compared to almost 80% today. These remaining blast furnaces are equipped with carbon sequestration technologies in 2050. To stay on track, in the near term, blast furnaces with CCUS, hydrogen, and biomass are used as bridge technologies, since they have the potential to be implemented at existing blast furnace facilities. In the longer term, blast furnace production is replaced by EAF-scrap and hydrogen-based DRI, which account for 62% and 27% of production in 2050, respectively.

Due in part to the abandonment of conventional blast furnace technology, unabated coal is phased out of the Chinese steel sector by 2050 in the 1.5°C scenario. **However, early action on coal in steel will be key. In 2030, only 9.5 EJ of unabated coal remains in use in the orderly scenario while 21 EJ remains in the delayed scenario.** The transition to increased production via hydrogen-based DRI technology leads to increased hydrogen use in the long-term. Currently, no hydrogen is used in China's steel industry; in the 1.5°C scenario, hydrogen contributes 2 EJ to the industry by 2050. To achieve the necessary level of emissions reductions, it is crucial that hydrogen and electricity come from low-carbon sources. In our 1.5°C orderly scenario, 38% and 45% of hydrogen production in China is green and blue, respectively in 2030. In 2050, 72% of hydrogen is green, and 27% is blue. The amount of electricity used in the industry increases in the 1.5°C scenario; from 710 TWh in 2020 to 750 TWh. Electricity generation is 73% clean in 2030 and entirely clean by 2050 in the 1.5°C scenario. Net CO_2 emissions from the electricity sector are projected to become negative by 2040.

Accelerated steel decarbonization in China is key to keeping 1.5°C alive. Without changes to the Chinese iron and steel industry, its cumulative emissions from 2020 to 2050 are projected at 59 $GtCO_2$. The measures described above have the potential to bring cumulative CO_2 emissions from the sector down to 23 $GtCO_2$, while delayed measures could bring emissions to 31 $GtCO_2$.

Key priorities for steel transition in China could include:

- Setting an ambitious decarbonization target for the steel sector, as part of the sectoral plans in the forthcoming"1+N" carbon peaking action plan.
- Ramping up the identification and closure of excess steelmaking capacity, retrofitting the remaining BF-BOF capacity and restricting steel capacity expansions to "net zero ready" technologies, such as EAF with scrap and DRI.
- Setting public procurement standards for use of lower carbon steel in public projects, tightening carbon-intensity requirements over time as clean steel technologies mature.
- Building on China's existing track record on circular economy, to scale up scrap sorting and recycling and maximize material efficiency potential in the steel sector.
- Accelerating the inclusion of steel and cement in the emissions trading system (ETS) to incentivize investments in cleaner production and safeguard these sectors against carbon tariffs introduced by trading partners, e.g. the EU's proposed carbon border adjustment mechanism.

4.2 Europe: A potential steel decarbonization policy front-runner

The steel sector is often described as the backbone of the European economy, indirectly employing more than 2 million people, and supplying key industries, automakers, construction and machinery (Bekaert, Van Hoey, Hagenbruch, & Zeumer, 2021). However, European steelmakers have faced considerable challenges since the global financial crisis 2008-09: a structural decline in demand (World

Steel Association, 2018),[12] increased international competition, volatile raw material prices and structural overcapacity (Bekaert et al., 2021).

In addition to these challenges, the European steel sector is about to enter an era of deeper structural change. The European Union (EU) has set the ambition for Europe to become the first climate-neutral continent by 2050 and in December 2020, the European Council voted to increase the EU's climate goal for 2030 to a 55% reduction of greenhouse gas (GHG) emissions on 1990 levels.[13] This will require a step-change in emissions reductions across the European economy, including from the steel sector, which currently accounts for roughly 5% of EU emissions (188 $MtCO_2$ in 2017).

Moreover, the EU only has a narrow policy window in which to act. In comparison to more newly industrializing countries such as India, the EU has an older steel fleet, with 48% of capacity requiring major reinvestments in the coming decade (Witecka et al., 2021). The key challenge here is in aligning policy and investment cycles. Policymakers need to send the right policy signals now to give plant owners the confidence to invest in low-carbon processes rather than lock in 20-25 more years of carbon-intensive production or see these sites shut down.

To bring the EU steel sector in line with a transition to climate-neutrality in 2050, its emissions have to fall by at least 48% by 2030 and by 97% by 2050, on 2020 levels. Emissions intensity in the steel industry needs to be reduced from 1.0 tCO_2/t of steel produced, to 0.60 tCO_2/t in 2030 and 0.030 tCO_2/t in 2050.

There are a set of currently underexploited demand-side levers that could reduce how much primary steel is required in the first place in Europe. **Shifts in design, efficient use of steel, direct reuse of steel and new business models could reduce steel demand by 25% by 2050.** In the 1.5°C scenario, material efficiency improvements bring production levels down to 123 Mt in 2050, a reduction of 28% on today's levels. Material efficiency measures have their own challenges – not least the need to coordinate a large number of players along supply chains. However, many of them are already deployable today, ensuring that demand can be contained to buy time for growth of hydrogen-based steel production in Europe in the meantime. With its Circular Economy Action Plan the EU already has a strong track record on circular economy and waste management it could build on to capture the full potential of these demand-side levers (European-Commission, 2020).

The EU steel sector will also need to see a large-scale shift in production capacity. BF-BOF is currently still the dominant production route for steel in Europe accounting for roughly 69% of steelmaking capacity, with EAFs with scrap accounting for 29% (Swalec & Shearer, 2021). **In our 1.5°C orderly steel**

[12] European steel demand still has not recovered from the global financial crisis of 2008 and was driven down further due to the pandemic (Worldsteel, 2021). Continued low steel demand is projected as a result of reduced demand for cars in Europe, decline in automotive exports, shift to localized corporate investment by importing countries in the engineering sector, reduced oil and gas development, and reduction in construction investments in the medium term (Espel, 2021).

[13] In our study Europe includes the UK (i.e. EU28). However, an in-depth analysis of UK specific steel policies went beyond the scope of this section. We, therefore, focus on EU policy efforts, also on the basis that these will continue to impact UK steel decarbonisation efforts. The UK government is expected to release a net-zero roadmap ahead of COP26, which could include key efforts directed at the steel sector specifically.

scenario, the share of steel produced via EAF with more than doubles compared to today, with EAF scrap producing 64% of steel in 2050.

Hydrogen-based DRI also scales up to account for 15% of steel production in 2050. Europe is currently viewed as a front runner in developing hydrogen-based steelmaking processes. Many of the EU's largest steel producers have pledged to be carbon neutral by 2050, including ArcelorMittal, ThyssenKrupp, SSAB, and Outokumpu, with SSAB planning to offer fossil-free steel as early as 2026. Europe accounts for roughly two-thirds of clean steel projects currently included in the Green Steel Tracker (Vogl et al., 2021). The world's first hydrogen-reduced sponge iron was produced at pilot scale in Sweden at the end of June 2021 (Heynes, 2021).

EU steelmakers are expected to take a variety of pathways across EU member states. The choice of technologies is likely to reflect access to infrastructure, e.g. low-cost renewable energy and eventually renewable-based hydrogen in sufficient quantities, availability of public funding and the specific political economy of steel making in each location. For example, while our 1.5°C scenario indicates a small but nonetheless critical role for CCUS in mitigating residual emissions from DRI-EAFs and blast furnaces in Europe, the historical reticence vis-à-vis CCUS makes that a much more unlikely outcome in some parts of Europe (Germany) than others (the Netherlands and the UK).

The technology shifts described above will require a major investment in the build out of renewable energy for electricity generation and the production of green hydrogen for steelmaking. Energy use in the EU steel industry is currently made up of 65% coal, 18% electricity, and 14% fossil-gas, with smaller shares from refined liquids, biomass, and hydrogen. The share of electricity used in the steel industry will have to more than double from 18% in 2019 to 40% in 2050, though the actual use will not increase substantially beyond the 107 TWh consumed in the sector today. By 2030, 60% of electricity is clean and net CO_2 emissions from the electricity sector become negative by 2040. Hydrogen use increases steadily, from 0.08 EJ in 2030, and 0.20 EJ in 2050--22% of projected energy use in the sector. In our 1.5°C orderly scenario, 75% of hydrogen produced is green and 24% is blue in 2030.

The measures described above have the potential to reduce cumulative CO_2 emissions from EU's steel sector from 2020 to 2050 by almost two thirds. Based on our projections, cumulative emissions amount to approximately 5.7 Gt CO_2 in the reference scenario, compared to 2.2 Gt with an orderly 1.5°C transition.

Concerns about carbon leakage have so far inhibited EU leadership on steel decarbonization. Policymakers have been reluctant to impose stringent climate policies that could affect EU steelmakers' competitiveness and risk carbon leakage. Perhaps the best example of this is the EU ETS, which is often presented as the main tool to decarbonize EU industry. Industrial sectors, including steel, continue to receive most of their emissions allowances for free,[14] dampening incentives to invest in cleaner production processes. As a result, emissions from the steel sector have remained largely flat since the early 2000s, aside from a sharp drop caused by the 2008/2009 economic crisis.

[14] According to data from the European Environmental Agency (EEA), industrial sectors covered by the EU ETS allowances for free to cover 99.67% of their verified emissions during the period 2013-2020 (own calculation).

Recently, however, the political narrative has started to shift. Transitioning towards more sustainable production processes is increasingly being recognized as an enabler and even a prerequisite, for the continued competitiveness of the EU steel sector. Growing confidence in the feasibility of transitioning the steel sector has opened up the political space for more concerted policy efforts.

To that end, the European Commission released its Fit-for-55 package in mid-July 2021, including a range of measures specifically aimed at accelerating industry decarbonization: additional support for early-stage commercialization of innovative production processes via Carbon Contracts for Difference (CCFDs), a more robust anti-carbon leakage system in the form of the proposed Carbon Border Adjustment Mechanism (CBAMs) covering the steel sector among other sectors and targets to ensure green hydrogen uptake and prioritization for industry sectors (Vangenechten & Lehne, 2021).

While these are encouraging steps, these policies will need to be carefully designed to ensure they create real incentives for steel companies to make the necessary investments. There is already a widespread perception backed up by numerous studies that heavy industry sectors have had a relatively free ride so far (Schep, Jujin, & Bruyn, 2021). To ensure that CBAMs and CCFDs do not contribute to that dynamic they will need to be accompanied by more stringent requirements for the steel sector to decarbonize and the phase-out of some of the supports (e.g. free emissions allowances) they benefit from currently.

With a large-number of multinational steel producers headquartered in Europe, recent leadership on near-zero emissions steel innovation and with a long track on ambitious climate policy, Europe is a key potential agenda-setter for the global steel market.

Key priorities for steel transition in the EU could include:

- Ensuring a fast agreement and adoption of policies under the Fit-for-55 Package, including the EU ETS and the CBAM proposal, to guarantee early and clear signals for the steel sector.
- Ramping up the expansion of renewable energy infrastructure, scaling investment and ensuring regulation supports this expansion (e.g. faster permitting for renewable energy, clear certification of renewable-based hydrogen).
- Focusing deployment of renewable-based hydrogen in sectors, including steel, where it will have the greatest mitigation potential, building on the targets for hydrogen use in industry sectors, laid out in the proposal for a revised Renewable Energy Directive.
- Introducing ambitious product requirements to enhance material efficiency, circularity and lower the carbon-content of steel under the upcoming Sustainable Products Initiative (expected early 2021) and the Energy Performance in Buildings Directive.
- Pursuing opportunities for coordination on steel decarbonization with trade partners to seek complementary approaches to carbon tariffs, product standards, subsidies and public procurement, e.g. with the US via the EU-US Trade and Technology Council.

4.3 India: The major growth market for net-zero steel production

India is the world's second largest producer of crude steel. With the country's rapid urbanization and infrastructure needs, this consumption is set to increase from 94 Mt in 2020 to 489 Mt in 2050 (Henbest, 2021). The Government's 2017 National Steel Policy aims to increase steel production to 300 Mt by 2030-31, more than twice its current production capacity (PWC, 2015). The Energy and Resources Institute (TERI) expects emissions from the sector could triple from 242 Mt in 2020 to 837 $MtCO_2$ by 2050 in their baseline scenario (Hall, Spencer and Kumar, 2020). The key challenge for India will be to reconcile sector's expansion with long-term emissions reduction targets.

The Indian government has not yet set a specific target for reducing emissions from the steel sector and there has been little debate about the role of heavy industry in meeting the country's climate targets (Del Bello, 2020). However, two of India's steel companies have reportedly adopted internal carbon pricing with others likely to follow suit (Sharma, Pujari, & Agha, 2021). While Tata Steel Europe has committed to be carbon-neutral by 2050, Tata Steel Ltd., which accounts for roughly 22% of India's crude steel production, has yet to commit to a long-term target. JSW Steel (~20% India's steelmaking capacity) has set an emissions intensity reduction target for 2030, representing a 40% cut in emissions on 2005 levels (Layek, 2021).

To achieve the 1.5°C target, India's steel sector emissions need to be fall by 46% by 2030 and 90% by 2050. This signifies an emissions intensity decrease from 2.8 tCO_2/t steel today to 0.68 tCO_2/t steel in 2030 and to 0.076 tCO_2/t steel in 2050.

A large part of this decrease stems from a shift away from carbon-intensive BF-BOF production routes towards cleaner processes: EAF with DRI, hydrogen-based DRI and EAF with scrap. The majority of India's steel (55%) is currently produced in EAFs and induction furnaces with 45% from BF-BOF production (Sharma et al., 2021). EAF with DRI CCUS and EAF with scrap need to become the dominant technologies in India in 2050, producing 42% and 36% of steel, respectively. Small scale CCUS projects are ongoing in India although the technology is still at an early stage of development. The Indian Government also introduced a Steel Scrap Recycling Policy in 2019 which has led to improvements in processing and recycling scrap. Both of these technology pathways would need to be strengthened by concerted policy efforts on the part of the Indian Government.

Hydrogen-based steelmaking is expected to play a large role in reducing the sector's emissions, particularly as many Indian steelmakers currently use DRI technology powered by coal rather than natural gas (Alfonso, 2021). This puts the sector in a good position to clean up a large part of its steelmaking capacity more easily by shifting to renewables-based hydrogen for these facilities (Swalec & Shearer, 2021). Hydrogen-based DRI is projected to contribute to 16% of steel production in 2050.

This shift in technology, and in particular the increase in renewables-based hydrogen demand, will require major infrastructure investments to ensure sufficient amounts of clean electricity. The introduction of hydrogen-based DRI production would bring hydrogen use to 0.035 EJ in 2030 and 0.87 EJ in 2050. In our 1.5°C orderly scenario, by 2050, 27% of hydrogen produced in India is blue and 72% is green. Electricity demand in the steel sector is projected to grow considerably, from 83 TWh to 360 TWh in 2050. In the 1.5°C scenario, India's electricity production is increasingly clean: in 2030, 85% of electricity production is clean, and unabated fossil fuels are entirely phased out by 2050. Net CO_2 emissions from the electricity sector become negative in 2040.

The Indian Government has laid out plans to expand renewable energy and hydrogen capacity to reap the benefits of its considerable renewable energy potential. It has set an ambitious renewable capacity target of 175 GW by 2022 and 450 GW by 2030. A National Hydrogen Energy Mission was announced in February 2021, with the aim of scaling green hydrogen production and utilization across sectors, with a target of ~1 million tons annual green hydrogen production by 2030 (Infrahub, 2021).

Shifting the Indian steel sector onto a 1.5°C pathway, would also signify a major reduction in unabated coal use. Some coal use remains in the Indian steel sector: 1.7 EJ unabated coal and 0.99 EJ TWh coal with carbon sequestration by 2030 and 0.16 EJ unabated coal and 1.5 EJ of coal with carbon sequestration by 2050. India is currently very dependent on imports for its metallurgical coal use: 85% of demand is met through imports (Business-Standard, 2021). A shift to non-coal-based steelmaking would greatly improve the resilience and economic security of the domestic steel sector, making it less vulnerable to international commodity price spikes.

While the future of India's steel market is largely characterized by an expansion in production, material efficiency also has an important role to play. **We estimate that material efficiency strategies could reduce demand by 18% in 2050, compared to the reference scenario.** Material efficiency improvements result in production levels nearing 470 Mt in India in 2050. With an estimated 36% increase in steel costs, from a combination of carbon pricing, investments in cleaner, more expensive technologies and fuels, production falls to 440 Mt.

As the major steel growth market, with strong experience in DRI production and vast domestic renewable potential, India is uniquely positioned to drive a clean steel production expansion, helping to strengthen India's global competitiveness and bolster its energy security.

Key priorities for steel transition in India could include:

- Developing an ambitious climate-aligned roadmap for the steel industry to reconcile the near-term capacity expansion with long-term emissions reduction objectives.
- Ensuring that new steel plants built under the planned capacity expansion are "net zero ready," i.e. investing in EAFs and DRI capacity that can more easily be shifted to cleaner energy feedstocks rather than locking in further BF-BOF capacity.
- Building on the ambitious renewable energy targets set, developing a robust assessment of the infrastructure expansion required to shift from coal-based DRI production to hydrogen-based DRI.

4.4 Japan: From declining demand and structural overcapacity to green steel innovator

Japan is the world's third largest steel producer and a major steel exporter. Japan's steelmakers have faced a turbulent period owing to import tariffs imposed by the US and China and the impact of the COVID-19 pandemic on trade. Domestic demand has been on a downwards trajectory since the 1990s, driven by population decline and increased competition from South Korea and China.

Japan's steel industry accounts for 14% of the country's total CO_2 emissions (Eguchi, 2021). The country's steelmakers are under pressure to set ambitious emissions targets in line with Japan's pledge to become carbon neutral by 2050. Nippon Steel and Kobe Steel have published plans to reduce their CO_2 emissions, pledging to reach carbon neutrality by 2050 with an emphasis on hydrogen-based steelmaking and EAF-scrap (Swalec & Shearer, 2021). In 2021, Nippon Steel unveiled plans to replace part of its BF capacity with a new EAF which will be powered by carbon-free electricity (Suda, 2021). Nippon has also joined with Kobe Steel and JFE to establish the COURSE 50 project which aims to demonstrate CCUS technologies in steelmaking (Course50).

To achieve the 1.5°C target, Japan's steel sector emissions need to be fall by 50% by 2030 and 97% by 2050. This would require an emissions-intensity reduction from 1.5 tCO_2/t steel to 0.94 tCO_2/t steel in 2030 to 0.078 t CO_2/t steel in 2050.

A substantial share of this emissions reduction can be attributed to an overall reduction in steel production and the discontinuation of conventional blast furnaces. **The adoption of a suite of material efficiency approaches reduces Japan's steel production by 21% in 2050 (down to 65 Mt), accounting for 14% of cumulative emissions reduction in 2050**. In our orderly 1.5°C scenario, average steel costs also rise by 67%, bringing demand down even further, to 58 Mt.

This also chimes with recent moves by steel makers to tackle excess capacity by shutting down blast furnaces instead of reinvesting in these sites. Nippon Steel released plans to shut down two blast furnaces, one at its Wakayama Works site in 2021 and one at its Kashima Works site in 2024 (Nippon, 2021). These plans were announced as part of a package of wider structural reforms to shift from existing BF-BOF capacity to cleaner processes and large EAFs. While these are steps in the right direction, the scale of steel overcapacity in Japan and the need to transition the sector in line with a 1.5°C compatible pathway, mean that far more concerted efforts to downsize and restructure the sector will be required both from the government and major steel producers.

Emissions reductions in the 1.5°C scenario are also driven by a shift from conventional blast furnaces to EAF with DRI technologies. In the near term (from 2025 already), bridging technologies are introduced: blast furnaces retrofitted with carbon capture technology, with hydrogen and biomass introduced as interim feedstocks and with EAF-DRIs fitted with carbon capture technology. In the long-term, EAF with DRI and blast furnace facilities are replaced with facilities fit for hydrogen-based DRI and EAF with scrap production. Today, Japan's steel fleet is comprised of 73% BF-BOF and 15% EAF production (Swalec & Shearer, 2021). In 2050, hydrogen-based DRI accounts for about 12% and EAF with scrap accounts for 53% of steel production.

Over the next decade, the Japanese government plans to allocate as much as ¥193.5 billion from its ¥2 trillion Green Fund to support the development of hydrogen-based steelmaking (Suga, 2021). The government is also said to be considering introducing a carbon pricing system to lower emissions from energy-intensive industries.

The iron and steel industry in Japan currently uses about 1.4 EJ of unabated coal. In the 1.5°C scenario, all of this coal is phased out by 2050. The major difference between orderly and disorderly technology transitions in our scenarios is the speed with which existing coal-based blast furnaces are retrofitted with carbon capture technologies. In 2030, blast furnaces with CCUS produce 10% of steel in the orderly scenario; in the same period in the disorderly scenario, blast furnaces with CCUS produce less than 1% of steel.

One of the primary challenges for CCUS deployment in the steel sector in Japan is the current focus on CCUS as a key lever for power sector decarbonization. The Ministry of Economy, Trade and Industry has published projections for 2050 envisioning large parts of the power sector still relying on thermal coal power equipped with CCUS. However, Japan has limited domestic geological storage capacity, meaning that storage will be finite and expensive. It will, therefore, be particularly important to reserve CCUS use for those applications where it could have the most potential, including for certain steel production sites with fewer options to shift to cleaner production processes. Another limiting factor will be the fact that CCUS demonstration is still in an early stage with just a handful of projects in the country.

In addition to CCUS, there is also a considerable increase in hydrogen use in the 1.5°C scenario, reaching 0.089 EJ in 2050. In the 1.5°C scenario, 37% of hydrogen produced in Japan in 2030 is blue and 40% is green. In 2050, 31% is blue and 68% is green. In line with this renewable-based hydrogen expansion and the shift to more EAF with scrap production, Japan's power sector will also need to rapidly decarbonize. Electricity use in the sector sees a slight decrease from about 68 TWh today to 60 TWh in 2050, at which point, unabated fossil fuels are phased out of electricity generation. Net emissions from the electricity sector become negative in 2045.

The 1.5°C transitions described above have the potential to reduce Japan's steel sector's cumulative CO_2 emission over the period between 2020 and 2050 from the 4.1 Gt projected in the reference scenario to around 1.7 Gt with an orderly 1.5°C transition.

As a major player in the global steel market, both as a crude steel exporter and an exporter of steel-intensive manufactured goods, Japan has a critical role to play in the global transition to a 1.5°C compatible net-zero steel sector.

Key priorities for steel transition in Japan could include:

- Developing a 1.5°C aligned net-zero roadmap for the steel sector, with intermediate targets for 2030, including a robust plan for identifying and closing excess steelmaking capacity, public financing to support steelmakers as they shift to low-carbon processes and sunset clauses for carbon-intensive steelmaking technologies.
- Mapping out power sector and CCUS infrastructure needs for steel sector decarbonization and integrating steel within plans to establish a hydrogen economy, including provisions to ensure hydrogen is deployed where it will have the greatest mitigation potential, including in the steel sector.

- Introducing ambitious green steel public and private procurement goals and supporting international initiatives such as the Clean Energy Ministerial Industrial Deep Decarbonization Initiative to drive demand for green steel internationally.
- As a long-time technological frontrunner, coordinating efforts to pool and scale up investments in research, development and deployment internationally, pursuing partnerships with developing countries, especially in Southeast Asia and India (with growing footprints of Japanese steel production and supply chain networks).

4.5 South Korea: A green new deal for steel

Steel is a mainstay of South Korea's economy and played a critical role in the country's growth trajectory. With major steel consuming sectors, auto and ship building, South Korea's economy is particularly steel-intensive. In recent years, however, steel demand has slowed, with sharp drops and slow recoveries in the wake of the 2008 financial crisis and the economic fallout from the COVID-19 outbreak contributing to overcapacity.

As the largest industrial emitter in South Korea, steel is directly responsible for 13% of national GHG emissions. Over 90% of these emissions are concentrated in just two companies, POSCO and Hyundai Steel. POSCO has a net-zero by 2050 commitment in place alongside a plan to transition its nine blast furnaces and plans to invest between 100-200 billion won in meeting tighter environmental rules which included efforts to increase the use of scrap steel (Chung, 2019).

The steel sector launched a Green Steel Committee in early 2021, committing to a target of net zero by 2050. These long-term commitments have yet to be followed up by near-term strategies. In contrast to Europe, for example, where green steel is expected to be commercially available by 2025, the green steel pilots in South Korea's pipeline are only due to come online by 2030 at the earliest.

The government has set strong climate targets with specific provisions for industrial sectors. President Moon Jae-in's 'green new deal' agenda established a national target to reach net-zero emissions by 2050 and will include funding for green hydrogen production (Gabbatiss, 2020). Since 2015, South Korea's emissions trading scheme has regulated emissions from the country's industries although large numbers of emissions allowances are handed out for free, reducing the incentive to cut emissions. Climate Transparency reports that South Korea has no specific policies that require new industrial installations to be low-carbon (Climate-Transparency, 2018) although the Government has recently threatened to levy a carbon tax on heavy emitters (EconoTimes, 2021).

To achieve the 1.5°C target, Korea's steel sector emissions need to fall by 51% by 2030 and 98% by 2050, on 2020 levels, implying an emissions intensity reduction from 1.3 tCO_2/t steel to 0.77 tCO_2/t steel in 2030 and 0.05 t CO_2/t steel in 2050. This is broadly in line with the government's own 2050 carbon neutrality scenario for the steel sector, which sees the steel emissions reduced by 95% by 2050, on 2018 levels.[15]

[15] Under the government's scenario, steel emissions reduce by 95% from 101.2 MtCO_2eq in 2018 to 4.6 MtCO_2eq in 2050.

The government foresees this coming about via a whole-sale shift to hydrogen-based steel production and the conversion of all blast furnaces to EAFs by 2050. Our order 1.5°C scenarios indicates exactly that shift: **To make the drastic reductions in steel emissions intensity necessary to meet 1.5°C targets, blast furnaces are phased out and replaced by EAF with scrap and hydrogen-based DRI production**. By 2050, in the 1.5°C scenario 37% of steel is produced by EAF with scrap.

Our 1.5°C scenario also foresees material efficiency strategies reducing steel demand by 22%, bringing production levels down to 44 Mt in 2050. Steel prices increase by about 90% by 2050, which brings demand down even further, to 38 Mt.

Coal contributes about 85% of the energy used in South Korea's steel sector today. **In the 1.5°C scenario, this share drops to 40% in 2030. Coal is completely phased out of steel production in South Korea by 2050.** The amount of electricity used in the steel industry drops by 21% over the 2020-2050 period. At present renewables make up a very small share of South Korea's electricity system. Our 1.5°C scenario relies on a large scale up of renewables capacity: 56% of electricity production in 2030 is clean. In 2050, 100% of electricity production is clean. The 1.5°C scenario also shows an increase in hydrogen use, from 0.0 EJ in use today to 0.14 EJ in 2050. In the 1.5°C scenario, 76% of hydrogen produced in South Korea is green and 23% is blue by 2050.

South Korea could limit cumulative CO_2 emissions from the steel industry over the 2020-2050 period to just 1.1 Gt in an orderly 1.5°C scenario. Without changes in the steel sector and upstream energy production, cumulative emissions are projected to reach about 2.6 Gt.

As the world's sixth largest steelmaker with ambitious climate commitments and policies at government and company level, South Korea is well positioned to help accelerate the global steel sector transition.

Key priorities for steel transition in South Korea could include:

- An immediate task will be to convert the ambitious long-term pledges and goals for the steel sector into immediate (pre-2030) policy and investment decisions.
- Unlocking the potential for a large expansion of EAF-scrap capacity to replace current blast furnaces by introducing targeted regulation to improve incentives for scrap retrieval, sorting and decontamination.
- As a major steel consuming economy, introducing green steel private procurement requirements for the auto-sector and appliance industry to drive demand for cleaner solutions.
- Introducing policies to ensure no new investment in coal-based steelmaking facilities.

4.6 US: A green steel comeback

The US is the fifth largest steel producer globally. After two decades of declining production, the US steel industry has experienced a recent resurgence as the trade tariffs introduced by the Trump administration raised the price of imported steels (Ferry, 2020). Steel demand decreased by 18% in 2020 due to the pandemic. However, the Biden administration recently announced plans for infrastructure investment over a multi-year period, which could drive up steel demand in the short run.

US steelmaking is dominated by EAF production using steel scrap. There are 99 EAF plants, owned by 51 companies, and nine integrated BF-BOF steel mills controlled by just three companies mainly located on the East Coast (Hasanbeigi & Springer, 2019). This high share of EAF scrap-based production, means that the US has one of the lowest energy- and carbon-intensities per ton of steel produced globally.

While the US leads on steel recycling globally, concrete private sector and government initiatives to accelerate steel decarbonization in the near-term have been lacking. The Biden Administration has pledged to halve economy-wide greenhouse gas emissions by 2030 (relative to 2005 levels) with the aim of reaching net-zero emissions by 2050. Biden is working with Democrats in Congress to pass a climate-focused spending bill that could include millions in grants to help steel, cement, and other manufacturers adopt product declarations on the embodied carbon emissions of materials (Yarmuth, 2021). However, the legislative text does not yet include procurement standards for infrastructure investments, only assistance for companies to carry out the product declarations and reduce embodied emissions in construction materials. In the US, concerted decarbonization policies and sectoral targets for industrial decarbonization have yet to be introduced.

In the meantime, US steel majors have started to make moves into cleaner steel production. U.S. Steel Corporation, which operates the largest integrated BF-BOF steel mill in the country, set a goal of achieving net-zero carbon emissions by 2050 and plans to use a higher share of EAF production to cut emissions in the short-term. Cleveland-Cliffs Inc. announced earlier this year that it would target a 25% reduction in greenhouse gas emissions by 2030 and is developing a carbon capture project at its Burns Harbor site (Buxbaum, 2021). It also recently acquired one of the largest processors and distributors of steel scrap in the US to bolster its scrap supply for its growing fleet of EAFs (Surran, 2021). In early October 2020, Nucor Corp. announced the launch of a line of net-zero carbon steel products and an offtake agreement with General Motors to start purchasing these products in 2022 (Downey, 2021). In contrast to a number of European-headquartered companies, however, none of the four major US steel producers currently have a plan to actually produce near-zero emissions steel before 2030. Nucor's net-zero steel will be recycled steel with offsets to negate the carbon used in the process.

To achieve the 1.5°C target, US steel sector emissions need to fall by at least 50% by 2030 and 99% by 2050, on 2020 levels. Emissions intensity of steel production in the US would need to drop from 0.84 tCO_2/t steel to 0.35 tCO_2/t steel in 2030 to 0.013 tCO_2/t steel in 2050.

A portion of the necessary emissions reduction can be made through reduced production levels. In our 1.5°C scenario, **material efficiency strategies reduce steel demand by 24%, accounting for a 32% reduction in cumulative emissions in 2050**. Material efficiency improvements bring production levels down to 78 Mt in 2050. Average steel price also increases by 15% by 2050, bringing demand down even further, to 73 Mt.

More than 50% of the emissions reduction in the 1.5°C scenario is driven by the phase out of carbon-intensive plants, including EAF with natural gas-based DRI and the nine current blast furnaces, and their replacement by cleaner technologies. Today, EAF with scrap, blast furnaces and EAF DRI account for 48%, 38% and 14% of steelmaking respectively. In the 1.5°C scenario, EAF scrap production grows to account for 72% and hydrogen-based DRI accounts for 22% of US steel production in 2050.

The continued increase in EAF scrap capacity is broadly in line with sector actions to date and builds on an existing comparative advantage of US steelmakers in producing good quality secondary steel. However, the shift to hydrogen-based steelmaking would require much more targeted investment in hydrogen demonstration projects than has been seen to date. So far there is just one hydrogen-steelmaking pilot in the US compared to 31 projects in the EU (Vogl et al., 2021). The US has, however, seen concerted public investment in iron ore electrolysis via the Boston Metal project, which could prove to be a promising mitigation lever (Boston-Metal, 2021).

This shift in steelmaking processes and technologies requires a major shift in energy feedstocks for the US steel sector, requiring a considerable built out of renewable energy capacity both for cleaner electricity to power EAFs and for the scale up of renewables-based hydrogen. **Unabated coal and gas are phased out by 2040 in the 1.5°C orderly scenario and by 2045 in the 1.5°C disorderly scenario.** Hydrogen and electricity become the predominant fuel sources, each supplying 40% of energy, respectively. Hydrogen use increases from the 0.00 EJ in use today to 0.20 EJ by 2050. In the 1.5°C scenario, about 78% of hydrogen produced in the US by 2050 is green. Total annual electricity use in the industry remains at about 0.20 EJ from 2020 through 2050. The share of clean electricity production increases from 64% in 2030 to 100% in 2050.

Changes within the steel industry combined with cleaner energy production in upstream sectors could reduce the US's cumulative steel CO_2 emissions over the 2020-2050 period from 2.5 Gt projected in the reference scenario to 0.77 Gt in an orderly 1.5°C scenario.

As a major climate player international and a frontrunner on steel recycling, the US can pave the way for more concerted international cooperation on the transition to net-zero steel. However, there is a diminishing window in which the US can up domestic ambition on industry decarbonization to ensure more active international engagement.

Key priorities for steel transition in the US could include:

- Developing a 1.5°C aligned net-zero roadmap for the steel sector, with intermediate targets for 2030.
- Introducing domestic targets for industrial decarbonization and a comprehensive policy framework to create an enabling environment that promotes business models for decarbonized steelmaking, including ambitious standards and public procurement requirements for "low carbon" and "net-zero steel" to drive demand and phase out remaining blast furnaces.
- As a key donor internationally, enabling transition finance for steel decarbonization in emerging and developing economies via multilateral development banks.
- Expanding technology and policy partnerships on near-zero emissions steel with developing countries via the B3W partnership (White House, 2021).

Chapter 5. Conclusions and Key Takeaways

An accelerated decarbonization trajectory for the global steel sector is key to keeping a 1.5°C pathway within reach. Global steel sector emissions will have to fall by at least 50% by 2030, and by 95% by 2050, on 2020 levels. Energy efficiency improvements, material efficiency measures, high scrap use, adoption of hydrogen-based production, cleaner upstream energy production, and deployment of CCUS technologies must occur in tandem to make these emissions reductions possible.

Despite growing momentum and encouraging commitments from the private sector, steel sector emissions continue to grow in line with robust and increasing global demand for steel. Far greater ambition in policymaking, technology deployment, and circular economy approaches will be needed to shift the sector to a 1.5°C compatible pathway. This will require urgent and concerted efforts from a wide set of stakeholders.

While the time frame considered in this report spans a 29-year period to 2050, we only have a very narrow window in which to act. Steelmakers across the key regions we studied face pivotal investment decisions in the next decade. In Europe, South Korea, Japan and the US, steelmakers need to decide what to do with aging fleets and how to minimize employment and other social impacts from those decisions.

Early action is also critically important in China and India. Given the scale of production in these two countries, delayed action in those two countries alone could result in over 14 Gt of additional cumulative CO_2 emitted from all sectors between 2020 and 2050--about 3% of the remaining global carbon budget to keep warming below 1.5°C with a 67% probability. China faces the challenge of a large and comparatively young existing emissions-intensive steel base and will need to explore options for retrofitting and early retirement. India is on the precipice of a major growth in steelmaking capacity where the crux will be to ensure that new plants are “net-zero-ready”, in other words able to accommodate clean technology retrofits once these are available.

Moreover, these requirements stand in stark contrast to the current planned steel investment pipeline. Three-quarters of steel capacity currently under construction is based on the most polluting BF-BOF route (Swalec & Shearer, 2021). Given the long lifetime of these plants (roughly 20-25 or more years depending on the location), any additional blast furnaces built after 2025 represent an important lock-in in emissions that is not in line with staying within the 1.5°C threshold.

The groundwork for the long-term emissions reductions set out in this report, therefore, needs to be established now. Next month’s 26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26) presents a pivotal moment in which to make these actions a reality. At COP26, the UK Presidency will be launching a new sectoral collaboration program, including for steel, bringing together countries to commit to ambitious coordinated action.

Below we share some key insights from this study that can create the conditions for accelerated steel decarbonization. While many of these will be appropriate across geographies, different national circumstances (age of current steel fleet, infrastructure requirements, and resource availability) will affect the relative importance, sequencing, and specific nature of necessary interventions.

5.1 Planning and governance for reaching net-zero steel

Targets and sectoral roadmaps play a key role in providing a clear policy signal on the expected pace and direction of transition in a given setting. As highlighted in the regional deep dives in Chapter 4, few national governments currently have ambitious targets for the steel sector specifically. Our study provides a first indication of what an 'ambitious target', or at least a target sufficient for staying within the 1.5°C threshold, would need to look like for the six largest steel producing regions. On the private sector side there has been a proliferation of company net-zero pledges. For the most part, however, these have yet to be followed up with sufficiently detailed plans on how companies expect to deliver them (Gardiner & Lazuen, 2021). This creates an opportunity to engage a wide array of actors, governments, private sector, academia, and civil society, in a process to establish an ambitious, shared vision for the future direction of the steel sector.

- **Set ambitious decarbonization targets for steel.** A key step towards meeting the decarbonization trajectories set out in this report, will be developing ambitious national sectoral roadmaps for reaching net-zero steel by 2050 at the latest. This requires active participation of a group of stakeholders, including governments, steel producers and consumers, labor representatives, civil society, and academia. Roadmaps are more effective if they include explicit near-term decarbonization targets for 2030 that can be incorporated into Nationally Determined Contributions in line with national climate goals. A key priority for steel producers will be to commit to net-zero by 2050 or earlier if they have not already done so, develop a detailed transition plan including near term targets for 2030 and have these scrutinized by an independent body.
- **Develop Just Transition plans for key steel producing regions.** As part of the process of establishing a national or sectoral steel roadmap, it will be important for governments to also develop a dedicated plan for how to manage employment and social impacts from steel sector transition, including provisions for re-training workers.
- **Identify and invest in priority infrastructure.** Our study highlights the importance of investing in new infrastructure (renewables-based electricity generation, electrolyzers to produce hydrogen from renewable sources, CO_2 transport and storage infrastructure, and steel scrap reverse logistics) to support the deployment of near-zero emissions steel technologies and to improve material efficiency in the sector. A robust understanding of infrastructure needs, coordinated research, development, and deployment plans, and near-term investment strategies are all needed to facilitate the investment in new, clean energy infrastructure.

5.2 Supporting the shift from carbon-intensive to near-zero emissions steel technologies

As highlighted above, an immediate challenge over the next decade is to create market signals that help shift investment from the current carbon-intensive steel production assets to clean, near-zero steel production.

Many of the technology options for decarbonizing steel discussed in this report are currently significantly more expensive than conventional production processes. Even in jurisdictions with higher carbon prices, e.g. the EU Emissions Trading Systems, breakeven carbon prices are much higher than what is currently considered likely (Sartor & Lehne, 2020). Investments in first commercial production sites using cleaner steel production technologies are also characterized by high levels of risk. The costs of these technologies will come down as they are scaled up but in the interim some form of direct support in the form of subsidies or CO_2 price risk mitigation instrument will be required to cover higher operating and capital costs, to ensure that near-zero emissions steel technologies can compete with incumbent carbon-intensive technologies.

- **Support near-zero steel demonstration projects.** A critical element of accelerating near-zero steel demonstration projects is to create enabling environment that promotes business models for decarbonized steelmaking. The exact means of this support will differ in different national contexts. In Europe, policymakers are exploring offering direct support, e.g. carbon contracts for difference (CCFDs), to cover higher operational expenditure for breakthrough clean production technologies. In other geographies, public financing for demonstration projects may come in the form of governments underlining transformational finance alongside the private sector.
- **Expand R&D capacity in the sector**. Industry stakeholders, governments, and research funds could work together to ensure further research support for near-zero emissions steel technologies that are still at earlier stages of development, e.g. iron ore electrolysis.
- **Accelerate the shift away from carbon-intensive technologies through policies.** The construction of new unabated blast furnaces (without CCUS), with lifetimes of roughly 20-25 years, poses a key risk to keeping a 1.5°C pathway in reach. One way to manage this risk would be to introduce sunset clauses to restrict steel capacity expansions to "net zero ready" technologies, e.g. DRI-EAFs which can more easily be converted to renewables-based hydrogen once it is available or converted into scrap-EAF sites. Other options include encouraging the switch to cleaner feedstocks and setting targets on % of near-zero emissions steel produced or sold.

5.3 Growing the market for near-zero emissions steel

Alongside direct support for the required technology and infrastructure, governments and steel consumers have a critical role to play in building demand for near-zero emissions steel. Mainstreaming cleaner steel procurement would transform the business case for steel producers – reassuring companies that they will be able to find a market for their often more expensive, lower carbon steel and thereby recover the costs of required investments. Studies have indicated that using more expensive green steel only marginally increases the cost of a final product for end-consumers, with intermediate producers able to pass through increased costs.[16]

The last year has seen encouraging progress on this front. Large steel consumers from the automotive, construction and renewable energy sectors have started signaling their demand for green steel. Early movers have been spurred on by consumer and investor pressure and the promise of new possibilities for value creation (Delasalle et al., 2021). More than ten companies have signed up to the Climate Group's voluntary SteelZero initiative pledging to secure 100% net-zero steel by 2050 at the latest. Despite growing momentum, these efforts still only represent a relatively small share of the overall steel market. Scaling up procurement commitments is needed to ensure that near-zero emissions steel goes from a niche, premium product to a mainstream commodity.

Moreover, there is still a lot of work to be done in defining what qualifies as "low carbon", "near-zero" and "net-zero" steel. Ambitious definitions tied to transparent and trusted processes for certifying adherence to those definitions could be a powerful tool in driving steel sector decarbonization. They could also drive increased transparency in steel emissions data, which is currently often self-reported and not standardized, meaning that a lot of trust is put in the steelmakers themselves. Better transparency of steel emissions data would also support investors seeking to support steel sector decarbonization.

- **Step up near-zero emissions steel public procurement.** Governments can grow markets for near-zero emissions steel by setting ambitious public procurement commitments, e.g. committing to purchase a specific volume of "green" or "net-zero" steel and setting targets for what percentage of the market should be near-zero emissions by a given date. National and local governments and public agencies could kick this process off by mandating the measurement of embodied carbon across public projects, with a view to tightening embodied carbon specifications over time.
- **Define and implement ambitious zero emissions steel product requirements.** There are currently a number of parallel processes in place working on defining "green" and "net-zero" steel. From the perspective of facilitating global near-zero emissions steel supply chains, a harmonized, international standard would be helpful. For example, an international standards committee, such as ISO 77.140.01, could convene expert stakeholders, steel consumers, and producers to establish an industry-wide methodology for measuring carbon intensity alongside other key indicators for defining "low carbon" and "net-zero" steel.
- **Scale up commitments from major steel-consuming companies.** Growing the market for lower carbon steel will also rest on steel customers committing to 100% "near-zero" or "net-zero" emissions steel procurement by 2050 or earlier, and/or joining a buyer's club initiative such as SteelZero or the First Movers Coalition (Rathi, 2021) to collectively signal demand and where

[16] The IEA estimates that using green steel increases the cost of a mid-sized home by just 0.2% and a mid-sized car by only 0.1%. (IEA, 2020)

possible enter into direct offtake agreements with low-carbon steel producers (Delasalle et al., 2021).

5.4 Seizing the full potential of circular economy and material efficiency for decarbonizing the steel sector

While our study underlines the importance of the deployment and development of breakthrough near-zero primary steelmaking technologies, we also find a huge and currently underexploited potential for demand-side levers. The adoption of a suite of material efficiency measures alongside scaling up steel recycling accounts for 50% of steel sector mitigation in 2050 to meet a 1.5°C trajectory. These approaches are mutually reinforcing, material efficiency can help increase scrap availability for steel recycling and they could together dramatically reduce how much primary steel we need in the first place. In contrast to CCUS and hydrogen, moreover, they are readily deployable today, allowing for progress on steel sector emissions in the next decade without having to wait for breakthrough technologies to mature.

Material efficiency and increased recycling have the added benefit of also addressing wider environmental challenges. By reducing primary resource extraction (iron ore, coal, renewables infrastructure needs) and decreasing overall waste production they help mitigate biodiversity loss and pollution and take pressure off local communities and indigenous groups who can be negatively affected by primary resource extraction.

In some ways, however, seizing this potential is a more complex, far-reaching challenge than shifting the primary steelmaking production base. It requires coordinating a large number of players along steel supply chains: from the designers who need to lightweight products and design for deconstruction, to the waste management companies who need to source, sort and return scrap, to the start-ups initiating new business models to change our consumption patterns surrounding steel-intensive products such as cars. This degree of coordination and the required framework will not be easily implementable everywhere. There is also vastly different potential for these levers between economies with an established building and car stock with valuable reuse and recycling potential versus national contexts in which the extant steel stock is only just being built up.

- **Improve incentives to recover, sort and recycle scrap steel.** A number of policies can help seize the full potential of circular economy approaches for steel decarbonization These include the introduction of steel recycling targets, product requirements mandating an increasing share of recycled steel in steel-intensive products, and policies to encourage the use of steel in ways that makes it more recoverable at end of first life, e.g. circular product design. Improving collection and sorting will also be critical. An improved understanding of current recycling networks, such as current export flows and the regulations playing into these dynamics, is needed. Dedicated R&D funding to improve scrap sorting and separation techniques could also help to reduce contamination by trace metals like copper and ensure good quality secondary steel.
- **Encourage efficient and reduced primary steel use.** Changes in construction regulation and building codes are also essential to encourage the re-use and to extend the lifetime of steel-

intensive assets, e.g. cars, buildings and white goods. Currently, recycling, reuse, and deconstruction often face regulatory barriers in national building codes and regulation.

5.5 Enhanced international coordination for net-zero steel

International coordination and cooperation on research, development, and deployment for steel decarbonization would facilitate better use of resources and help prevent gaps in funding, bringing down the development costs of technologies, and ensuring their diffusion internationally. International alignment on standards for "low carbon", "near-zero" and "net-zero" steel and harmonized procedures and methodologies for reporting on the emissions-intensity of steel production would improve transparency, data collection, ensure a level playing field, and, ultimately, facilitate the greening of steel supply chains globally.

There has been a recent proliferation of platforms and initiatives providing opportunities for international cooperation on steel decarbonization. The Leadership Group for Industrial Transition (LeadIT) was launched by the governments of Sweden and India in 2019 to provide a platform for collaboration and lesson sharing for countries and companies committed to accelerating industrial decarbonization (LeadIT, 2020). The Mission Possible Partnership brings together CEOs from carbon-intensive industries, financiers and customers to agree on ambitious decarbonization roadmaps (Mission-Possible-Partnership, 2021). In June 2021, two more initiatives were launched: the G7 Industrial Decarbonization Agenda (UK-G7-Presidency, 2021) and the Industrial Deep Decarbonization Initiative (IDDI) which aims to commit 10 national governments to green public procurement policies for steel within the next three years (UNIDO, 2021).

There are, however, still important gaps that need to be filled if these initiatives are going to deliver the necessary ambition. First, with the exception of India's role in LeadIT and IDDI, the majority of the initiatives and action on industrial decarbonization at the international level has been driven by a handful of European countries, the US, and Canada. While it is important for some countries to lead, it is equally important that these efforts are inclusive. Second, the most recent initiatives in particular have yet to be fleshed out. They look good on paper but will need the backing and buy-in of major steelmaking economies to deliver action. Third, the emphasis so far has been on convening, lessons sharing, and collaboration – these are critically important, but for steel decarbonization to accelerate, we will need a high-ambition group committing to clear decarbonization targets and roadmaps.

Next month's COP26 presents a pivotal opportunity to see a high-ambition group take shape. The UK Presidency will be launching a new sectoral collaboration program, including for steel, bringing together countries to commit to ambitious coordinated action.

- **Expand existing international initiatives on steel decarbonization.** As discussed above, it is critical that the current international initiatives are inclusive, engaging major steel producing countries across geographies.
- **Enhance long-term ambition and near-term actions on steel decarbonization**. COP26 offers a chance for major steel producing countries to demonstrate real leadership on steel. To deliver a

1.5°C steel industry, both credible and ambitious long-term targets and compatible near-term actions are needed.

- **Support and expand joint R&D on zero-emissions steel at the international level**. Governments could pool and scale up investments in research, development and deployment. Mission Innovation is set to launch a new dedicated industrial decarbonization mission under the leadership of the Austrian government at COP26.

- **Enable transition finance for emerging and developing economies**. Multilateral development banks (MDBs) are starting to shift their focus to industrial decarbonization, but they require additional funding to take this forward. The World Bank's Climate Investment Fund, with participation from regional MDBs, has a new industrial decarbonization fund looking for donor replenishment. Governments and MDBs could play an important role in scaling up investment, mobilizing targeted support and technical assistance for industry decarbonization, and strengthening the Green Climate Fund to further facilitate the steel sector transition.

- **Establish a level playing field**. Several of the options discussed above (direct subsidy support for clean steel production technologies, product standards and requirements) and others being explored by key geographies (the EU's proposal for a CBAM) run into challenging trade policy territory. Discussions around trade and concerns about global overcapacity have in the past created barriers for international collaboration. A dedicated space for dialogue on these issues to develop a common approach on how to deal with carbon in traded goods, exploring coordination on CBAMs and carbon pricing, and agreements on subsidy support, could help break this impasse.

Appendix 1. Steel Production Technologies Considered in this Study

Technology	Description	Maturity	Examples	Emissions intensity	Challenges
Blast furnace/basic oxygen furnace (BF-BOF)	Metallurgical coal and iron ore are heated in a blast furnace. Coal acts both as a heat source and removes the oxygen from iron ore, leaving liquid iron, ready to be struck into steel in the basic oxygen furnace	Readily available at competitive cost	~61.3% of steel is produced via this route (Swalec & Shearer, 2021)	2.2 tCO_2/t steel (Swalec & Shearer, 2021)	Coal is difficult to replace in BF-BOF pathways as it is used for producing high temperature heat (1,100 °C in coking oven and 1,650-2,200°C in BF), as well as part of the chemical reaction to reduce iron ore (Andrea, Serdoner, & Whiriskey, 2018). This leaves few mitigation options aside from retrofitting with carbon capture technology.
Blast furnace with biomass (BF-biomass)	Uses biomass as an alternative reductant or fuel to metallurgical coal in the blast furnace	Demonstration projects; limited by biomass availability in most regions	ArcelorMittal plant in Belgium is testing substitution of coal with biocoal (Jacobs, 2021)	Reduction by 0.28 to 0.59 tCO_2/t steel with pulverized biomass injection (PBI), depending on BF technology and biomass source (Feliciano-Bruzual, 2014)	Emissions intensity and technical feasibility depend on biomass type (Feliciano-Bruzual, 2014). The highest level of substitution is only achievable with upgraded forms of biomass (IEA, 2020), but even the use of charcoal can impose technical limits on installation size. The limited availability of sustainable biomass, for which multiple sectors will compete, also reduces scalability. Sustainable biomass also has trade-offs regarding air quality, biodiversity, land use, and food security (Catuti & Elkerbout, 2020).
Blast furnace with hydrogen (BF-H2)	Uses hydrogen as an auxiliary reducing agent in the blast furnace	Demonstration projects	Thyssenkrupp has been testing hydrogen as a reducing agent in	1.73 tCO_2/t steel (-21.4%) using strictly renewable hydrogen (Yilmaz, Wendelstorf, & Turek, 2017).	While hydrogen can reduce the need for coal in both the coke plant and the BF, it can only act as an auxiliary reducing agent (Andrea et al., 2018). It

			blast furnaces since 2019 (IEA, 2020)	1.57 tCO_2/t steel (-28.8%) if the electricity used in the steelmaking process is also renewable (Fan & Friedmann, 2021)	is not technically possible to only use hydrogen, hence the use of coal cannot be fully eliminated (Nogami, Kashiwaya, & Yamada, 2012). Emissions also depend greatly on the source from which hydrogen is produced (Andrea et al., 2018)
Blast furnace with CCUS (BF-CCUS)	Captures CO_2 emissions from the blast furnace gases or from cogeneration plant gases	Demonstration projects	COURSE 50 in Japan completed BF-CCUS testing phase and plans on reaching full commercial scale by 2030 (IEA, 2020)	0.81 tCO_2/t steel (-63%) depending on BF configuration (Witecka et al., 2021)	The full extent of emissions reduction depends on the ability for large-scale permanent storage or use of captured CO_2. High capture rates still have to be proven through demonstration projects. CCUS does not completely eliminate emissions, as very high capture rates (>90%) are difficult to achieve. The application of carbon capture technologies incurs a penalty in energy efficiency that increases with capture rate. Moreover, there are multiple emission points in BF-BOF installations, increasing the technical complexity required for CO_2 capture (mostly from the blast furnace, but also from basic oxygen furnace and the coking plant (Witecka et al., 2021)
Electric arc furnace with scrap (EAF-scrap)	Steel scrap is melted in an electric arc furnace	Readily available at competitive cost	EAFs account for ~20.2% of steelmaking capacity (Swalec & Shearer, 2021)	0.3 tCO_2/t steel indirect emissions (-86%) (Swalec & Shearer, 2021)	The limited availability of scrap and necessity for primary steel in the production of high-quality steel for some applications mean that an EAF-scrap pathway cannot currently cover all steel production needs. Emissions

					intensity can also vary based on the carbon intensity of the electricity used.
Fossil-gas based direct reduced iron with electric arc furnace (DRI-EAF-Fossil)	Iron ore is reduced by carbon monoxide and H_2 in a shaft furnace heated by natural gas, then, iron is melted with scrap steel in an EAF	Readily available	Planned large-scale DRI-EAF plant at ArcelorMittal Dunkirk, initially to run on natural gas (ArcelorMittal, 2020)	0.75 tCO_2/t steel with natural gas (-66%) (Witecka et al., 2021) 1.3–1.8 tCO_2/t steel with coal (-40.9%) for the COREX/FINEX process and 3.2 t CO2/t steel (+45.5%) for the rotary kiln process (Swalec & Shearer, 2021)	Not a fully decarbonized process, risk of fossil-gas lock-in. The carbon intensity of steel production could also be affected by variations in methane emissions, which also need to be taken into account. The carbon intensity of the electricity used affects the overall emissions even more than in EAF-Scrap installations.
Electric arc furnace with direct reduced iron with CCUS (DRI-EAF-CCUS)	Captures CO_2 emissions from the shaft furnace	Available at high cost	Two DRI plants operated by Ternium in Mexico since 2008 have a capture rate of 5% of CO_2 emissions (IEA, 2020)	0.57 tCO2/t steel (-74.1%) (IEA, 2020)	The full extent of emissions reduction depends on the ability for large-scale permanent storage or use of captured CO_2. High capture rates still have to be proven through demonstration projects. Does not completely eliminate emissions, as very high capture rates (>90%) are difficult to achieve. The application of carbon capture technologies incurs a penalty in energy efficiency that raises with capture rate.
Electric arc furnace with hydrogen (DRI-EAF-H2)	Pure H_2 reduces iron ore, which is then melted with scrap steel in an EAF	Demonstration projects	HYBRIT EAF-DRI-H2 pilot plant became the first to supply fossil-free steel to a customer (Vattenfall, 2021).	0.71 t CO_2 / t steel (-67.7%) depending on source of hydrogen (Swalec & Shearer, 2021)	Emissions can vary based on the sources from which hydrogen is produced. For example, steam methane reforming (SMR) is associated with both CO_2 and CH_4 emissions. Hydrogen produced from electrolysis can achieve very low emissions, but this depends on

					type of electricity used. A carbon intensity of electricity under 200g CO_2/kWh is needed for electrolytic hydrogen to have lower emission levels than hydrogen from SMR. Moreover, EAF installations also need a source of carbon for making steel from iron ore, which can add around 53 kgCO_2/t steel (Vogl, Åhman, & Nilsson, 2018). The carbon can come from pulverized coal, captured CO_2, biomethane or other sources of biogenic carbon, each option having a different impact on overall emissions

*Note: Iron ore electrolysis is not considered in this study as it is still at an early stage of development. However, it is included in the IEA's 2020 Steel Technology Roadmap and could yet play an important role in steel sector decarbonization.

Appendix 2. Scenario Matrix

We explores 15 scenarios in this study. The three scenarios highlighted in the table below are representative reference, orderly 1.5°C, and delayed 1.5°C scenarios discussed throughout the report.

Emissions Pathways	Timing of transition	Steel Sector Mitigation Strategies				
		Energy efficiency	Material Efficiency	Recycling	Hydrogen	CCUS
Reference	**N/A**	**Ref**	**Ref**	**Ref**	**Ref**	**No**
	N/A	Adv	Ref	Ref	Ref	No
	N/A	Ref	Adv	Ref	Ref	No
	N/A	Ref	Ref	Adv	Ref	No
	N/A	Adv	Adv	Adv	Ref	No
Orderly 1.5°C Transition	Immediate	Ref	Ref	Ref	Ref	Ref
	Immediate	Adv	Ref	Ref	Ref	Ref
	Immediate	Adv	Adv	Ref	Ref	Ref
	Immediate	Adv	Adv	Adv	Ref	Ref
	Immediate	Adv	Adv	Adv	Adv	Ref
	Immediate	Adv	Adv	Adv	Ref	Adv
	Immediate	**Adv**	**Adv**	**Adv**	**Adv**	**Adv**
	Immediate	Adv	Adv	Adv	Adv	No
Delayed 1.5°C Transition	**Delayed**	**Adv**	**Adv**	**Adv**	**Adv**	**Adv**
	Delayed	Adv	Adv	Adv	Adv	No

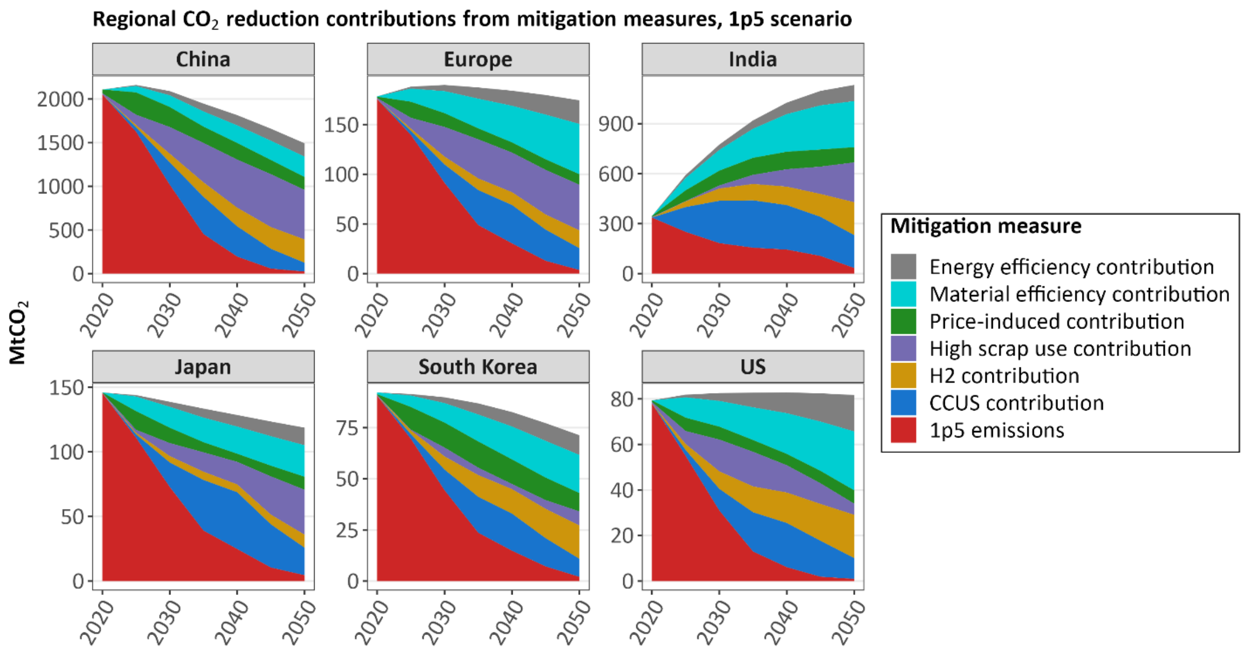
Appendix 3. Comparison to IEA Scenarios

Report source	IEA Iron and Steel Technology Roadmap – SDS	IEA Iron and Steel Technology Roadmap – Faster Innovation Case	IEA Net-zero by 2050	E3G & PNNL 1.5°C Steel
Energy system goal	2°C / net-zero 2070	1.5°C / net-zero 2050	1.5°C / net-zero 2050	1.5°C / net-zero 2050
Steel sector goal relative to 2019 CO_2 emissions	2.3 Gt CO_2 emitted in 2030 1.2 Gt CO2 emitted in 2050 0.3 Gt CO_2 emitted in 2070 54% reduction in direct, process emissions by 2050	0.3 Gt CO_2 emitted in 2050 88.5% reduction in direct, process emissions by 205018	1.8 Gt CO_2 emitted in 2030 0.2 Gt CO_2 emitted in 2050 92% reduction in direct, process emissions by 2050	1.7 Gt CO_2 emitted in 2030, 0.10 Gt CO_2 emitted in 2050, 95% reduction in direct, process emissions by 2050
Share of steel production using EAF	29% in 2019; 57% by 2050	Assumed same as SDS	24% in 2020; 37% by 2030; 53% by 2050	12% EAF with DRI, 11% using EAF with scrap in 2020; 1.3% DRI-EAF-fossil fuel, 18% EAF-DRI-EAF-CCUS, 47% EAF with scrap in 2050
Scrap as share of input	32% in 2019; 45% by 2050	Assumed same as SDS	32% in 2020; 38% by 2030; 46% by 2050	11% in 2020; 24% in 2030; 47% in 2050
Material efficiency	Responsible for 40% of cumulative emissions reductions relative to 2019 baseline by 2050	Reduces steel demand by 19% relative to 2019 by 2050	Reduces steel demand by 20% relative to 2020 by 2050	Reduces global steel demand by 19% relative to reference scenario (2500 Mt) 2050 Contributes 21% of emissions reduction relative to baseline in 2050 Responsible for 17% of cumulative emissions reductions from 2020 to 2050
Technology performance improvements (BAT and	Technology improvements (BAT and best practices) 21% of cumulative emissions reductions by 2050		While the NZE cites the importance of installing BAT and optimizing operational efficiency of equipment, they do not	20% energy efficiency improvement by 2050 for all technologies.

best practices)			provide estimated emissions savings from technology performance improvements	Contributes 12% of emissions reduction relative to baseline projection in 2050
Technologies still in development /prototype phase	Responsible for 30% of cumulative emissions reductions by 2050 Responsible for approximately 40% annual emissions savings in 2050	Introduced to market by 2026 Responsible for approximately 75% annual emissions savings in 2050	Responsible for 54% of cumulative emissions reductions by 2050	Contributes 30% of emissions reduction relative to baseline projection in 2050
Hydrogen-based DRI	Responsible for 8% of cumulative emissions reductions by 2050 15% of steelmaking capacity equipped by 2050 Introduced to market by 2030 One electrolytic hydrogen-based DRI plant built per month after market introduction	Introduced to market by 2026. Two 100% renewable hydrogen-based DRI plants built per month after market introduction	29% steelmaking capacity equipped by 2050	19% of steel production in 2050 Responsible for approximately 19% annual emissions savings in 2050 Introduced in 2025
CCUS (including blue hydrogen-DRI)	Responsible for 16% of cumulative emissions reductions by 2050 Introduced to market by 2030 One 1 Mt CO_2 captured per year CCUS project installed every 2–3 weeks after market introduction Reaches 400 Mt CO_2 captured per year by 2050	Introduced to market by 2025 Two 1 Mt CO_2 captured per year CCUS projects built every month after market introduction	53% steelmaking capacity equipped by 2050 Reaches capture total of 670 Mt CO_2 by 2050	27% steelmaking capacity equipped by 2050 Reaches capture total of 490 Mt CO_2 by 2050
Iron ore electrolysis	Not deployed	5% of steelmaking capacity equipped by 2050 Introduced to market by 2030 One plant built every two months from 2030 to 2050	13% of steelmaking capacity equipped by 2050	Not included

Appendix 4. Regional Mitigation Contributions

Chapter 4 explores the implications of a 1.5°C compatible steel decarbonization pathway for the six largest steel producing countries and regions: China, Europe, India, Japan, South Korea, and the US, and discusses the impact of different mitigation strategies on steel decarbonization in these regions. The Chart below shows emissions pathways for each of the deep dive regions and contributions of different mitigation strategies to emissions reduction in an orderly 1.5°C scenario, compared to the reference scenario. These mitigation strategies include energy efficiency improvement, material efficiency improvement, price-induced reduction in steel production, recycling and scrap use, hydrogen, and CCUS.



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